31 March 2022

Dear Associate Editor,

Dear Dr. Claire Masteller,

Please find below a detailed point-by-point response (black) to your comments (blue). Revised paragraphs of the manuscript are reproduced with tracked changes (new text, ~~removed text~~) below our responses.

We hope you appreciate our response to your constructive remarks, and that you will consider this revised version for publication in *Earth Surface Dynamics*. We want to sincerely thank you for helping to improve our manuscript.

Best regards,

Olivier Gourgue

## Associate Editor

Thank you for your submission to *Earth Surface Dynamics*. Two reviews of the manuscript were generally positive and agreed that the results represent a novel contribution focused on the role of vegetation in modeling marsh morphodynamics. The reviewers asked for some clarifications throughout the manuscript that I feel have been sufficiently addressed.

Thank you for approving our responses to the referee comments.

I have gone through the revised manuscript and am suggesting some minor edits throughout to streamline, mostly focused on the introduction and methods.

Thank you for these additional suggestions. See our detailed point-by-point response below.

I would also encourage the authors to discuss the impact (or lack thereof) of the different vegetation scenarios on the results in the main text. I am aware that a more detailed discussion of this is included in the discussion, but because part of the novelty of the study is the application of the fine-scale vegetation model, I think the additional work done by the authors should be summarized in the main text.

With all due respect, we want to remind that the scope of the present paper is on tidal marsh restoration and how different restoration design options can impact the biogeomorphic development of tidal marshes. The impact of vegetation dynamics (through different vegetation scenarios) is an interesting theoretical model experiment that we have already addressed in a previous paper (Schwarz et al., 2018) and that we further explore in another paper in preparation.

Although it is not the main scope of the paper, we understand that the vegetation dynamics is an important aspect of the model. That is why we support our main study with variants of the reference scenarios to explore the model sensitivity to some aspects of the vegetation dynamics. In order not to distract the reader from the main scope of the paper, the technical details and the related results are presented as supplementary material (Table S1, Figures S1 to S3). However, these additional scenarios are also briefly presented in Sect 2.3.3 and the related results are summarized in Sect. 3.1 (3rd paragraph). Following your suggestion, we now also discuss them briefly in Sect. 4.2 (2nd paragraph).

Sect. 2.3.3

In the reference model scenario, vegetation establishes randomly following different colonization strategies (i.e., either homogeneously with relatively high probability of establishment but no possibility to expand laterally, or patchily with relatively low probability of establishment but possibility to expand laterally to form growing patches – Sect. S1.2, supplementary material) in areas where environmental stressors allow for it (Sect. 2.1.2). This is the expected behavior supported by field observations for the three selected species representative for pioneer, middle and high marsh vegetation (Sect. S1.5.2, supplementary material). To illustrate the impact of the vegetation dynamics on the biogeomorphic feedbacks and the model results, we also consider six variants of the reference model scenario (Table S1, supplementary material).

Sect. 3.1 (3rd paragraph)

Overall, the presence of vegetation slightly increases the rate of platform accretion in the Northern basin, although the speed of colonization has nearly no influence on the mean platform elevation 50 years after de-embankment (Fig. S1a, supplementary material). In the Southern basin, neither the presence of vegetation nor the speed of colonization seems to affect sediment accretion on the platforms (Fig. S1b, supplementary material), which suggests that the hydrodynamics is predominant in that part of the restored marsh. Locally, the vegetation dynamics can have remarkable geomorphic effects, such as the maintenance or disappearance of pre-excavated channels, whether we consider no vegetation, the reference vegetation dynamics, or instantaneous colonization (Fig. S2, supplementary material). In general, vegetation input parameters have a rather limited impact on the long-term morphodynamics (Fig. S3, supplementary material).

Sect. 4.2 (2nd paragraph)

However, to our knowledge, this paper presents the first application of a tidal marsh biogeomorphic model accounting for relevant fine-scale interactions (less than 1 m$^2$) between flow and stochastic, patchy vegetation establishment patterns, as well as their long-term impact (several decades) at the landscape scale (several km$^2$) on vegetation and landform development. Previous studies were either limited to smaller domains (order of 1 km$^2$ or less – Temmerman et al., 2007; Best et al., 2018; Schwarz et al., 2018; Bij de Vaate et al., 2020; Wang et al., 2021), coarser grid resolutions (order of 100 m – Mariotti and Canestrelli, 2017), shorter simulation periods (order of 1 decade – Brückner et al., 2019), more simplified hydro-morphodynamics (Craft et al., 2009; Alizad et al., 2016; Spencer et al., 2016; Mariotti, 2020; Mariotti et al., 2020) or more simplified vegetation dynamics (D'Alpaos et al., 2007; Belliard et al., 2015). However, our model does not include certain processes that are accounted for in other recent marsh models, but that are considered not relevant for this specific study case, such as wind waves (Mariotti and Canestrelli, 2017; Best et al., 2018; Mariotti, 2020) and pond dynamics (Mariotti et al., 2020). While previous studies showed that vegetation dynamics can considerably impact tidal channel morphodynamics (Schwarz et al., 2018; Temmerman et al., 2007), our model results suggest that it is not a dominant process in the case studied here. Locally, the vegetation dynamics can affect the sustainability of certain channels in the Northern basin (Fig. S2, supplementary material), but overall, sediment accretion on the platforms is much more sensitive to hydrodynamic processes such as SLR and sediment supply (Fig. 6) than to vegetation dynamics (Fig. S1 and S3, supplementary material). This calls for further research on the environmental conditions under which the vegetation dynamics can be more impactful on the morphodynamics (e.g., lower tidal range).

Because these are mainly comments on the text, not on the methods or analysis, I am marking these as minor revisions.

## Minor edits

Line 58: Replace "while" with "then".

Line 67: Replace "develop" with "continue to develop over time".

Lines 67-70: Replace "For example, several studies point at many restored sites that, in comparison with natural tidal marshes, underperform in terms of (…)" with "For example, several studies indicate that restored sites underperform in term of (…) when compared to their natural counterparts".

Sect. 1 (2nd paragraph)

Managed realignment, which consists in shifting the line of coastal defense structures landward of their existing position, can create space for tidal marsh restoration or creation. This practice has grown in popularity over the last two decades (French, 2006; Turner et al., 2007), especially in the context of coastal squeeze and landward movement of the mean low water mark due to SLR and storms (Doody, 2013). Practically, a second line of defense is built landwards, ~~while~~ then the first one is breached. The number and size of breaches are important design choices (Hood, 2014, 2015) and vary greatly between projects (e.g., Friess et al., 2014; Dale et al., 2017). As breaches become the inlets of the restored marshes, they have an important control on water and sediment volumes entering and leaving the system during each tidal cycle, and hence on sediment accretion rates (Oosterlee et al., 2020). Other important design measures may involve excavating an initial channel network and treating soil conditions to facilitate soil drainage (O'Brien and Zedler, 2006), planting manually vegetation tussocks to ensure vegetation encroachment (Staver et al., 2020), or building hydraulic structures to control the tidal range and create optimal ecological conditions for vegetation development (Maris et al., 2007; Oosterlee et al., 2018). These design choices are mainly driven by restoration objectives and local environmental conditions. Yet, there is high uncertainty in how restored tidal marshes continue to develop over time. For example, several studies ~~point at many~~ indicate that restored sites ~~that, in comparison with natural tidal marshes,~~ underperform in terms of biodiversity (Wolters et al., 2005; Mossman et al., 2012), topographic diversity (Lawrence et al., 2018), groundwater dynamics (Tempest et al., 2015; Van Putte et al., 2020) and biogeochemical functioning, including carbon sequestration (Santín et al., 2009; Suir et al., 2019) when compared to their natural counterparts. These outcomes can potentially hamper marsh ecosystem functions and the initial restoration objectives.

Line 72: Remove "yet so important".

Line 72: Replace "for example" with "in some cases".

Line 77: Remove "opinion".

Line 83: Remove "that are based on state-of-the-art scientific knowledge, and".

Line 83: Replace “allow” with “are able”.

Sect. 1 (3rd paragraph)

The rate at which tidal marshes develop in restoration projects is highly uncertain~~, yet so important~~. ~~For example~~ In some cases, sediment accretion rates determine whether restored tidal marshes can keep pace with local rates of SLR (Kirwan et al., 2010; Vandenbruwaene et al., 2011a; Webb et al., 2013; Kirwan et al., 2016). The establishment rate of pioneer vegetation and the succession towards climax vegetation may depend on small windows of opportunity that are very difficult to predict (Chambers et al., 2003; Hu et al., 2015; Cao et al., 2018). Furthermore, the rate of development is at the center of the tension between public perception and restoration objectives. The public ~~opinion~~ is often very critical towards marsh restoration by managed realignment, as it implies the loss of valuable land, laboriously reclaimed by previous generations (Temmerman et al., 2013). On the one hand, fast development allows to quickly reach target habitats, which may support a positive public perception, but involves the risk of fast development towards a monotone climax ecosystem state. On the other hand, slow development (e.g., including bare mudflats) increases the risk of negative public perception in the first years, but may lead to long-term persistence of high habitat diversity with different stages of succession. All these examples illustrate the need for modeling tools ~~that are based on state-of-the-art scientific knowledge, and~~ that ~~allow to~~ can predict how fast restored tidal marshes develop and how development rates can be steered by restoration design.

Line 208: Unclear what “(Sect. 2.1)” is referencing. I’d suggest adding the vegetation species by name here.

Sect. 2.2 (2nd paragraph)

Local environmental conditions are determinant for the development of restored ecosystems (Liu et al., 2021). The Scheldt Estuary, here defined as the tidal part of the Scheldt River, is a semidiurnal macrotidal estuary extending over 160 km. At a gauge station near Bath (Fig. 2b), the tidal range has been recorded to vary on average from 4.21 m at neap tides to 5.76 m at spring tides during the period 2011-2015, and the MHWL to rise at a rate of 5.7 mm yr-1 during the period 1931-2004 (Wang and Temmerman, 2013). This MHWL rise rate is used here as proxy for SLR rate (Sect. 2.3). The study site lies in the brackish zone of the estuary, which is characterized by a steep gradient in salinity, with values ranging from 5 to 18 PSU (Van Damme et al., 2005; Meire et al., 2005). Therefore, only a limited number of vegetation species (~~Sect. 2.1~~ e.g., *Aster tripolium*, *Scirpus maritimus* and *Phragmites australis*) can cope with the local environmental conditions. The local SSC is influenced by the presence of a maximum turbidity zone, where large volumes of cohesive sediments are concentrated and continually resuspended by the tidal flow (Baeyens et al., 1997; Chen et al., 2005; Meire et al., 2005). At the study site, the current average SSC is estimated at 63 mg l-1 (Sect. S2, supplementary material). Sediment accretion in marshes of the Scheldt Estuary is dominated by the external supply by tides of suspended sediments, mostly of mineral nature, while organic matter only accounts for about 10% of the measured accretion rates (Temmerman et al., 2004). For this reason, our model does not explicitly simulate organic matter accretion locally produced by vegetation.

Lines 256-259: This seems like an important detail. I suggest taking it out of parentheses and just making it its own sentence.

Sect. 2.3.3

In the reference model scenario, vegetation establishes randomly following different colonization strategies ~~(i.e., either homogeneously with relatively high probability of establishment but no possibility to expand laterally, or patchily with relatively low probability of establishment but possibility to expand laterally to form growing patches – Sect. S1.2, supplementary material)~~ in areas where environmental stressors allow for it. Pioneer marsh vegetation establishes homogeneously with a relatively high probability of establishment but with no possibility to expand laterally. Middle and high marsh vegetation establish patchily with a relatively low probability of establishment but with the possibility to expand laterally to form growing patches (Sect. 2.1.2). This is the expected behavior supported by field observations for the three selected species ~~representative for pioneer, middle and high marsh vegetation~~ (Sect. S1.5.2, supplementary material). To illustrate the impact of the vegetation dynamics on the biogeomorphic feedbacks and the model results, we also consider six variants of the reference model scenario (Table S1, supplementary material).

Line 262: Are these different form the models in Table 1? What is the basis for those models only appearing in the supplement and not the main text? Particularly if one of the key advances of this study is to include the vegetation feedbacks in the modeling study.

As mentioned above, the scope of the paper is on tidal marsh restoration and how different restoration design options can impact the biogeomorphic development of tidal marshes. This is investigated with the scenarios presented in Table 1. To support our model results, we also explored the model sensitivity to some aspects of the vegetation dynamics with additional scenarios presented in Table S1. In order not to distract the reader from the main scope of the paper, this table, which contains rather technical details, is presented as supplementary material.

Line 339: What do you define as positive impact? Add a sentence to be more specific here.

Sect. 3.1 (3rd paragraph)

Overall, the presence of vegetation ~~has a positive impact on~~ slightly increases the rate of platform accretion ~~rates~~ in the Northern basin, although the speed of colonization has nearly no influence on the mean platform elevation 50 years after de-embankment (Fig. S1a, supplementary material). In the Southern basin, neither the presence of vegetation nor the speed of colonization seems to affect sediment accretion on the platforms (Fig. S1b, supplementary material), which suggests that the hydrodynamics is predominant in that part of the restored marsh. Locally, the vegetation dynamics can have remarkable geomorphic effects, such as the maintenance or disappearance of pre-excavated channels, whether we consider no vegetation, the reference vegetation dynamics, or instantaneous colonization (Fig. S2, supplementary material). In general, vegetation input parameters have a rather limited impact on the long-term morphodynamics (Fig. S3, supplementary material).

Lines 345-346: It is difficult to evaluate just how much the vegetation is having an effect, particularly when it looks like the bulk of the deposition is occurring when the vegetation has yet to colonize or is still very sparse.

With all due respect, we believe that this is what this paragraph is about. In the case studied here, because of the local environmental conditions (e.g., high tidal range), the morphodynamics does not seem to be very sensitive to the vegetation dynamics. We have added a paragraph in the discussion to clarify it.

Sect. 4.2 (2nd paragraph)

However, to our knowledge, this paper presents the first application of a tidal marsh biogeomorphic model accounting for relevant fine-scale interactions (less than 1 $m^2$) between flow and stochastic, patchy vegetation establishment patterns, as well as their long-term impact (several decades) at the landscape scale (several $km^2$) on vegetation and landform development. Previous studies were either limited to smaller domains (order of 1 $km^2$ or less – Temmerman et al., 2007; Best et al., 2018; Schwarz et al., 2018; Bij de Vaate et al., 2020; Wang et al., 2021), coarser grid resolutions (order of 100 m – Mariotti and Canestrelli, 2017), shorter simulation periods (order of 1 decade – Brückner et al., 2019), more simplified hydro-morphodynamics (Craft et al., 2009; Alizad et al., 2016; Spencer et al., 2016; Mariotti, 2020; Mariotti et al., 2020) or more simplified vegetation dynamics (D'Alpaos et al., 2007; Belliard et al., 2015). However, our model does not include certain processes that are accounted for in other recent marsh models, but that are considered not relevant for this specific study case, such as wind waves (Mariotti and Canestrelli, 2017; Best et al., 2018; Mariotti, 2020) and pond dynamics (Mariotti et al., 2020). While previous studies showed that vegetation dynamics can considerably impact tidal channel morphodynamics (Schwarz et al., 2018; Temmerman et al., 2007), our model results suggest that it is not a dominant process in the case studied here. Locally, the vegetation dynamics can affect the sustainability of certain channels in the Northern basin (Fig. S2, supplementary material), but overall, sediment accretion on the platforms is much more sensitive to hydrodynamic processes such as SLR and sediment supply (Fig. 6) than to vegetation dynamics (Fig. S1 and S3, supplementary material). This calls for further research on the environmental conditions under which the vegetation dynamics can be more impactful on the morphodynamics (e.g., lower tidal range).

Given that this is one of the stated novelties of the paper, some explicit evaluation of this would be helpful to clarify this point for readers. I recognize that this information is in the supplement, but some of those findings can be briefly summarized in the main text. There are sections for the impact of SSC and the impact of inlet design, so the authors may consider also adding a short note about the vegetation impacts.

As mentioned above, the scope of the paper is on tidal marsh restoration and how different restoration design options can impact the biogeomorphic development of tidal marshes. The additional scenarios to explore the model sensitivity to some aspects of the vegetation dynamics are presented in Sect 2.3.3 and the related results are summarized in Sect. 3.1 (3rd paragraph) and now discussed in Sect. 4.2 (2nd paragraph). However, in order not to distract the reader from the main scope of the paper, we decided to have no specific section on the impact of vegetation dynamics in the results and discussion sections, and to present the related figures as supplementary material.

Sect. 2.3.3

In the reference model scenario, vegetation establishes randomly following different colonization strategies (i.e., either homogeneously with relatively high probability of establishment but no possibility to expand laterally, or patchily with relatively low probability of establishment but possibility to expand laterally to form growing patches – Sect. S1.2, supplementary material) in areas where environmental stressors allow for it (Sect. 2.1.2). This is the expected behavior supported by field observations for the three selected species representative for pioneer, middle and high marsh vegetation (Sect. S1.5.2, supplementary material). To illustrate the impact of the vegetation dynamics on the biogeomorphic feedbacks and the model results, we also consider six variants of the reference model scenario (Table S1, supplementary material).

Sect. 3.1 (3rd paragraph)

Overall, the presence of vegetation slightly increases the rate of platform accretion in the Northern basin, although the speed of colonization has nearly no influence on the mean platform elevation 50 years after de-embankment (Fig. S1a, supplementary material). In the Southern basin, neither the presence of vegetation nor the speed of colonization seems to affect sediment accretion on the platforms (Fig. S1b, supplementary material), which suggests that the hydrodynamics is predominant in that part of the restored marsh. Locally, the vegetation dynamics can have remarkable geomorphic effects, such as the maintenance or disappearance of pre-excavated channels, whether we consider no vegetation, the reference vegetation dynamics, or instantaneous colonization (Fig. S2, supplementary material). In general, vegetation input parameters have a rather limited impact on the long-term morphodynamics (Fig. S3, supplementary material).

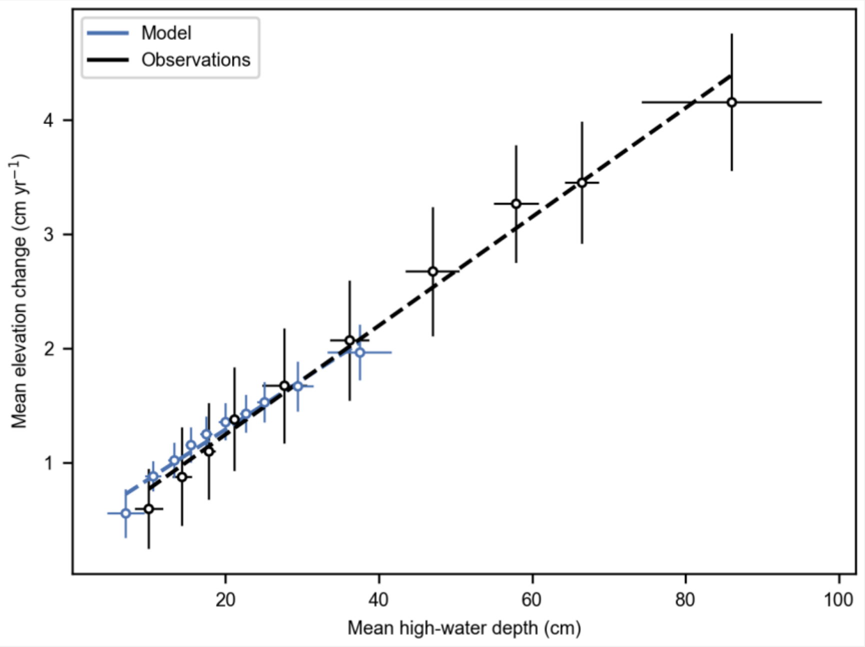
Sect. 4.2 (2nd paragraph)

However, to our knowledge, this paper presents the first application of a tidal marsh biogeomorphic model accounting for relevant fine-scale interactions (less than 1 $m^2$) between flow and stochastic, patchy vegetation establishment patterns, as well as their long-term impact (several decades) at the landscape scale (several $km^2$) on vegetation and landform development. Previous studies were either limited to smaller domains (order of 1 $km^2$ or less – Temmerman et al., 2007; Best et al., 2018; Schwarz et al., 2018; Bij de Vaate et al., 2020; Wang et al., 2021), coarser grid resolutions (order of 100 m – Mariotti and Canestrelli, 2017), shorter simulation periods (order of 1 decade – Brückner et al., 2019), more simplified hydro-morphodynamics (Craft et al., 2009; Alizad et al., 2016; Spencer et al., 2016; Mariotti, 2020; Mariotti et al., 2020) or more simplified vegetation dynamics (D'Alpaos et al., 2007; Belliard et al., 2015). However, our model does not include certain processes that are accounted for in other recent marsh models, but that are considered not relevant for this specific study case, such as wind waves (Mariotti and Canestrelli, 2017; Best et al., 2018; Mariotti, 2020) and pond dynamics (Mariotti et al., 2020). While previous studies showed that vegetation dynamics can considerably impact tidal channel morphodynamics (Schwarz et al., 2018; Temmerman et al., 2007), our model results suggest that it is not a dominant process in the case studied here. Locally, the vegetation dynamics can affect the sustainability of certain channels in the Northern basin (Fig. S2, supplementary material), but overall, sediment accretion on the platforms is much more sensitive to hydrodynamic processes such as SLR and sediment supply (Fig. 6) than to vegetation dynamics (Fig. S1 and S3, supplementary material). This calls for further research on the environmental conditions under which the vegetation dynamics can be more impactful on the morphodynamics (e.g., lower tidal range).

Lines 359-360: To me, this seems like something worthwhile to highlight in the main text if this type of vegetation model has not been used at this scale before.

We have moved former Fig. S4 and S5 into the main manuscript (new Fig. 4).

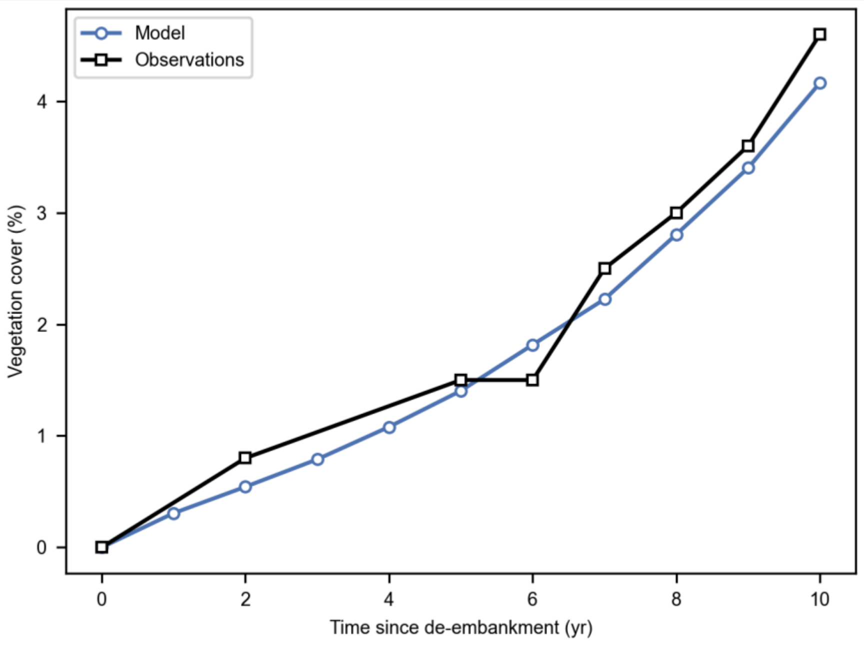
Former Fig. S4



~~Figure S4: Reference model scenario (#1). Mean elevation change (between years 18 and 50 for model results, between 1931 and 1963 for observations) vs. mean high-water depth (in year 18 for model results, in 1931 for observations). Model results and observations are respectively split into 10 sub-samples of equal size (Sect. 2.4.4). Markers and error bars represent the means and standard deviations of each sub-sample. Dashed lines represent linear regressions of the sub-sample means. Model results are on grid nodes that remained vegetated between years~~

~~18 and 50. Observations are from areas that remain vegetated between years 1931 and 1963 in an established marsh nearby the study site (Sect. 2.4.1) and have been rescaled to account for differences in SSC in both sites (Sect. S2).~~

Former Fig. S5



~~Figure S5: Reference model scenario (#1). Development of vegetation cover after de-embankment (blue) compared to observations in another restored marsh close to the study site (black).~~

New Fig. 4

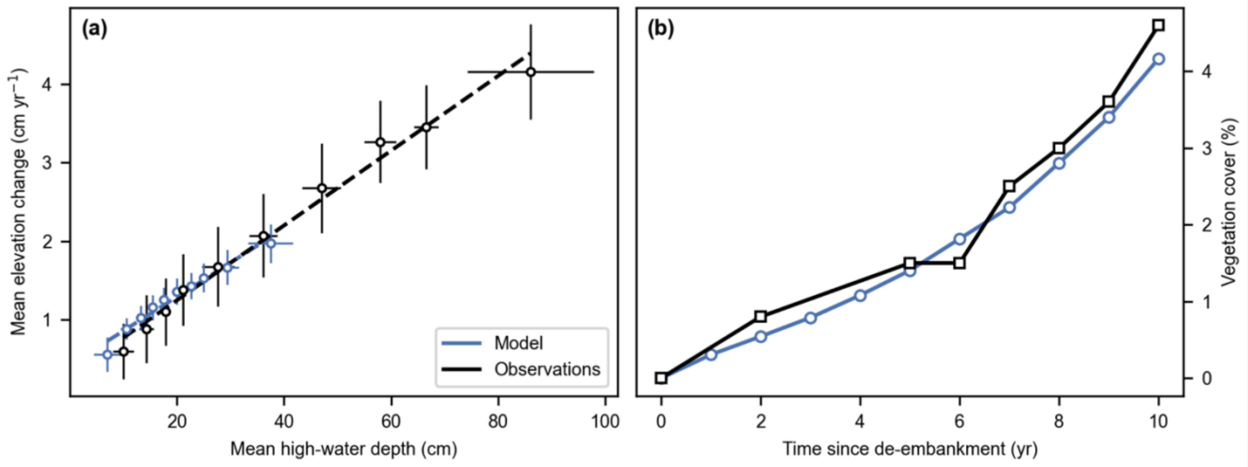


Figure 4: Reference model scenario (#1). (a) Mean elevation change (between years 18 and 50 for model results, between 1931 and 1963 for observations) vs. mean high-water depth (in year 18 for model results, in 1931 for observations). Model results and observations are respectively split into 10 sub-samples of equal size (Sect. 2.4.4). Markers and error bars represent the means and standard deviations of each sub-sample. Dashed lines represent linear regressions of the sub-sample means. Model results are on grid nodes that remained vegetated between years 18 and 50. Observations are from areas that remain vegetated between years 1931 and 1963 in an established marsh

nearby the study site (Sect. 2.4.1) and have been rescaled to account for differences in SSC in both sites (Sect. S2, supplementary material). (b) Development of vegetation cover after de-embankment compared to observations in another restored marsh close to the study site (Sect. S3, supplementary material).