

Referee's report of 'Bioturbation enhances C and N contents on near-surface soils in resource-deficient arid climate regions but shows adverse effects in more temperate climates' submitted by Diana Kraus et al. to EGU sphere.

##1st referee

In this paper, the authors investigate the effect that excavating animals have on physical (grain size: silt, clay and sand) and chemical (macronutrients such as carbon (C), nitrogen (N) and phosphorus (P)) soil properties along an ecological gradient. They predict that bioturbation will increase 1) the proportion of fine-grained soil and 2) C, N and P content in disturbed soil compared to undisturbed soil. In addition, they expect that these effects will be greater in arid regions compared to regions with more temperate climate. They find that bioturbation had no effect on the physical soil properties. However, they state that disturbed soils had higher content of C and N compared to undisturbed soils.

Where this paper is informative, provide an overview of the literature and show an understanding of the research topic, I feel there are several problems with this study.

General comments:

1) The authors do not provide the reader with all background information needed for him/her to understand and follow the story. For example, there is no information on what animals are the bioturbators in this study. Is this paper about invertebrates or vertebrates disturbing soil? Depending on what type of animals are excavating soil, the extent of them digging may most likely differ significantly.

→ Thank you for drawing attention for the vague representation of bioturbators. We will include that the mounds created by the animals were from vertebrates and we will also cite a paper (Übernicket et al., 2021) which lists which bioturbators are present in Chile. This paper also draws attention to the fact that the distribution of Chilean burrowing mammal species changes with latitude and altitude along Chile. Because of that, the species in the four study sites are composed of 27 out of the total 45 Chilean burrowing vertebrates. In the research site Pan de Azúcar Übernicket et al. found 13 documented burrowing vertebrate species, in the research site Santa Gracia 13, in the research site La Campana 14 and in the research site Nahuelbuta 11 bioturbating vertebrate species. Thereby, Übernicket et al. documented that very few species are present along the entire studied gradient such as two foxes (*Lycalopex griseus*, *L. culpaeus*), two grass mice (*Abrothrix olivaceus*, *A. longipilis*), Darwin's leaf-eared mouse (*Phyllotis darwini*) and the introduced common house mouse (*Mus musculus*).

2) Hypothesis 3 is very similar to hypotheses 1 and 2 and needs to be more specific.

→ Thank you for this hint. We will rephrase the third hypothesis to separate it more from the first two hypotheses. We will write: "The impact on the macronutrient contents (such as C, N and P) through bioturbators is greater in the resource-limited arid region as bioturbation activity is higher due to the food and shelter need of the bioturbating animals than in the humid region harboring denser vegetation".

3) In the Method section the authors mention they used three study sites for this paper with arid, semi-arid and Mediterranean climate. However, there is no info what study site (i.e. Pan

de Azucar, Santa Gracia and La Campana) belongs to what climate. This info can only be found in the legends of the figures.

→Thank you for this comment. We will include the climates to the research sites within the methods text, too.

4) No info is provided on the size or volume of the mounds, or the percentage of the landscape that is covered by mounds. However, this may be important for small- and large-scale landscape effects. Also, how far away from mounds were the 'control' soil samples collected? How fresh/old were the samples collected from the mounds?

→Thank you for this question. We will cite the previous study (Kraus et al., 2022) which includes the mound volume (there it is called "excavated soil volume"). In addition, we will mention that the mounds and controls were very close to each other since they were collected from the same 10 m x 10 m plot. We can add that the excavated mound volume was highest in the semi-arid site Santa Gracia (9.1 ± 9.7 no/ 100 m^{-2}) and remained similar in the other three sites (Pan de Azúcar: 2.8 ± 2.9 no/ 100 m^{-2} , La Campana: 5.6 ± 8.7 no/ 100 m^{-2} , Nahuelbuta: 2.2 ± 2.1 no/ 100 m^{-2}). We will also mention that we cannot evaluate how old the samples were but the mound soil was moist and differed in color (we can also attach an exemplary photo) and this is why we can assume that the soil collected from the mounds was fresh.

5) Results are often based on 'raw data' in the supplemental material (Table S1 and S2) and graphs, but often lack statistical analysis to back them up. When statistics are provided the results turn out to be relatively weak or non-significant.

→The reviewer is correct in stating that our results are mostly weak or non-significant. Nevertheless, we are confident that our work adds to the role of bioturbators on physical and chemical soil properties as we also extensively discuss our results with previous work within the literature review (Supplementary table S10).

6) Some tables in the supplemental material are not mentioned in the text and could be omitted (i.e. S4, S6, S9). In general, tables could be combined, e.g. for silt/clay/sand and C/N. Info in some tables is missing, e.g. S3: no info on clay; S5, S7 and S8: the study site 'La Campana' is mentioned in the legend but not in the actual table. Other tables need more info: S2: how was the '%input' calculated and what does it mean? S10: what does '(zono-)biome' mean?

→Thank you for this advice, we will merge the tables on the results of the GLMMs S4, S5, S6, S7, S8 and S9 and through this reduce the supplementary material. We will explain how we calculated the percentage of input for the soil properties where we considered control as 100 percent and the added up the percentage of the mound soil sample. We will also explain that this is the enrichment due to bioturbation. In addition, we will include a brief definition of zonobiome which is "The group of biomes constituting a particular ecozone" in the caption of Table S10.

7) The results of the physical soil properties have been omitted from the discussion and are not mentioned at all. However, this should be discussed nonetheless.

→Thank you for this advice. In the lines 298-307 we discuss the physical soil properties but we now extended the discussion according to your advice can also elaborate this discussion more.

Specific comments:

Introduction

Line 95: Hagenah and Bennett 2013 worked in the Fynbos region which has a more Mediterranean-type if climate (MAP: 471 mm, MAT: 11-24 °C). Calling it 'arid region' is incorrect.

→Thank you for this comment, we will correct this mistake.

Line 101: there is an extra space after ...'from'. I would remove the commas in front of/behind 'arid'. There should be a comma behind 'regions'.

→Thank you for this improvement, we will correct this.

Lines 103-105: I do not understand this sentence. That needs to be rewritten.

→Thank you. We will rewrite this sentence to make it clearer: "Animals living in resource-rich environments, such as temperate regions, tend to require less energy investment in digging. Consequently, burrowing becomes an advantageous strategy for animals inhabiting areas with limited resources."

Lines 106-107: There is a mistake in this sentence. It should either read 'we aim to analyse **if** the magnitude of the impact... or 'we aim to analyse **to what degree the** impact of bioturbation...'

→Thank you, we will change this sentence as suggested.

Lines 109-110: '..' where bioturbation activity and its effects will appear on a larger scale'. What do you mean by this. This needs to be clarified.

→Thank you for this comment. We will now explain the scale aspect in more detail as follows: "if there is more bioturbation activity, we expect bigger impacts on soil properties".

Results

Lines 238-240: C and N increased along a climate gradient from Azucar to Campana. I do not see that in the figure provided. There are no stats to back this up. This is what I see in the graph: St. Garcia: lowest, Azucar: medium, Campana: highest.

→ Thank you. We will rewrite these sentences to explain the patterns the right way.

Lines 240-246: No stats are provided to back up this statement.

→ Thank you for this comment. According to your suggestion, we will now mention whenever results are only descriptive

Lines 249-250: ...'we present just silt, C and N here'. I do not understand what you mean by this. Please clarify.

→ Thank you. Here, we will include that we mean we just present silt, C and N out of all soil properties because some of them are correlated and thus, show similar patterns.

Lines 252-253:' Pan de Azucar explaining 5% of the model variation'... I do not see that in Table S5.

→ Thank you. We will include this result in table S5.

Lines 253-256:'silt content decreased in Santa Gracia and La Campana'... If the results are non-significant then there is no difference.

→ Thank you for this comment. We will omit this sentence now.

Line 255: 'In all research sites, the silt content increased with increasing hillslope'. What does that mean biologically? Is this relevant for your study?

→ We agree with the reviewer and will omit this result as it is not relevant for this study.

Lines 257-258: I do not understand what you are saying here since you speak in 'stats terms'. Rather write in a way that the reader can understand the biological meaning of the results.

→ Thank you for this comment. We will rephrase this sentence to make it easier to understand the statistics. It now reads: "The models for C and N contained the significant predictors mound density, vegetation cover and hillslope explaining 31% of the variation in the response variable (AIC = 730.6, $p < 0.001$, Supplementary Table S7)."

Line 258: ...'31% of the variation'....Where can I find this value? It is not in Table S7.

→ Thank you. We will do as suggested and include this result in table S7

Discussion:

Lines 287 and 289: should be 10% for semi-arid zone and 44% for Mediterranean zone according to the table provided.

→Thank you. We will again check and include the right value.

Lines 298-307: Depending on the 'age' of the mound soil that was collected, one should see a difference between disturbed and undisturbed soils. Maybe samples collected in this study were too old?

→Thank you. We will consider your comment for the discussion and add how we could assume that the mounds were freshly created due to the darker looser appearance of the soil.

Line 224-335: A lot of excavating animals dig in the soil in search for food, and not for shelter. However, since no info is provided what animals created the mounds in this study, it is hard to tell.

→Thank you. Like already mentioned before, we will provide a source where the different bioturbators in Chile are listed.

Table 1

The legend is missing info on the climate type of the three study sites.

The annual precipitation given for 2019 is rather low compared to the average which explains why 'La Campana' has been categorised as 'Mediterranean' climate (here: 63.8 mm, MAP: 367 mm).

→Thank you. We will consider these comments. We will include climate information in the legend. We can explain the low precipitation citing a paper (Garreaud et al., 2020) that shows that 2019 was an extremely dry year in central Chile.

Figure 1

More info needs to be provided in the figure legend. For instance, what are the stripes within and outside of the boxes for?

→Thank you. We will provide more information. We will also extend the table description with the median and standard deviations of the boxplots.

Figure 3

This figure is too small compared to figures 1 and 2. The way it is set up now, it is hard to read.

→ Thank you. We will increase the size of this figure.

###2nd referee

Thank you for the opportunity to review “Bioturbation enhances C and N contents on near surface soils in resource-deficient arid climate regions but shows adverse effects in more temperate climates” by Kraus et al. This paper is, in overall, an interesting work, but I believe that the manuscript should be rejected because there are quite many issues that I feel cannot be resolved by revisions.

The biggest issue is that the results do not contribute to testing the hypotheses in the paper. The hypotheses include big words like resource limitation, decomposition of OM, the accumulation of bioturbators’ excrements, and food and shelter need of bioturbating animals. However, none of these are carefully defined nor measured in this study.

The second issue is that the results and discussion are underachieved, considering the efforts described in the Methods. Apparently, LiDAR is available at the sites (line 170), but detailed morphological characteristics of hillslopes are missing, nor are the morphological characteristics of mounds. Grain size distribution should be available from Pario device, but only categorical grain size (% sand, silt, vs clay) is presented and compared. N- vs. S- facing plots were constructed, but no discussion of the difference between the slope aspects was made (no explanation about no discussion either). Mound densities in the plots could be interesting and were collected, but they were only presented as driving variable.

The third issue is that basic information about the site is oddly missing. For example, there is no discussion of the organisms responsible for bioturbation in general and for creating mounds in particular. Soil information is missing as well, while soil texture and major nutrient contents are the biggest part of the results.

There are also some odd expressions. It is not clear at all what “near surface soil”, a term that is used throughout the text, means. Also, the authors consider C as macronutrients along with N and P. It is also puzzling that only total N and P are considered while not all of total N and P are available for plant uptakes. This applies to the climate regimes of the sites. Table 1 suggests that all three sites have precipitations less than 64 mm per year, but they were described as arid, semi-arid, and Mediterranean. I also like to see a bit more careful referencing of published works. For example, in 299-305, several works were cited to form a possible explanation for a finding, but the required mechanisms are highly sensitive to the nature of mounds, climate, vegetation, slopes, etc. Are those cited studies share those that are similar to the study sites enough to provide explanations? I don’t know, but I hope I can learn obtain enough information on such questions.

Below, I list the issues line by line.

1. soil texture “by” either sorting or mixing. Insert “by.”

→Thank you for this comment. We will insert “by”.

2. The authors repeatedly say “physical properties” followed by clay, silt, and sand contents. I think the author can simply say either texture or grain size distribution.
3. The same applies to “chemical contents” followed by macronutrients C, N, and P. It can be simply written as “major nutrients (N and P) contents.”

→Thank you. We chose soil properties to refer to either chemical macronutrients or to physical soil compartments to make these terms comparable. But we will consider your suggestion.

4. According to table 1, the precipitation ranges from 9.4 mm to 63.8 mm. Those are all arid climates. How do the authors define arid, semi-arid, and Mediterranean?

→Thank you for this comment. To describe the climate of the research sites, we added Table 1 with different characteristics.

53-54: There are older and more classic papers on ecosystem engineering.

→Thank you. We will check for older and more classic papers on ecosystem engineering and here include them, such as Jones et al., 1994.

65-66: “at the surface at the near-surface soil”. This is an odd phrase. The authors keep using “near-surface soil” throughout the paper. What does it mean? Does it mean that soil is not at the land surface? Or are they referring to 0-5 cm or 0-10 cm or A or A and B horizons? I found this description very confusing.

→Thank you for this comment. Within the introduction, we will include a sentence on the near surface-soil which are the first few centimeters covering the organic soil layer and the upper part of the A-horizon.

71: I am not sure if it is a good idea to group C as macronutrients. Organic matter contributes to soil fertility, but it is not considered a nutrient.

→Thank you for this comment. However, previous already published studies also grouped C as a macronutrient.

74-76: However, many studies on exotic earthworms in N. America found the opposite.

→Thank you for this comment. We will include that we here just evaluated bioturbating vertebrates and so the focus is not on earthworms.

81-83: I don't know the literature cited. However, how does physical digging directly increase soil N? I am also surprised that bioturbators increase N in the soil by bringing up the N from deeper soil because total N content, most of time, decreases with increasing soil depth. What N (total N, organic N, Nitrates, etc) are the authors referring to?

→Thank you.

84-86: This sentence is difficult to understand.

→Thank you. We will rephrase the sentence (“This increase of N contents due to bioturbating animals is indirectly caused through the removal of N-enriched plants from the soil surface to either feed on them or to create burrows and dens.”) to make it easier to understand.

91-93: This sentence should be more specific about the soil materials brought up to enrich P.

→Thank you. We will consider your comment while rephrasing this sentence.

100-103: This does not make sense. The literature is clear in saying that bioturbation is more vigorous in temperate ecosystems than in arid ecosystems. Probably, the authors are referring to something else.

→Thank you for this comment. However, Wilkinson et al., 2009 summarized that bioturbation activity decreases from arid to temperate because arid regions are resource-limited. In a previous study of ours (Kraus et al., 2022), we saw the same pattern.

108: magnitude of bioturbation → magnitude of the impacts of bioturbation.

→Thank you. We will rephrase this sentence incorporating your advice.

114 and 135: comparable topography, size and geology in Chile. What is meant by “size”?

→Thank you. Here we mean that the study sites covered similar topographic areas. By “size”, we mean the size of the analyzed four catchments.

123: As far as I can tell, there is no examination or data related to “the decomposition of OM” and “the accumulation of bioturbators’ excrements” in this study. These two are not part of the hypothesis tested in this study.

→Thank you for this comment. You are right that we did not experimentally examine the decomposition of OC and the accumulation of bioturbators’ excrements. However, here we only use these terms to explain why incorporation of macronutrients might occur due to bioturbation.

127-128: This study does not look into “food and shelter need of the bioturbating animals”. This should not be a part of the hypothesis tested in this study.

→Thank you for the comment. However, here we only use the part about “food and shelter of the bioturbating animals” to explain why we expect to find differing patterns in varying climate regions.

126-128: The authors assume that the least precipitation site is more resource-limited. But no data is provided for the assumption. How is resource defined? How is limitation defined? I am puzzled that the resource limitation is a part of the hypothesis.

→Thank you for this comment. In the lines 100-103 we provide already published studies proving this pattern. We can elaborate explaining how resource and limitation are defined.

Study area:

- The paper's classification of arid, semi-arid, and Mediterranean does not seem to be in accord with the climate data in Table 1.

→Thank you for this comment. We will have a look at the classification and the table again and improve it.

- It is surprising that the study area description does not mention the animal species involved in bioturbation and their behavior. Who creates mounds and how?

→Thank you. We will provide a sourced (Übernicketl et al., 2021) that elaborates on the bioturbators in Chile.

- It is also surprising that the study area description does not discuss soil at all. What types of soils are found at those sites?

→Thank you for this comment. In the lines 138-139 we talk about soil classifications and cite the relevant paper for the study sites (Oeser et al., 2018). But we can broaden this description more.

Data collection

168: What is meant by "hillslope"? A hillslope has many characteristics that can be measured by LiDAR.

→Thank you. By "hillslope" we mean the slope along a hillside. We can include a better definition of the hillslope.

169-173: I don't see those data in the results. What are the reasons that the analyses of LiDAR and vegetation characterization are not shown? Are those cited papers method papers or the papers where those data were published? I cannot tell them by the way the sentences and citations were written.

→Thank you. Yes, those cited papers are the method papers that published these data. We wanted to cite the authors who provided these data and also to give the reader the opportunity to read how these data were taken or processed.

181: Any useful information in the coarse fragment data?

→Thank you. Since our focus are the fine fragments, we do not include coarse fragment data.

179-191: This tool allows continuous grain size distribution. Then why present only sand, silt, and clay contents? They could have compared full grain size distribution, which might show more differences between the sites. Those compartmentalized grain sizes may not tell you the complete story.

→ Thank you for this comment. However, just like previous published studies on the effect of bioturbation on soil texture, we were just interested in the finer soil compartments which are the ones that might be transported upward by bioturbation just like mentioned in the introduction.

Statistical analysis:

212: Mound density could have also been treated as a response variable. It remains unknown how the mound density differs between sites and between N- vs. S- facing slopes.

-The authors had the opportunity to compare N- vs. S-facing slopes, but this analysis was not done. I am curious why this analysis was not done.

→ While doing some previous analysis, we realized there is not difference between the slopes. This is why we did not consider slopes when conducting this study.

230-234: How are the literatures selected? How many? There should be some guidelines for the literature review here. Also it is a bit dissatisfactory that the outcomes from the literature review are featured only in the supplement.

→ Thank you. We tried to find an equal amount of literature for each zonobiome that we could. We will consider including the literature review in the paper itself instead of the supplementary.

249: What are the variables that are correlated? What do they suggest?

→ Thank you. In table S3, the correlated variables are printed in bold which are : C – P; C – N; clay – sand, clay – silt, silt – sand. As these variables are correlated, they should follow the same patterns. This is why we did not illustrate results of all of them.

263: “due to bioturbation” --> Does it actually mean “in mounds”?

→ Thank you. Yes, due to bioturbation means that the soil was taken from mound samples. We can change that phrase in the manuscript.

283: This C input should be defined more in detail and robustly. Does the term “input” imply that the difference is always due to additional materials that bioturbators add to the materials? Also, the C input is presented in a ratio (%), but the equation shows only subtraction.

→ Thank you. We will define C input better. By “C input” we mean the enrichment of C due to either the incorporation of food like plants or plant parts or feces. We will elaborate on the equation.

297-308: This explanation sounds more like wishful thinking. Soil erosion and vegetation patches are extremely heterogeneous in arid environments and site-specific. Therefore, it is important to assess the relevance of the locations, erosion mechanisms, and vegetation of the cited studies.

→Thank you for this comment. We will rephrase this paragraph considering your additional information.

322-324: This explanation appears as wishful thinking. The relative turnover time of those elements depends on the forms or fractions of P, N, and C. There are no measurements on those in this study.

→Thank you. We will consider rewriting this sentence including your information.

1. This study does not address this hypothesis given that there is no definition and no measurements of concomitant available resources.

342-344: According to the methods, this study has vegetation data. Oddly, the authors do not use the data. Instead, they cite published studies. Also, those potential mechanisms do not include the potential variability of soil properties.

→Thank you. We use the vegetation data we obtained like mentioned in the lines 170-171.