

***Interactive comment on “Reviews and syntheses:
²¹⁰Pb-derived sediment and carbon accumulation
rates in vegetated coastal ecosystems: setting the
record straight” by Ariane Arias-Ortiz et al.***

Ariane Arias-Ortiz et al.

ariane.arias@uab.cat

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Dear Dr. Sarin,

Below, please find our response to the comments raised by the reviewers to the manuscript entitled “Reviews and syntheses: ²¹⁰Pb-derived sediment and carbon accumulation rates in vegetated coastal ecosystems: setting the record straight”, along with a description of the changes we suggest to improve the manuscript. We are very grateful to the reviewers for their thoughtful and constructive comments and we address below each of the points they raised.

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Ariane Arias-Ortiz on behalf of the authors

RESPONSE TO COMMENTS BY ANONYMOUS REFEREE #3

General comments: Overall, a very valuable contribution to the literature. This is a helpful synthesis of the literature that will be a go-to for those in the field, and it is also an interesting modeling exercise that sheds light on the processes producing various ^{210}Pb patterns. My main concern is that the manuscript provides an overly optimistic view of the errors associated with complex ^{210}Pb profiles, for reasons explained below.

We sincerely thank the reviewer for acknowledging the interest of our work as well as for his/her constructive comments, which were very helpful in improving the manuscript. We will include in the revised manuscript a more throughout discussion showing the implications of estimating accumulation rates in complex ^{210}Pb profiles.

1. Specific comments: As the authors note in Table 4, patterns II, III, and IV can have multiple causes. Especially common, and especially problematic, is the difficulty in distinguishing between mixing and an increase in MAR. The simulation studies in this paper don't address this adequately because they separate the mixing simulations from the increased sedimentation simulations. For the mixing simulations, for example, "the CF:CS model was applied below the depth of the visually apparent SML (3 cm) in scenarios A and B to avoid overestimation of MAR" (Appendix). But if you didn't know this profile was created by mixing, how would you know that you would be overestimating MAR rather than accurately estimating an increase in MAR? In other words, in the real world, how would you know whether it was mixing (so leave out the SML) or increased MAR? True, the mixing and increased sedimentation profiles in Figure 3 do look somewhat different, but I am not convinced that in the real world they are so easily distinguished. Bottom line: I am concerned that if the authors tested the error in non-ideal profiles without knowing what caused them, they would find higher errors than those shown in Figure 5.

RESPONSE: We agree that mixing and increasing mass accumulation rate processes

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are difficult to distinguish, however there are some complementary analyses that can help to distinguish each of these processes. Such actions/analyses are explained in section 4, particularly in subsections 4.1, 4.2 and 4.3 of the original version of the manuscript (pages 12-15). We think it is indeed interesting to show to the reader the consequences of mismatching the process and how they translate in higher errors in sediment and Corg accumulation rates (CAR).

ACTIONS after Editor's consideration: In the revised version of the manuscript we will run the ^{210}Pb models in mixing simulations assuming that the observed anomalies were caused by increased mass accumulation rates and vice versa in increasing sedimentation simulations. We will add a discussion in section 3.2.6 "General remarks" (page 11, following line 20) related to the resulting MAR and CAR if the incorrect process is assumed and dating models are applied. CAR results of incorrect process interpretation will be also plotted in Figure 5 so the reader can easily be aware of the potential errors associated if the processes causing anomalies in ^{210}Pb concentration profiles are not well identified. In addition, we will reorganize section 4 according to the processes simulated in section 3 (mixing, increasing MAR, erosion, changes in grain size and OM decay). Thus, the alternative analyses and potential actions will be merged into a single section so it is straightforward for the reader to pick actions to identify each of these processes. Section 4 will be restructured as follows:

"4. Approaches and guidelines

4.1 General validation of ^{210}Pb models

- Artificial radionuclides
- Geochemical information of sediments

4.2 Mixing or Rapid sedimentation

- Geophysical analyses (i.e, X-ray radiographies, CAT scans)
- Short-lived radionuclides

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- Geochemical element profiles

4.3 Erosion

- Excess ^{210}Pb inventories in reference and disturbed sites

4.4 Heterogeneous sediment composition

- Normalization of excess ^{210}Pb profiles

- ^{226}Ra profiles"

2. Related to the above: the authors choose not to create a CRS estimate for the profiles with erosion. That is fine as long as one knows that erosion is a factor. In the real world, minor deviations from the ideal inventory (especially the small ones shown in the tidal marsh half of Figure 3c) do not generally preclude investigators from applying the CRS method. I would strongly encourage the authors to apply CRS to these profiles to get a sense of how large the associated errors are. At a minimum, they should caution others not to use the CRS method with profiles that show deviations from the expected inventory.

RESPONSE and ACTIONS: We agree and we will also apply the CRS model to the simulated eroded profiles and plot the results in Figure 5. Additionally, in section 3.2.6 "General remarks" (page 11), text will be added to emphasize those problems associated to the application of the CRS model in incomplete sediment records, and the even older ages for deeper sections and the bias in calculated MAR and CAR as explained by MacKenzie et al. (2011).

REFERENCES:

-MacKenzie, A. B., Hardie, S. M. L., Farmer, J. G., Eades, L. J. and Pulford, I. D.: Analytical and sampling constraints in ^{210}Pb dating, *Sci. Total Environ.*, 409(7), 1298–1304, doi:10.1016/j.scitotenv.2010.11.040, 2011.

3. The authors use their results to suggest in Figure 5 and Table 4 that pretty much any

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^{210}Pb profile is dateable (except those with extreme OM concentrations). However, in the real world, some profiles are likely to be altered in more complex ways than the simulations shown here – by mixing and erosion and different grain sizes. I believe that some profiles may just be too altered to be retrievable, and would suggest using extreme caution in interpreting Types V, VI, and VII. Section 4 of the paper is very helpful in suggesting alternative approaches that can help disentangle various factors, but it is in tension with Figure 5 (and the abstract), which suggest that those are not necessary, since maximum error is only 20% anyway.

RESPONSE: This is correct, and we probably failed to capture this point in the original version of the manuscript. Although some research reports extremely altered sediment profiles, these are few since a literature bias exists towards those profiles where dating or MAR estimates could be achieved. However, as the reviewer comments, more often than not, some profiles are likely to be altered by a composite of processes, leading to types V and VI. This is especially true in seagrass ecosystems that present lower sedimentation rates and can occur in sand-dominated substrates, where ^{210}Pb is less preferentially adsorbed. For instance, Saderne et al. (2018) collected 9 and 11 sediment cores in seagrass and mangroves of the Red Sea, respectively, but none of the seagrass and only 4 of the mangrove sediment cores were useful for the determination of MAR and CAR. In the revised version of the manuscript we will capture this point raised by the reviewer through 3 main actions (see below)

ACTIONS after Editor's consideration:

- We will modify the deep mixing simulation (scenario C) so mixing influences the entire excess ^{210}Pb profile to simulate type V profile forms. Both results, assuming the process causing this anomaly in the ^{210}Pb profile is mixing or fast accumulation rate, can be plotted in Figure 5, which indeed will increase the errors associated to the estimation of mean MAR and CAR. Text in the abstract and in the results section "3.2.6 General remarks" of the original version of the manuscript will be modified accordingly.

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- Section "4. Approaches and Guidelines" will include a short text recommending being critical with the data and acknowledging when a profile is not datable. Text will read: "Using the above procedures, it has been possible to determine mean accumulation rates and, in some instances, also obtain credible chronologies. However, we should be especially cautious in those sites where sediments might be altered by multiple processes (leading to profile types V or VI) and where other chronological tools are not available (e.g., ^{137}Cs). Sites/Cores that have slow accumulation rates and/or intense mixing are unlikely datable, since the excess ^{210}Pb concentration profiles may be unsolvable and overprinted by other post-depositional processes. Environments with complex sedimentation that results in significant variations in grain size and irregular deposition (e.g., hiatal surfaces or erosion) may also be difficult or impossible for calculating accumulation rates. Mistakes would include assigning discrete ages in mixed sediments or extrapolate an age-depth model for a core that should be considered undatable to depths down the core or to nearby sites."

- In Table 4, a new recommended action will be added for profile types V, VI provided the other recommended actions fail: "Acknowledge that the core cannot be used for geochronology/ MAR and CAR cannot be estimated accurately".

REFERENCES:

- Saderne, V., Cusack, M., Almahasheer, H., Serrano, O., Masqué, P., Arias-Ortiz, A., ... & Duarte, C. M. (2018). Accumulation of carbonates contributes to coastal vegetated ecosystems keeping pace with sea level rise in an arid region (Arabian Peninsula). *Journal of Geophysical Research: Biogeosciences*, 134, 1498-1510.

4. It would be helpful if the Supplementary Tables in Excel had formulas rather than just values, to make it easier to understand how the simulations were done.

RESPONSE: We agree and we will add formulas in the supplementary Tables.

5. I think the authors could emphasize more strongly that they are looking at the 100-

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year average MAR and Corg-MAR, not the patterns over time. For example, the y-axis in Figure 5 (or at least the figure caption) could say “100-year Corg burial.”

RESPONSE: We agree with the reviewer and in the revised version of the manuscript we will make this point clearer, not only in Figure 5 but also in the Methods and Results sections of the revised version of the manuscript.

ACTIONS after Editor’s consideration:

- In the Methods section “2.2 Numerical simulation” (page 6) text will be added (line 22) “The CF:CS and CRS dating models were applied to altered excess ^{210}Pb profiles to determine the average MAR for the last century.”

- In the Results section “3.2 Simulated sediment and Corg accumulation rates (MAR and CAR)” (page 8) text will be added in line 7 “We estimated mean 100-yr MAR and CAR for the simulated profiles by applying the CF:CS and CRS models, and results were compared with those from their respective ideal non-disturbed ^{210}Pb profiles.”

- In the Results section “3.2.6. General remarks” (page 11; line 11), text will be added: “Among ecosystems, average last 100-yr MAR and CAR derived from both the CF:CS and the CRS models were less vulnerable to anomalies in mangrove/tidal marsh compared to seagrass sediments” and in lines 16-17 “The decay of OM in very rich organic sediments (> 50% OM) was the process that caused the largest deviations in average 100-yr MAR and CAR in all ecosystems”.

- In Figure 5, the figure caption will be modified to read as “Figure 5. Ratio of average 100-yr Corg accumulation rates (CAR) between simulated and ideal ^{210}Pb profiles produced by various sedimentary processes. (a) seagrass and (b) mangrove/tidal marsh habitats.”

6. Does this analysis only apply to Corg burial? There will be an audience interested in the equivalent of Figure 5 for the MAR itself, which presumably would be easy to make.

RESPONSE: The ratio between ideal vs. disturbed CAR (Fig. 5) mostly represents

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variations in MAR, therefore Figure 5 would look similar for MAR ratios between ideal and disturbed profiles as it is explained in the Figure 5 caption in the original version of the manuscript. For our simulations the C content was considered to be the same in both the disturbed and the ideal excess 210Pb profiles, meaning that the mixed sediments or the newly deposited ones had same Corg (%DW) as those in the ideal non-disturbed profile (2.5% in seagrass sediments and 8% in mangrove/tidal marsh sediments). While any disturbance of the sedimentary record would also affect Corg concentrations due to changes in biogeochemical processes within sediments, the potential and magnitude of such effects is unclear, and therefore, they were not considered here. The aim of the manuscript is to estimate how errors in the estimation of MAR using 210Pb would affect resulting CAR rates and how these errors can be minimized.

ACTIONS after Editor's considerations:

-We will modify Figure 5 caption to make the point above clearer: "Figure 5. Ratio of average 100-yr Corg accumulation rates (CAR) between simulated and ideal 210Pb profiles produced by various sedimentary processes. (a) seagrass and (b) mangrove/tidal marsh habitats. Error bars represent SE of the regression and SE of the mean using the CF:CS and CRS models, respectively. Ratios of simulated/ideal sedimentation rates (MAR) are equal to those of CAR, determined from multiplying MAR by the fraction of Corg in sediments (Eq. 3), which was considered constant between ideal and simulated profiles. In simulations of increasing sedimentation and organic matter decay, new MAR and CAR were estimated for ideal 210Pb profiles to represent real changes in accumulation, organic matter decay and associated changes in sediment mass with depth."

- We also will add text in the results section where Figure 5 is referenced (page 8, lines 8-10) "The estimated deviations in accumulation rates from those expected under ideal conditions are shown in Figure 5 for seagrass and mangrove/tidal marsh ecosystems. These deviations are driven by variations in MAR estimates caused by anomalies in the 210Pb concentration profiles."

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- And in the Methods section (page 6; lines 21-27): "...the Corg accumulation rate (CAR) was estimated through equation 3 assuming average sediment Corg contents of 2.5% and 8% in seagrass and mangrove/tidal marsh, respectively, in both ideal and simulated sediment profiles".

7. Table 4 is too long and repetitive; there must be a way to condense it, since the options for each outcome are the same.

RESPONSE: We agree with the reviewer. Actions after Editor's consideration: We can present the information in Table 4 using a diagram rather than a table. Please, see the figure attached to the author's response.

8. I found the boxes helpful, except for Box 4, which is different from the others and not necessary in my opinion.

RESPONSE: We agree and will remove Box 4 from the current version of the manuscript after Editor's consideration.

9. I understand the logic of including the methods in an appendix – mostly because they are quite long and detailed. But it is important for the reader to understand what the authors are doing. The authors might consider including in the methods a more detailed description than what is there now (but still less detailed than in the appendix).

RESPONSE: Since the manuscript is already long and dense, the addition of a description of each simulation would be repetitive to what is in the appendix. Table 3 summarizes each simulation, while also being included in the Methods section.

ACTIONS after Editor's consideration: We will add further details in section "2.2 Numerical simulations" in the original version of the manuscript (page 6, lines 21-22). Text will be modified to read: "Ideal profiles were then altered to simulate the following processes/scenarios: mixing (surface and deep mixing), increasing sedimentation (by 20%, 50%, 200% and 300%), erosion (recent and past), changes in sediment grain size (coarse and heterogeneous) and OM decay (under anoxic and oxic conditions,

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and with labile OM contribution in sediments containing 16.5% and 65% OM). See Table 3 for a summary description of the modelled scenarios and refer to Appendix A for a detailed description of the methodology used to perform each simulation.”

10. Section 2.1 doesn't seem like it should be in the methods.

RESPONSE: We agree with the reviewer that most of the information would be best located in the introduction section.

ACTIONS after Editor's consideration: We will move section 2.1 to the introduction as a new section 1.1. ²¹⁰Pb dating models. The equation and methods to estimate Corg accumulation rates (page 5, lines 24-28), however, will be kept in the Methods section.

11. The authors mention a literature review several times, but the only detail is provided on p. 4 line 27ff. in establishing that CIC, CRS, and CFCS are the most commonly used approaches. Is this the same literature review that was used to construct Figure 2? Please clarify. Also, they probably missed some of the literature by not including the term Pb-210, which is sometimes used instead of ²¹⁰Pb. (There are almost certainly more than 150 uses of ²¹⁰Pb in the salt marsh literature.)

RESPONSE: The publications we used to construct Figure 2 are cited in section "3.1 Types of excess ²¹⁰Pb concentration profiles" (page 6-7) and in the caption of Figure 2. These examples are part of the literature review but more cases could be cited, especially for mixing types II, III and IV in all vegetated coastal ecosystems. We believe that the examples provided are representative of the diversity of ²¹⁰Pb concentration profiles encountered by researchers. The web of Science search was a simple search meant to identify the dating models generally used in vegetated coastal ecosystems, while showcasing examples of the sedimentary processes driving ²¹⁰Pb distribution. We agree with the reviewer that we missed some tidal marsh and mangrove studies by not including the term Pb-210 or lead-210. Using the keywords mangrove sediment, salt marsh/saltmarsh/tidal marsh sediment, seagrass sediment AND ²¹⁰Pb/Pb-210/lead-210 produces 85, 198 and 26 results, respectively for each ecosystem.

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ACTIONS after Editor's consideration:

- We will update our search in the Web of Science for all ecosystems also including the term Pb-210 and lead-210.

- In section "3.1 Types of excess 210Pb concentration profiles" we will modify the statement in page 7 lines 32-33 "Our literature review reveals that various sedimentary processes might produce similar types of excess 210Pb concentration profiles" to "These examples identified from the literature reveal that various sedimentary processes might produce similar types of excess 210Pb concentration profiles".

- A clarification will be added in Figure 2 caption: "Figure 2. Sketch of seven sedimentary types of excess 210Pb concentration profiles in sediments from vegetated coastal habitats identified from the literature (see references included) . . .".

12. The reason for excluding the CIC method – the absence of ideal profiles – is not persuasive as currently expressed. The other methods also suffer when there are deviations from the ideal profile, which is exactly what the authors explore. Perhaps more of a justification for excluding CIC could be given?

RESPONSE: In most sediment systems, variations in accumulation rate may occur in response to natural processes or anthropogenic influences. Under some such circumstances, the CRS or CIC models could be suitable, but more often than not, the CRS model is applied as it usually yields more reasonable results than that of the CIC in both fresh and marine environments (Appleby, 2008; Appleby et al., 1983; Breithaupt et al., 2014; Oldfield et al., 1978). The application of the CIC model requires a monotonic decrease in excess 210Pb concentrations with depth that usually occur in lakes but rarely occur in coastal environments. Sediment disturbances like mixing or changes in the sedimentation rate may result in excess 210Pb activities leading to age reversals that prevent the construction of an age model. The CRS model, in contrast, suffers less with non-monotonic features in the 210Pb record and is relatively insensitive to mixing (Appleby and Oldfield, 1992). Because of the general preference and widely applica-

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tion of the CRS model over the CIC model under varying sediment accumulation rates we excluded the CIC model in our simulations.

In some cases, the CIC model could be preferred over CRS model. These are locations where primary sedimentation rate has remained relatively constant (we still observe a monotonic decrease in excess ^{210}Pb specific activities) but there is a hiatus in the sediment record caused by an erosion event, where sediment focusing is a major factor or where there have been major hydrological changes. However, these approaches are site specific and each data set must be evaluated independently for consistency with one or other of the dating models.

ACTIONS after Editor's consideration:

- We will remove the statement in page 5, lines 6-8 that points to CIC as not being appropriate to date vegetated coastal sediments and we will change it for: "The variability of accumulation rates, the progressive loss of matter because of organic matter degradation, and the post-depositional sediment disturbances causing variations in the initial ^{210}Pb concentration have resulted in the CRS model being the most widely used means of deriving ^{210}Pb chronologies".

- Then, text will be added after the description of the CRS model (page 5, lines 16-21) to highlight the situations where the CIC model might be preferred "Although the CRS model often yields more reasonable results than that of the CIC in both fresh and marine environments (Appleby, 2008; Breithaupt et al., 2014; Oldfield et al., 1978; Sanders et al., 2016), the CIC model might be preferred at locations where sediment focusing is a major factor, significant hydrologic changes have occurred or there are hiatus in the sediment record caused by erosion events (Appleby, 2008). These approaches are site specific and each data set must be evaluated independently for consistency with one or other of the dating models, and therefore the CIC model has been excluded from the simulations presented in this study."

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- Appleby, P. G.: Three decades of dating recent sediments by fallout radionuclides: a review, *The Holocene*, 18, 83–93, doi:10.1177/0959683607085598, 2008.

- Appleby, P. G. and Oldfield, F.: Applications of lead-210 to sedimentation studies, in *Uranium-series disequilibrium: applications to earth, marine, and environmental sciences*, edited by M. Ivanovich and R. Harman, Clarendon Press, Oxford., 1992.

- Appleby, P. G., Oldfield, F. and Physics, T.: The assessment of 210Pb data from sites with varying sediment accumulation rates, *Hydrobiologia*, 103, 29–35, doi:10.1007/BF00028424, 1983.

- Breithaupt, J. L., Smoak, J. M., Smith, T. J., Sanders, C. J., Smoak, J. M., Smith, T. J. and Sanders, C. J.: Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades, *J. Geophys. Res. Biogeosciences*, 119, 2032–2048, doi:10.1002/2014JG002715, 2014.

- Oldfield, F., Appleby, P. G. and Battarbee, R. W.: Alternative 210Pb dating: results from the New Guinea Highlands and Lough Erne, *Nature*, 271(5643), 339–342, doi:10.1038/271339a0, 1978.

13. I'm not sure the distinction between Types VI and VII is necessary. They are both characterized by low inventories, regardless of profile shape.

RESPONSE: We do not agree, type VI show an extreme situation with almost negligible excess 210Pb concentrations that in most of the cases will be undatable. Type VII, because of sediment erosion, might be undatable too, but some researchers may not consider erosion and date it anyhow. We would like to keep the distinction of the two profile types in the revised version of the manuscript after Editor's consideration.

RESPONSE TO COMMENTS BY ANONYMOUS REFEREE #4

The review paper presented by Arias-Ortiz discuss the use of the 210Pb dating technique to estimate the rate of mass accumulation in vegetated coastal ecosystems.

Such information is indeed very important in considering the significant role of vegetated coastal habitats (tidal marsh, mangrove, seagrass) as sinks of carbon. Over the last 150 years, ^{210}Pb is the only tool that permits to calculate sediment and carbon accumulation rates (SAR/CAR) in such environments. However, the application of the ^{210}Pb -based method is not tricky in these environments. The authors aim to illustrate the models usually applied to calculate SAR or MAR in these setting. This article is extremely timely as there is a growing interest in better estimate C source/sink. The authors are presenting in a correct way the principle and the conditions of the ^{210}Pb method. Although the article is mostly dedicated to the models, there are some recommendation on the ^{210}Pb determination and a comment of the interest of additional time marker (like ^{137}Cs) or normalisation.

We sincerely thank the reviewer for acknowledging the interest of our work as well as for his/her comments, which were very helpful in improving the paper.

1. In fact I regret that the authors do not develop the experimental section. Indeed, it would be of great interest to provide recommendations about sampling: core description, porosity determination etc.

RESPONSE to comment 1 and 4: Since questions 1 and 4 of reviewer #4 target the same issue (i.e. development of an experimental section prior to ^{210}Pb analyses), we addressed them together below.

Discussing sampling and sample-handling is not a simple task that should include plenty of aspects if it is done properly. For instance, estimation of porosity, dry bulk density, which types of corers to use, how to extrude or slice the sediment, preservation of the interface or a discussion of the analytical methods. Some available manuals/chapters dealing with all these aspects already exist, such as Brenner and Kenney, (2013) or IAEA-TECDOC-1360, (2003), and we will cite them in the revised version of the manuscript to provide the reader with additional guidelines for coring, sampling and sample-handling. However, developing the above-mentioned aspects goes beyond the

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scope of the manuscript. We, however, agree in adding some guidelines to consider the type of sample, which is related to reviewer's comment 4.

ACTIONS after Editor's consideration: We will modify the text in section 4. Approaches and Guidelines (page 12, lines 1-15) to briefly develop some basic sampling and sample-handling procedures to achieve good ^{210}Pb profiles. We also will provide some references that the reader could use to expand on the topic such as Brenner and Kenney (2013) and IAEA-TECDOC-1360 (2003). The suggested text will read as:

“Researchers can have control over some factors such as coring, sampling, or sample-handling, that can create artifacts in ^{210}Pb profiles and contribute to dating error. Guidelines for core sampling for the analysis of ^{210}Pb and other radionuclides have been described in detail, for example, in Brenner and Kenney (2013) and in IAEA technical report IAEA-TECDOC-1360 (2003). Some knowledge on the expected sedimentation rate is useful to decide how to section a sediment core for ^{210}Pb measurements, as well as the length that a core must have to reach the excess ^{210}Pb horizon. Core sectioning should be planned such appropriate resolution in terms of ^{210}Pb dating is achieved, reconciling what is technically feasible while securing enough material to conduct analyses of ^{210}Pb and other parameters (e.g., grain size, other radionuclides, metals, organic matter or nutrients) (IAEA-TECDOC-1360, 2003). Low sedimentation rates ($\sim 1\text{-}2\text{ mm yr}^{-1}$) mean that the entire excess ^{210}Pb inventory will be captured in the uppermost 20 cm of the sediment. In such situation, fine sectioning intervals (0.5 - 1 cm) are required. Longer cores (of about 100 cm) should be collected if high sedimentation rates are expected (several mm yr^{-1}) and these can be sliced at thicker intervals, without compromising the temporal resolution of the ^{210}Pb record. If sedimentation rates are not known a priori, it is best to choose fine sampling intervals (e.g., at 0.5 cm along the upper 20 cm and at 1 cm below 20 cm) to ensure sufficient resolution. After collection, a visual description (e.g., colour, texture, presence of roots, organisms or layers) of the sediments contained in the corer and measurement of parameters such as water content, organic matter or grain size are relatively low-cost actions that

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provide information to interpret ^{210}Pb distribution. Indeed, the type of sediment (e.g., fine vs. coarse, rich in carbonates, homogeneous or with organic debris embedded) is a factor that should be considered (IAEA-TECDOC-1360, 2003). Reliable sedimentation histories are difficult to obtain in vegetated coastal sediments consisting of coarse particles or coarse-grained carbonates where excess ^{210}Pb is less preferentially adsorbed (Wan et al., 1993). In such situations, the analysis of ^{210}Pb in the smaller sediment fraction (i.e. $< 63\mu\text{m}$ or $< 125\mu\text{m}$) is recommended to concentrate ^{210}Pb and reduce the dilution effect caused by coarse fractions. This methodology has been applied in mangrove ecosystems from arid regions (Almahasheer et al., 2017) where excess ^{210}Pb flux is very low, and in Florida Bay carbonate-rich seagrass sediments (Holmes et al., 2001). Similarly, large organic material such as roots and leaves should be removed from the sediment samples prior to ^{210}Pb analyses as these will contribute to the dilution of the excess ^{210}Pb specific activities.”

REFERENCES:

- Brenner, M. and Kenney, W. F.: Dating Wetland Sediment Cores, in *Methods in Biogeochemistry of Wetlands*, edited by R. D. DeLaune, K. R. Reddy, C. J. Richardson, and J. P. Megonigal, pp. 879–900, Soil Science Society of America, Madison., 2013.
- IAEA-TECDOC-1360: Collection and preparation of bottom sediment samples for analysis of radionuclides and trace elements., International Atomic Energy Agency, IAEA, Vienna., 2003.
- Almahasheer, H., Serrano, O., Duarte, C. M., Arias-Ortiz, A., Masque, P. and Irigoien, X.: Low Carbon sink capacity of Red Sea mangroves, *Sci. Rep.*, 7(1), 9700, doi:10.1038/s41598-017-10424-9, 2017.
- Holmes, C. W., Robbins, J., Halley, R., Bothner, M., Brink, M. Ten and Marot, M.: Sediment dynamics of Florida Bay mud banks on decadal time scale, *Bull. Am. Paleontol.*, 361, 31–40, 2001.

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- Wan, G. J., Liu, J. and Li, B.: The Isotopic Character and the Remobilization of Lead at the Top of Sediment in Erhai, Chinese Sci. Bull., 38(2), 139–142, doi:10.1360/sb1993-38-2-139, 1993.

2. It is also important to precise more clearly the advantage of gamma counting compared to alpha counting. In addition to avoid chemistry step, gamma spectrometry has the major advantage to determined simultaneously ^{210}Pb and its supported parent (^{226}Ra), ^{137}Cs , ^{228}Th , ^7Be , ^{40}K among others.

RESPONSE: Both gamma and alpha counting have pros and cons. Gamma counting avoids the radiochemical step, allows determining the concentrations of various radionuclides simultaneously and sample preparation is nondestructive. However, it has higher limits of detection compared to alpha spectrometry, requires relatively large amount of sample and requires correction for self-adsorption at low energies (i.e. for Pb-^{210}). Indeed, the efficiency calibration is not straightforward. In addition, gamma detectors are costly compared to alpha detectors, and this fact can limit the number of detectors a laboratory can have and thus the sample throughput. Most often, the analysis employed is dependent on the instrument availability of the laboratory, therefore in our manuscript we did not provide with details about the measuring techniques of ^{210}Pb . However, in the revised version of the manuscript, we will add some text about the advantage of using gamma spectrometry in the determination of ^{226}Ra , as the referee suggested in comment 12, below.

ACTIONS after Editor's consideration:

- We will state more clearly where to find the information about measuring approaches in the revised manuscript. Text that is in page 14, lines 11-12 in the current version will be modified to read: "(for a detailed description of the laboratory analysis of these radioisotopes and advantages and disadvantages of each method see Corbett and Walsh (2015) and Goldstein and Stirling (2003))".

- Then we will highlight the advantage of gamma compared to alpha spectroscopy in

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section 4.4. ^{226}Ra concentration profiles (page 15, lines 4-6) of the current version of the manuscript, text will be modified to read: “Excess ^{210}Pb concentrations are determined by subtracting supported ^{210}Pb to total ^{210}Pb concentrations assuming it is in equilibrium with ^{226}Ra . This is straightforward when gamma spectrometry is employed since the total ^{210}Pb and supported ^{210}Pb (i.e., ^{226}Ra) can be quantified simultaneously. In occasions, particularly when ^{210}Pb is determined by alpha spectrometry, ^{226}Ra is not measured, and supported ^{210}Pb is most often determined from the region of constant and low ^{210}Pb concentrations at depth, or alternatively, from a number of determinations of ^{226}Ra via gamma spectrometry or liquid scintillation counting (LSC)”.

REFERENCES: - Corbett, D. R. and Walsh, J. P.: ^{210}Pb and ^{137}Cs : establishing a chronology for the last century, in Handbook of Sea-Level Research, edited by I. Shennan, A. J. Long, and B. P. Horton, pp. 361–372, John Wiley & Sons, Ltd., 2015.

- Goldstein, S. J. and Stirling, C. H.: Techniques for measuring uranium-series nuclides: 1992-2002, Rev. Mineral. Geochemistry, 52, 23–57, doi:10.2113/0520023, 2003.

3. I am surprised that the authors mentioned ^{228}Th as a potential dating/bioturbation tracer. In such coastal environment, I usually use ^{228}Th as ^{232}Th its grandfather to trace the detrital fraction. It is a good way to normalize also radionuclide activities.

RESPONSE: The use of ^{228}Th as indicated by the reviewer is a possibility, indeed. But then, excess ^{228}Th has been also used to determine sedimentation and mixing rates in coastal sediments (Hancock and Hunter, 1999; Huh et al., 1987). In vegetated coastal ecosystems some researchers have used excess ^{228}Th to estimate fast rates of particle deposition in mangroves (e.g., Alongi et al., 2005) or, together with ^7Be and ^{234}Th , mixing (Sharma et al., 1987; Smoak and Patchineelam, 1999). In section "4.6 Normalization of excess ^{210}Pb concentrations and sieving of sediments" of the original version of the manuscript we suggest the normalization of ^{210}Pb profiles to organic matter content, grain size, or aluminum that traces the lithogenic fraction as

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well, as these are the most common variables used to normalize ^{210}Pb profiles in the literature.

ACTIONS after Editor's consideration: we will add text in section 4.1 Short-lived radionuclides (^{234}Th , ^{228}Th , ^7Be) (page 12) to explain briefly the origin of excess ^{228}Th . "A constraint to the use of excess ^{228}Th is that sediments must contain a lithogenic/detrital fraction, as is mostly the case in vegetated coastal sediments."

REFERENCES:

- Alongi, D. M., Pfitzner, J., Trott, L. a., Tirendi, F., Dixon, P. and Klumpp, D. W.: Rapid sediment accumulation and microbial mineralization in forests of the mangrove *Kandelia candel* in the Jiulongjiang Estuary, China, *Estuar. Coast. Shelf Sci.*, 63, 605–618, doi:10.1016/j.ecss.2005.01.004, 2005.
- Hancock, G. J. and Hunter, J. R.: Use of excess ^{210}Pb and ^{228}Th to estimate rates of sediment accumulation and bioturbation in Port Phillip Bay, Australia, *Mar. Freshw. Res.*, 50(6), 533, doi:10.1071/MF98053, 1999.
- Huh, C.-A., Zahnle, D. L., Small, L. F. and Noshkin, V. E.: Budgets and behaviors of uranium and thorium series isotopes in Santa Monica Basin sediments, *Geochim. Cosmochim. Acta*, 51(6), 1743–1754, doi:10.1016/0016-7037(87)90352-8, 1987.
- Sharma, P., Gardner, L. R., Moore, W. S. and Bollinger, M. S.: Sedimentation and bioturbation in a salt marsh as revealed by ^{210}Pb , ^{137}Cs , and ^7Be studies, *Limnol. Oceanogr.*, 32(2), 313–326, doi:10.4319/lo.1987.32.2.0313, 1987.
- Smoak, J. M. and Patchineelam, S. R.: Sediment mixing and accumulation in a mangrove ecosystem: evidence from ^{210}Pb , ^{234}Th and ^7Be , *Mangroves Salt Marshes*, 3, 17, 1999.

4. I think it is also important to point out the need to well consider the samples. In the case of sediments presenting coarse fraction or vegetal debris, it could be useful to separate the fine sediment fraction, that supports ^{210}Pb , from the other fractions (that

dilute its activity). In fact it is the first step to do: how to obtain the best ^{210}Pb profile depending of the sediment. It could help to reduce variability in the ^{210}Pb profile. The authors need to develop this aspect. In fact I am convinced that some model adaptations are not required if sampling and measurements are done in an appropriate way (see figure panel D why measure with the sandy fraction).

RESPONSE: We agree in adding some guidelines to consider the type of sample, since this was also raised in comment 1, we paste here the relevant text

ACTIONS after Editor's consideration: We will modify the text in section 4. Approaches and Guidelines (page 12, lines 1-15) to briefly develop some basic sampling and sample-handling procedures to achieve good ^{210}Pb profiles. The suggested text will read as: "After collection, a visual description (e.g., colour, texture, presence of roots, organisms or layers) of the sediments contained in the corer and measurement of parameters such as water content, organic matter or grain size are relatively low-cost actions that provide information to interpret ^{210}Pb distribution. Indeed, the type of sediment (e.g., fine vs. coarse, rich in carbonates, homogeneous or with organic debris embedded) is a factor that should be considered (IAEA-TECDOC-1360, 2003). Reliable sedimentation histories are difficult to obtain in vegetated coastal sediments consisting of coarse particles or coarse-grained carbonates where excess ^{210}Pb is less preferentially adsorbed (Wan et al., 1993). In such situations, the analysis of ^{210}Pb in the smaller sediment fraction (i.e. $< 63\mu\text{m}$ or $< 125\mu\text{m}$) is recommended to concentrate ^{210}Pb and reduce the dilution effect caused by coarse fractions. This methodology has been applied in mangrove ecosystems from arid regions (Almahasheer et al., 2017) where excess ^{210}Pb flux is very low, and in Florida Bay carbonate-rich seagrass sediments (Holmes et al., 2001). Similarly, large organic material such as roots and leaves should be removed from the sediment samples prior to ^{210}Pb analyses as these will contribute to the dilution of the excess ^{210}Pb specific activities."

Other comments: 5.the authors need to check the manuscript in order to verify the terms and acronyms (like Db and not D for bioturbation).

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RESPONSE: The following acronyms will be revised and unified throughout the manuscript: D for Db: Bioturbation Corg-MAR for CAR: Carbon accumulation rate

6. Page 2 line 24: “ ^{210}Pb is not affected by interannual variability”: to moderate ^{210}Pb s fluxes could have some variability although moderate

RESPONSE: text will be corrected as suggested - “ ^{210}Pb flux is moderately affected by interannual variability”.

7. Page 3 line 3: and subsequent fallout

RESPONSE: Text will be added as suggested.

8. Page 4 (and in all the text): be careful to use correctly concentration and activity

RESPONSE: We agree with the reviewer that some of these terms were not correctly used throughout. Concentration is equally used as specific activity throughout the manuscript, these both refer to activity per unit of mass, while the single term activity should be used when referred to decays per unit of time. Inventory refers to activity per unit of area.

ACTIONS after Editor’s consideration: We will revise all the entries for activity, specific activity and concentration in the current version of the manuscript and check for its correct use based on the above.

9. CIC model/ I disagree with the statement CIC is not appropriate. This model could be useful in some sediment core presenting event-deposit (like flood). Such deposits could be sand, but also fine sediments that could present lower ^{210}Pb s (compared to surrounding layers). In fact, CIC could be useful to check dating when it is difficult to precisely define the thickness of such deposits.

RESPONSE: We agree with the reviewer; indeed, the CIC model can be more appropriate than the CRS model and useful in situations where there is a hiatus in the sediment record caused by an erosion event, there are significant hydrologic changes

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or sediment focusing is a major factor.

ACTIONS after Editor's consideration:

- We will remove the statement in page 5, lines 6-8 in the current version of the manuscript that points to the CIC model as not being appropriate to date vegetated coastal sediments and we will change it for: "The variability of accumulation rates, the progressive loss of matter because of organic matter degradation, and the sediment disturbances causing variations in the initial 210Pb concentration have resulted in the CRS model being the most widely used means of deriving 210Pb chronologies".

- Then, text will be added after the description of the CRS model (page 5, lines 16-21) to highlight the situations where the CIC model might be preferred "Although the CRS model often yields more reasonable results than that of the CIC in both fresh and marine environments (Appleby, 2008; Breithaupt et al., 2014; Oldfield et al., 1978; Sanders et al., 2016), the CIC model might be preferred at locations where sediment focusing is a major factor, significant hydrologic changes have occurred or there are hiatus in the sediment record caused by erosion events (Appleby, 2008)."

10. page 7 type II: lower activities could be also explained by dilution by roots for example, so it is important as indicated previously to provide recommendations for sampling.

RESPONSE: Large organic debris like roots should be removed from the sediment samples prior the sample preparation for alpha or gamma spectrometry analyses. This aspect will be included in the revised version of the manuscript in section 4. Approaches and Guidelines. Since this was also raised in comment 1 and 4, we paste here the relevant text:

ACTIONS after Editor's consideration: We will modify the text in section "4. Approaches and Guidelines" (page 12, lines 1-15) to briefly develop some basic sampling and sample-handling procedures to achieve good 210Pb profiles. The suggested text will



read as: “ Similarly, large organic material such as roots and leaves should be removed from the sediment samples prior to ^{210}Pb analyses as these will contribute to the dilution of the excess ^{210}Pb specific activities.”

11. 13 line 30-34: the presence of large OC concentration or vegetal (like leaves) could promote high concentration of Cs due to mobility. So care is required with ^{137}Cs .

RESPONSE: We agree that, in addition to the mobility of ^{137}Cs due to the reasons we indicated in the manuscript, ^{137}Cs concentration profiles can also be affected by the presence of organic matter, and can be accumulated in leaf litter and living roots, this will be included in the revised manuscript.

ACTIONS after Editor’s consideration: text will be added to also take into consideration this aspect in page 4 lines 1-3: “High contents of organic matter can also affect the distribution of ^{137}Cs in sediments as it is preferentially accumulated in leaf litter and may be absorbed by living roots (Staunton et al., 2002).”

References:

- S. Staunton, Camille Dumat, A. Zsolnay. Possible role of organic matter in radiocaesium adsorption in soils. 2002 Journal of Environmental Radioactivity, 58, 163-173.

12. page 15 line5-7: not clear, it seems there is a confusion between alpha (that requires to assume the rather constant ^{210}Pb activities correspond to the supported ^{210}Pb) and gamma (that determines both ^{210}Pb and ^{226}Ra)).

RESPONSE: This will be clarified in the revised version of the manuscript.

ACTIONS after Editor’s consideration: Text in page 15 line 5-7 will be modified as: “Excess ^{210}Pb concentrations are determined by subtracting supported ^{210}Pb to total ^{210}Pb concentrations assuming it is in equilibrium with ^{226}Ra . This is straightforward when gamma spectrometry is employed since the total ^{210}Pb and supported ^{210}Pb (i.e., ^{226}Ra) can be quantified simultaneously. In occasions, particularly when ^{210}Pb is determined by alpha spectrometry, ^{226}Ra is not measured, and supported ^{210}Pb

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is most often determined from the region of constant and low ^{210}Pb concentrations at depth, or alternatively, from a number of determinations of ^{226}Ra via gamma spectrometry or liquid scintillation counting (LSC) along the core”

Interactive comment on Biogeosciences Discuss., <https://doi.org/10.5194/bg-2018-78>, 2018.

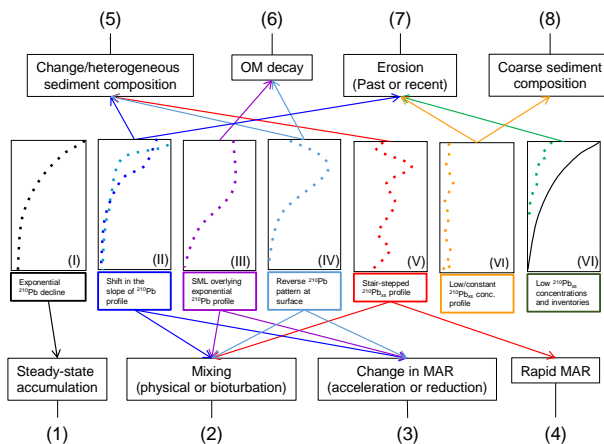
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- (1) Steady-state accumulation
- ✓ Use independent tracers to validate chronology
- (4) Rapid MAR
- ✓ Analyse short-lived radionuclides.
 - ✓ Analyse ^{226}Ra if supported ^{210}Pb is not reached.
 - ✓ Historical records of event sedimentation
 - ✓ The profile is undatable by ^{210}Pb , need of independent tracers.
- (2) Mixing (physical or bioturbation)
- ✓ Check if depth distribution of other elements is homogeneous w/ depth.
 - ✓ Analyse short-lived radionuclides at the ML.
 - ✓ Check for burrowing evidence → e.g. X-ray radiographs or visual description of sed. core.
 - ✓ CRS or CF-CS model below SML → check residence time of ^{210}Pb in SML.
 - ✓ If type V_a profile is undatable and cannot be used for accumulation-rate calculations.
- (5) Change/heterogeneous sediment composition
- ✓ Check grain size distribution, DBD and OM content profiles.
 - ✓ Normalize radionuclide concentrations to the parameter driving $^{210}\text{Pb}_{\text{ex}}$ distribution.
 - ✓ Analyse ^{226}Ra in all sections.
 - ✓ CF-CS model in normalized profiles.
 - ✓ CRS model if shape of the normalized profile remains unchanged.
- (7) Erosion (Past or recent)
- ✓ Compare $^{210}\text{Pb}_{\text{ex}}$ inventories with those at a reference site.
 - ✓ Check for coarser grain size.
 - ✓ Presence of short-lived radionuclides at reference site to check entire core recovery.
 - ✓ CF-CS or CIC models to estimate mean MAR.
- (3) Change in MAR (acceleration or reduction)
- ✓ Use independent tracers to validate MAR in regions with different slope.
 - ✓ Check for variations in geochemical or physical parameters in the profile.
 - ✓ Test sensitivity to acceleration according to DBD and apparent MAR.
 - ✓ Check historical records of natural or anthropogenic events.
 - ✓ Apply CRS, or CF-CS model piecewise.
- (6) OM decay
- ✓ Only if OM is high (> 30%) and mostly labile (0.01-0.03 d^{-1})
- (8) Coarse sediment composition
- ✓ Analyse radionuclides in the fine sediment fraction (sieve to $63\ \mu\text{m}$ or $125\ \mu\text{m}$) → check new profile
 - ✓ ^{226}Ra by gamma spectroscopy
 - ✓ Check for records of event sedimentation
 - ✓ If sieving increase $^{210}\text{Pb}_{\text{ex}}$ concentrations but its shape is similar, the profile is undatable and cannot be used for accumulation-rate calculations.

Fig. 1. Table 4: new diagram