

# Global chocolate supply is limited by low pollination and high temperatures

Corresponding Author: Professor Thomas Wanger

**This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.**

**Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.**

Version 0:

Decision Letter:

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Dear Professor Wanger,

Your manuscript titled "Global chocolate supply is limited by insufficient pollination, higher temperatures and reduced rainfall" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication in its current form, but would be interested in considering a revised version that fully addresses these serious concerns.

In particular, we require that you:

- demonstrate that pollination, temperatures and rainfall limits global chocolate supply
- clarify and fully justify your statistical approach, adjusting your approaches and re-running models as necessary.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

**When resubmitting, please provide a point-by-point response to the reviewers' comments.** Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred.

**Important:** The response to reviewers must not include any figures, tables or graphs. If you wish to respond to the reviewer reports with additional data in one of these formats, please add them to the main article or Supplementary Information, and refer to them in the rebuttal. Due to current technical limitations, any figures, tables, or graphs embedded in your rebuttal will not be included in the peer review file, if published.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Alice Drinkwater, PhD  
Associate Editor  
Communications Earth & Environment  
@CommsEarth

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## REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript combines pollination data from three cocoa production countries to provide evidence that potential yield is not achieved mainly due to pollination limitation, followed by physiological and climatic factors.

The different hand pollination levels combined with the SETAR model are an excellent strategy for demonstrating the pollination deficit. The analysis of climate and tree factors provides helpful information for cocoa producers. These results alert us that this production system needs to develop strategies to mitigate the impacts of global warming and changes in precipitation patterns.

My two concerns for the paper are that: 1) it is not clear why the 0% hand pollination treatment or open pollination treatment is not the one used to present the results instead of the estimated from the model and why the differences between the estimated value and the experimental value are so big.

2) It needs to be more precise about what part of the data is already published.

Reviewer #2 (Remarks to the Author):

The study is about the impacts of pollination and some agrometeorological factors on the yield of cacao in Brazil, Ghana, and Indonesia. The paper presents new findings but somehow does not reflect what is indicated in the title. In general, to say that cacao yield is limited by "increased temperature and reduced rainfall", long-term climatic data is needed. The pollination experiment was also not explicitly described in the Methods making it difficult to provide a conclusion that cacao yield is indeed limited by pollination. Thus, in its current form, I recommend the manuscript be rejected for publication. Nevertheless, the general comments and suggestions are provided below and also on the pdf file of the manuscript to improve the paper.

## Methodology

1. It is also important to indicate here the spacing of each cacao tree in the study plots. Although it is not within the scope of the study, this could be a factor that might influence pollination. Practically, pollinators can visit more flowers if they are adjacent to each other.
2. I suggest mentioning how you select the flowers in each tree for hand pollination and how you made sure that it only received pollen from hand pollination and not from insect pollination. Mention also the time when you did the pollination. In addition, please also mention where or what is the source of pollen for all the sites (you only mentioned it in Indonesia sites). Did it come from other cacao tree(s)?
3. Lines 413-414: It is important to mention here the total number of cacao trees in each pollination treatment. The same comment as in Ghana study sites, mentioning the details of the pollination experiment is very important.

## Results:

1. Since it was not mentioned in the Methodology the total number of hand-pollinated flowers, it is difficult to imagine the average pod yield in percent (Table 1). For each pollination treatment, the result could be better presented by mentioning the number of hand-pollinated flowers that developed into pods.
2. Please clarify here what you mean by "yield" e.g. number of pods. You also need to consider that yield differs among cultivars. So, even if you performed hand-pollination, the yield will vary depending on the cultivar.
3. The statement in Line 230 is strong and yet it was not fully established in the paper.
4. In Line 264, you mentioned "The result also suggests that changing precipitation patterns under climate change could have negative impacts on cocoa pollinators and therefore yield". To say this statement, long-term historical climate data is needed for analysis which is out of the scope of the study.

## Conclusion

Some statements in the conclusion appear like a discussion. Revision is necessary reflecting the objective and the findings of the study.

## Other comments:

Many statements are constantly repeated in the methodology, results, and even caption of the figures (e.g. Lines 87-94). Some statements do not reflect the figure being discussed (e.g. 446-447; 453).

## Reviewer #3 (Remarks to the Author):

The manuscript "Global chocolate supply is limited by insufficient pollination, higher temperatures and reduced rainfall" proposes to study the relative contribution of pollination and climate variables on cocoa yield, by combining data collected in Brazil, Ghana and Indonesia. Overall, I found the manuscript interesting and original, but several major concerns need to be addressed (marked as [MAJOR], see below, in addition to other minor comments), especially regarding statistics and the experimental design, which may lead to different results when revised.

## ### Line-by-line comments ###

L24. "the first methodologically consistent": There is a risk of excessive criticism of the current research.

L25. "environmental factors": Only climate variables are considered in this study. This terminology should be clarified here and elsewhere.

L34. "severely limited by too little pollination": This may be exaggerated given the 17% increase with hand pollination.

L62. "pollination limitation": Why not using pollination deficit as usually used in the literature?

L72. "the first methodologically consistent": see comment in abstract

L75. "but taken together, the data spans three continents": Most statistics consider the 3 regions separately. Please correct this for more accuracy in the work done.

L79. "natural pollination": It is not clear what you mean by natural pollination (animal pollination + wind pollination?), while above you talk about insect and animal pollination. Please clarify

L82. According to your statistical analyses, you focus only on climate variables. Please clarify for more accuracy the work done

L87. Please unify the presentation of the method for the 3 regions together to better detail the standardisation of the protocol.

L91. "Supplementary Materials: Materials and Methods, Study years": I did not find this section.

L92-93. It is not clear what this list of six percentages means. Is it the percentage of hand-pollinated flowers per tree? Please clarify

L93-94. I could not find this section in the supplementary material. Is it Table S2? If so, there is no information about the percentages shown there.

[MAJOR 1] L102. The country is considered here as a fixed factor, not as a random factor. Please rerun your statistics with the good model structure.

[MAJOR 2] L102-106. I did not understand this part. In this regression, the percentage of hand pollination should be plotted on the x-axis and the cocoa yield (number of pods) on the y-axis. Also, the contribution of animal pollination should be calculated as the % pod set obtained with 0% hand pollination. I did not get this explanation in the calculation. Please clarify or correct if necessary.

[MAJOR 3] Table 1. Based on Figure S1, there is a clear country effect, with the Indonesian sites having many more pods with animal pollination only (0% hand pollination) compared to the other two countries. Could this effect be related to the variety grown in Indonesia rather than the contribution of animal pollination?

L160-170. Methodological details that should only be presented in the methods section to avoid repetition. I also found this in the previous results section.

[MAJOR 4] L171-175. So you have not included soil type and land management in the study. Please correct this throughout the manuscript.

L176-194. Very repetitive with the methods section.

L196. "by water availability": Please keep the variable in the model without interpretation. You have analysed the effect of precipitation in August. Water availability is an interpretation that could be misleading.

[MAJOR 5] L197-205. Throughout this part it is not clear whether you have combined all three regions into a single model (for models 1, 2 and 3) and, if so, how you have standardised the measures of the explanatory variables. This point is also not clear in the methodology as all the sites are presented separately with different levels of detail. Please standardise the presentation of the study areas (with the 3 regions in a single paragraph) and then add an independent paragraph with details of the standardised measures of tree height, plantation age, shade tree, litter thickness, etc.

L230. This cannot be concluded from the analysis carried out. See my comment in the Methods section.

L356. Text font is not standard in method section.

L373-379. Not clear what the distance between sites is and possible spatial autocorrelation or spatial non-independence. Please clarify

L390-392. Repetitive with text in results.

[MAJOR 6] L397-400. This is not enough information to understand the meaning of the percentages. How many flowers were hand pollinated for the 100% category and how many were removed from a tree with, say, 200 flowers counted within 2m? Still 40 flowers were HP and you removed 160 non-HP flowers, or 200 flowers were HP and you removed none? It's very important to be clear on this point as it could change the interpretation of the results.

L401-437. It is difficult to read the description of the study regions where different information is presented for each region. Also, the analysis was done by combining the 3 study regions, so I did not understand why the 3 study regions were split into separate paragraphs in the methods. Also, please refer to the countries as 'study regions' and not as study sites. The sites are the statistical units, while the study region is a fixed factor in the analysis. Please standardise the description of study regions and sites.

L404. So you have a single study site in this country? Please correct this information in all other parts of the manuscript.

[MAJOR 7] L405-409. Here you are talking about multiple study sites, but there is no spatial independence within the sites (in the same area) and there is a high risk of spatial autocorrelation, which should be taken into account in the statistics. L413-417. Repetitive between study areas, should be unified in a single section and more detailed (see comment above)

[MAJOR 8] L419-420. Same comment as for Brazil, in Indonesia there is a single study area with pseudoreplications within it (no spatial independence), called study plots. Spatial autocorrelation needs to be tested and taken into account in the statistics.

L430-437. Repetitive between study areas, should be unified in a single section and more detailed (see also comment above)

L446-447. Perhaps the authors are referring to Figure S2, although this figure is not very clear (unit of colour legend, names of variables not very visible).

L446-447. What do you mean by covariation? Do you mean colinearity? Correlation? Not clear how this is calculated.

L452-456. This is not clear. What do you mean by co-varied? What analysis was done and what is the result? (I assumed you were referring to Figure S2, but the correlation matrix is not visible enough to interpret the results).

[MAJOR 9] L460-461. Therefore, you are not considering soil in the study and this parameter should be removed throughout the manuscript.

[MAJOR 10] L464-466. There is an issue here with the error structure of the model. Given that you have controlled the number of flowers monitored per tree (e.g. 200 flowers), you should consider a logistic error structure based on the pod set (success vs. failure of a flower to give a pod) and rerun your models accordingly. The results may be different.

L468-469. Not sure I understand what you mean. Country is considered as a simple factor in the model. How do you interpret this "combined effect"?

L469-471. This is not understandable. See my comment in the result

[MAJOR 11] L472-495. You have run complex models which seem to be relevant. However, I do not see anywhere a presentation of the sample size to assess whether you have enough degrees of freedom to run such complex models. I believe that the sample size may be too small to run such models, particularly by splitting the analysis by country.

Table S4: the section of the supplementary material should be spitted in several tables (one per model) and edited as a table (here are the R outputs with a lot of information that are not used)

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Version 1:

Decision Letter:

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Dear Professor Wanger,

Your manuscript titled "Global chocolate supply is limited by low pollination and high temperatures" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alice Drinkwater, PhD  
Associate Editor  
Communications Earth & Environment  
@CommsEarth

#### REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

My comments were addressed entirely. The manuscript clearly describes the analysis and the implications of the results.

Reviewer #2 (Remarks to the Author):

The manuscript was greatly improved although there are still a few minor comments that could be addressed.

Lines 176-180:

It is a bit confusing. Please check these values because in Figure 2, they are all negative (temperature and cocoa tree density). It has the same meaning as Lines 236-238. However, the way it is written could be confusing. I suggest to be consistent with the writing style.

Please remove the extra parenthesis in (+18%).

Lines 231-232:

I suggest explaining very briefly why precipitation and leaf litter decomposition do not affect pollinator activity.

Lines 299-302 and 305-307:

I think there is no need to justify your recommendations because it has already been discussed in the Results and Discussion section.

In the Methods section specifically in the subsection "Pollination experiment", please clarify what you mean by "replicate trees".

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**Manuscript number:** COMMSENV-24-1410-T

**Title:** Global chocolate supply is limited by low pollination and high temperatures

**Journal:** Communications Earth and Environment

Dear Dr. Drinkwater and Reviewers,

Thank you for your review of our manuscript. Your comments have substantially improved the quality of our work.

Below each comment you will find our point-by-point responses to the comments in *blue italic*.

We hope that our revised manuscript is now suitable for publication in Communications Earth and Environment.

Best regards,

Thomas Cherico Wanger  
on behalf of all co-authors



## Response to Reviewer Comments:

### Reviewer #1 (Remarks to the Author):

**R1-1.** It is not clear why the 0% hand pollination treatment or open pollination treatment is not the one used to present the results instead of the estimated from the model and why the differences between the estimated value and the experimental value are so big.

*For the 0% hand pollination treatment we only have data on the number of pods harvested, not on the number of flowers pollinated. As for most plants, the number of mature fruits is smaller than the number of flowers that receive pollination. Thus, we estimate the number of flowers that received pollination, as explained in the Methods (L422-430):*

*‘For Question i, the percentage of flowers that received pollen in the 0% hand pollination (‘natural pollination’) treatment was calculated by creating a standard curve of number of pods harvested against hand pollination percentage for the 20-100% treatments using a log-linked generalised linear model (GLM) with a Poisson error structure ( $R^2 = 0.74$ ), and controlling for country by including it as a fixed effect. Goodness of fit was graphically checked using a q-q plot and residuals vs fitted graphs. The statistical model fitted was:  $\text{Pollination\_Percentage} \sim \text{Intercept} + \text{Country} + \text{Number of Pods}$ . The percentage of flowers per tree in the 0% hand pollination treatment receiving effective natural pollination was calculated by locating the observed number of pods from the 0% HP treatment on the fitted line (Supplementary Figure 1).’*

**R1-2.** It needs to be more precise about what part of the data is already published.

*We specify this aspect now in L88-93:*

*‘The hand pollination experiment was conducted at ten sites in Bahía, Brazil during 2018-2019, eight study sites in the Western Region of Ghana during 2019-2020, and eight sites in Central Sulawesi, Indonesia during 2017 (Table S2, <sup>27, 30</sup>). The data on fruit set and fruit development under increased hand pollination in Brazil and Indonesia have been published in location-specific studies (see <sup>27, 30</sup>), and are presented here in a planned, integrated, multi-continent comparison to identify global trends.’*

### Reviewer #2 (Remarks to the Author):

**R2-1.** The paper presents new findings but somehow does not reflect what is indicated in the title. In general, to say that cacao yield is limited by “increased temperature and reduced rainfall”, long-term climatic is data needed.

*We changed the title to better reflect our findings:*

*“Global chocolate supply is limited by low pollination and high temperatures”*

**R2-2.** The pollination experiment was also not explicitly described in the Methods making it difficult to provide a conclusion that cacao yield is indeed limited by pollination.

*We have now expanded the Methods section where we describe the pollination experiment from L381-420:*

*“A standard protocol was used across all three countries to determine how much natural pollination was occurring and test for pollination-limitation<sup>27</sup>. In each study plot, replicate trees were selected for each of six treatments: 0% (natural pollination), 20%, 40%, 60%, 80% and 100% hand pollination (HP). In Brazil there was one tree in each of the six HP treatments, and ten study plots, for a total of 10 trees per treatment and 60 trees total. In Ghana we used six trees in each of the six HP treatments, and eight study plots, for a total of 36 trees per treatment and 288 trees total. The Ghana experiment was repeated twice in successive years, using different trees, making a total of 576 trees over the two years. In Indonesia there were eight trees in the 0% and 20% HP treatments and twelve trees in the 40-100% HP treatments, and eight study plots, for a total of 64 trees in the experiment. Thus, the number of trees used to calculate the average pod yield for each treatment was: Brazil = 10, Ghana = 48, Indonesia = 8 (0-20%) and 12 (40-100%); and a grand total of 700 trees were included in the experiment across all treatments and all three countries.*

*In the hand pollination experiment, 0% HP (natural pollination) does not refer to pollinator exclusion; rather, natural pollination represents the control where all flowers are left undisturbed and pollination occurs by arthropod pollinators, as well as any instances of wind or water pollination. For the 20-100% treatments, on each study tree the total number of flowers present up to 2m height from the base of the tree (~13% of the flowers on the whole tree<sup>27</sup>) was counted on the day of treatment, and the number to be pollinated calculated. For example, if the tree was in the 20% HP treatment, and 200 flowers were counted up to 2m height from the base of tree, 40 flowers would be hand pollinated and 160 would be removed, whereas, if the tree was in the 100% HP treatment, and 200 flowers were counted up to 2m height from the base of tree, 200 flowers would be hand pollinated and none would be removed. For the 20%-80% HP treatments, all flowers that were not hand pollinated (‘unpollinated’) were removed from the tree to avoid the unpollinated flowers receiving natural pollination. Across all countries and all treatment, the average number of flowers below 2m on each tree before treatment was 226 (SD = 117, min = 16, max = 700). Hand pollinated flowers remaining on the tree were not covered after treatment, so may have received additional natural pollination, but as all flowers remaining on the tree had already been hand pollinated, and this was not a test of hand pollination technique, additional natural pollination would not have invalidated the results. Cocoa flowers open for 22-24hrs, after which, if unfertilized, they abscise<sup>58</sup>. Thus, each day the tree was visited during the hand pollination experiment, the flower count, hand pollination, and unpollinated flower removal was repeated. Flowers to be hand pollinated were randomly selected among the flowers*

*present on the tree, and the pollen used to hand pollinate flowers came from a minimum of three separate cocoa flowers located in an adjacent area not included in the study<sup>59</sup>. In Brazil, hand pollination was conducted from January to February 2019, and pods were counted from March to April 2019<sup>27</sup>. In Ghana, hand pollination was conducted August to October 2019 and January to April 2020, and pods were counted from May to July and September to December 2020. In Indonesia flowers were hand-pollinated from April to May 2017, and pods were counted from October to December 2017.”*

**R2-3.** It is also important to indicate here the spacing of each cacao tree in the study plots. Although it is not within the scope of the study, this could be a factor that might influence pollination. Practically, pollinators can visit more flowers if they are adjacent to each other.

*Tree spacing and plot size are now explained in more detail on L325-329:*

*“The average cocoa tree diameter at breast height (dbh) per plot was determined by measuring the dbh of all trees within 2m left and right of a diagonal transect of the plot; dbh of all trees included in the experiment was also recorded. Density of cocoa trees was determined by counting all trees within the study plot and extrapolating to obtain the trees/ha value.”*

**R2-4.** I suggest mentioning how you select the flowers in each tree for hand pollination and how you made sure that it only received pollen from hand pollination and not from insect pollination. Mention also the time when you did the pollination. In addition, please also mention where or what is the source of pollen for all the sites (you only mentioned it in Indonesia sites). Did it come from other cacao tree(s)?

*Sensu our reply to your comment R2-2, we have now expanded the Methods section where we describe the pollination experiment in detail that addresses all these questions from L381-420 (we do not paste the text section here again to save some space).*

**R2-5.** Lines 413-414: It is important to mention here the total number of cacao trees in each pollination treatment. The same comment as in Ghana study sites, mentioning the details of the pollination experiment is very important.

*Sensu our reply to your comment R2-2, we have now expanded the Methods section where we describe the pollination experiment and answer the question above (L381-393):*

*“A standard protocol was used across all three countries to determine how much natural pollination was occurring and test for pollination-limitation<sup>27</sup>. In each study plot, replicate trees were selected for each of six treatments: 0% (natural pollination), 20%, 40%, 60%, 80% and 100% hand pollination (HP). In Brazil there was one tree in each of the six HP treatments, and ten study plots, for a total of 10 trees per treatment and 60 trees total. In Ghana we used six trees in each of the six HP*

*treatments, and eight study plots, for a total of 36 trees per treatment and 288 trees total. The Ghana experiment was repeated twice in successive years, using different trees, making a total of 576 trees over the two years. In Indonesia there were eight trees in the 0% and 20% HP treatments and twelve trees in the 40-100% HP treatments, and eight study plots, for a total of 64 trees in the experiment. Thus, the number of trees used to calculate the average pod yield for each treatment was: Brazil = 10, Ghana = 48, Indonesia = 8 (0-20%) and 12 (40-100%); and a grand total of 700 trees were included in the experiment across all treatments and all three countries.”*

**R2-6.** Since it was not mentioned in the Methodology the total number of hand-pollinated flowers, it is difficult to imagine the average pod yield in percent (Table 1). For each pollination treatment, the result could be better presented by mentioning the number of hand-pollinated flowers that developed into pods.

*It would be unwieldy to report a list of every tree in the study (700 trees) with the number of flowers that matured into fruit. We have added average numbers of flowers per tree on L98-99 to allow the reader to understand the average rate of flower conversion to mature fruit:*

*“Only flowers below 2m were included in the experiment, and the average number of flowers below 2m on each tree before treatment was 226 (SD = 117).”*

**R2-7.** Please clarify here what you mean by "yield" e.g. number of pods.

*The text on L 125 now reads “A student’s t-test found that yield (i.e., pods per tree) [..]”*

**R2-8.** You also need to consider that yield differs among cultivars. So, even if you performed hand-pollination, the yield will vary depending on the cultivar.

*We now more explicitly discuss the potential impact of cultivar on yield on L128-134:*

*“We acknowledge that cocoa tree variety and age would also be expected to affect yield; for example, the higher overall numbers of pods in all treatments from the Indonesian sites compared to the Brazilian and Ghanaian sites may be influenced by the cocoa variety. However, in our study, cocoa variety and age correlated with country (Supplementary Table 2), whereas the pattern of increasing pod number with increasing hand pollination was consistent across countries. This result indicates that there was an effect of the pollination treatment, independent of any effects of variety or age.”*

**R2-9.** The statement in Line 230 is strong and yet it was not fully established in the paper.

*The statement is supported by the results and is now clarified the text (L190) now reads:*

*“Specifically, in Question i, pod yield in the 100% hand pollination treatment was significantly higher than in the natural pollination treatment, where there was 16.7% pollination on average, and in Question iii, Model 3, increasing hand pollination increased yield by up to 20%.”*

**R2-10.** In Line 264, you mentioned “The result also suggests that changing precipitation patterns under climate change could have negative impacts on cocoa pollinators and therefore yield”. To say this statement, long-term historical climate data is needed for analysis which is out of the scope of the study.

*The text has been removed. Our revised models no longer find precipitation to be a significant factor.*

**R2-11.** Many statements are constantly repeated in the methodology, results, and even caption of the figures (e.g. Lines 87-94).

*Thank you for pointing this out. Repeated statements have been removed.*

**R2-12.** Some statements do not reflect the figure being discussed (e.g. 446-447; 453).

*Thank you for paying attention here. The figure number has been corrected.*

### **Reviewer #3 (Remarks to the Author):**

**R3-1.** L24. “the first methodologically consistent”: There is a risk of excessive criticism of the current research.

*We simplified the text in L25-27:*

*“We present a global analysis of pollination, cocoa tree, plantation, and climate factors affecting cocoa yield, with experimental data from three major cocoa-producing countries: Brazil, Ghana and Indonesia.”*

**R3-2.** L25. “environmental factors”: Only climate variables are considered in this study. This terminology should be clarified here and elsewhere.

*‘Environmental factors’ has been changed to ‘climate factors’ throughout the manuscript.*



**R3-3. L34.** "severely limited by too little pollination": This may be exaggerated given the 17% increase with hand pollination.

*The text now reads 'A multi-country analysis shows cocoa yield is limited by too little pollination and threatened by climate warming.'*

**R3-4. L62.** "pollination limitation": Why not using pollination deficit as usually used in the literature?

*Thank you for asking for clarification here. 'Pollination deficit' is a less commonly used and less specific synonym in the pollination biology literature. 'pollinator limitation' means fruit production is limited by number or efficacy of available pollinators. 'pollen limitation' means fruit production is limited by number or quality of available pollen. <https://www.ipbes.net/>. We now provide these specific definitions in the text (L64-68):*

*"In addition, because arthropod pollination is essential for fruit production in most cocoa varieties, low abundance or efficacy of available pollinators (pollinator limitation), lack of compatible pollen (pollen limitation), or cultivar selection can mean that the flowers on a cocoa tree do not receive sufficient pollen and do not set fruit, resulting in reduced yield.*

**R3-5. L72.** "the first methodologically consistent": see comment in abstract

*The text in L75-77 now reads :*

*"Here we present a global analysis of the factors affecting cocoa yield, with the rare advantage that the data are from methodologically consistent experiments in three major cocoa-producing countries: Indonesia, Brazil and Ghana."*

**R3-6. L75.** "but taken together, the data spans three continents": Most statistics consider the 3 regions separately. Please correct this for more accuracy in the work done.

*Thank you for this clarifying comment. It is correct to say that the dataset spans three countries. Results for Questions 1 and 2 are presented by country, but are then compared across countries, which would not be the case in a single country study. Moreover, the largest analysis was done for Question 3, in which Models 1, 2 and 3 combine data from all three countries.*

**R3-7. L79.** "natural pollination": It is not clear what you mean by natural pollination (animal pollination + wind pollination?), while above you talk about insect and animal pollination. Please clarify

*The text is now clarified (L96-98:*

*“Natural pollination in cocoa is mainly by arthropods<sup>23</sup>, but any occurrences of wind or water pollination would also be included in our definition of natural pollination.”*

**R3-8.** L82. According to your statistical analyses, you focus only on climate variables. Please clarify for more accuracy the work done

*‘Environmental factors’ has been changed to ‘climate factors’ throughout the manuscript.*

**R3-9.** L87. Please unify the presentation of the method for the 3 regions together to better detail the standardisation of the protocol.

*The brief summary in the Results section (L88) has been clarified:*

*“The hand pollination experiment was conducted at ten sites in Bahía, Brazil during 2018-2019, eight study sites in the Western Region of Ghana during 2019-2020, and eight sites in Central Sulawesi, Indonesia during 2017 (Supplementary Table 2). The data on fruit set and fruit development from the experiments in Brazil and Indonesia have been published in location-specific studies (see<sup>27, 30</sup>), and are presented here in a planned, integrated, multi-continent comparison to identify global trends.”*

*The Methods section has been extensively rewritten to simplify, clarify and unify the description of the methods used in the three countries (L313ff. – we do not paste this section here to save space).*

**R3-10.** L91. “Supplementary Materials: Materials and Methods, Study years”: I did not find this section.

*Thank you for paying attention to the details here. In L96, we now reference Methods, and specifically Supplementary Table 2.*

**R3-11.** L92-93. It is not clear what this list of six percentages means. Is it the percentage of hand-pollinated flowers per tree? Please clarify

*The text in L94-96 is now clarified:*

*“In each study site a study plot was established, and replicate trees were selected for each of six treatments: 0% (natural pollination), 20%, 40%, 60%, 80% and 100% hand pollination (HP) (Methods, Supplementary Table 2, <sup>27</sup>).”*

*The hand pollination experiment is further explained in the Methods section.*

**R3-12.** L93-94. I could not find this section in the supplementary material. Is it Table S2? If so, there is no information about the percentages shown there.

*Thank you for paying attention to the details here. In L96, we now reference Methods, and specifically Supplementary Table 2.*

**R3-13.** [MAJOR 1] L102. The country is considered here as a fixed factor, not as a random factor. Please rerun your statistics with the good model structure.

*Thank you for identifying this error in the text. Country is included in this model as a fixed effect. The description is now corrected in the manuscript. The text on L422-426 now reads:*

*“For Question i, the percentage of flowers that received pollen in the 0% hand pollination (‘natural pollination’) treatment was calculated by creating a standard curve of number of pods harvested against hand pollination percentage for the 20-100% treatments using a log-linked generalised linear model (GLM) with a Poisson error structure ( $R^2 = 0.74$ ), and controlling for country by including it as a fixed effect.”*

**R3-14.** [MAJOR 2] L102-106. I did not understand this part. In this regression, the percentage of hand pollination should be plotted on the x-axis and the cocoa yield (number of pods) on the y-axis. Also, the contribution of animal pollination should be calculated as the % pod set obtained with 0% hand pollination. I did not get this explanation in the calculation. Please clarify or correct if necessary.

*Thank you for this comment. You are correct in interpreting what was stated in L100-104. We have now clarified the corresponding methods section (L422-430):*

*“For Question i, the percentage of flowers that received pollen in the 0% hand pollination (‘natural pollination’) treatment was calculated by creating a standard curve of number of pods harvested against hand pollination percentage for the 20-100% treatments using a log-linked generalised linear model (GLM) with a Poisson error structure ( $R^2 = 0.74$ ), and controlling for country by including it as a fixed effect. Goodness of fit was graphically checked using a q-q plot and residuals vs fitted graphs. The statistical model fitted was:  $\text{Pollination\_Percentage} \sim \text{Intercept} + \text{Country} + \text{Number of Pods}$ . The percentage of flowers per tree in the 0% hand pollination treatment receiving effective natural pollination was calculated by locating the observed number of pods from the 0% HP treatment on the fitted line (Supplementary Figure 1).”*

**R3-15.** [MAJOR 3] Table 1. Based on Figure S1, there is a clear country effect, with the Indonesian sites having many more pods with animal pollination only (0% hand pollination) compared to the other two countries. Could this effect be related to the variety grown in Indonesia rather than the contribution of animal pollination?

*We now more explicitly discuss the potential impact of cultivar on yield on L128-134:*



*“We acknowledge that cocoa tree variety and age would also be expected to affect yield; for example, the higher overall numbers of pods in all treatments from the Indonesian sites compared to the Brazilian and Ghanaian sites may be influenced by the grown cocoa variety. However, in our study cocoa variety and age correlated with country (Table S2), whereas the pattern of increasing pod number with increasing hand pollination was consistent across countries. This result indicates that there was an effect of the pollination treatment, separate from any effects of variety or age. “*

**R3-16.** L160-170. Methodological details that should only be presented in the methods section to avoid repetition. I also found this in the previous results section.

*The Methods section has been extensively rewritten to simplify, clarify and unify the description of the methods and eliminate repetition in the results section.*

**R3-17.** [MAJOR 4] L171-175. So you have not included soil type and land management in the study. Please correct this throughout the manuscript.

*Thank you for this important comment. We have indirectly addressed the access to and availability of soil resources through cocoa dbh, plantation age, and cocoa tree density, as an indirect measure of inter-tree competition for soil resources, and depth of leaf litter as a measure linked to soil organic matter. We have made this explicit in L262-264:*

*“In Model 3, access to and availability of soil resources was investigated indirectly through cocoa dbh, plantation age, and cocoa tree density, as indirect measures of inter-tree competition for soil resources, and depth of leaf litter as a measure linked to soil organic matter.”*

**R3-18.** L176-194. Very repetitive with the methods section.

*The Methods section has been extensively rewritten to simplify, clarify and unify the description of the methods and eliminate repetition in the results section.*

**R3-19.** L196. “by water availability”: Please keep the variable in the model without interpretation. You have analysed the effect of precipitation in August. Water availability is an interpretation that could be misleading.

*The text has been removed to enhance clarity.*

**R3-20.** [MAJOR 5] L197-205. Throughout this part it is not clear whether you have combined all three regions into a single model (for models 1, 2 and 3) and, if so, how you have standardised the measures of the explanatory variables. This point is also not clear in the methodology as all the sites are presented separately with different

levels of detail. Please standardise the presentation of the study areas (with the 3 regions in a single paragraph) and then add an independent paragraph with details of the standardised measures of tree height, plantation age, shade tree, litter thickness, etc.

*As noted in our response to your comment R3-6, it is correct to say that the dataset spans three countries. Results for Questions 1 and 2 are presented by country, but are then compared across countries, which would not be the case in a single country study. Moreover, the largest analysis was done for Question 3, in which Models 1, 2 and 3 combine data from all three countries. When the models are described we state which data are used (L166-175):*

*“To address Question iii, we used three General Linear Models (GLMs) to determine the impact of pollination, cocoa tree, plantation, and climate factors on cocoa pod production. **Model 1:** We combined natural pollination (0% hand pollination) data from all three countries to test whether cocoa tree, plantation, or climate factors explain patterns of natural pollination and pod production. **Model 2:** We combined 100% hand pollination data from all three countries to determine whether cocoa tree, plantation, or climate factors explain pod production when there is full pollination, i.e. no pollination limitation. **Model 3:** Data from all countries and all hand-pollination treatments except the 0% pollination treatment were used to understand the relative impact of cocoa tree, plantation, or climate factors compared to controlled levels of pollination on pod production (Supplementary Table 4).”*

*The Methods section has been extensively rewritten to clarify the description of the methods used in the three countries. As the data was collected following a standardized protocol, post-hoc standardization was not necessary.*

**R3-21.** L230. This cannot be concluded from the analysis carried out. See my comment in the Methods section.

*As also mentioned in response to comment R2-9, the statement is supported by the results. To clarify this, the text now reads (L190):*

*“Specifically, in Question i, pod yield in the 100% hand pollination treatment was significantly higher than in the natural pollination treatment, where there was 16.7% pollination on average, and in Question iii, Model 3, increasing hand pollination increased yield by up to 20%.”*

**R3-22.** L356. Text font is not standard in method section.

*Text fonts have been standardized.*

**R3-23.** L373-379. Not clear what the distance between sites is and possible spatial autocorrelation or spatial non-independence. Please clarify

*Tree and plot spacing and plot size are now explained in more detail on L315-322:*

*“The study was conducted at eight study sites near Tarkwa-Breman in the Wassa-Amanfi district in the Western region of Ghana during 2019-2020; ten study sites in Ilhéus, Southern Bahia, Brazil during 2018-2019 <sup>30</sup>, and eight study sites in the Napu Valley region near Lore Lindu National Park, Central Sulawesi, Indonesia during 2017 <sup>27</sup> (Supplementary Table 2). Study plots in Brazil were separated by a minimum of 100 m, Ghana by 70m, and Indonesia by 200 m. Tree spacing in Brazil and Indonesia was ~3.5 m (average 800 and 763 trees/ha, respectively), and in Ghana was ~6 m (average 280 trees/ha) (Supplementary Table 2). In Ghana each study plot was 40x40m, in Brazil each was 20x20m, and in Indonesia each was 10x10m.”*

*We use wind, precipitation, temperature range, ground temperature, soil type, diameter at breast height, total flowers, surrounding vegetation, litter thickness, shade trees, canopy cover, tree density, plantation age, pollination percentage, number of pods, and tree identity as variables in our models. Except from natural pollination, none of the variables would be affected by a distance of <70m between the plots. For natural pollinators, the maximum distance covered is assumed to be 7m between trees (Toledo-Hernández et al. 2017). As spatial autocorrelation is, therefore, unlikely to affect our results, we did not include a correcting random effect structure, smoothing term or an additional coordinate variable in the model, all of which would have made the model structure unnecessarily complex.*

**R3-24.** L390-392. Repetitive with text in results.

*This section has been extensively rewritten to eliminate repetition*

**R3-25.** [MAJOR 6] L397-400. This is not enough information to understand the meaning of the percentages. How many flowers were hand pollinated for the 100% category and how many were removed from a tree with, say, 200 flowers counted within 2m? Still 40 flowers were HP and you removed 160 non-HP flowers, or 200 flowers were HP and you removed none? It's very important to be clear on this point as it could change the interpretation of the results.

*We have clarified this in the text in L394-403:*

*“In the hand pollination experiment, 0% HP (natural pollination) does not refer to pollinator exclusion; rather, natural pollination represents the control where flowers are left undisturbed and pollination occurs by arthropod pollinators, as well as any instances of wind or water pollination. For the 20-100% treatments, on each study tree the total number of flowers present up to 2m height from the base of the tree (~13% of the flowers on the whole tree <sup>27</sup>) was counted on the day of treatment, and the number to be pollinated calculated. For example, if the tree was in the 20% HP treatment, and 200 flowers were counted up to 2m height from the base of tree, 40 flowers would be hand pollinated, whereas, if the tree was in the 100% HP treatment, and 200 flowers were counted up to 2m height from the base of tree, 200 flowers would be hand pollinated and none would be removed.”*

**R3-26.** L401-437. It is difficult to read the description of the study regions where different information is presented for each region. Also, the analysis was done by combining the 3 study regions, so I did not understand why the 3 study regions were split into separate paragraphs in the methods. Also, please refer to the countries as 'study regions' and not as study sites. The sites are the statistical units, while the study region is a fixed factor in the analysis. Please standardise the description of study regions and sites.

*The description of the study regions have been extensively rewritten to simplify the description of the methods used in the three countries. Also, we renamed study sites into study regions. The adjusted methods section reads as follows (L315-344):*

*“The study was conducted at eight study sites near Tarkwa-Breman in the Wassa-Amanfi district in the Western region of Ghana during 2019-2020; ten study sites in Ilhéus, Southern Bahia, Brazil during 2018-2019<sup>30</sup>, and eight study sites in the Napu Valley region near Lore Lindu National Park, Central Sulawesi, Indonesia during 2017<sup>27</sup> (Supplementary Table 2). Study plots in Brazil were separated by a minimum of 100 m, Ghana by 70m, and Indonesia by 200 m. Tree spacing in Brazil and Indonesia was ~3.5 m (average 800 and 763 trees/ha, respectively), and in Ghana was ~6 m (average 280 trees/ha) (Supplementary Table 2). In Ghana each study plot was 40x40m, in Brazil each was 20x20m, and in Indonesia each was 10x10m.*

*Data on the following site characteristics was recorded, as they were hypothesized to affect the abundance and species diversity of cocoa pollinators<sup>26, 39, 49</sup>: cocoa variety, grafting, and tree age were reported by the site owners (Supplementary Table 2). The average cocoa tree diameter at breast height (dbh) per plot was determined by measuring the dbh of all trees within 2m left and right of a diagonal transect of the plot; dbh of all trees included in the experiment was also recorded. Density of cocoa trees was determined by counting all trees within the study plot and extrapolating to obtain the trees/ha value. Canopy cover in Ghana was measured using the canopy-scope<sup>55</sup>, and an average canopy cover score for each study plot was based on the measurements from the middle of the plot and the four corner points. In Brazil and Indonesia average canopy cover per plot was calculated by taking four photographic images randomly located within each plot using a 13 mm wide-angle lens. The camera was held 4 m above the ground and photos were taken under sunny conditions. The software ImageJ (<https://imagej.net/ij/>) was used to convert images to gray-scale and calculate the canopy cover as the percentage of black pixels<sup>56</sup>. All sites in the three countries were categorized as either ‘low’ = 0-39% or ‘high’ = 40-100% canopy cover. The presence or absence of non-cocoa shade trees in the study plot was noted during the quantification of cocoa tree density. Complexity of vegetation surrounding each study plot was classified as: ‘homogenous (simple)’, when the plot was surrounded by a single species or human-simplified ecosystem (farm, single species plantation, or grass field); or ‘heterogenous (complex)’, when the vegetation surrounding a plot contained high floral diversity (primary or secondary forest or wetland). Litter depth was determined by averaging the depth of litter (cm) on the soil surface from the plot centre and near the four corners of the plot using a meter ruler.”*

**R3-27.** L404. So you have a single study site in this country? Please correct this information in all other parts of the manuscript.

*The Methods section describing the study sites has been simplified and clarified as detailed in comment R3-26.*

**R3-28.** [MAJOR 7] L405-409. Here you are talking about multiple study sites, but there is no spatial independence within the sites (in the same area) and there is a high risk of spatial autocorrelation, which should be taken into account in the statistics.

*As mentioned in response to your comment R3-23, based on the described plot spacing (L315-322) and none of the measured variables being affected by a minimum distance of 70m between the plots, our study sites should not be affected by spatial autocorrelation. We, therefore, did not include a correcting random effect structure, smoothing term or an additional coordinate variable in the model, all of which would have made the model structure unnecessarily complex.*

**R3-29.** L413-417. Repetitive between study areas, should be unified in a single section and more detailed (see comment above)

*The Methods section describing the study sites has been simplified and clarified as detailed in comment R3-26.*

**R3-30.** [MAJOR 8] L419-420. Same comment as for Brazil, in Indonesia there is a single study area with pseudoreplications within it (no spatial independence), called study plots. Spatial autocorrelation needs to be tested and taken into account in the statistics.

*As mentioned in response to your comment R3-23 and R3-28, based on the described plot spacing (L315-322) and none of the measured variables being affected by a minimum distance of 70m between the plots, our study sites should not be affected by spatial autocorrelation. We, therefore, did not include a correcting random effect structure, smoothing term or an additional coordinate variable in the model, all of which would have made the model structure unnecessarily complex.*

**R3-31.** L430-437. Repetitive between study areas, should be unified in a single section and more detailed (see also comment above)

*The Methods section describing the study sites has been simplified and clarified as detailed in comment R3-26.*

**R3-32.** L446-447. Perhaps the authors are referring to Figure S2, although this figure is not very clear (unit of colour legend, names of variables not very visible).



*The Figure number has been corrected. Supplementary Figure 2 has been modified to simplify interpretation and the figure text size has been increased.*

**R3-33.** L446-447. What do you mean by covariation? Do you mean colinearity? Correlation? Not clear how this is calculated.

*‘Co-variation’ has been replaced with ‘correlation’ throughout the manuscript.*

**R3-34.** L452-456. This is not clear. What do you mean by co-varied? What analysis was done and what is the result? (I assumed you were referring to Figure S2, but the correlation matrix is not visible enough to interpret the results).

*‘Co-variation’ has been replaced with ‘correlation’ throughout the manuscript.*

*Supplementary Figure 2 has been modified to simplify interpretation and the figure text size has been increased.*

**R3-35.** [MAJOR 9] L460-461. Therefore, you are not considering soil in the study and this parameter should be removed throughout the manuscript.

*Thank you for pointing this out. In order to fully assess yield effects soil may play an important role. We therefore extracted this data in the first place, but did not find sufficient variation across out study regions. To preempt criticism from the readership, we prefer to retain the information on soil data acquisition and analysis in the manuscript. We do, however, state clearly that the data could not be used due to intercorrelation with our country variable (L374-379):*

*“Soil type is expected to affect cocoa yield, so for each study site soil data was extracted from the Global High-Resolution Soil Profile Database for Crop Modelling Applications<sup>57</sup>. The resolution of the soils data meant that all sites within each country were assigned the same soil classification: Brazil was Ferric Luvisol, Ghana was Xanthic Ferralsol, and Indonesia was Humic Acrisol. As soil type was highly correlated with the ‘Country’ variable, it was not included as a variable in the models and was not included in any analyses.”*

**R3-36.** [MAJOR 10] L464-466. There is an issue here with the error structure of the model. Given that you have controlled the number of flowers monitored per tree (e.g. 200 flowers), you should consider a logistic error structure based on the pod set (success vs. failure of a flower to give a pod) and rerun your models accordingly. The results may be different.

*As explained on L450, a Poisson error structure was chosen for the GLMs because the pod count data is a count. We have not controlled the number of flowers monitored per tree. The pollination experiment is explained in detail in L380-420. To*

save space and as an example excerpt, how the hand pollination experiment was conducted, it reads:

*“For the 20-100% treatments, on each study tree the total number of flowers present up to 2m height from the base of the tree (~13% of the flowers on the whole tree<sup>27</sup>) was counted on the day of treatment, and the number to be pollinated calculated. For example, if the tree was in the 20% HP treatment, and 200 flowers were counted up to 2m height from the base of tree, 40 flowers would be hand pollinated and 160 would be removed, whereas, if the tree was in the 100% HP treatment, and 200 flowers were counted up to 2m height from the base of tree, 200 flowers would be hand pollinated and none would be removed.”*

**R3-37.** L468-469. Not sure I understand what you mean. Country is considered as a simple factor in the model. How do you interpret this "combined effect"?

*The text has been removed to avoid confusion.*

**R3-38.** L469-471. This is not understandable. See my comment in the result

*We have now clarified the corresponding methods section (L422-430) also in response to comments R1-1 and R3-14:*

*“For Question i, the percentage of flowers that received pollen in the 0% hand pollination (‘natural pollination’) treatment was calculated by creating a standard curve of number of pods harvested against hand pollination percentage for the 20-100% treatments using a log-linked generalised linear model (GLM) with a Poisson error structure ( $R^2 = 0.74$ ), and controlling for country by including it as a fixed effect. Goodness of fit was graphically checked using a q-q plot and residuals vs fitted graphs. The statistical model fitted was:  $\text{Pollination\_Percentage} \sim \text{Intercept} + \text{Country} + \text{Number of Pods}$ . The percentage of flowers per tree in the 0% hand pollination treatment receiving effective natural pollination was calculated by locating the observed number of pods from the 0% HP treatment on the fitted line (Supplementary Figure 1).”*

**R3-39.** [MAJOR 11] L472-495. You have run complex models which seem to be relevant. However, I do not see anywhere a presentation of the sample size to assess whether you have enough degrees of freedom to run such complex models. I believe that the sample size may be too small to run such models, particularly by splitting the analysis by country.

*Thank you again for paying attention to the details here. The Degrees of Freedom are now presented in Supplementary Table 3 and show that our models can be applied to the available datasets.*

**R3-40.** Table S4: the section of the supplementary material should be spitted in several tables (one per model) and edited as a table (here are the R outputs with a lot of information that are not used)

*Thank you for this suggestion. The table begins with summary information and each Model is then separately presented as the full model and the AIC selected Model. We have provided detailed information here because the details of the AIC-selected models underpin Figure 3 and all discussion of the model results for Question iii on L166-259. We decided to keep all information in one Table S4 to avoid referencing, multiple tables for the same approach in the main text.*



**Manuscript number:** COMMSENV-24-1410A

**Title:** Global chocolate supply is limited by low pollination and high temperatures

**Journal:** Communications Earth and Environment

Dear Dr. Drinkwater and Reviewers,

Thank you for your review of our manuscript. Your comments have substantially improved the quality of our work.

Below each comment you will find our point-by-point responses to the comments in *blue italic*.

We hope that our revised manuscript is now suitable for publication in Communications Earth and Environment.

Best regards,

Thomas Cherico Wanger  
on behalf of all co-authors

## Response to Reviewer Comments:

### Reviewer #1 (Remarks to the Author):

My comments were addressed entirely. The manuscript clearly describes the analysis and the implications of the results.

*Great – thank you for your important feedback to improve our work.*

### Reviewer #2 (Remarks to the Author):

The manuscript was greatly improved although there are still a few minor comments that could be addressed.

*Thank you. We have addressed all the remaining comments below and in the manuscript.*

Lines 176-180:

It is a bit confusing. Please check these values because in Figure 2, they are all negative (temperature and cocoa tree density). It has the same meaning as Lines 236-238. However, the way it is written could be confusing. I suggest to be consistent with the writing style.

*We adjusted the section from L.176-180 as follows, which is now consistent with the reported values in Fig. 2.:*

*“The results of **Models 1, 2 and 3** show the effects on pod yield from: **higher pollination percentage** (+20%), **higher temperatures** (higher temperatures in December, during the warm season in Brazil and Indonesia <sup>32</sup> (-22 to -31%), and the presence of shade trees (+3 to 9%)), and **access to and availability of soil resources** (larger cocoa trees (dbh (+19%), plantation age (+18%)), cocoa tree density (-6 to -14%), and leaf litter (+9%))”*

Please remove the extra parenthesis in (+18%).

*The second parenthesis here is needed to close the dbh and plantation age parenthesis (larger cocoa trees (dbh (+19%), plantation age (+18%)), [..]) in the sentence.*

Lines 231-232:

I suggest explaining very briefly why precipitation and leaf litter decomposition do not affect pollinator activity.

*We expanded the sentence as follows:*

*“This suggests that in contrast to previous studies <sup>42, 43, 44, 45</sup>, in our study precipitation and decomposing plant material did not affect pollinator activity (Figure*

*2, Supplementary Table 5), which may be, for instance, due to differences in pollinator communities in different localities and the sampling times.”*

Lines 299-302 and 305-307:

I think there is no need to justify your recommendations because it has already been discussed in the Results and Discussion section.

*Thank you for this suggestion. However, we prefer to keep the justifications as the conclusions provide a concise summary that may be the only part – besides the Abstract – that is read by the reader.*

In the Methods section specifically in the subsection “Pollination experiment”, please clarify what you mean by “replicate trees”.

*Thank you for pointing this out. We don’t use the term ‘replicate tree anymore and rephrased into*

*“In each study plot, one tree was selected for each of six treatments [..]”*