# Response to Reviewer 1

We would like to thank the anonymous reviewer for his or her constructive comments. In this response we provide an answer to all the comments and the indicate the changes that will be applied in the revised manuscript.

**Comment 1:** *My major concern is about the validity of one assumption in the model. I am not fully convinced and expect a better justification. Because the model does not represent the river routing process, it uses floodplain connectivity to simulate the transport of sediment along hydrological pathways. However, by doing so, it implicitly assumes all sediments as sand and gravels (non-cohesive sediment) and represents the transport of cohesive and non-cohesive sediment in the same way. But the cohesive sediments (loam and silt) can be transported by rivers efficiently and most of them would not be deposited. Further, loam and silt may be the major type of sediments that are generated from hillslope erosion (especially for interrill and rill erosion considered by RUSLE). As shown in the results, the current method can cause the severe underestimation of sediment and C that are transported to oceans.*

**Answer:** We understand the reviewer's concern regarding the absence of an explicit representation of rivers and river routing in CE-DYNAM. We agree that in this way we treat the transport of all sediments types (cohesive and non-cohesive) in the same way, which can lead to uncertain sediment and POC fluxes carried away by rivers. However, our model assumption does not imply that all sediment are in the form of coarse material, instead, the main assumption is that the majority of the eroded soil and transported sediment is fine sand, silt and loam. This assumption is supported by the fact that the sediment residence time is calculated based on observed floodplain deposit ages of the Rhine (Hoffmann et al. 2007, 2008, 2013). These studies show that most of the deposits in the floodplains are overbank deposits that consist of fine sediment such as sand, loam, silt and clay and organic material. The long residence time (up to 2000 years) that they measured for the floodplains based on the C14 signature of C associated with sediment samples show that the fine sediment can stay buried for a long time in the floodplains. Although the model lacks explicit river process representations, it reproduces the spatial variability in floodplain sediment and C storage across the Rhine sub-basins as is shown by table 3 of this manuscript and by a previous study where we validated the global sediment budget model (Naipal et al., 2016, ESD). It should be noted that the model has been developed and calibrated to simulate long-term changes in sediment and carbon storage on land and not the short-term variations in sediment and POC fluxes carried by rivers.

Finally, the model produces a sediment export flux at the end of the year 2005 of 1.6x$10^7$ tonnes per year, which is a magnitude higher than the measured suspended sediment flux of about 3.15x$10^6$ tonnes per year (Asselman et al.,2003). The higher sediment flux is the result of absent riverine processes in CE-DYNAM such as sediment burial behind dams, and the fact that we assume an equilibrium state for the Rhine catchment based on the period 1850-1860 where agricultural soil erosion rates were already high. The simulated total cumulative sediment export of 2.5 Gt for the Rhine over the period 1850-2005 is about 36 % of the cumulative gross soil erosion flux of 6.8 Gt. This sediment flux leads to a cumulative POC export of about 0.14 Tg of C for the Rhine over the period 1850-2005 (based on a new simulation S2, see more details in the following paragraph below). This is 0.2 % of the cumulative C erosion flux. The yearly POC flux at the end of the year 2005 is 0.02 tC km$^2$ year$^{-1}$ (normalized over the total basin area), which is an order of magnitude lower compared to other studies who found 0.9 tC km$^2$ year$^{-1}$ (Beusen et al., 2009; Soribas et al., 2016).

This underestimation in POC in CE-DYNAM is most likely a result of the high sediment residence time of floodplains downstream of the Rhine and the absence of increased plant productivity of floodplains, leading to the decomposition of a large fraction of the deposited C. We tested the effect of the sediment residence time on the resulting lateral C fluxes of the model and find that they do not change the POC export of the Rhine significantly (see our detailed response to comment 2 of reviewer 2). Increased plant productivity of floodplains is shown to contribute significantly to the higher SOC stocks of floodplains compared to hillslopes, and to the export of DOC and POC to rivers (Van Oost et al., 2012; Hoffmann et al., 2013).

***Changes to the manuscript:*** We will address the model uncertainty related to the POC export and include the above mentioned findings in section 4.1 on the limitations of the model.

New transient simulation S2 based on an improved equilibrium state

We redid the simulation S2 for the Rhine catchment using a different model spin-up. In the old spin-up we let the model run continuously for 2000 years, whereas in the new spin-up we ran the model for 3000 years and calculated analytically the temporary equilibrium state of the floodplain SOC pools every 10 years. This new spin-up method resulted in the floodplain SOC pools being close to equilibrium at the end of the 3000 year spin-up period, where the yearly change in the floodplain SOC stocks was less than 0.001% of the total floodplain SOC stock. Therefore, it was not needed to subtract the additional increase in the SOC stocks resulting from the disequilibrium state from those of the transient simulation (see section 2.11). The new transient simulation S2 resulted in different absolute values for the C budget of the Rhine. However, the main conclusions did not change. We also performed an uncertainty analysis with a minimum and maximum soil erosion scenario, based on the uncertainty ranges in the rainfall erosivity and land cover factors of the Adjusted RUSLE model. The revised manuscript will contain the new figures and tables. In addition, section 3 will be modified to include the new results with uncertainty ranges.

**Specific comments**

**Comment S1:** *L70-72: These two references are relevant to this sentence.*

*Galy, V., Peucker-Ehrenbrink, B., & Eglinton, T. (2015). Global carbon export from the terrestrial biosphere controlled by erosion. Nature, 521, 204–207.https://doi.org/10.1038/nature14400*

*Tan, Z., Leung, L. R., Li, H., Tesfa, T., Vanmaercke, M., Poesen, J., ... Hartmann, J. (2017). A Global data analysis for representing sediment and particulate organic C carbon yield in Earth*

*System Models. Water Resources Research, 53, 10,674–10,700. https:// doi.org/10.1002/2017WR020806*

**Answer:** We will add these references in the revised manuscript

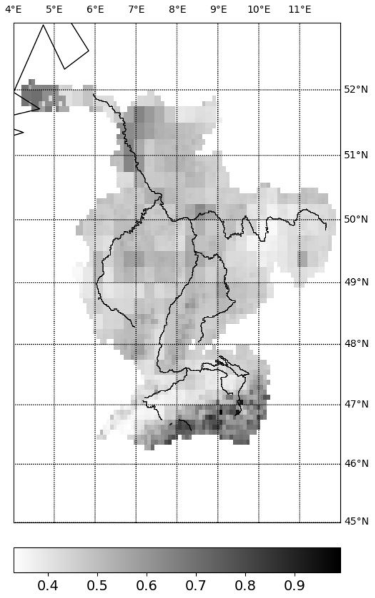
**Comment S2:** *L117: it should be noted that as discussed in Naipal et al. (2015), the formulation of R factor is related to climate type. So in the millennia time scale, one area may need different R factors due to the change of climate.*

**Answer:** This is right. In the paper of Naipal et al. (2016), where the global sediment budget model is applied for the last millennium, we take the change in climate in the calculation of the erosivity into account. For this study, we assume that the climate zones as defined by the Koeppen-Geiger climate classification have not changed drastically since 1850 AD.

***Changes to manuscript*:** We will mention this assumption in the methods section

**Comment S3:** *L170: Reference for Eq. 5? Also, I recommend to show the spatial variability of the f factor in the Rhine catchment.*

**Answer:** This equation has been adopted from the study of Naipal et al. (2016), that presents the global sediment budget model for the Rhine. We will include the reference to this equation in the revised manuscript and add the spatial variability of the *f* factor in the supplementary document.



Supplementary figure: Spatial variability of the floodplain deposition factor (f)

**Comment S4:** *L192: This may be true for sand and gravel sediment (the majority of floodplain sediment) that Hoffmann et al. (2008) studied. But for cohesive sediment (loam and silt), they can be transported through river channels to oceans without the large fraction of deposition (at least not as large as what is set in this model). They are also the major sediments of soil erosion.*

**Answer:** See our answer to the previous comment, where we argue that most of the floodplain sediment studied by Hoffmann et al. (2008) consists mostly out of organic material (gyttja, peat) and fine sediments (fine sand, loam, silt) in overbank deposits (see table 2 in Hoffmann et al., 2008). These fine sediments are a result of long-term soil erosion on the hillslopes. Also a large part has been transported and deposited in the floodplains under major storms, such as the one in the 14th century (Bork et al., 2003). In this study (Table 3, section 3.1) and a previous study on the millennial sediment storage of the Rhine (Naipal et al., 2016) we show that by getting the scaling relationships as found by Hoffmann et al. (2013) right, the sediment residence time is realistic.

To show the potential effects of a different sediment residence time on the SOC storage and POC flux, we performed a sensitivity study where we changed the basin average sediment residence time to be 50% higher or 50% lower but keeping the maximum sediment residence time at 1500 years. We find that the low sediment residence scenario leads to a 43% higher cumulative C export flux of the Rhine catchment, while the high sediment residence scenario leads to a 15% lower export flux compared to default conditions. However, the impacts of a modified sediment residence time on the total SOC storage of the Rhine are non-linear. The results of this sensitivity study will be summarized in table 5 in the discussion section of the revised manuscript. See changes to the manuscript in our response to reviewer 2, where we describe in the model sensitivity analysis in more detail.

**Comment S5:** *L202: Similar above, this routing scheme may be fine for floodplain but whether it is appropriate for river sediment routing is questionable. And river sediment routing transports large amounts of sediment and POC from hillslopes to oceans.*
**Answer:** See our response to comments 1 and S1

**Comment S6:** *L322-326: Could you make the meanings of each term in RHS of these equations more clearly? Especially, I do not very understand what the second term of RHS of Eq. 16 stand for. Also in Eq. 17, what is the difference between 1/(τ *365) and kiout for SOCFLi(0,t) in the third term?*
**Answer:** The second term at the RHS of Eq. 16 stands for the C flux flowing into soil layer z from the soil layer z+1 below, and is related to the C export flux of the floodplain part of a grid cell. When the topsoil layer loses C due to sediment routing, the C from the subsoil layer ‘moves’ upward as is also done for C loss due to soil erosion (section 2.7). In Eq. 17 $ki_{out}$ stands for the C import rate from the neighboring grid cells. We will provide a short explanation of each term in the equations 16 and 17 in the revised manuscript.

**Comment S7:** *L431-432: Or as argued by Tan et al. (2018), rainfall erosivity itself tends to be less variable if using large scale rainfall data to calculate it.*
***Answer:*** We agree with this statement and will add a comment in the revised manuscript mentioning the effect of the spatial resolution.

**Comment S8:** *L455: could the map of these 13 sub-basins be shown?*

***Answer:*** We will include a map of the sub-basins of the Rhine catchment in the supplementary information.

**Comment S9:** *L471-473: if much more sediment was generated but sediment deposition may still follow the long-term level, where did this additional sediment go? I suspect that it mostly was transported to oceans, a process not or poorly represented in the current model.*

**Answer:** We agree that a large part of the sediment is transported out of the catchment, more specifically 36% of the cumulative gross soil erosion rates over the entire period (see our response to the first comment). We aim to explicitly represent riverine processes in a future study on the further development of CE-DYNAM where we also plan to include the impact of dams on the sediment export. However, the focus of this study lies on the redistribution of soil and C on land and their effect on the land-atmosphere C exchange, rather than on the riverine export fluxes of sediment and C.

**Comment S10:** *L474: that only 0.2% of sediment is exported out of the catchment is too low to believe. Are there any data to support it?*

**Answer:** See our answer to comment 1

**Comment S11:** *Section 4.2: The model also does not represent the impact of water management (such as flooding control) on floodplain connection.*

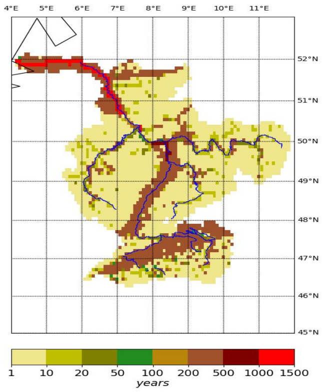
***Answer:*** This is correct. We assume a 'natural' state of the catchment where the main river channel is not managed and the floodplains are more or less dynamic. We will specify this in the revised manuscript.

***Changes to manuscript*:**

**Section 4.1:** In CE-DYNAM we assume a ‘natural’ state of the catchment where the main river channel is not managed and the floodplains are more or less dynamic. This may affect the behaviour of the POC export and residence time of C in floodplains.

**Comment S12:** *Figures: As discussed above, I recommend to add a few more figures (in either supplementary or appendix) to show the 13 sub-basins of the Rhine catchment and the spatial variability of the floodplain factor f and the sediment residence time τ .*

**Answer:** We added these figures in the supplementary info



Supplementary figure: Spatial variability of the floodplain sediment residence time (tau)

**Comment S13:** *Figure 2: What does the gray level stand for? Elevation?*

**Answer:** The gray level stands for elevation, where the darker colors represent higher elevations. We added this information in the figure caption of the revised manuscript.

**Comment S14:** *Figure 3: What does the x-axis mean? Why do not you do a cell-to-cell comparison instead?*

**Answer:** The x-axis represents bins or evenly spaced ranges between the minimum and maximum total yearly soil erosion rates of the Rhine. A cell-to-cell comparison does not show a clear result due to the large variability in erosion rates. We find a quantile plot like figure 3 more useful to see for which erosion ranges the rates differ significantly between the models. For example, from Fig. 3A we can see that for the higher soil erosion rates (bins 2-10) CE-DYNAM produces a lower average compared to the erosion data of Cerdan et al. (2010).

**Changes to manuscript:** We revised the figure caption to include the information on the bins.

**Comment S15:** *Figure 4. Do you have another way to convey the message? It looks messy currently.*

**Answer:** We agree that this figure does not convey the message properly, after reviewer 2 had a similar opinion. We also think that the figure is not very important. However, we will keep the text where we explain that the spatial variability of soil erosion rates are dominated by erosivity and slope as is shown by similar studies using a higher model resolution.

**Changes to manuscript:** We will remove this figure from the manuscript

**Comment S16:** *References: Generally good. I recommend to also acknowledge the progress in other groups to represent soil erosion at large scale numerical models, such as Pelletier (2012) and Tan et al. (2018).*

**Changes to manuscript:** We will acknowledge these studies in the introduction and will add the references in the revised manuscript.