Reply letter

Dear Editor and Reviewers,

Below, we have copied the relevant sections of the editors and the two reviews (copied sections are given in black, italic font). We have addressed the reviewers' comments separately, and provide our reply below (reply is given in blue font). The reply to the Anonymous Referee #1 is on p.2 and the response to the Anonymous Referee #2 is given on p.10. Furthermore, a track-change version of the manuscript is provided at p. 21 of this document.

1. Reply to the Editor

Dear Authors,
Following the general and specific comments of the two reviewers, a major revision of your manuscript is required to reconsider your study in SOIL. Please take all the comments of the reviewers carefully into account before resubmitting your paper.
Three aspects were underlined by both reviewers, which therefore should be especially handled with care. (i) You should be clearer regarding your assumptions and should discuss the consequences of these assumptions in more detail (especially regarding yield/biomass relations; constant agricultural management etc.). (ii) Both reviewers mentioned several times that your data utilized from Bakker et al. 2004 need to be described in more detail. (iii) There is a large number of formal errors in the manuscript which need to be removed.
Following reviewer #1, I also have some general doubts regarding the three relations given in Fig. 1, which are used to explain why erosion results in a yield decline (nutrient depletion, physical hindrance and water availability). I suggest, to discuss these reasons, but do not over interpret this as the data basis seemed to be quite weak.
Best regards,
Peter Fiener

Dear Editor, thank you for the comments. We carefully revised the manuscript according to the suggestions made by you and both reviewers. You will find the answers to their questions/suggestions and where they have been integrated into the revised manuscript below.

As for the three aspects pointed out by you:

(i) We clarified the assumptions of the model regarding agricultural practices and yield/biomass relationship on P3 L30. We further discuss the implications of our assumptions (i.e. no evolution in agricultural practices and omitting the difference between crop productivity and yields) in section 4.1 "Model limitations" (P17 L6).
(ii) We now present a substantially improved description of Bakker's data, i.e. how they were obtained, scaled and what they represent in section 2.1 (P3 L8).
(iii) We carefully checked the manuscript to correct the formal errors.

Finally, we agree that these interpretations of the yield decline to soil truncation are associated with substantial uncertainty. We therefore removed these interpretations from the manuscript to focus on the effect of the mathematical form of the erosion-crop productivity link on the SOC losses and vertical C fluxes.

Reply to the reviewers

Below, we have copied the relevant sections of the two reviews (copied sections are given in black, italic font). We have addressed the reviewers' comments separately, and provide our reply below (reply is given in blue font).

2.1 Anonymous referee #1

I found this a generally well written and interesting manuscript on a timely topic.

Thank you for this positive assessment

However I feel that the authors have to sharpen their arguments and they should remove several formal weaknesses (especially regarding mathematical notation and use of units), which make it difficult understanding the text.

The manuscript deals with the influence of accumulating erosion on yield and in turn on carbon sequestration. However, it ignores basic agronomic knowledge and agricultural concepts and thus has (presently) limited real-world relevance. From an agronomic point of view it is very clear that soil truncation has NO influence on yield in contrast to the basic assumption by the authors. My strong statement is easily proven because highest yields are possible without any soil (for extreme examples see the conceptual studies for a future Mars mission). What changes is not yield but the effort-yield relationship. The effort may increase to maintain yield. Some erosion effects can be changed with little or even no effort (e.g. nutrient losses in over-fertilized landscapes); other may require more effort (e.g., irrigation to compensate losses in water holding capacity). The authors may wish to argue that their relation holds true for a given and constant effort. Such behaviour may be found in controlled plot experiments but it is agronomically invalid because it would require that a farmer stops making decisions while in fact he has to decide and adjust his management every day. There is no other explanation why farmers accept soil losses that are above what soil scientist regard tolerable than that they regard the increase in effort to maintain yields smaller than the efforts needed to lower erosion. Note that usually it is assumed that erosion decreases productivity. This is something different than yield and switching from productivity to yield is not a trivial modification and would call for a discussion of its implications.

We welcome this insightful comment. We clarified in our manuscript that our study is based on observed relations between biomass productivity and soil erosion. We would like to emphasize that the data used to construct the functional relationships are not derived from manipulation experiments but from the comparative analysis of eroding soils and their stable non-eroding counterparts (same slope position) that have received the same management and external inputs. They represent actual farm management practices and we therefore argue that they are representative and have some real-world relevance. We have worded this more carefully in the revised manuscript (P3 L30).

We agree that farmers in high-input systems will take measures to compensate the loss in crop yields. Agricultural intensification has resulted in increased yields and this has masked the expected decline related to erosion. However, as several studies pointed out (see Fenton et al. 2005, Reyniers et al, 2006, Kosmas et al., 2001), these measures may not be sufficient in low to medium input production systems and may not fully compensate the decline in productivity, particularly when nutrient losses are not the main cause but water availability or subsoil constraint. Finally, even in high-input systems, it has been conclusively demonstrated that the within-field varia of biomass production are related to topography-driven erosion processes (e.g. Reyniers et al 2006): this implies that erosion contributes to a decline in productivity, relative to non-eroding conditions, even when overall productivity increases. This is the focus of our paper and we therefore not consider changes in effort in our analysis.

The presented data do not result from an assumption about the relationship between soil erosion and biomass productivity but from observed cases in eroding landscapes under controlled amendment. We discussed these points section 2.1 (P3 L8, Data meta-analysis) and in section 4.1 (P17 L8, Model limitations).

I wonder why EPIC was not used. Doesn't this do essentially the same job but allows a better control of agronomic practices and all other parameters that influence yields (which all are completely ignored in the manuscript). EPIC would allow deriving yields from productivity. This also leads to the next influence that the authors do not consider: some causes of productivity decline by soil truncation are difficult to remove while this is easy for others. For instance the authors expect the largest effect on SOC decline from a loss of nutrients due to erosion (although this is pure speculation). Such a loss of nutrients would be easy and cheap to replace in many countries. Reversibility of productivity again points to the importance of the effort-yield relationship.

The main goal of the paper was to assess the potential impact of soil erosion on crop productivity and yield, assuming no changes in external inputs. Although we agree that it would be interesting to include the effects of agricultural management practices in the model, this is beyond the scope of our study. Furthermore, the required input data to constrain the spatio-temporal evolution of external inputs for the case studies (covering several decades) are simply not available. We could use EPIC but this would substantially increase the uncertainties associated with our model simulations. Finally, we agree that in intensively managed systems, fertilizer applications compensate for erosion-induced nutrient losses and that nutrient loss may not be the most important effect of erosion. Rooting space and water availability are more likely to be key issues. However, by representing different functional forms, we present all possible cases. We discuss this in the revised manuscript (P18L10 and P18L33).

In our study, we used the relationship between soil truncation (as a result of soil erosion) and relative yields published by Bakker et al. (2004) in a process-based SOC model. The simple model structure allows us to keep the number of input parameters in balance with the available data input. We also emphasize that the model used here has several advantages such as the detailed profile (i.e. with depth) - representation of SOC profiles, as well as its temporal evolution in response to erosion. However, we carefully revised the literature review on mechanistic SOC models, and further clarify the scope of our paper in the introduction (see P2 L16) and in the discussion (P17 L7, Section 4.1).

The basic relation between soil depth and yield is given in figure 1. This figure suggests that the study used data but this is misleading. In fact only one conceptual relation was used although the authors suggest that this relation can be separated into three different cases. My main critique regarding this figure is twofold:

(i) It ignores a fourth rather common case, namely that productivity first increases with increasing soil truncation (often up to a truncation of 20 cm to 40 cm) and then starts to decrease. This behaviour can be found in many loessial landscapes and the effect is so strong that at least in former times without subsidies farmers paid higher prices for land where the clay depleted AE horizon had been lost and the better structured Bt horizon improved the properties of the Ap.

Figure 1 is based on data that were published in the review paper by Bakker et al. (2004) on “The crop productivity-erosion relationship: an analysis based on experimental work”. This publication compiled data from 24 experimental studies, and they analyzed the effect of soil truncation on yield by comparing the yield to a reference yield. Following their review, we used a subset of these data that exemplify the relationship between soil truncation and yield based on field experiments from comparing paired-plots. In the dataset published by Bakker et al (2004), there is one case study (Olson et al 1999) where an increase in yield was observed as a result of soil truncation. This change was reported to be maximum 1.1 times the reference yield, and was observed after 25cm of soil truncation:

The Olsen et al (1999) study shows a decline in relative yield to 0.9 for the first 7.5 cm of soil truncation, followed by a slight increase to 1.1 relative yield. Furthermore, in the Belgian loess belt, Reynier et al (2006) studied the effect of soil truncation on yield and found that, even with soil amendment, yields were lower on the slopes than on the plateau as a result of soil truncation and removal of topsoil. Fenton et al. (2005), and Gregorich et al (1998) came to similar conclusions for sites in the US, and Dusar et al. (2011) and Kosmas et al. (2001) for the Mediterranean Region. The latter two studies indicated that, even with input of fertilizers, yields were decreasing, relative to stable parts of the landscape, as a result of soil erosion.

We agree with the reviewer that a yield increase is possible for specific cases but the available data suggests that it may not be representative for a more generally applicable soil erosion – productivity relationship. We discuss this issue in the revised manuscript on P17 L9 and P18 L10.

(ii) The interpretation of these three conceptual cases is brave. The authors explain a steep decrease in yield at little truncation by nutrient limitation. This is quite opposite to text book knowledge of plant nutrition. Since the early times of Mitscherlich we know from the law of diminishing returns that a reduction in nutrient availability has little effect when starting at high availability. For the topic of the manuscript it is completely irrelevant whether the one curve is caused by nutrient loss and the other curve is caused by loss of water holding capacity. These interpretations, which are repeatedly treated in the manuscript like truth although any proof is missing, should entirely be removed.

Based on the experimental data published in the meta-analysis by Bakker et al (2004), we have identified one mathematical expression that allows to express the change in relative yield as a result of soil truncation. The use of a simple mathematical expression facilitates its integration in the SOC dynamics model. Bakker et al. (2004) state that, following the literature, the three main regressors explaining yield losses due to soil truncation are water-availability, nutrient depletion and physical hindrance.

We agree with the reviewer (and the editor) that the interpretation of the three functional forms is not always straightforward. As this is not the main point of the paper, we revised the manuscript and removed these interpretations.

I would suggest that the authors strictly follow the rule of notation in mathematics. E.g.: sometimes they ignore the multiplication sign and AB means A × B, in other cases AB means one variable; sometimes variable are in italics, sometimes not; sometimes even mathematical signs are in italics (it should be dt). Units are similarly ambiguous (e.g., the unit coulomb is reported but not meant). I suggest following the "Guide for the Use of the International System of Units (SI)" (https://physics.nist.gov/cuu/pdf/sp811.pdf).

We apologize for this. We made the necessary corrections to the annotations.

The data that were used to calibrate the model come a bit out of the blue. "we used data from ten study sites" but I am not sure whether the five references distributed within this paragraph were the origin of the data. Without clear reference there is no information about their reliability and the boundary conditions under which they were carried out.

Our apologies for this confusion. In fact, the data that were used to calibrate the model were presented in Van Oost et al. (2007), and the characteristics of each site are summarized in the supplementary material of Van Oost et al (2007). To avoid redundancy, we referred to Van Oost et al. (2007). We modified the text and clarified the source of the source of the data in section 2.4 (P7 L24, citations correspond to the paper presenting each site, when available) and section 2.5 (P9 L3). Furthermore, we clarified how observed values of SOC losses and vertical fluxes were obtained from Van Oost et al. (2007) data in section 2.5 (P9 L3).

Some assumptions inherent in the model and some equations seem doubtful and would need better justification or modification:

(i) The model treats organic manure and plant residues identical (eqn 2). I wonder whether this is true because digestibility of fresh plant material is around 75%. Hence only 25% is left after the passage of the digestive tract and it is likely to assume that he remaining 25% are more resistant to further degradation than the initial material. Furthermore, in solid manure often stabilization processes take place that do not occur with plant residues on the field.

Manure and residues have a different humification coefficient values (respectively 0.3 and 0.125) which, in effect, leaves different amounts of C entering the first layer of the soil profile. These values result from parameter calibrations presented in the original ICBM model paper by Andren and Katterer (1997). We clarified the manuscript at P5 L16.

(ii) Surprisingly, the humification factor then distinguishes between manure and crop residues although this is not possible at this stage anymore because eqn2 has already mixed manure, crop residues and other young carbon into one young pool.

At each time step, the humification values are calculated based on the input from crop and manure at the considered time step, then the values of the C pools are computed. For the sake of clarity, the order in which the equations are presented in the text differs from the order of the calculations in the model. This probably caused the confusion and we clarified this in the revised manuscript at P5 L13.

(iii) The model considers only temperature as climate and edaphic (!?) factor (which temperature is not said), while usually soil moisture is the most dominant influence on SOC stabilisation (see Jenny 1941).

We argue that soil temperature is important for the C mineralization rate and the evolution of the SOC stocks. The ICBM model takes the moisture into account in the factor "r" (climatic factor) (Andren and Katterer, 1997).

(iv) The model does not consider any preferential loss of SOC or clay by erosion. The results may thus only be valid for tillage erosion.

We agree with the comment that we did not include selective erosion. However, based on several studies (e.g. Wang et al., 2010, 4 years monitoring), the observed enrichment is relatively small (1.3) which indicates that most of the erosion occurs under aggregated form, at least in fine-textured soils. We developed this issue in the discussion at P18 L10.

(v) Only roots incorporate SOC into subsoil. Bioturbation, leaching and other processes are omitted.

It is correct that our model does not take these processes into account. We argue that at a timescale of 60 to 200 years, SOC dynamics are largely dominated by soil redistribution processes and that bioturbation and leaching, although important processes on long timescales, account for a minor part of SOC fluxes and dynamics in this context (Doetterl et al., 2016, Minasny et al., 2015, Kirkels et al., 2014). We identified and discussed this shortcoming in a revised version of the manuscript in the point 4.1 "Model limitations" (P17 L7).

(vi) It is not clear, what follows in the model below 100 cm depth. I had the impression hard rock (i.e. the model does not shift the entire soil profile downward, when topsoil is lost). In this case, the model would be far too simple because hydrology then becomes tricky. Lateral water movement could not be ignored anymore when large parts of the soil were removed. Modelling would be easier and the results likely more realistic if soft rock would follow below.

We consider the following boundary condition: the soil properties (SOC, clay) observed at 1 m depth are representative for the soil/soft rock below 1 m. In the model implementation, SOC and clay content in the 100th layer are assumed to represent the soil characteristics below 1 m. Assuming a constant bulk density of the soil, soil characteristics are advected upward in response to soil erosion, proportionally to the amount of removed topsoil. As a response to soil erosion, the soil properties of the 100th layer are also continuously advected upward. In the physical hindrance case, the amount of coarse fragments is actually given by the low absolute clay content (in volume). We described this boundary condition more clearly in the revised manuscript at P7 L6).

(vii) Eqn (9) seems to be wrong because all carbon that leaves the young pool is delivered to the atmosphere although large part of this carbon (see humification factor) enters the old pool.

Equation 9 is simply the difference between the input of carbon entering the soil and the mineralized carbon leaving the young and old pools. Eq 9 is based on Fig. 1 from Andren and Katterer (1997) who developed the ICBM model. We checked Eq 9 with the original ICBM formulation (Andren and Katterer, 1997) and it is correctly presented in our manuscript.

(viii) A value of 0.55 or 0.6 seems to be more appropriate for alpha than 0.7. This could have considerable influence on the results.

The authors decided to use RRMSE for optimization (eqn (10)). Why? Isn't this a bad decision because it puts larger weight on layers with low SOC content although those layers are rather unimportant and relative measuring error is larger there? The authors also seem to have forgotten that they used RRMSE because they frequently report units of RRMSE (e.g. in Fig. 2) although this parameter cannot have a unit.

We argue that the shape of the SOC profile is as important as topsoil SOC content for our study. As Kirkels et al. (2014) pointed out, SOC stock and lateral fluxes follow a two-phase evolution in which the very high rate of loss in the first decades is followed by a period of lower loss rates. The evolution is similar for the vertical C fluxes as the C uptake increases fast at the beginning of the erosion period while the rate of increase is slowing down over time. This temporal evolution is due to the lower SOC content in the subsoil. Hence, the shape of the SOC profile determines the intensity and evolution of both lateral and vertical C exchanges. As these fluxes are a key part of our analysis, the RRMSE was used so that parametrization of the SOC profile would ensure a good representation of (i) observed SOC profile and (ii) an accurate representation of the impact of soil erosion on C fluxes. We added a short justification of the use of RRMSE at P8 L21.

Is a model error of 93% or even 121% acceptable (see Table 1b)? I would not be satisfied. Table 2a+b: How can the contribution of all parameters sum up to more than 100%?

The model error is indeed high for the cumulative vertical C fluxes, in contrast to the prediction of the SOC stock loss. We point out in the discussion that this discrepancy is mainly due to the fact that site-specific data is lacking to fully reconstruct the initial conditions and management options. Secondly, the long timescales considered should be considered when analyzing the model errors. Nevertheless, we would like to emphasize that the model predictions are in the correct order of magnitude and the relative differences between the sites are well represented.

In FAST analysis, the sum of contributions can be more than 1 when two (or more) variables are correlated. In our case, erosion rate and yield response to soil truncation are correlated. We clarified this point in the text at P13 L17.

Table 2b: How can erosion rate have an influence on the result although erosion rate was set constant?

A FAST analysis can show small positive contributions for constant parameters when (i) the number of runs is too small and (ii) due to mathematical dispersion. This also applies to negative contributions. We clarified this point at P13 L17 and in the table caption.

The Results chapter does not differ in style and content from the preceding chapters, which were assigned to Material and Methods. Most results are in fact reported in the preceding chapters. The manuscript requires better structuring

We substantially revised the manuscript and this has resulted in an improved separation of materials and methods from results.

Fig. 4: Units of the left panel? Shouldn't be a time unit in the right panel? What do the black lines denote?

The left panel represents the relative SOC loss $1 - \frac{\text{SOC (final)}}{\text{SOC (initial)}}$. It is thus without dimension.

Fig. 5+6 are in poor quality. Use the same font size as in fig. 4

This may be due to the compression applied to the file when submitting the manuscript. We provided figures with better quality.

Fig. 7: the information about the treatments is repeated three times (twice in the figure and once in the caption). What do the boxes and whiskers show (there is no convention on this)?

The boxes represent the interquartile range and whiskers represent the 95 % quantiles of the distribution. We corrected the information and added a description of the meaning of the boxes and whiskers in Figure 7 caption.

I didn't like the Discussion. What I missed at the very beginning is a paragraph about the assumptions and simplifications of the model and which influence they can have on the results (a little bit on this can be found at the very end but this is not stringent enough). Be more critical regarding your work. This would increase its value. At the moment it is of little value for me because I do not know under which conditions the results would apply and under which conditions nothing could be said. Studies are cited which seem to be in agreement with your results but this does not mean much. It only becomes meaningful if we know your assumptions and simplifications because then we also know that these assumptions and simplifications would not be important for the other study.

On the other hand there are parts in the discussion that could be written even without the preceding results (e.g. the last paragraph of chapter 4.1). They could be deleted in order not to increase the length of the discussion. Also all speculations about hindrance or nutrients should be deleted. They are all unsubstantiated and misleading.

We agree with this comment and we added a paragraph on model simplifications and assumptions in the revised manuscript (see section 4.1, P17L7). We also removed the less relevant parts of the discussion and modify the discussion as suggested by the reviewer.

Details:

In general, the use of blanks is strange. After semicolon the authors do not like blanks. Also periods are often omitted (e.g. in i.e.)

We corrected the typos and mistakes in the manuscript.

Figure 2 only allows for yield reduction. Yield increase would also be possible (as in the already mentioned case of alfisols or in the case where an acidified topsoil is lost; there may be more cases).

See discussion above. However, based on your comment, we discussed the implication of increasing yields on our results (P19 L4).

I wonder why the authors used different orientation of Table 1a and 1b. The same orientation in both parts would be possible. I suggest using the same orientation as in Table 1b also in Table

1a because this is the standard orientation (variables in columns, cases in rows). Table 1 b shows the vertical C balance. In all other cases this is called vertical C flux (at least I assume that this is the same). Be consistent.

We changed the orientation Table 1.

Fig. 3: Aren't the red profiles calibrated profiles (the word "simulated" would then be misleading). I thought the manuscript was about arable soils but apparently these soils do not have a plough horizon. Is the manuscript about grassland or woodland soils?

We agree that these are calibrated profiles and corrected the text. The study is only for arable lands, and we did not take tillage into account, only water erosion.

The manuscript frequently reports 1000 parameters. Fortunately the model has less. I guess the authors mean 1000 parameter sets.

We apologize for this, it is correct that we generated 1000 sets of parameters values. We carefully checked the manuscript and clarified it.

There are many more technical details (e.g. inconsistent tenses, omitted periods and blanks, inconsistent formatting of references) but given that large changes are necessary it does not make sense reporting these details.

We carefully revised the manuscript, and pay attention to the formatting of text, references and tables.

2.2 Anonymous Referee #2

GENERAL COMMENTS

The interdependencies of erosion and soil carbon balance have been investigated in many model-based studies. In a next step, vegetation should be explicitly included in integrated simulation approaches. Therefore, the authors tackle a relevant topic.

The general approach of the study is suitable to investigate the interdependency of erosion, plant growth and soil carbon balance. Nevertheless, the implications of the chosen implementation are not clearly addressed and are not sufficiently considered in the interpretation of the results. The study contains several flaws, which need to be addressed by the authors to make the results publishable in SOIL (see below).

In addition, the manuscript is not carefully prepared, hard to read, and hard to understand. This is mainly due to the lack of a common thread and to the fact that the authors use different terms for the same thing throughout the manuscript (e.g. net flux and cumulative flux and vertical flux, erosion and soil truncation, etc.). The mathematical notation is not clear and does not follow a general concept. Therefore, the text requires a complete revision to make it suitable for a scientific journal.

The necessary clarifications on terminology and mathematical notations have been made in the final manuscript.

SPECIFIC COMMENTS

In the following paragraphs, I address the main problems I found concerning methodology and presentation of the study:

The study applies a very simple SOC model together with an equation that relates yield to erosion and an approach to translate this into depth-dependent carbon input to the soil. From my point of view, this model must not be labeled "integrated“, since that would require a plant growth model. Therefore, the title of the paper should be changed. The same applies to the statement the model would dynamically link crop yields, soil properties and SOC dynamics. The model does not contain a dynamic link from soil properties to crop yields but a static assumption on the effect of erosion.

The authors use two scenarios, one of which they call FB (feedback). However, Fig. 2 and the model description reveal, that actually there is no feedback loop in the model. Using the term “feedback” is therefore misleading. I suggest using a term like “yield effect”.

A central point of the study is that agricultural yield changes with soil truncation. However, there is no direct link between these variables. Soil carbon input depends more on total biomass than on yields. However, the fraction of the harvested plant organs from the total biomass (harvest index) is physiologically controlled and therefore it is variable. As the authors point out, there can be different causes for the effect of erosion on plant growth. In the real world, farmers take measures to compensate for these effects. These simplifications need to be addressed when describing the general approach of the study and have to be included in the discussion. In this context, objective iii where the authors state their intention to investigate long-term effects of erosion on crop growth also needs to be rewritten.

In the current version of the model, there is no explicit link between soil properties and crop yields. Our study is based on a published relationship between soil erosion (expressed as soil truncation) and relative yield. The data about these relationships were obtained by field experiments comparing yields in eroding plots with yields in non-eroding areas. Hence, our data implicitly represents the aforementioned effects. The soil properties, SOC dynamics and C input (derived from yields/biomass productivity) are integrated as SOC dynamics depend on clay content and C input which are influenced by soil erosion. These links are therefore explicit. We thus reformulated carefully the title and the text so that the difference between explicit and implicit links are clear. The feedback term has been adapted to clarify that it represents the indirect effect of erosion on SOC dynamics through yield reduction.

We agree that yield and biomass production are two different concepts, which are often mixed in the literature and common language. In this paper, we are talking about biomass productivity in response to soil erosion and we agree that farming practices will try to cope with declining biomass production. We clarified it in the implementation (see i.e. P4 L1) and discussion that we are assuming constant agricultural management practices (P17 L7).

In the results, the authors present data on relative yield. Here, an explanation on how the reference value was set by Bakker et al. (2004) is missing. This is crucial in order to assess the results.

We selected data from comparative plots in which the original studies compared yield obtained in non-to slightly eroded soil with yield in eroded soil. Relative yields were calculated as following: relative yield is set to 1 for the non-or slightly eroded soil and fractions of that for yields on eroded soils. Hence, a relative yield of 1 indicates that there is no change in the yield, values < 1 represent yield losses and values > 1 yield gains. We clarified this in the text and figure captions (P3 L12 and P4 L3)

The model description is hard to understand because different terms are used for the same thing (e.g. input from crops vs. flux from the atmosphere). It requires a more precise presentation. In addition, the following points have to be addressed:
- the timestep of the model has to be given
- equation 2 and 3: If h≠ 1, where does (h − 1)kyrY go? This is only implicitly stated in Eq. 9
- using 100 soil layers seems very detailed compared to the very general assumptions on vegetation effects and C input from roots. Why did the authors choose 1 cm for layer thickness? - Eq. 9: it should be stated, that this is just the sum of equations 2 and 3. One could factor out r, which would also simplify Eq. 3
- values for δ, kyt0, and kot0 are missing
- Eq. 4 contains manure input, however there is no further information on this

The model time step is 1 year. We added this information at P4 L19.

Equation 2 and 3: the quantity (1-h)*k*r*Y represents the mineralized/respired fraction leaving the young C pool. We added this information at P5 L9.

We used 100 soil layers to have a very fine representation of the vertical soil profile and advection in response to soil erosion. We found that the model was sensitive to the vertical SOC profile and using a coarse resolution resulted in substantial numerical dispersion and smoothing. In addition, as the model computational performance was very good, there is no need for a low vertical resolution. We added this information at P7 L2.

Eq. 9 is the sum of both equations. However, Eq 2 and Eq 3 are the classic way to present ICBM equations. We refer to Andren and Katterer, 1997 and SPEROS model presentations by Van Oost et al. (2005), Dlugoss et al. (2012), Nadeu et al. (2015).

Values for k_y and k_o are respectively 0.8 and 0.006 yr^{-1} and δ is 2.91 (dimensionless). These values will be added to the manuscript. We added these values at P5 L9.

It also remains unclear, how soil truncation is modelled. Are layers removed from the top? Are the properties of the existing layers altered while keeping the overall soil depth constant? This has to be presented (considering the proposed effect of soil depth on plant growth).

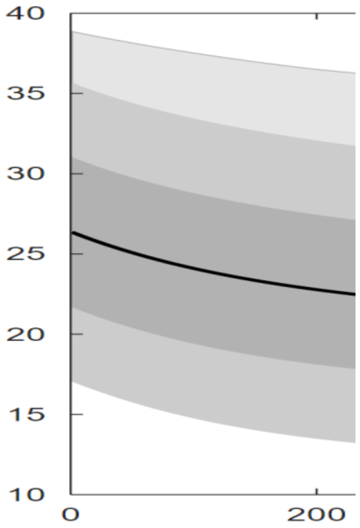
Soil truncation is modelled by removing soil properties from the top of the profile. Assuming a constant bulk density, the considered depth does not change over time but the soil characteristics are advected upward in response to soil erosion. Soil properties are advected upwards in proportion to the amount of soil removed (see e.g. Van Oost et al, 2005, Dlugoss et al., 2012, Nadeu et al. 2015). At the bottom of the profile, a constant boundary condition is assumed and its properties are progressively included in the soil profile proportionally to the amount of removed topsoil, resulting in an effective truncation of the soil profile characteristics. We clarified how the vertical transfer is represented at P7 L1.

The next point concerns the model validation. As far as I understood the text, the same observational data was used for validation and calibration. If I got this wrong, clarifying text has to be added. If I am right, this is not a validation but an evaluation. Nevertheless, a validation is required and can be accomplished by using a leave-one-out or bootstrapping approach. As I also commented in the context of the long-term experiment, the validation needs to be conducted with the same set of perturbed parameters as the following experiments. The text states that Fig 3 shows a comparison of simulated SOC content and observations. This comparison should also include uncertainty information resulting from the 1000 simulation runs with perturbed parameters.

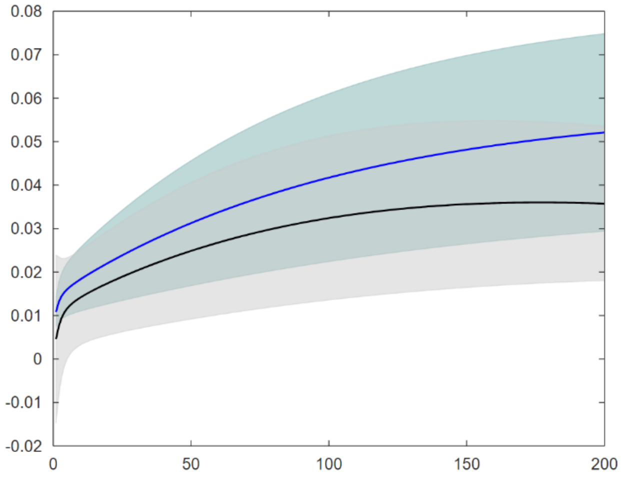
We share the concerns raised by the reviewer: we realize that we have not sufficiently explained how the model calibration and evaluation was implemented. We would like to emphasize that we do not calibrate the model parameters on observed SOC losses or soil-atmosphere SOC exchange. We simply fitted the three model parameters that control the shape of the SOC depth profile on stable sites only. This procedure therefore only estimates the initial conditions of the model for each site and should not be considered when evaluating the performance of the model. This is also the reason why we did not include uncertainty ranges in figure 3 as only a single profile was available for each site. In a second phase we evaluate the model using observational data on SOC losses and soil-atmosphere exchange in response to erosion. Importantly, we did not use this data to inform/calibrate the model. We therefore believe that this represent a robust way to evaluate/validate our model. We have adjusted the text to make this approach clearer. We performed site-specific simulations as SOC parametrization, clay content, erosion rate and length of the simulations were specific for each site (see Van Oost et al. (2007) paper): however, these are estimates and are associated with substantial uncertainty. To address this issue, we performed an uncertainty analysis: For each of the 10 sites, we created a set of 1000 scenarios for which parameter values were randomly chosen in a narrow range around their published values in Van Oost et al. (2007). These values, associated ranges and lengths of simulations are given in Table 1a. We clarified the calibration/parametrization procedure in P7L25 and better separated the calibration description from the evaluation description (P9L2) to avoid confusion.

After the model validation, the reader will be interested in results of the model runs. How does SOC and C-exchange with the atmosphere develop over time? The authors should present timeseries that enable the reader to get an idea of how the model works. If the data were available, a comparison to observations would be desirable.

The time-series resulting from our simulations are available and could easily be included in the paper. SOC stock evolution follows a classic two phase evolution: the profiles quickly lose a large amount of carbon during the first decades, and the rate of SOC loss is then decreasing over time due to the lower SOC content of the exposed subsoil. When the yield effect is weak, a steady-state is observed whereby the laterally exported SOC is replaced by new C coming from plant inputs. When the yield effect is strong, it takes a longer time to come to steady-state SOC stocks or there is no steady-state. However, due to the large range of simulations performed (1000) with a large range of parameters, it is rather difficult to visually synthetize the information into a graph (see figures inserted below). Furthermore, to our knowledge, long-term observational data on yearly C fluxes nor SOC stock evolution are not available in literature. Hence, we chose not include it for clarity.



SOC stock evolution (t/ha) for the FB dataset. Solid line denote the mean of the 1000 simulations, shaded areas represente one standard deviation (dark grey), two standard deviations (middle grey).



Annual vertical C fluxes (kg./m²) for the CTL datase (blue) and for the FB dataset (grey). Postive value represents a net C capture from the atmosphere to the soil, negative values represents a net C emission from the soil to the atmosphere. Solid lines denote the mean of the 1000 simulations, sahded areas represente one standard deviation.

Concerning the long-term experiment, it remains unclear, why a second set of perturbed parameters was generated. In order to evaluate the results, the experiments have to be conducted with the validated model and the same sets of parameter values. In addition, information on the scientific basis of the choice of value ranges for the parameters is missing. This is of great importance if the intention of the FAST analysis is to compare the tested parameters regarding their influence on the overall variability. This is because the value ranges used for the parameters have an effect on the resulting explained total variance. In order to interpret the FAST results in the way the authors do, it has to be argued why the value ranges are comparable. Using the same relative ranges is not appropriate due to different relative ranges of the respective parameters in the field. An appropriate method is to use published ranges of observed values together with estimates of uncertainty. If these are not available, reasons for the estimates of plausible ranges have to be given.

The model validation was done comparing the model predictions against observations using site-specific data. These data are displayed in Table 1 and Figure 3. We added a relative uncertainty range around these observations to account for natural variability and errors in measurements at the site-scale. A range of B exponent was attributed to each site, in line with each site's description of soil depth description and climate type. For each individual site, we generated 1000 sets of parameters, which values were inside the range of this specific site. We performed 1000 simulations which time length was site-specific (i.e. 1000 simulations with the parameters of Belgium 1 site, 1000 simulations with the parameters of UK site, etc.). Therefore, the resulting SOC losses and vertical C fluxes can directly be compared to the observed values as the erosion and SOC parameters were close to the observations.

The long-term experiments should be considered as an exploration of the model behavior at longer time-scales. We therefore performed a numerical long-term experiment on the total range of the observed parameter values regardless of the sites considered in the model evaluation: i.e. from the smallest value to the highest value found in the table, with the notable exception of erosion rate, which range was extended further based on erosion data across Europe and the USA. We generated 1000 sets of parameters based on this total range of values (as presented in table 2). Specifically, the range of the yield-effect exponent was chosen to cover the whole set of yield values per unit of soil truncation as extracted from Bakker et al. (2004) and this was presented in the first part of the manuscript. The root-depth parameter indicates the root penetration in the soil and its value was taken so that 95% of the roots are distributed in the first 35 cm to 65 cm with respective φ values of 4 to 6, with 30 to 45% in the first 20 cm. These values are in accordance with previous SPEROS parametrization obtained by inverse modelling (Dlugoss et al., 2012, Nadeu et al, 2015). As for the mineralization distribution, the given range indicates a turnover rate at 1 m depth of 137 to 700 years for the slow C pool which is in line with the centennial turnover rate found in deep colluvium by Wang et al. (2014) or Van Oost et al (2012).

We thus argue that the interpretation of the SOBOL/FAST analysis is valid and we will more clearly identify in the text where the ranges of the parameters come from.

We better explained how the dataset were built and in which simulations they were used in section 2.5 (model evaluation, site-specific datasets) and 2.6 (long-term experiments, extended-range datasets).

It also is not clear to me, which set of model runs was used for the analysis in sections 3.3 and 3.4. Is this based on the same results as the FAST analysis?

The results for the long-term simulations (200 years) in section 3.3, 3.4 are based on a set of 1000 scenarios randomly chosen in the range of values specified in Table 2a. This set was also used in the FAST analysis. We better clarify the use of each dataset in sections 2.5 and 2.6.

Finally, the study requires a comprehensive discussion on the transferability of the results to the real world. Especially the implications of the simplifications in the model on the transferability have to be dealt with. In addition, the authors should discuss the role of the farmers adjusting their choice of crops, management practices and harvest residuals, etc. This is tackled shorty in the final sentences of the discussion, but this is not sufficient. Other important points to be discussed are the dependency of yield on plant growth, on nutrient availability, and on access to water. All this can alter the harvest index and therefore the relation of soil carbon input and yield.

We added and clarified the aspect related to the model limitations and the agricultural practices adaptation in the extended discussion about the study limitations (see section 4.1 and P17 L23). As for the dependency between yields, nutrient availability or water availability, these agronomic aspects have been discussed abundantly in the literature (e.g. Bakker et al in their review (2004), Christinsen and McElya (1988), Lal et al. (1999) or Larson et al. (1985)). However, following the comments of Reviewer 1 and the editor, we removed the interpretations of yield reactions to nutrient limitations, soil depth or water availability to focus on the mathematical form, except in section 4.2 (discussion). Furthermore, we consider that a more detailed analysis of the biological effects of soil truncation of plant growth is outside the scope of this paper.

In the beginning of the discussion, results are compared to Berhe at al. (2005), which, in contrast to the present study, found a carbon sink. Explanation is required why this is rated as a support of the new results.

Berhe et al (2005) found a carbon sink related to the C uptake from the atmosphere occurring in eroding areas. Our study found that erosion can result in a carbon sink (in terms of vertical C fluxes) as the balance is often positive with C being added to the soil. Our study however emphasizes that this C uptake can be overestimated in modelling studies if the long-term evolution of the yields is omitted.

In the final paragraph, the authors reveal, that with B>1.1 there was no effect on yield. If this is the case throughout the study, the manuscript can be simplified by stating this in the beginning and removing this aspect in the results section.

We refer to our reply to reviewer#1. The main goal of our study was to explore the effect of biomass productivity decrease on SOC losses and vertical C fluxes. We acknowledge that the model is relatively simple and required assumptions about the relationship between the C input and the biomass productivity. We agree that the relationship between C input and biomass can be dependent on the amount of residues left on the field but under the absence of data, it is difficult to correctly represent this. When B is larger than 1.1, the simulation period was not sufficiently long to push the system with a heavily convex relationship to the tipping point, leading to a relatively low response of the C stocks and vertical fluxes to the addition of such a feedback.

DETAILED COMMENTS AND TECHNICAL CORRECTIONS

We thank the reviewer for the suggestions. For the sake of clarity, we only answer individual comments relative to understanding, clarifications, and precisions. All other comments about typo, references or re-phrasing which do not required detailed answers will be addressed in the revised manuscript.

Use the same font and italics for symbols in equations and text unless there is an explicit rule given by the journal.

The journal asks for equation symbols to be in italic when used in the text. The necessary changes were made.

Improve the graphical quality of the figures.

We improved the quality of the figures.

p1l22: why negative numbers for an increase in SOC losses?

This is a mistake as the numbers represent the relative C stock changes. We corrected it.

p3l14: this is a meta-analysis, not an analysis of meta-data

We agree with this comment changed it throughout the manuscript.

p4l3-4: unclear why a clay-fraction can replace explicit accounting for soil depth

The clay fraction can be given in absolute terms, i.e. the volume of clay in a given volume of substrate (soil + rock fragment) or in relative terms as the fraction of clay in the remaining space, not occupied by rock fragments. In our case, the clay fraction is accounted for in the model by the absolute volume of clay per volume of substrate. We further assumed that the relative fraction of clay in the remaining space and the bulk density of the soil are constant. Hence, the absolute amount of clay indirectly indicates how much rock fragment is contained in the substrate, which is a proxy of soil depth as 100% of rock fragment is representing the bedrock level. In the case of deep soft rock, the absolute clay content shows little variation between the topsoil and the bottom of the profile. In the case of physical hindrance, the clay content is highly reduced at the bottom of the profile. We provided a better explanation of this simplification in section 2.1.

p5l1: there are two van Oost 2005 papers in the references. Please specify. The same applies to some references to van Oost et al. (2007)

The references were corrected.

P5l26, Eq. 7: K has to be lower case since rates were introduced lower case in Eqs. 2 and 3. In Eqs. 4, 6, and 9 dependency on time and/or layer is denoted by t and z in parentheses.
Therefore: k(t, z). In addition: explain to the reader that this is used for ky and ko p5l27: Sentence incorrect
p5l30: refer to equation 4

Changes have been made, and ky and ko were defined (P5 L9)

p5l31: to make it easier for the reader to understand the overall model setup, state the source of the cumulative soil truncation data

We added the information about the link between erosion and cumulative soil truncation at P3 L27 (which is the annual erosion rate * time, as erosion rate does not vary).

p7l9: two instead of 2
p7l13: remove second full stop

We corrected this.

Table 1 a: What does "period of cultivation“mean? A single number does not define a period.

The period of cultivation is the total duration of cultivation between the start of cultivation on the considered field and the date of the final analysis. We corrected the header to “time since start of cultivation” in table 1.

Table 1 a: the caption mentions data for two simulated scenarios, which cannot be identified in the table. In addition, site description and results should not be in the same table

The caption was wrong and has been corrected accordingly to the content of the table.

p10l2: where do the years come from? Were these the same for each site? Is this somehow connected to the periods in table 1?

In this case, these are different from the period of cultivation as the ^{137}Cs was released in the atmosphere and deposited after the nuclear bomb testing. In the literature and following Van Oost et al. (2007), we took 1954 as the standard date of ^{137}Cs deposition on the earth surface (Ritchie and McHenry, 1990). This date is considered to be identical for all sites. As the erosion rate derived from ^{137}Cs tracer were valid for the period post-1954, the integration of cumulative vertical C fluxes was done over the period from 1954 to the date of the C inventories realized in each individual site rather than over the entire period of cultivation. We added these details in section 2.5 (P9 L4)

p10l3: what is the "period of interest“?

This is the period of cultivation for SOC losses or the period between 1954-date of sampling for the vertical fluxes. We clarified the manuscript (P9 L6)

P10l5: the parameter sets were not obtained by calibration. This only applies to the mean values.

Correct, we changed the text.

P10l10: You investigate the feedback effect in the model. This is not a potential effect. Only transferring it to the real world makes it potential.

Correct, we adapted it.

P10l10: what does the "c.“ mean?

c. stands for “calibrated” years.

Table 2: use the same symbols as in the text; φ was introduced as a carbon input profile, not a root density profile. This also applies to p13l13 and p13l16

We will check the use of the symbols.

p11l11: instead of "typical values“, state how the numbers were computed

These numbers of SOC losses were obtained by calculations based on the data provided by Van Oost et al. (2007): stable profile SOC stock, lateral SOC fluxes, vertical SOC fluxes and erosion rate for each site. The total C losses was calculated by integrating lateral SOC fluxes, vertical SOC fluxes and calculating a mass balance to obtain the total SOC lost over the cultivation period. The observed relative SOC loss is the ratio between the total SOC loss and the observed SOC stock. We clarify the method in the manuscript.

Figure 4: consequently use upper or lower case letters to address the graphs of the figure

We will adapt this.

p12l1: the highest observed SOC loss is said to be 0.19. However, in Fig 4 a, the highest red circle is slightly above 0.2.

We apologize, this is a mistake in the text.

Figure 5: If the same variable is on both y-axes, the axis labels have to be the same. Figures 5 and 6: When comparing simulation and observation or results from different scenarios, the graph should be square.

We made the necessary changes.

P19l5: Bouchoms et al. (2017) missing in list of references -> use a reference managing software to avoid this

We carefully checked the formatting of references, and make sure that the list is complete.

P19l6: this is a nice explanation of the possible interaction of processes. The authors should consider presenting this in the introduction.

Thanks for this suggestion, however, we think this explanation does not integrate well in the introduction logical development.

P19l20f: sentence unclear

We clarified the sentence which is describing the three processes involved into the C sink resulting from erosion (P21 L15).

Evaluating the ~~interaction between sediment fluxes,~~effects of soil erosion and productivity decline on soil carbon dynamics ~~and biomass production~~ using ~~an integrated~~a model-based approach

Samuel Bouchoms[1], Zhengang Wang[2], Veerle Vanacker[1], Kristof ~~-~~Van Oost [1]
[1]TECLIM - Georges Lemaître Centre for Earth and Climate Research, Université Catholique de Louvain, Louvain-la-Neuve BE 1348, Belgium;
[2] School of Geography and Planning, Sun Yat-sen University, Guangzhou, 510275, China
Correspondence to: Kristof Van Oost (Kristof.vanoost@uclouvain.be)

Abstract. ~~During the last centuries, forest clearance has led to an increase of the erosion rates by one to two orders of magnitude.~~ Sustained accelerated soil erosion alters key soil properties such as nutrient~~, water~~ availability, water holding capacity, soil depth and ~~soil~~ texture, which in ~~turns~~turn have detrimental effects on crop ~~yields~~productivity and therefore reduce C input to soils. In this study, we applied a ~~1D~~1-D soil profile model ~~dynamically linking~~that links soil organic carbon (SOC) turnover, soil erosion and ~~crop yield at the profile scale.~~biomass production. We ~~extracted a~~ used observational data to constrain the relationship ~~linking crop yield to soil erosion based on available literature and categorized them into three functional forms: high sensitivity to erosion, linear response and low sensitivity to erosion. We tested and validated~~between soil erosion and crop productivity. Assuming no changes in effort, we evaluated the model performance in terms of SOC stock evolution and soil-atmosphere C exchange using published observational data from 12 catchments across Europe and the USA. Model ~~evaluation~~simulations showed that accounting for ~~the~~ erosion-~~crop yield feedback~~induced productivity decline (i) increased SOC losses by ~~20~~37 % on average relative to a scenario where these effects were excluded, and (ii) improved the prediction of SOC losses ~~predictions, particularly for higher cumulative soil erosion, compared to the results obtained without the feedback. Cumulative vertical carbon fluxes were reduced by 15 to 71% compared to the no-feedback model, although the large variability highlighted the need to perform site-specific adjustments of the erosion-crop yield relationship. Exploration of parameter sensitivity to SOC parameters and erosion showed that long-term simulations of both SOC loss and vertical C fluxes were primarily influenced by the erosion rate, the yield response to erosion and the depth distribution of the mineralization rate of organic matter. Our simulations~~when substantial soil truncation takes place. Furthermore, erosion-induced productivity decline further ~~highlighted the increased SOC losses (-3 to -17%) and reduced C uptake from the atmosphere (-30%) in the erosion-crop yield feedback scenario, compared to the no-feedback scenario~~reduced soil-atmosphere C exchange by up to 30 % after 200 years~~, as well as the importance of the functional form of the erosion-crop yield relationship. Together, this modeling study shows~~ of transient simulations. The results are thus relevant for longer-term assessments and they stress the need for integrated soil-plant models that ~~including the effects of erosion on crop yields has a large potential to reduce uncertainties associated with the estimation of the C~~ operate at the landscape scale to better constrain the overall SOC budget ~~in landscapes subjected to erosion.~~ .

~~Keywords: soil erosion, crop productivity, feedback, soil organic carbon, modelling~~

1 Introduction

The soil system represents one of the most important carbon (C) pools by storing around 1417 ~~PgC~~Pg C in the upper first meter. As a result, its impact on the global C cycle and climate has been widely recognized and studied (Hiederer and Köchy, 2011; Houghton, 2007; Crowther et al., 2016). The terrestrial carbon cycle is mainly driven by soil-atmosphere exchanges; vegetation takes up carbon from the atmosphere and provides input into the soil in forms of root excretions and plant residues while biologic activity and in-situ mineralization release carbon from soils back to the atmosphere~~ from soils~~ (Houghton, 2007).

Through ~~the removal of natural~~ vegetation ~~for~~ disturbance and agricultural extension, human activities have had an important impact on the soil system, not only by changing the soil C cycle, but also ~~by~~ increasing soil erosion rates ~~by~~ up to two orders of ~~magnitude (Vanacker et al., 2013).~~magnitudes (Vanacker et al., 2013; Gregorich et al., 1998; Montgomery, 2007). Soil erosion affects vegetation growth and biomass production by changing soil physical and chemical properties related to soil fertility such as water holding capacity, nutrient status or soil depth ~~(Kirkels et al., 2014;~~Bakker et al., 2004). Effects of soil erosion on crop productivity have intensively been studied during the past decades for a wide range of pedological and climatic conditions (Kosmas et al., 2001; Bakker et al., 2004; Fenton et al., 2005; Gregorich et al., 1998). ~~Despite highly variable results, these~~ These experimental studies have indicated that ~~in absence of fertilizers, yields~~for a given agricultural management practice, crop productivity and yield tend to decrease when soil is subject to erosion (Bakker et al., 2004; den Biggelaar et al., 2003; Larney et al., 2016). Hence, on the long term, reduced biomass production ~~will~~is expected to result in an additional loss of SOC due to decreasing ~~soil~~ C inputs in the soils (Gregorich et al., 1998; Doetterl et al., 2016; Kirkels et al., 2014). Although large uncertainties ~~still~~ remain ~~concerning~~about the strength and the ~~mathematical~~ form of the relationship between crop growth and soil erosion, the general tendencies have ~~now~~ been identified through data meta-~~data analysis~~analyses (e.g. Bakker et al., 2004; Chappell et al., 2012).

In addition to changes in soil C inputs, human-induced erosion also ~~results~~resulted in ~~the subsequent intensification of lateral SOC losses through erosion and~~ lateral redistribution of soil particles across the ~~landscape~~ landscapes and subsequent SOC losses (e.g. Van Oost et al., 2005a). ~~Three processes mainly govern~~Soil redistribution by erosion affects SOC dynamics ~~under the impact of erosion:~~through an enhanced mineralization during transport, ~~the~~a replacement of eroded C by new ~~photosyntate~~photosynthates at eroding sites, and ~~the~~ burial and preservation in depositional areas (Stallard, 1998; Harden et al., 1999; Van Oost et al., 2007b; Lal~~.,~~, 2003; Hoffmann et al., 2009; Wang et al., ~~2014a~~2014). Although each of ~~the described~~these three processes is individually relatively well understood, the result of their ~~interaction~~interactions at the landscape scale is still poorly constrained (Kirkels et al., 2014). ~~To our knowledge, the negative feedbacks on soil C inputs in response to erosion, and how it changes over time, have not received much attention when studying erosion-carbon cycling~~

~~interactions (Harden et al., 1999). Therefore, a~~A dynamic representation of the interactions between soil erosion, crop growth and SOC ~~content~~turnover is needed in order to better constrain the overall C ~~balance~~fluxes in eroding landscapes (Chappell et al., 2015; Harden et al., 1999).

~~Mechanistic SOC~~ During the last years, several coupled soil erosion-C turnover models have been ~~developed following two different approaches: the first approach explicitly~~presented: some of them are point models ~~vegetation dynamics~~ that operate at the soil profile scale (e.g. Billings et al 2010, Harden et al., 1999; Manies et al., 2001). Other are spatially explicit and focus on the representation of geomorphic processes and SOC turnover in ~~relation~~a three-dimensional context (e.g. Dialynas et al., 2016, Fiener et al., 2015, Van Oost et al., 2005, Wilken et al., 2017). They operate at timescales from single events (e.g. tRIBS-ECO, Dialynas et al., 2016; MCST-C, Wilken et al., 2017) to ~~soil and climate conditions, but has a limited description of the soil component and its dynamics (Kaplan et al., 2012;Doetterl et al., 2016). This approach is~~annual (Van Oost et al., 2005) while others (e.g. Vanwalleghem et al., 2013; Rosenbloom et al., 2006; Yoo et al., 2006) focus on long-term landscape evolution. The point-models have a detailed representation of soil-plant systems and are typically ~~useful~~based on the CENTURY ecosystem model (e.g. Harden et al., 1999; Liu et al., 2003; Lugato et al., 2016). The CENTURY model simulates the dynamics of C, nitrogen, phosphorus, and sulphur for different plant-soil systems (Parton, 1996) and can be modified to represent erosion-induced C losses or gains (e.g. Harden et al., 1999; EPIC, Izaurralde et al., 2001, 2007). The key advantages of this approach are that it (i) allows to represent management practices and (ii) to simulate how plant-derived C inputs evolve over time with ongoing erosion. Most of the aforementioned models were developed as short-term decision-making tools for agricultural (or grassland) management. These models not only have allowed us to predict the consequence of specific management options, they also provided insights into the geomorphic soil plant-response at different spatial scales. However, most models were applied to reproduce the temporal evolution of soil-atmosphere C exchange of a specific study site (Manies et al., 2001; Liu et al., 2003) or were applied at larger spatial scales ~~and it represents well the effects of land use and vegetation change on soil properties, including SOC stocks (Kaplan et al., 2010;Kaplan et al., 2012). The second approach couples erosion and SOC models where (i) landscape and vegetation descriptions are limited and the effect of land cover on SOC dynamics is often reduced to a quantification of the total C input to soils (Doetterl et al., 2016;Minasny et al., 2015;Van Oost et al., 2005a;Wang et al., 2014b). Although this approach is considered to enhance~~(e.g. Lugato et al., 2016) but without thorough model validation due to the lack of observational data. To our ~~understanding of eroding landscape dynamics~~knowledge, few ~~efforts have been made to link these two approaches to represent the interaction between soil redistribution, SOC dynamics and the feedback of erosion on biomass production (Kirkels et al., 2014;Doetterl et al., 2016).~~

~~This study~~ studies addressed how erosion-induced productivity decline influences C turnover and soil-atmosphere C exchange in detail. This study proposes a step in ~~further~~ that direction by explicitly and dynamically linking crop ~~yields~~productivity, soil properties and SOC dynamics in a ~~process-based~~ soil profile model to explore the longer-term (i.e. decades to centuries) effect of soil erosion on SOC stocks and fluxes. The model dynamically accounts for vertical soil-atmosphere C exchange, lateral SOC displacement and C ~~input into the soil at the profile scale. Specifically, our~~inputs into the soil at the profile scale. Rather than using a process-based soil-plant model, which face issues such as parameter estimation and model structure selection (e.g. Beven, 2007), we propose a parsimonious approach where erosion-crop productivity relations are implemented based on observed erosion-productivity relations. Our objectives are (i) to ~~develop an integrated process-based model linking SOC dynamics, crop yields and soil redistribution (ii) to~~ evaluate the performance of ~~the~~a parsimonious coupled model by confronting model simulations to available observational data~~,~~ and (~~iii~~ii) to investigate the longer-term (~~ie~~i.e. centennial) effect of erosion on crop ~~growth~~productivity and SOC dynamics at the profile scale.

2. Material and methods

2.1 Erosion effect on crop ~~yields: Metadata~~ productivity: data meta-analysis

~~This study used the data compiled by Bakker et al. (2004) to constrain the relationship between erosion intensity and crop yields as this is one of the most comprehensive meta-analysis. Only paired-plot experiment were selected~~To represent the effect of erosion on crop productivity, we opted for an empirical approach based on the dataset of 24 studies compiled by Bakker et al. (2004). This dataset is one of the most comprehensive meta-analysis available and evaluates crop productivity response to soil erosion for a broad set of environmental conditions, crop growth constraints, soil conditions and experimental methodologies. Only data from comparative-plots were included in our analysis as Bakker et al. (2004) pointed out that this method is the most ~~realistic at estimating the effect~~appropriate to estimate erosion effects on crop productivity. This approach compares plots with different degrees of erosion ~~on crop~~ but similar characteristics in terms of landscape position, slope and management practise. Crop yields~~.~~ ~~Following the~~ relative to non-eroding conditions were reported by Bakker et al. (2004) where a relative yield of 1 indicates that there is no erosion-induced change in yield, values smaller than one represent yield losses and values larger than 1 yield gains. In their meta-analysis~~ of Bakker et al. (2004),~~, Bakker et al. (2004) stated that three functional forms of erosion~~—~~–crop ~~yield~~productivity relationships are possible (Fig. 1~~) :~~): a rapid and ~~nonlinear~~non-linear decrease of crop ~~yield~~productivity as a function of soil truncation, a linear decrease~~ corresponding to the influence of soil depth~~, and a slow and ~~nonlinear~~non-linear decrease due to reduction of water availability (Bakker et al., 2004). We explored the full range of constraints of soil truncation on crop productivity using the following equation: ~~We explored the full range of constraints of soil truncation on crop yields using the following equation:~~

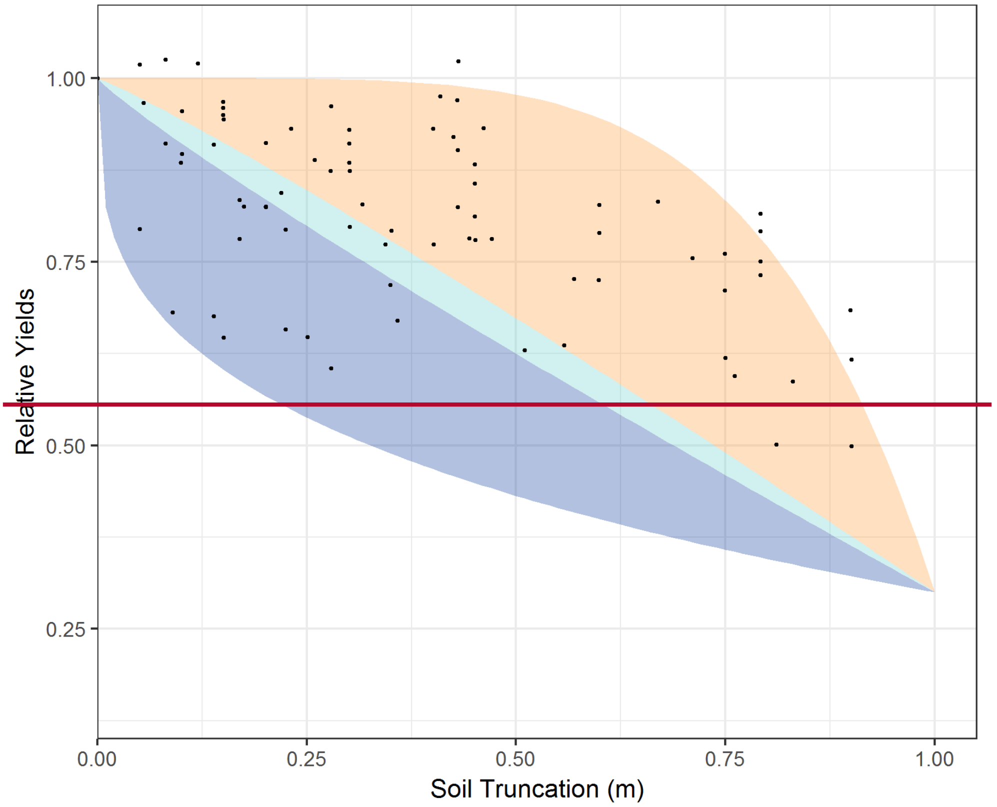
~~$\mathrm{Ydr} = -\alpha\,.\,\mathrm{Tr}^{\mathrm{B}} + 1,$~~

~~(1)~~

$$Ydr = -\alpha\,\mathrm{Tr}^{\mathrm{B}} + 1 \qquad (1)$$

where *Ydr* is the relative yield~~ (compared to a reference yield of 1 for no-erosion),~~, *Tr* is the cumulative soil truncation since the start of cultivation (m), *α* is the maximum yield reduction and *B* is the power law exponent linking the relative crop yield to soil erosion. ~~In our simulations, only the power-law exponent B varies, allowing to fully consider the wide range of relationships that are reported in literature. The concave form (with B < 0.9) can be related to the nutrient depletion case whereby the removal of nutrient-rich topsoil layers by erosion quickly affects crop growth (Bakker et al., 2004). As the depth distribution of nutrients~~

~~typically follow an exponential evolution with depth, the constraints on crop growth become less important for more intense soil truncation (Bakker et al., 2004). The linear form (with 0.9 ≤ B ≤ 1.1) is related to soil depth limiting crop yields where soil depth limits the space available for root growth. In this case, physical hindrance decreases crop yields as soon as the root growth is limited by a compacted soil layer. The convex form is related to water availability, where crops that are typically not very sensitive to water limitation are not affected by soil truncation until a certain threshold beyond which crop yields are reduced quickly (Bakker et al., 2004). Based on an analysis of the Bakker et al. (2004) data, alpha was set to 0.7 (Fig. 1). Finally, soil depth is indirectly taken into account as the input clay content profile is given in absolute percentage of volume (ie % of clay in a given volume of soil including coarse fragment).~~



Based on the analysis of the Bakker et al. (2004) data, α was set to 0.7 (Fig. 1). Soil depth was indirectly considered using an a clay content profile which is represented as a fraction of the soil volume. It should be noted that the relationships between relative yield and soil truncation described and discussed hereafter assume no differences in agricultural practices between eroding and non-eroding conditions. Hence, there is no specific adaptation in practices or effort to counteract the decline. Furthermore, when assuming that a linear relation between crop yield and biomass production is reasonable, the relative yields as presented by Bakker et al (2004) are proportional to biomass productivity. We hereafter refer to crop productivity and assume no change in agricultural practices or efforts during our simulations.

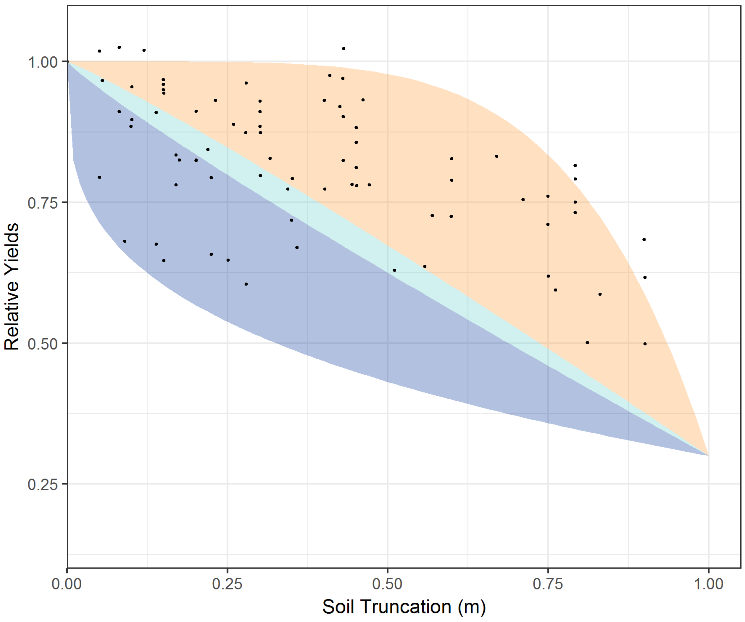


Figure 1~~:~~ – Relative crop ~~yields~~yield decrease as a function of soil truncation~~, as shown from yields desurfacing~~ based on paired-plot experiments. ~~Datapoints~~Observations are taken from the ~~metadata analyses~~data meta-analysis presented by Bakker et al. (2004). Values larger than one indicate a gain in crop productivity and values smaller than one indicate a loss of crop productivity. The three shaded areas represent the space of the relationships investigated in our study. Dark blue, cyan and orange shades denote respectively the ~~nutrient depletion~~ concave relationship (B =< 0.9~~, concave relationships), physical hindrance (0.9 < B < 1.1,~~), linear relationship (0.9 < B < 1.1) and ~~water availability cases~~convex relationship (B > 1.1~~, convex relationships~~).

2.2 The SOC turnover model

2.2.1 ICBM

Building on existing work, we used a SOC turnover model that is coupled to a dynamic representation of the SOC and clay profiles in response to ongoing erosion (Fig. 2). SOC cycling ~~is~~was represented by a depth explicit version of the Introductory Carbon ~~Balance~~Fluxes Model (ICBM, Andren and Katterer (1997)) which has been implemented in ~~couple of a soil erosion~~coupled models (e.g. Van Oost et al~~,~~., 2005). ICBM is a two-~~pool~~pools carbon model simulating SOC transfer from the roots, residue and manure to a 'young' C pool, transfer from the 'young' pool to an 'old' C pool and C mineralization in both pools (Andren and Katterer, 1997). The model time step is 1 year. SOC fluxes are described by the following equations:

~~SOC fluxes are described by the following equations:~~

$$\frac{dY}{dt} = i - k_y \cancel{rY\,,}\; r\,Y\,, \qquad (2)$$

$$\frac{dO}{dt} = h\,k_y \cancel{rY}\; r\,Y - k_o \cancel{rO,}\; r\,O, \qquad (3)$$

Where *Y* (Mg C ha^{-1}) and *O* (Mg C ha^{-1}) are respectively the young and old SOC pools and k_y (yr^{-1}) and k_o (yr^{-1}) their turnover rates (Andren and Katterer, 1997). *i* stands for the total carbon input which is the sum of the input from the crops (*ic*) and manure (*im*). The transfer from the young pool to the old pool, calculated at each time step, is proportional to the humification factor (*h*) and the climatic and edaphic conditions which are condensed in the r coefficient (Andren and Katterer, 1997). Values for k_y and k_o are respectively 0.8 and 0.006 yr^{-1}. Note that the quantity *(1-h)* k_y *r Y* represents the mineralized/respired amount of C leaving the “young” pool.

The humification factor is estimated as follows:

$$h(z) = \frac{ic(z)*hc+im(z)*hm}{ic(z)+im(z)} e^{0.0112^{(cl(z)-36.5)}}, \qquad (4)$$

~~with~~

Where *ic(z)* and *im(z)* are the C ~~input~~inputs from crop and manure at the depth *z*, *hc* and *hm* the humification coefficient for respectively crops and manure, and *cl(z)* the clay content at depth *z* (%). Humification coefficients equal 0.3 and 0.125 respectively for *hc* and *hm*. At each time step, the humification values are calculated based on the C input from crop and manure at the considered time step, then the values of the C pools are computed.

The climate factor *r*~~,~~ is corrected for the local climate using a Q_{10} relationship based on temperature (Andren and Katterer, 1997).

$$r = 2.07^{\frac{T-5.4}{10}}, \qquad (5)$$

~~where~~

Where *T* is the mean annual temperature (°C).

The model is depth-explicit ~~as it~~and considers a depth-dependent C input and mineralization rate (Nadeu et al., 2015; Van Oost et al., 2005b; Wang et al., ~~2014a~~2014). While manure and residue-derived C input only affect the topsoil layers, the carbon input from plant roots is distributed throughout the soil profile using the following relationship:

$$\varphi(z) = \begin{cases} 1, z \leq z_r \\ \exp(-\delta(z - z_r)), z > z_r \end{cases}, \qquad (6)$$

With $\varphi(z)$ the ~~relative~~ root~~-~~ density profile from which C input from roots are derived ~~C input~~ at depth z, z~~, z the soil depth (m),~~ is given in meters, z_r is the depth of the ~~top soil~~topsoil where ploughing is assumed to homogenize the SOC content and δ is the root density coefficient.

The turnover rates of the SOC pools ~~at each~~as a function of depth are computed as an exponential function:

$$\cancel{K_{tz}}$$

$$k_{tz} = \cancel{k_{t0}} k_{t0} \exp(ur \cancel{*} z), \qquad (7)$$

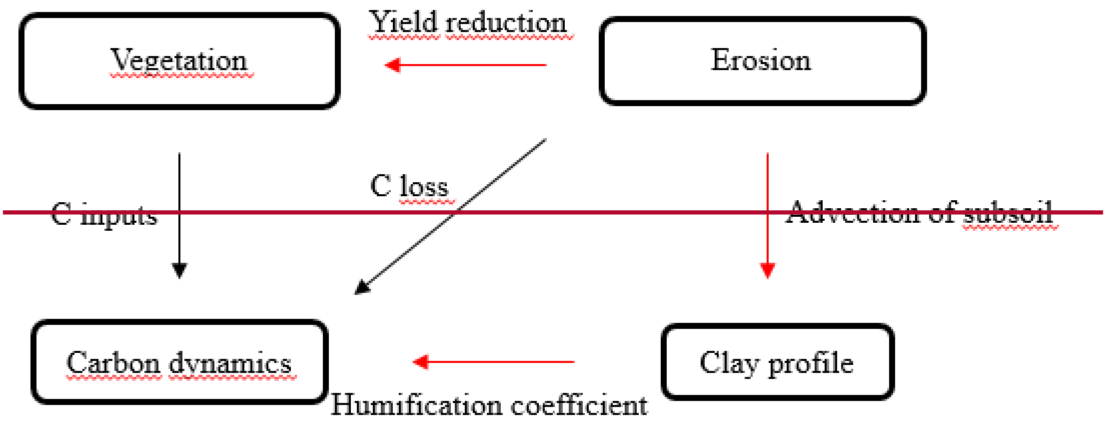
~~With~~

Where *ur* is a dimensionless coefficient of depth attenuation, k_{t0} (yr^{-1}) is the turnover rate at the soil surface~~.~~ and ~~K_{tz}~~k_{tz} (yr^{-1}) represents the SOC turnover rate at depth *z*. The function applies to both k_y and k_o.

The model starts with ~~a~~ prescribed SOC and ~~soil profile having an initially defined~~ clay content ~~distribution~~profiles. Carbon turnover is then coupled to the clay content ~~depth~~ profile through a depth-dependent humification factor~~. Yields are~~ (Eq.4). Crop productivity is updated each year following Eq. 1, in relation to the cumulative soil truncation. Crop ~~yields affect~~productivity affects the SOC content by modifying the amount of soil C inputs. Under the absence of site~~-~~-specific data ~~on the relation between yield and soil C inputs~~, we here assume a linear relationship between ~~the~~ crop ~~yield~~productivity and ~~the~~soil C ~~input~~inputs:

$$i(t) = i(0\cancel{)*})\,Ydr(t)\,, \qquad (8)$$

Where *i(t)* is the C input at the time *t*, *i(0)* the initial C input and *Ydr* the relative yield at time *t* compared to initial yield. The implications of this assumption are discussed further.



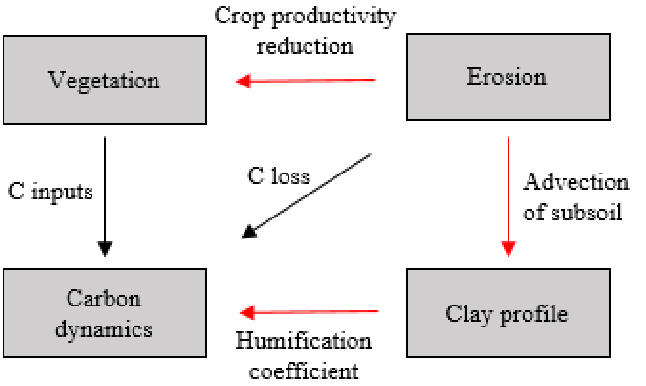


Figure 2~~: conceptual framework~~ – Schematic representation of ~~processes represented in~~ the model. Black arrows ~~designate~~depict processes included in published versions of the model (Nadeu et al., 2015) and red arrows represent the new processes included in ~~earlier versions of depth-discretized ICBM and red arrows highlight the added explicit processes in~~ this study.

2.~~2.2~~3 Model implementation

The ~~initial~~ soil profile has a constant thickness of 1 meter and ~~is~~was represented by 100 layers of 1 cm, each layer being characterized by its own clay content, SOC content, C input and turnover rates. This very fine representation of the vertical soil profile and advection in response to soil erosion is required due to sensitivity of the model to the vertical discretization as a coarse resolution typically results in substantial numerical dispersion and smoothing. Test simulations showed that 100 layers represent a good compromise between computational efficiency and limited dispersion.

At the bottom of the profile, we assumed constant boundary conditions. Soil truncation was modelled as an upward advection of soil properties where the advection rate~~.~~ was proportional to the amount of soil removed by erosion at the surface. As we ~~assume~~assumed a constant bulk density of the fine soil fraction, the amount of clay and SOC vertically transferred between layers ~~is~~was proportional to the amount of erosion (upward transfer~~) (Van Oost et al., 2005a).~~). The SOC content in the profile ~~is~~was then updated each year ~~as a~~in response to the vertical advection of matter, ~~the~~new C ~~input~~inputs at the ~~soil~~ surface and the clay content evolution following erosion~~ or deposition.~~. The model keeps track of the SOC and clay content per layer~~,~~ and tracks the evolution of ~~the~~ crop ~~yield~~productivity over time.

After ~~performing~~ a model spin-up without erosion ~~for~~allowing the C pools to reach equilibrium, we performed transient simulations where the soil profile ~~is~~was modified by erosion. During the ~~simulation period~~simulations, erosion rates are assumed to be constant through time. We presented the results in terms of the total SOC content evolution for the ~~1m~~1 m profile and the net vertical C ~~balance~~fluxes exchanged with the atmosphere. The annual ~~vertical balance, i.e. the~~ net vertical ~~exchange~~flux of C between the soil and the atmosphere, ~~of a~~ integrated over the 100 soil ~~layer~~layers at ~~depth z and~~a time *t* ~~is~~was calculated as follows:

~~$Cv\,(z,t) = i(z,t) - ((1-h)\,k_y rY(z,t) + k_o rO(z,t)),$~~
~~(9)~~

$$Cv\,(t) = \sum_{z=1}^{100} i(z,t) - k_y\,(1-h)(r\,Y(z,t) + k_o\,r\,O(z,t)) \qquad (9)$$

Where *Cv(~~z,~~t)* is the amount of carbon exchanged between the soil ~~layer at a depth z~~profile and the atmosphere at time *t* and z is the depth of the layer. Positive vertical carbon fluxes denote C fluxes from the atmosphere to the soil while negative vertical carbon fluxes represent a C emission to the atmosphere. We evaluated the cumulative ~~balance~~vertical C fluxes by integrating the vertical carbon fluxes over the entire duration of the simulation.

2.~~2.3~~4 Model parametrization and calibration

~~In this study~~To explore a wide range of environmental conditions, we ~~use published estimates of lateral SOC losses~~parametrized and ~~net vertical C exchange that were derived from ^{137}Cs as a tracer for erosion while~~calibrated the ~~C balance was derived from space for~~

~~time substitutions (Van Oost et al, 2007). We used data on erosion rates and duration of the erosional disturbance~~SOC profiles for ten study sites ~~in~~across Europe and the US ~~to estimate SOC loss and vertical C exchange.~~ based on the published data reported by Van Oost et al. (2007). Eight sites were located in Europe and ~~2~~two sites in the US. The European sites represent a ~~diversity~~broad range of soil and/or climate conditions. Belgian, English and Danish sites ~~are~~were located in temperate ~~climates~~regions and ~~vary~~mainly varied from each other by their ~~climate,~~ erosion ~~rate~~rates and soil properties: from loamy soils with relatively high erosion rates in Belgium toward more clay-loam soils and slightly lower erosion rates in for the Danish and English ~~and Danish~~ sites (Table ~~1b~~1) (Quine and Zhang, 2002; Heckrath et al., 2005)~~.~~. The ~~two Belgian sites are sampled in nearby catchments and differ from each other by their topographic position: Belgium 1 being on steeper slope with higher erosion rate than Belgium 2. American~~US sites were ~~sampled in catchments~~located in Iowa and are characterized ~~with~~by fine-textured loamy to silty soils and a temperate continental climate (Ritchie et al., 2007). ~~Due to their deep soils and humid climate, all of the aforementioned sites are therefore more prone to experience nutrient depletion constraint ($B < 0.9$) than soil thinning or water availability shortage.~~ Mediterranean sites were characterized by a warm and ~~drier~~dry climate, clayey soils, high erosion rate (except for the ~~Greeke case~~Greek site) and similar cultivation periods (Table 1). ~~The Spanish sites differ by their topographic characteristics with steeper slope, shallower soils and higher~~ As no local data were available for the Spanish and Portuguese sites, SOC data representing stable profiles were taken from the national surveys. For the other sites local data were used. The form of the erosion~~-rate~~-production relationship for each site was derived from the information presented in the ~~first site (Van Oost et al, 2007).~~ original experimental studies (Table 1) and we use a range for parameter *B* to represent uncertainty. The Greek, Spanish and Portuguese sites experienced intense soil thinning ~~(Greece and Spain, $0.9 < B < 1.1$)~~ or a mix of soil thinning and water availability constraints ~~(Portugal)~~ (which was linked to, respectively, a linear ($0.9 < B < 1.1$) and a convex evolution of crop productivity in response to soil erosion (Bakker et al., 2004; Kosmas et al~~,~~., 2001; Van Oost et al~~, 2007). For the Spanish and Portuguese sites, reference SOC data (ie representing stable profiles) were taken from the national surveys while for the other sites local data was used (Van Oost~~., 2007). Belgian, Danish, English and US sites were more prone an alteration of crop productivity in response to topsoil losses which was linked to a concave evolution of the crop productivity ($B < 0.9$) (Bakker et al~~, 2007~~., 2004).

~~We~~

The initial conditions for the model runs were estimated ~~the initial SOC profile using site-specific observations and~~as follows: the ~~reported mean annual temperature and clay content for each site. Based on this information,~~parametrization procedure considered the ~~following~~three model parameters ~~were optimized for each site~~that control the shape of the SOC depth profile: C inputs at the surface (*ic*, Eq 4), the root-derived C input at depth *z* ($\varphi(z)$, Eq 6) and the depth attenuation of C mineralization (*ur*, Eq 7). ~~We~~Based on the reported mean annual temperature, clay content and the observed profile reported in Van Oost et al. (2007), we optimized the shape parameters of the SOC profiles for each of the 10 sites using an inverse modelling procedure (Dlugoss et al., 2012). It should be noted that the model parameters are only optimized ~~the values~~for the representation of a stable, i.e. non-eroding, SOC profile and, hence, represent the initial SOC profile of each site. As only one depth-explicit SOC profile was available per site, no uncertainty range could be calculated. We optimized the model parameters by minimizing the relative root mean square error (RRMSE) between the observed and simulated SOC profile (Eq. 10).

$$RRMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\frac{C_{i,s}-C_{i,o}}{C_{i,o}})^2}, \quad (10)$$

Where *N* is the layer number, $C_{i,s}$ is the simulated carbon content of the layer *i* (%) and $C_{i,o}$ is the carbon content observed at the depth of the mid-point layer *i*. *N* varies for each site due to -data sampling~~ (Fig 3).~~.

~~We explicitly accounted for the uncertainties associated with the estimation of model parameters during the transient simulations by building a set of 1000 model parameters sets for each site. The parameter sets combine fixed values (for temperature) and randomly generated parameters in a prescribed range assuming a uniform distribution: *ur* and *φ* were allowed to vary by +/- 2% around the optimum value. Erosion rate, clay content and yield reduction exponent (when available in observations) were constrained around the reported values per sites, with respective tolerances of +/- 0.05 mm.yr^{-1} around the reference erosion rate and +/-2% around the published clay content (Table 1, Van Oost et al, 2007). We produced two sets of 1000 simulations: with and without erosion-yield feedbacks (respectively designated by the FB and CTL abbreviations) to evaluate the effect of the erosion-crop yield relationship. SOC losses were calculated for the same periods as reported in the empirical study (Table 1).~~

~~Table 1: (a) Characteristics of the study sites used for the model validation.~~We used the RRMSE metric to parametrize the SOC profiles as it ensures that both the SOC content in the topsoil and in the subsoil (i.e. the profile shape) are accurately captured by the model. This is a crucial element, as these attributes will control both the C lateral and vertical C fluxes.

Table 1 – Observed characteristics of the study sites used for the model evaluation. Site selection~~,~~ observed range of relative SOC loss and cumulative vertical ~~balance~~fluxes are from Van Oost et al (2007). ~~Modeled range of SOC losses and cumulative vertical C balance for the no-feedback (CTL) and the erosion-crop yield feedback scenario (FB). RRSME is calculated over the whole 1m profile between observed and optimized SOC profile, (b) RRMSE of the CTL and FB scenario for each location and as well as the RRMSE of each scenario, including all observations (all).~~

~~(a)~~

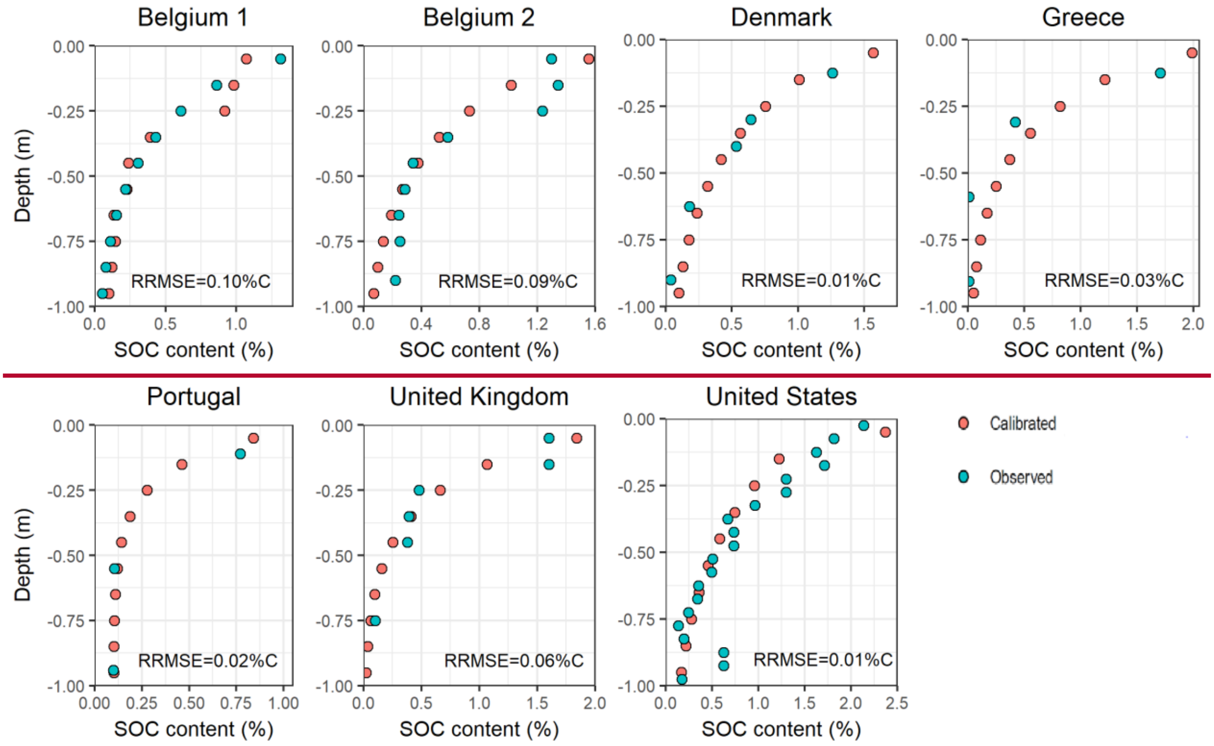
~~Location~~	~~Belgium$_1$~~	~~Belgium$_2$~~	~~Denmark~~	~~Greece~~	~~Portugal~~	~~Spain$_1$~~	~~Spain$_2$~~	~~UK~~	~~USA~~
~~Period of cultivation (yr)~~	~~80~~	~~100~~	~~68~~	~~74~~	~~66~~	~~66~~	~~66~~	~~55~~	~~143~~

Location	Time since start of cultivation (yr)	Time since ^{137}Cs deposition (yr)	~~46~~Erosion rate (mm yr^{-1})	~~46~~Model erosion rate range (mm yr^{-1})	Topsoil clay content (%)~~44~~	Yiel reduct forr (*B*)~~4~~
Belgium1~~Erosion rate (mm.yr^{-1})~~	80	46	1.13 ~~0.97~~ ~~0.99~~ ~~0.4~~	1.~~09~~1 – 1.15	~~1.68~~5 ~~1.13~~	0.8 -
Belgium2	100	46	0.97	0.95 – 1.05	6	
Denmark	68	44	0.99	0.95 – 1.05	30	
Greece	74	43	0.4	0.35 – 0.45	28	
Portugal	66	42	1.09	1.05 – 1.15	18	
Spain1~~Model erosion rate range (mm.yr^{-1})~~	~~1.1-1.15~~66	~~0.95-1.05~~42 ~~0.95-1.05~~ ~~0.35-0.45~~	1.~~05-1.15~~68	1.65~~-~~ – 1.7	45	0.9 – ~~1.~~
Spain2~~Topsoil clay content (%)~~	~~5~~66	~~6~~42	1.13~~30~~	~~28~~1.1 – 1.15 ~~18~~ ~~45~~	52	~~15~~0.
UK~~Yield reduction form (*B*)~~	55	43	~~0.8-~~0.95	0.~~8-~~9 – 1.0~~.95~~	15	0.8~~-~~ 0.9
USA	143	49	1.14	1.1 – 1.17	15	0.8 –
USA	143	49	0.99	0.95 – 1.15	15	

~~(b)~~

	~~Relative SOC Loss~~		~~Vertical C balance (kgC.m^{-2})~~	
~~Location~~	~~RRMSE CTL~~	~~RRMSE FB~~	~~RRMSE CTL~~	~~RRMSE FB~~
~~Belgium1~~	~~0.18~~	~~0.03~~	~~0.16~~	~~0.60~~
~~Belgium2~~	~~0.54~~	~~0.78~~	~~0.19~~	~~0.42~~
~~Denmark~~	~~0.07~~	~~0.04~~	~~0.48~~	~~0.70~~
~~Greece~~	~~0.47~~	~~0.46~~	~~0.53~~	~~0.47~~
~~Portugal~~	~~0.15~~	~~0.06~~	~~0.45~~	~~0.58~~
~~Spain1~~	~~0.15~~	~~0.13~~	~~0.10~~	~~0.001~~
~~Spain2~~	~~0.09~~	~~0.13~~	~~0.35~~	~~0.48~~
~~UK~~	~~0.31~~	~~0.42~~	~~0.30~~	~~0.48~~
~~USA1~~	~~0.56~~	~~0.31~~	~~0.14~~	~~0.39~~

~~USA2~~	~~0.50~~	~~0.23~~	~~0.14~~	~~0.40~~
~~All~~	~~0.93~~	~~0.63~~	~~0.83~~	~~1.21~~



~~Figure 3: Measured (blue) and simulated (red) SOC profiles for the specific sites (Van Oost et al., 2007). Data of the Spanish sites were not available and the same SOC profile has been used for both US sites.~~

2.~~2.4~~5 Model ~~validation~~evaluation

We performed a model ~~validation~~evaluation using empirical observations on SOC losses and cumulative vertical C fluxes (Table 1) (Van Oost et al., 2007). In a first step, we calculated the observed SOC losses and cumulative vertical C fluxes for each ~~sites~~site based on the data of Van Oost et al (2007). The carbon ~~balances~~fluxes were derived from soil erosion measurements using ^{137}Cs as a tracer. As ^{137}Cs fallout originates from nuclear bomb testing, 1954 is considered as the starting point of the ^{137}Cs integration time (Ritchie and McHenry, 1990). The carbon budgets therefore integrate over the period beginning in 1954~~-1996 (~~ and ending at the date of sampling~~)~~. Van Oost et al. (2007) reported values of mean annual vertical C fluxes and lateral C fluxes based on the evaluation of data from c. 1400 soil profiles. We computed the observed cumulative vertical C fluxes by summing the annual rates provided by Van Oost et al (2007) over the period ~~of interest while~~ between 1954 and the ~~relative~~ date of ^{137}Cs sampling. SOC losses were derived ~~from the annual lateral C fluxes and the initial C profile. In a second step, we ran site-specific~~ by considering the differences between the cumulative lateral fluxes and the cumulative vertical fluxes over the entire cultivation period. The difference between the initial SOC content and the SOC content at the end of the simulation represents the total amount of SOC lost due to erosion. To allow for an inter-site comparison, these values were then scaled relative to their site-specific initial SOC content. These data provided the empirical reference against which our simulation results are evaluated.

To account for the uncertainty related to the estimation of the initial SOC profiles and site conditions, we created for each of the 10 sites, a set of 1000 scenarios for which parameters values were randomly chosen in a narrow range around their optimal (for initial SOC status) and reported values (for site specific conditions) in Van Oost et al. (2007). Therefore, each of the site-specific parameter set combines fixed values (for temperature) and randomly generated parameters inside a prescribed range assuming a uniform distribution: *ur* and φ were allowed to vary by ± 2 % around the optimal value. Erosion rate, clay content and yield reduction exponent (when available in observations) were selected using the reported values for each site, with respective tolerances of ± 0.05 mm yr^{-1} around the reported erosion rate and ± 2 % around the reported clay content (Table 1). We performed two sets simulations~~ using the 1000-parameters sets obtained from the calibration~~: one set including the effect of erosion on crop productivity (FB) and one without the erosion effect on productivity (CTL) to evaluate the effect of the erosion-crop productivity relationship on SOC losses and cumulative vertical C fluxes (see ~~section 2.2.5~~Fig. 3 and Table ~~1~~2). Finally, we confronted the results ~~to~~with the observations and evaluated performances of our model for both CTL and FB~~ scenarios. We further quantified the effect of adding the feedback in~~ .

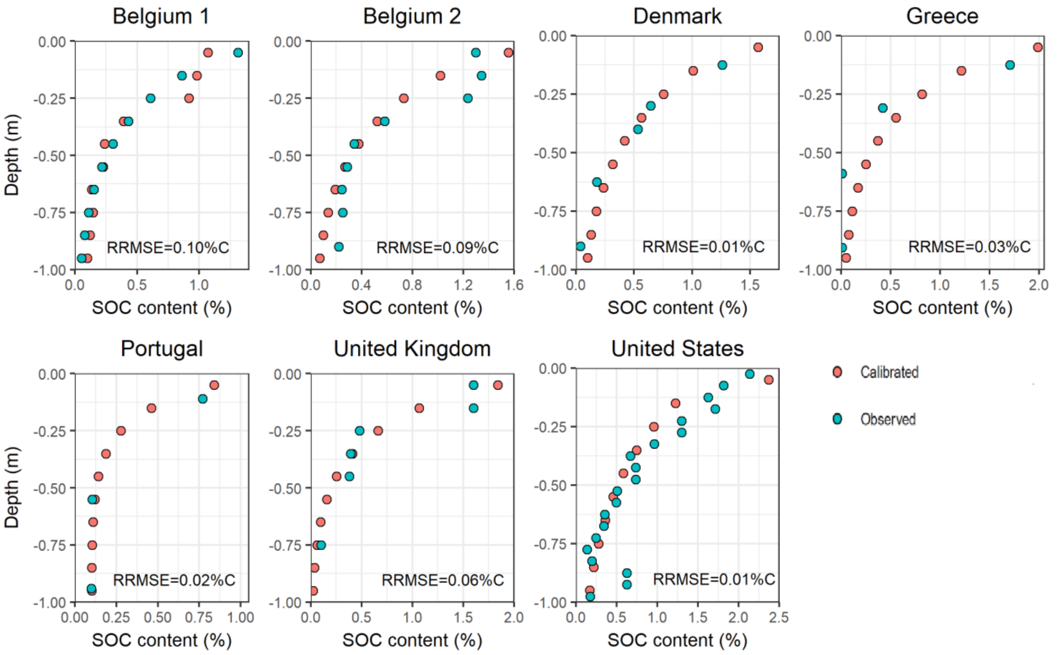


Figure 3 – Measured (blue) and optimized (red) SOC profiles that were used to initialise the model~~ by comparing the performances (i.e. RRMSE) of each scenario.~~ .

~~2.~~2.~~5~~6 Long-term experiment

~~After the model evaluation, we further~~ We explored the ~~behavior~~behaviour of the model by running additional long-term simulations (200 years) where we focused on the ~~potential impact of including the yield reduction feedback in landscape modelling~~ effect of crop productivity on the overall C budget on longer timescales~~ (i.e. c. 200 years)~~. We built ~~another 1000 model parameters sets in which the~~ two sets of 1000 scenarios in which model parameters values were randomly generated, assuming a uniform distribution, in an extended range corresponding to the minimum and maximum observed values of selected sites (see Table 3). Selected parameters include the distribution of root depth and carbon mineralization rate, the initial clay content (*cl*), erosion rate (*E*) and ~~yield~~crop productivity response to erosion (exponent *B*) vary in a ~~large but realistic range (Table 2).~~ larger range than the site-specific set of parameters generated previously (Table 3). This extended range is dictated by the difference between the smallest and largest values provided by Van Oost et al. (2007), while erosion rates were extended up to 3 mm yr^{-1}, which represents a high erosion case which can be found for example in Mediterranean countries (De la Rosa et al., 2000). The root-depth parameter indicates the root penetration in the soil and its value is taken so that 95 % of the roots were distributed in the first 35 cm to 65 cm with respective values of ϕ of 4 to 6 (30 % to 45 % of the roots in the first 20 cm). These values are in accordance with previous SPEROS parametrization obtained by inverse modelling (Dlugoss et al., 2012, Nadeu et al., 2015). As for the mineralization distribution, the given range resulted turnover rates at 1 m depth of 137 to 700 years for the slow C pool ($1/k_{t,z}$, Eq. 8), which is in line with the centennial turnover rate found in deep colluvium by Wang et al. (2014) or Van Oost et al (2012). In order to explore the effect of clay content, we linearly ~~scale~~scaled the initial clay content profile (*cl*) creating an effective range of clay content from 5~~% to 45% in the top soil (Table 2). The values for all these parameters were randomly generated assuming a uniform distribution. We used~~ % to 45 % in the topsoil (Table 3). We performed two analysis based each one based on a 1000 scenario set: in analysis A, the erosion rate was allowed to vary from scenario to scenario while, in the second set of 1000 scenarios (analysis B) the erosion rate was set as a constant to 1 mm yr^{-1} (Table 3b). The use of these two different analysis approaches allows for an easier identification of the role of erosion.

We performed a SOBOL procedure based on the Fourier Amplitude Sensitivity Test (FAST) to assess the contribution of each individual parameter to the global variance of the results (Cukier et al., 1973; Cukier et al., 1975). ~~We performed the FAST analysis with all the parameters varying between scenarios with the observed erosion rates (derived from Table 1a) and a uniform erosion rate of 1 mm.yr^{-1} in Table 2b~~Finally, using the set of 1000 randomly-generated scenarios with variable erosion rate (analysis A), we evaluated the impact of the erosion-crop productivity link on the SOC content and vertical fluxes after 200 years by comparing the results produced by the model in FB configuration (including the effect of erosion on productivity) and in CTL configuration (no effect of erosion on crop productivity). Note that in these long-term simulations, the reference productivity does not change as we assume constant agricultural practices. We discuss the implication of this hypothesis in the discussion.

~~Finally, using the same set of 1000 randomly-generated parameters, we evaluated the impact of the erosion-yield feedback on the SOC content and vertical balance by comparing the results produced by the model in FB configuration (erosion-yield feedback) and in CTL configuration (no erosion-yield feedback).~~

~~**Table 2**: Selected parameters, range of tested values and results of the FAST analysis. The FAST analysis results can be interpreted as the relative contribution of each parameter variability to the total variance of the selected output, i.e.ie the relative SOC loss compared to the initial SOC content and the cumulative vertical C fluxes at the end of the 200 years transient simulations. The asterisk designate the parameter accounting of more than 15% of the total variance. Table 2a include the effect of the erosion intensity with a large range of erosion tested while Table 2b assumes a constant erosion rate of 1 mm.yr^{-1}.~~

~~(a)~~ ~~Parameter~~	~~Symbol~~	~~Range~~	~~Relative contribution of each parameter to the relative SOC content losses variance after 200 years~~	~~Relative contribution of each parameter to the cumulative vertical C fluxes variance after 200 years~~
~~Erosion rate *~~	~~E~~	~~0.1 – 3 mm/yr~~	~~0.705*~~	~~0.194*~~
~~Erosion feedback on yields *~~	~~B (Eq 1)~~	~~0.3 – 4~~	~~0.220*~~	~~0.544*~~
~~Clay profile scaler~~	~~Cl (Eq 5)~~	~~0.3-2.5~~	~~0.064~~	~~-0.035~~
~~Distribution of carbon mineralization with depth~~	~~Ur (Eq 7)~~	~~4 – 6~~	~~0.124~~	~~0.103~~
~~Root density profile with depth~~	~~φ(z) (Eq 6)~~	~~1 – 3~~	~~0.090~~	~~0.015~~

~~(b)~~

~~Parameter~~	~~Symbol~~	~~Range~~	~~Relative SOC content losses after 200 years~~	~~Cumulative vertical C fluxes~~
~~Erosion rate~~	~~E~~	~~1 mm.yr^{-1} (fixed)~~	~~0.044~~	~~-0.370~~
~~Erosion feedback on yields*~~	~~B (Eq 1)~~	~~0.3 – 4~~	~~0.703*~~	~~0.701*~~
~~Clay profile scaler~~	~~Cl (Eq 5)~~	~~0.3-2.5~~	~~0.061~~	~~-0.037~~
~~Distribution of carbon mineralization with depth*~~	~~Ur (Eq 7)~~	~~4 – 6~~	~~0.214*~~	~~0.216*~~
~~Root density profile with depth~~	~~φ(z) (Eq 6)~~	~~1 – 3~~	~~0.137~~	~~0.010~~

3 Results

3.1 Model evaluation

In this section, we ~~perform a validation~~first assess the performance of the model ~~by comparing our calibrated simulation results with available data from the literature. Observations~~ in ~~Table 1 are taken from Van Oost et al. (2007a). The range~~reproducing the initial SOC profiles of each site based on the calibration procedure (Fig. 3). As Figure 3 shows, the static adjustment of parameters ~~used~~governing the SOC profile shape for ~~calibration is displayed~~each sites resulted in ~~Table 1 and Fig 3 shows the comparison between the optimized SOC profiles and the observations.~~a good representation of the SOC profile. All estimated initial SOC ~~profile are~~profiles were close to the observations for each of the sites, with a RRMSE ranging between 0.01 to 0.09 (Fig. 3). In a second step, we evaluated the model based on the results obtained after the site-specific simulations by comparing the SOC losses and cumulative vertical fluxes to the observed losses and fluxes derived from Van Oost et al. (2007) data.

Table 2 – RRMSE of CTL (Control dataset, no effect of erosion on crop productivity assumed) and FB (Feedback dataset, effect of erosion on productivity included) dataset for each location and as well as the RRMSE of each dataset, including all observations (all). RRSME is calculated over the whole 1m profile between observed and optimized SOC profile.

	Relative SOC Loss		Vertical C fluxes (kg C m^{-2})	
Location	RRMSE CTL	RRMSE FB	RRMSE CTL	RRMSE FB
Belgium1	0.18	0.03	0.16	0.60
Belgium2	0.54	0.78	0.19	0.42
Denmark	0.07	0.04	0.48	0.70
Greece	0.47	0.46	0.53	0.47
Portugal	0.15	0.06	0.45	0.58
Spain1	0.15	0.13	0.10	0.001
Spain2	0.09	0.13	0.35	0.48
UK	0.31	0.42	0.30	0.48
USA1	0.56	0.31	0.14	0.39
USA2	0.50	0.23	0.14	0.40
All	0.93	0.63	0.83	1.21

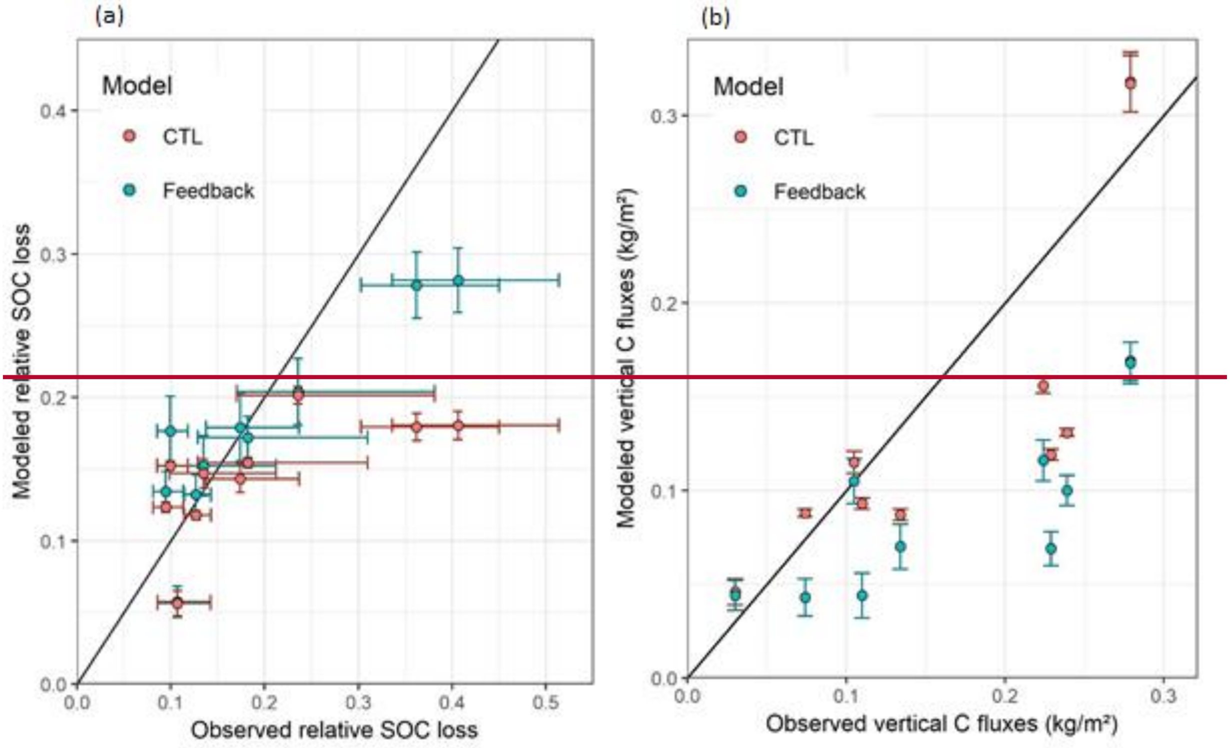
~~%~~Hereafter, the C ~~to 0.09%C (Fig. 3). The observed SOC losses~~ relative ~~to~~C loss will be reported as a fraction of the initial SOC content~~-~~. The observed relative amount of eroded SOC at the end of the simulation varied between 0.09 ~~+/-~~ ± 0.02 (UK) and 0.41 ~~+/-~~ ± 0.08 (USA), with ~~typical~~most of the values around 0.15 ~~+/-~~ ± 0.05 of the initial content. Figure 4a clearly ~~show~~shows a cluster of SOC losses in this range (Table ~~1b~~2, Fig. 4a). Site-specific simulations ~~produce~~produced SOC losses, which are in line with the ones estimated ~~by~~using Van Oost et al (2007~~).~~) data. Without ~~feedback~~the effect of erosion on productivity, the model produced relative SOC losses ranging from ~~only~~a 0.05~~+/-~~ ± 0.01 (Greece) to 0.~~19 +/-~~23 ±0.01 (USA) of the initial carbon content.

~~Inclusion of~~

Including the erosion-~~yield feedback~~crop productivity relationship (FB) increased SOC losses by 20 % on average but ~~showed a strong spatial variability related to the feedback nature.~~simulation results were highly variable. Simulations for sites characterized by ~~soil thinning~~a linear erosion-productivity relationship or ~~water availability limitation~~a convex relationship did not result in substantial additional SOC losses ~~-~~(Table 1): for example, the Greek and Spanish sites exhibited only ~~around~~a 1% increase in SOC ~~losses~~loss, relative to ~~the control scenario~~CTL (Fig. 4a). On the contrary, sites ~~where nutrient depletion~~with a concave relationship (B < 0.9) ~~was the dominant factor for yield reduction~~ clearly showed an increase of both mean SOC loss and of the associated standard deviation compared to ~~the~~ CTL ~~scenario.~~

. Adding the ~~feedback~~effect of erosion on productivity while using the same parameters improved the overall accuracy with an RRMSE of 0.63 for FB compared to 0.93 for CTL when all sites are ~~taken into account~~were considered (Table 1). ~~–~~The model performances ~~are~~were highly site-dependent: the addition of ~~the feedback~~declining productivity in response to erosion increased the prediction accuracy for the ~~cases~~environments where cumulative soil truncation was substantial (e.g~~..~~. Belgium 1, Portugal, and USA) while it decreased the accuracy for ~~cases~~environments with small soil truncation (Fig. 4a, Table 1). ~~The~~ FB ~~scenario~~ was able to reproduce the observed trend in which higher cumulative soil truncation leads to higher SOC losses. ~~This shows that the addition of the feedback is important, particularly when soil truncation has been intense. However~~Finally, it should be noted that the margins of error of both CTL and ~~feedback modeled~~FB modelled SOC losses are overlapping, except for the American sites.

The observed values for the vertical C fluxes ranged from 0.030 ~~kgC.~~kg C m^{-2} to 0.279 ~~kgC.~~kg C m^{-2} (Fig. 4b). The simulations without ~~feedback~~crop productivity decline under erosion produced results~~,~~ which are of the same order of magnitude as the results from Van Oost et al (2007) with an RRMSE of 0.826 ~~kgC.~~kg C m-^{2}. ~~-~~Despite ~~an accurate~~the good prediction of the observed trend, simulations tended to underestimate vertical carbon fluxes, particularly for the higher cumulative soil truncation ~~cases~~environments (Fig. 4b, Table 1). Including the ~~feedback~~effect of erosion on productivity reduced vertical carbon fluxes by 34% in average relative to ~~the~~ CTL ~~scenario~~ and reduced the accuracy of the model with a RRMSE of 1.026 ~~kgC.m^{-2}~~ (Fig. 4b, Table 1).



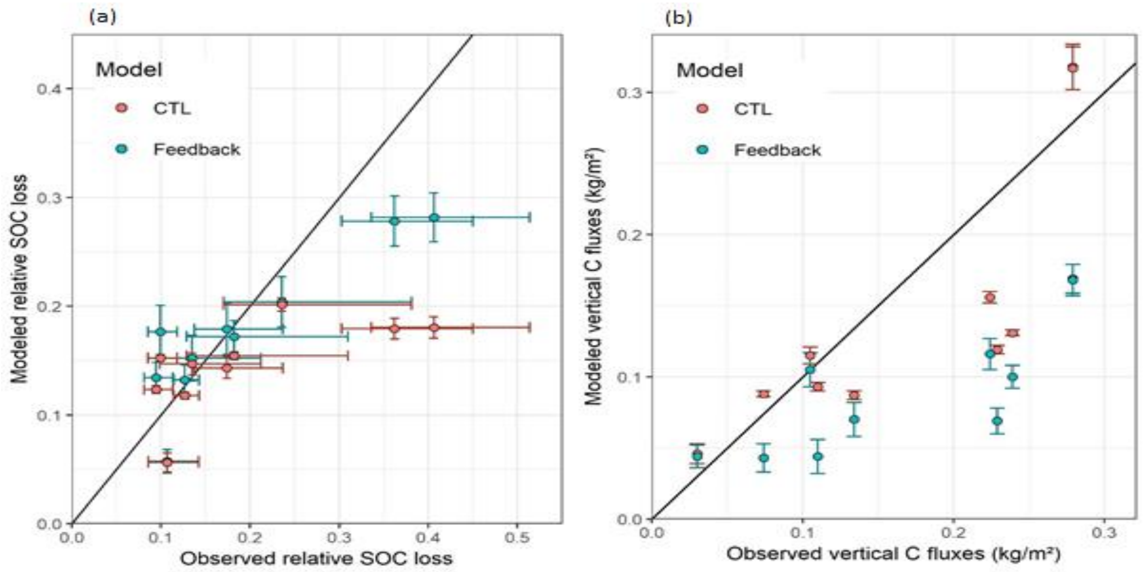


Figure 4~~:~~ – Modelled against observed (~~A~~a) relative SOC losses and (~~B~~b) vertical C fluxes. ~~Colors~~Colours denote the different ~~scenarios~~datasets: Control ~~scenario~~dataset (CTL, red) and ~~feedback scenario~~the dataset including the effect of erosion on productivity (FB, blue). Error bars represent one standard deviation from the mean for both observed and ~~modeled~~modelled values.

3.2 Long-term simulations: ~~Sensitivity~~sensitivity analysis

~~Moving from the model validation to the long term modelling, the following sections present the results of the 200 years simulations using the wider range of randomly generated parameters (see model implementation).~~

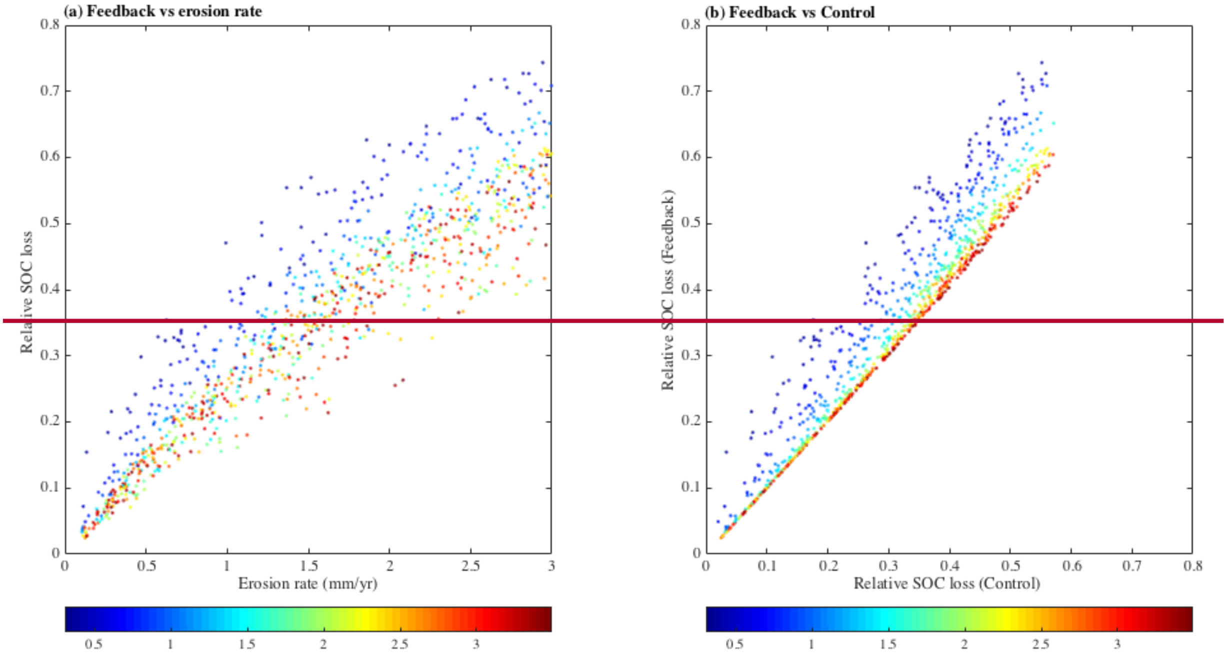
We performed a model sensitivity analysis to explore the model ~~behavior~~behaviour. The results of the FAST procedure are reported in Table ~~2a~~ 3. In addition, a sum of the contribution to the global variance may exceed 1 when two or more variable are correlated, which is the case here between erosion rate and ~~2b. Changes in SOC stock were~~ the crop productivity response. In analysis A (i.e. erosion is included), the relative SOC loss was almost entirely controlled by (i) the soil erosion rate (70 % of the total variance) and (ii) the functional form of the erosion ~~feedback~~effect on ~~yields~~crop productivity (22 % of the total variance) (Table ~~2a~~3a). Similar observations are valid for the cumulative vertical ~~balance~~C fluxes, although ~~it is~~ vertical fluxes were more sensitive to ~~yield~~crop productivity reduction than the erosion rate. ~~Mineralization distribution with~~The factor controlling the depth attenuation of C turnover was the third major factor influencing SOC losses and the cumulative C ~~balance~~fluxes, accounting for ~ 10 % of the variability. It should be noted that clay content and root depth distribution only played ~~only~~ a minor role in our analysis. When the variability ~~in~~due to erosion ~~rate~~ was excluded from the analysis~~,~~ (analysis B), both SOC loss and the vertical carbon fluxes were mainly sensitive to the functional form of the ~~feedback~~link between erosion and yield (70 % of the variance) and the mineralization rate distribution with depth (21 %) (Table ~~2b~~3b). The root depth distribution had ~~an~~a weak effect~~, although much weaker,~~ on relative SOC loss only (13 % of the variance). The model simulations showed a strong positive correlation between SOC loss and erosion rate as well as with the functional form of the yield reduction (~~color~~colour scale, concave if ~~b<1~~B =< 0.9, linear ~~when b ~ ~~if 0.9 < B < 1.1 and convex relationship when B > 1.1) (Fig. 5a).

Table 3 – Selected parameters, range of tested values and results of the FAST analysis. The FAST analysis results can be interpreted as the relative contribution of each parameter variability to the total variance of the selected output, i.e. the relative SOC loss compared to the initial SOC content and the cumulative vertical C fluxes at the end of the 200 years transient simulations. Table 3a represents analysis A where erosion intensity was allowed to vary while Table 3b represents analysis B where a constant erosion rate was used. “ns” stands for “non-significant”. The sum of the contribution to the global variance may exceed 1 when two or more variable are correlated.

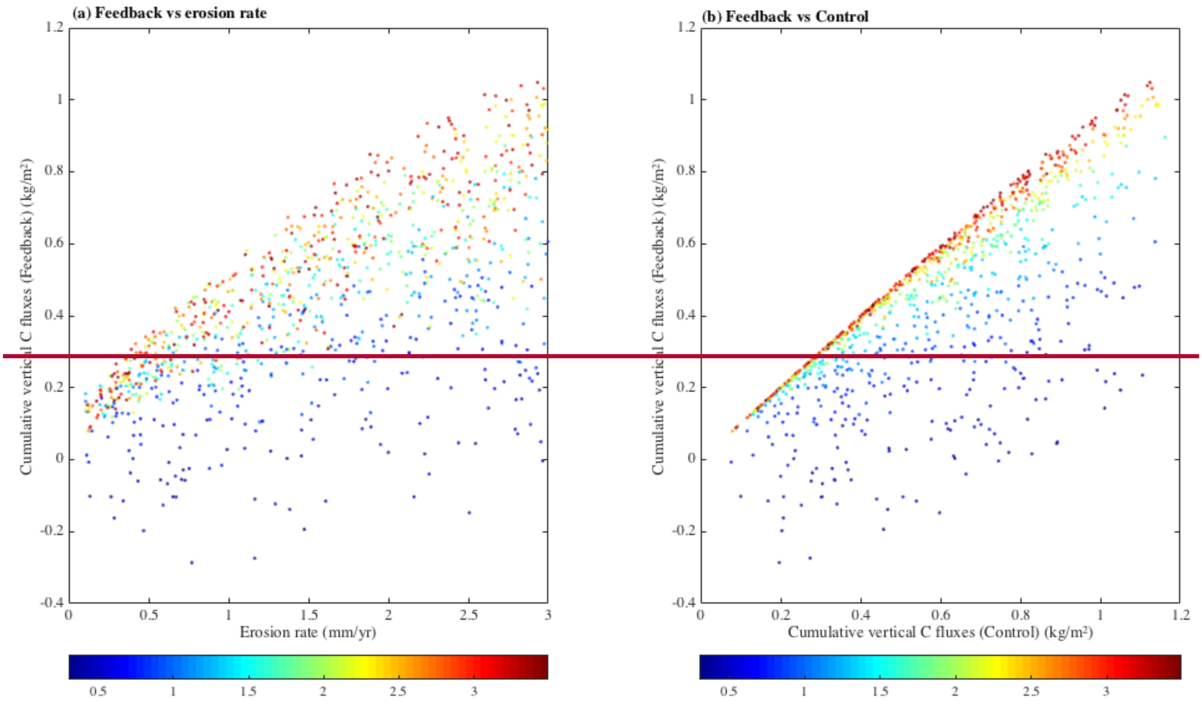
(a) Parameter	Symbol	Range	Relative contribution of each parameter to the relative SOC content losses variance after 200 years	Relative contribution of each parameter to the cumulative vertical C fluxes variance after 200 years
~~when b > 1) (Fig.~~				
Erosion rate (mm yr^{-1})*	*E*	0.1 – 3	0.705	0.194
Erosion effect on productivity *	*B* (Eq. 1)	0.3 – 4	0.220	0.544
Clay profile scaler	*Cl* (Eq. 5)	0.3 – 2.5	ns	ns
Distribution of carbon mineralization with depth	*Ur* (Eq. 7)	4 – 6	0.124	0.103
Root density profile with depth	$\varphi(z)$ (Eq. 6)	1 – 3	ns	ns

(b) Parameter	Symbol	Range	Relative contribution of each parameter to the relative SOC content losses variance after 200 years	Relative contribution of each parameter to the cumulative vertical C fluxes variance after 200 years
Erosion rate (mm. yr^{-1})	*E*	1 (fixed)	ns	~~ns~~
Erosion effect on productivity*	*B* (Eq. 1)	0.3 – 4	0.703	0.701
Clay profile scaler	*Cl* (Eq. 5)	0.3 – 2.5	ns	ns
Distribution of carbon mineralization with depth*	*Ur* (Eq. 7)	4 – 6	0.214	0.216
Root density profile with depth	φ(z) (Eq. 6)	1 – 3	0.137	ns

~~5a). The variability of the relative SOC loss to yield reduction was substantially larger for concave than for convex relationships. Although the same observations can be made for the vertical carbon fluxes, as the FAST analysis indicated, the influence of erosion was less important than the shape of the yield decrease. Fig. 6 also shows that, the vertical carbon fluxes can be close to zero or even negative for those cases where erosion resulted in a large reduction in C input (and this represents a net emission of C to the atmosphere).~~



~~Figure 5: (a) Relative SOC loss after 200 years for the feedback scenario as a function of erosion rate (mm.yr-1). (b) Relative SOC loss for the FB scenario against the relative SOC loss of the CTL scenario, for all the erosion rates. The colors scale represents the exponent B value, standing for the yield constraint form: B<0.9 exhibits a high sensitivity to small truncation (concave relationship) and B>1.1 shows low sensitivity to small soil truncation (threshold relationship, convex). If 0.9<B<1.1, yields decrease linearly with soil truncation.~~



~~Figure 6: (a) Cumulative vertical C fluxes (kgC.m^{-2}) after 200 years for the feedback scenario as a function of erosion rate (mm.yr-1). (b) Cumulative vertical C balance (kgC.m^{-2}) for the FB scenario against the cumulative vertical C balance (kgC.m^{-2}) loss of the CTL scenario, for all the erosion rates. The colors scale represents the exponent B value, standing for the yield constraint form: B<0.9 exhibits a high sensitivity to small truncation (concave relationship) and B>1.1 shows low sensitivity to small soil truncation (threshold relationship, convex). If 0.9<B<1.1, yields decrease linearly with soil truncation.~~

3.3 Long-term SOC stock loss

Simulated relative SOC ~~losses~~loss after 200 years ranged ~~from~~between 0.02 ~~to~~and 0.77 of the initial ~~stock~~content, depending on the erosion rate and the ~~feedback type. For the FB scenario~~erosion-productivity relation used. In FB, the average SOC loss ~~for the 1000 simulations equaled~~equalled 0.38 with a standard deviation of 0.18 (Fig. 5 and Table ~~3). In cases of~~ 4). When erosion rates were lower than 0.5 mm~~.~~ yr^{-1}, the simulated SOC loss ~~is~~was limited to 0.20 of the initial content ~~but increases~~and then increased almost linearly ~~up~~ to 0.2 to 0.5 at an erosion rate of 1.5 mm~~.~~ yr^{-1}. Higher soil ~~truncation~~erosion rates ~~exhibit~~resulted in a smaller variability in SOC losses~~ with respective range of~~. For example, a relative SOC loss of 0.32 to 0.60 ~~and 0.40 to 0.70,~~was simulated for an erosion rate of 2 mm~~.~~ yr^{-1} ~~and 3 mm.yr^{-1}.~~

. For ~~the~~ CTL ~~scenario~~ (Fig. 5b), SOC losses ranged ~~from~~between 0.02 ~~up to~~and 0.57 ~~of the initial carbon content depending on the feedback strength and the soil truncation~~, with a mean loss of 0.31 and a standard deviation of 0.14 (Fig. 5b and Table ~~3~~4). When including ~~feedback~~the effect of erosion on productivity in our simulations (FB ~~scenario~~), SOC losses increased, particularly ~~for the high sensitivity cases (i.e. nutrient depletion~~when using a concave and ~~soil thinning). Comparing the~~ linear erosion-productivity relationship). Relative to CTL ~~with the FB scenario, FB~~ , the addition of the relationship between erosion and crop productivity further ~~enhanced~~increased SOC loss by an additional 3 % to 17 % (average 7~~%) of the initial SOC content~~ %) after 200 simulation years (Fig. 5b and Table ~~3). Furthermore,~~

~~adding the feedbacks created more variability as indicated by the increase of the standard deviations shows.~~4).

When considering a period of 200 years, ~~nutrient depletion~~the concave relationship (B~~<~~ =< 0.9) resulted in the strongest relative SOC losses with an average ~~loss~~eroded fraction of 0.43~~+/-~~ ± 0.18 (range of 0.05 to 0.74) when compared to the results obtained in ~~the~~ CTL ~~scenario~~ (Fig. 5 and Table ~~3~~4). In contrast, ~~physical hindrance~~a linear relationship (B~1~~,)~~) had a weaker effect (~~0.~~mean eroded fraction of 0.36 ~~+/-~~± 0.16 of ~~average relative SOC loss,~~ the initial C stock, ranging from 0.04 to 0.68) while water availability (B > 1.1~~.1,)~~) had ~~virtually no~~the weakest effect on the mean relative SOC loss with ~~0.~~an eroded fraction of 0.34 ~~+/-~~ ±0.15~~,~~ (ranging from 0.02 to 0.65~~ to compare to~~) of the initial SOC stock (Fig. 5b, Table ~~3).~~4).

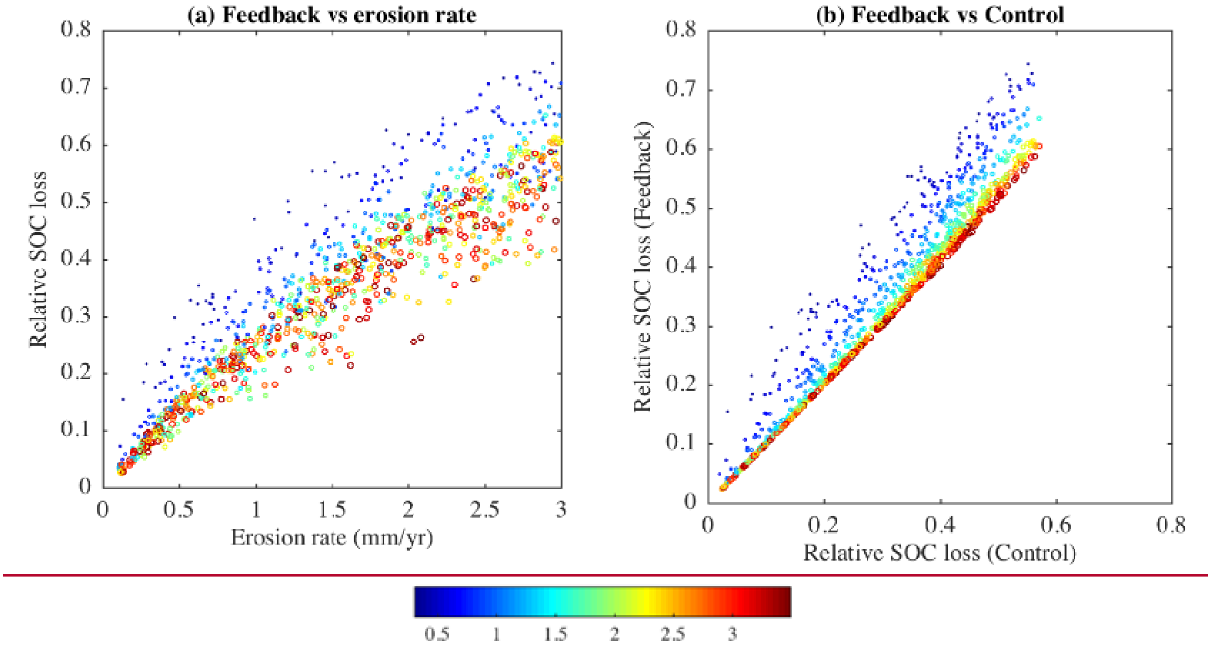


Figure 5 – (a) Relative SOC loss after 200 years for the dataset including the effect of erosion on productivity (FB) as a function of erosion rate (mm yr^{-1}). (b) Relative SOC loss for FB against the relative SOC loss of CTL, for all the erosion rates. The colours scale represents the exponent B value, where B < 0.9 a concave relationship and B > 1.1 represents a convex, threshold relationship. When 0.9 < B < 1.1, productivity decreases linearly with soil truncation.

3.4 Vertical carbon fluxes

~~We present the~~ The net cumulative ~~amount of~~ carbon ~~uptake from~~ flux between the soil and the atmosphere ~~to the soil (positive values) or emitted by the soil (negative values) due to erosion~~ after 200 years of transient simulations ~~(Fig.7).~~is represented in Figure 7. Provided that C input ~~remains~~ remained constant and unaffected by erosion ~~in our simulations~~ (CTL ~~scenario~~), a higher erosion rate resulted in an increased ~~the total~~net C uptake into soils due to the enhanced dynamic replacement~~, i.e. positive vertical carbon fluxes (Fig~~ (Fig. 6). For ~~the~~ CTL~~ scenario~~, vertical carbon fluxes increased almost linearly by 0.28 ~~kgC.~~kg C m^{-2} for each additional 1 mm~~.~~ yr^{-1} of soil erosion. ~~It should be noted that the variability increases as well when increasing the cumulative soil truncation, because of depth-dependency of the SOC mineralization rate.~~

As expected, ~~the~~ FB~~ scenario~~ resulted in substantially lower ~~values for the~~ vertical carbon fluxes (Fig. 6). However, most of the simulations still resulted in net C uptake with an average value of 0.41 ~~+/-~~kg C m^{-2} ± 0.21 ~~kgC.~~kg C m^{-2} (- 30 % compared to ~~the~~ CTL~~ scenario~~) (Table ~~3~~4, Fig. 6, Fig. 7). While higher erosion rates ~~resulted in higher values of~~generally increased the erosion-induced vertical carbon fluxes, ~~the~~ FB ~~scenario~~ induced a much larger variability, relative to ~~the~~ CTL ~~scenario~~, particularly ~~in the case of nutrient depletion and physical hindrance (Fig~~for the concave ~~6). Furthermore, the simulations showed the large effect of nutrient depletion and physical hindrance on the vertical carbon fluxes; relative to CTL, FB reduced the vertical carbon fluxes by 71%~~ and ~~45%, respectively (Table 3, Fig 6). Conversely, convex~~linear relationships (Fig. 6). ~~resulted in estimates which were very similar to the CTL scenario in terms of mean response, range and variability (Table 3, Fig 7).~~

~~Table 3: Relative SOC loss and cumulative C fluxes (kgC.m^{-2}) after 200 years of transient simulations for the CTL dataset and the FB dataset. Results are given for the whole FB dataset and for the sub-sets of the FB dataset corresponding to nutrient depletion, physical hindrance and water availability.~~

	~~Relative SOC loss~~	~~Cumulative vertical C fluxes (kgC.m^{-2})~~

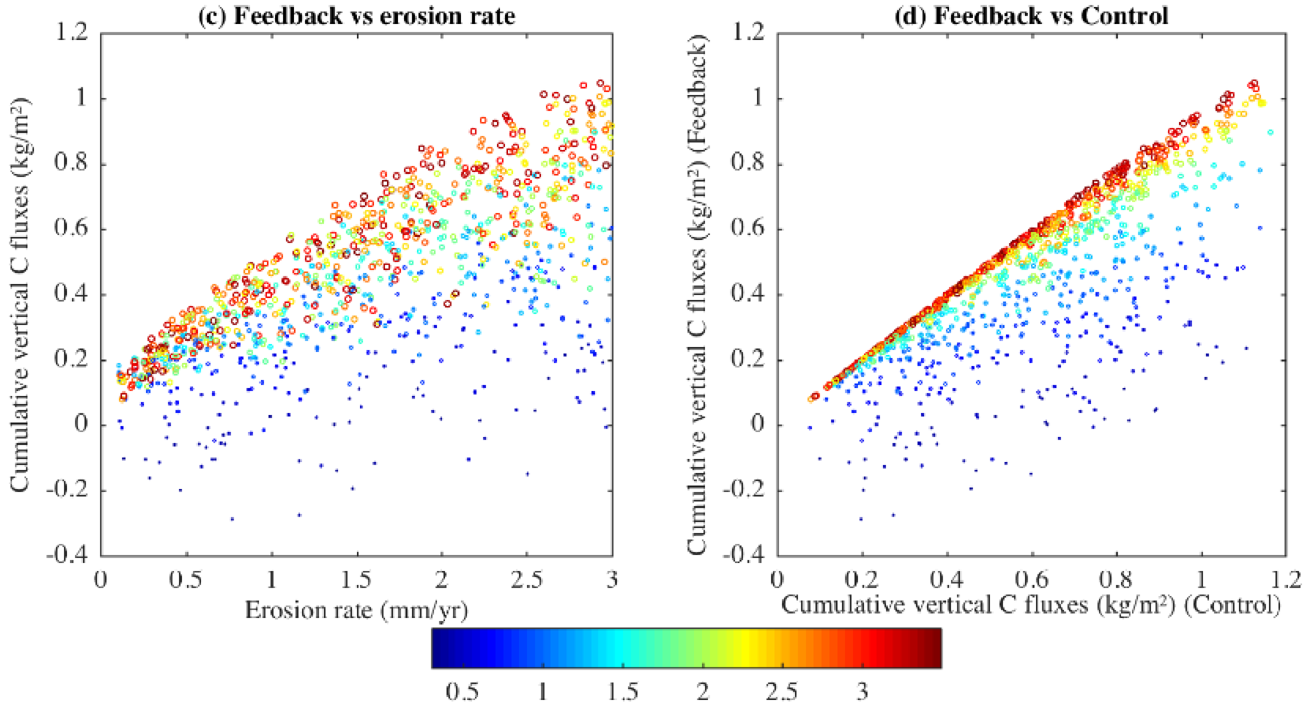
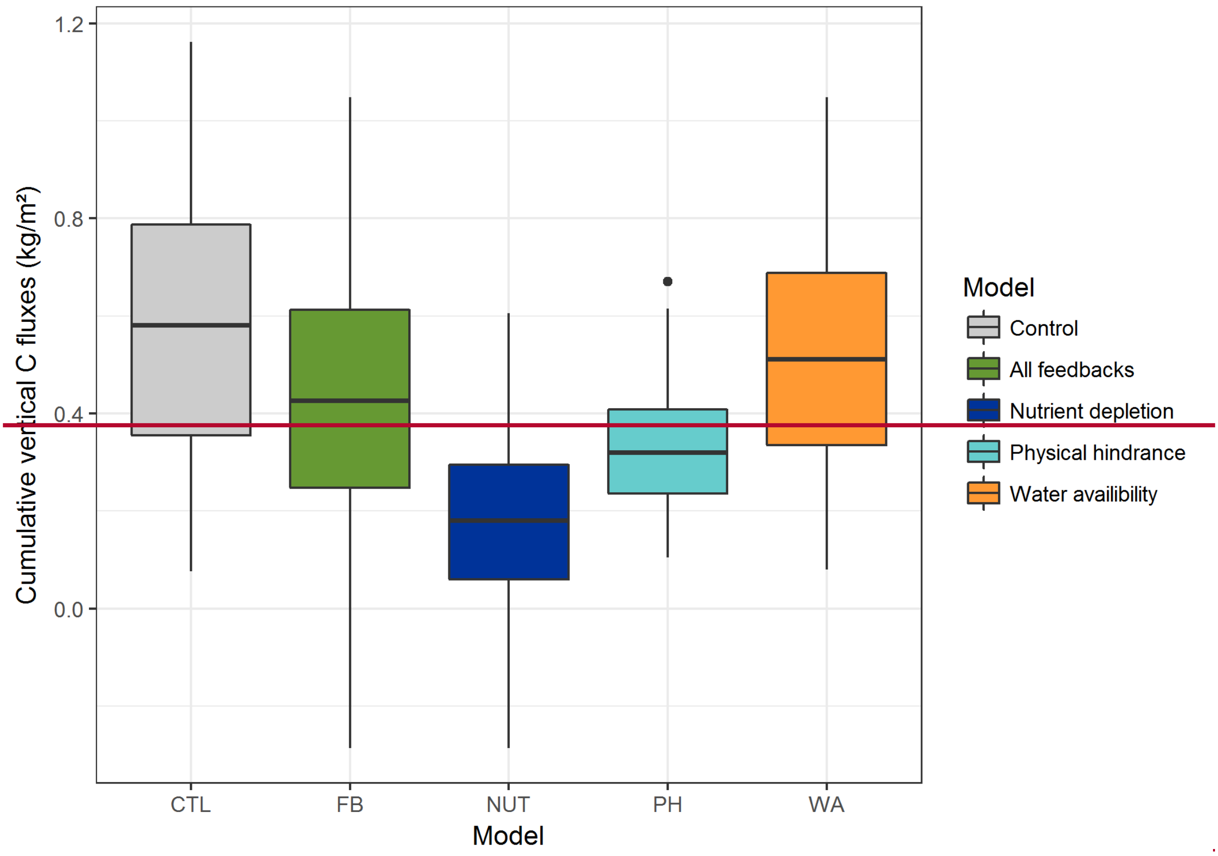


Figure 6 – (c) Cumulative vertical C fluxes (kg C m-^{2}) after 200 years for the dataset including the effect of erosion on productivity (FB) as a function of erosion rate (mm yr^{-1}). (d) Cumulative vertical C fluxes (kg C m-^{2}) for FB against the cumulative vertical C fluxes (kg C m-^{2}) loss of CTL, for all the erosion rates. Positive cumulative vertical fluxes represent a net uptake into soils, while negative values represent a net loss to the atmosphere. The colours scale represents the exponent B value, where B < 0.9 a concave relationship and B > 1.1 represents a convex, threshold relationship. When 0.9 < B < 1.1, productivity decreases linearly with soil truncation.

~~-~~	~~Range~~	~~Mean~~	~~Standard deviation~~	~~Range~~	~~Mean~~	~~Standard deviation~~
~~CTL~~	~~0.02 - 0.57~~	~~0.31~~	~~0.14~~	~~0.06 - 1.17~~	~~0.59~~	~~0.25~~
~~FB~~	~~0.05 - 0.74~~	~~0.37~~	~~0.17~~	~~-0.29 - 1.05~~	~~0.41~~	~~0.21~~
~~Nutrient depletion~~	~~0.05 - 0.74~~	~~0.43~~	~~0.18~~	~~-0.29 - 0.61~~	~~0.17~~	~~0.18~~
~~Physical Hindrance~~	~~0.04 - 0.67~~	~~0.35~~	~~0.16~~	~~0.1 - 0.67~~	~~0.32~~	~~0.12~~

~~Water Availability~~	~~0.02 – 0.65~~	~~0.34~~	~~0.16~~	~~0.08 – 1.05~~	~~0.52~~	~~0.22~~



~~Figure 7: Comparison the cumulative vertical C balance (kgC.m^{-2}) between the CTL dataset (grey) and the FB dataset (colors) after 200 years of transient simulations. Positive values indicate a net flux from the atmosphere to the soil. Green, blue, light blue and orange represent respectively the FB scenario results, nutrient depletion, physical hindrance and water availability. Nutrient depletion, physical hindrance and water availability statistics are subsets of the FB scenario results dataset.~~

4 Discussion

4.1 ~~Inclusion of the feedback~~Model limitations

Our study is based on ~~the SOC~~ several assumptions which are related to (i) the modelling framework and (ii) external factors such as agricultural practices. The first category of assumptions is mainly related to the simplifications made in linking crop productivity to C dynamics as we assumed a linear relation between C input and crop productivity. This relation may vary due to biological adaptation of plants to stress. Particularly, in shallow-soil environments, plants tend to adapt their root morphology and increase their root density in response to limited rooting-depth, leading to a slower decline of both C inputs and C stocks over time (Bardgett and van der Putten, 2014; Bardgett et al., 2014; Jin et al., 2017; Kosmas et al., 2001). This implies that our assumption may result in an underestimation of soil C inputs and hence an overestimation of the C stock losses. The model provided estimations of vertical carbon fluxes which were of the correct order of magnitude and represented the relative differences between the sites well, nevertheless, there is an overall and substantial underestimation of the net vertical fluxes. Although we derived the functional form of the effect of erosion on crop productivity from Bakker et al (2004), biomass productivity reduction impacts on SOC and vertical carbon fluxes (Figure 5) should be carefully interpreted. SOC content and cumulative vertical fluxes are much more sensitive to concave (B < 0.9) than threshold relationships (convex, B > 1.1), although this observation is a direct consequence of the nature of the mathematical function used. With only the exponent B varying, the different yield reduction functions used here intersect each other only when the soil truncation is zero or equals 1 meter; under the absence of observational data it is difficult to verify this assumption. Furthermore, the investigated soil truncation range in our simulations (60 cm) was not sufficient to surpass the threshold of yield degradation when B > 1.1 (i.e. convex relationships).

~~As shown by our simulations, accounting for erosion-crop yield feedbacks increases SOC losses by 3% to 17% relative to the CTL scenario, depending on the cumulative amount of soil truncation and the functional form of the erosion-crop yield feedback. Our results are supported by the findings reported by previous studies (Berhe et al (2005), Gregorich et al. (1998), Lal (2004), Quinton et al. (2010) or Starr et al. (2000)) that suggested that the modfication of key soil properties (such as nutrients, water retention capacity) by erosion degrades the agronomic quality of the soil and decreases the SOC stock triggered by a C input decline.~~

~~The model evaluation showed that, for both the~~

Furthermore, in our model C enrichment and preferential detachment were set to unity and we did not consider C leaching and bioturbation through the profile. The first process has been recognized as being important when evaluating lateral C fluxes, and particularly C export (Wilken et al., 2017). Soil C leaching and bioturbation are two important factors in long timescale SOC dynamics, however, in agricultural catchments, SOC fluxes are likely dominated by soil redistribution while other processes play a minor role at the considered timescales (Doetterl et al., 2016, Kirkels et al., 2014, Minasny et al., 2015).

Given the relatively large uncertainty on the simulated vertical C fluxes, it can be argued that site-specific relations are required to improve the predictive power of the model. This is particularly the case for concave relationships where our model overestimated the losses and underestimated C uptake. Even if we treated the different forms of biomass response to soil erosion as separate cases, these three relationships are not mutually exclusive under real conditions. Depending on soil erosion rates and soil properties, an eroding profile could experience different biomass responses over time: in a first phase, productivity may primarily respond to topsoil properties alteration by soil erosion. After several decades of soil erosion, soil depth limitations may exert a growing constrain on crop productivity, surpassing the initial topsoil related constraints.

Assumptions related to external factors include those made with respect to changes in agricultural practices. To build the relationship between erosion and crop productivity, we used data derived from comparative analysis of eroding soils and their stable non-eroding counterparts (same slope position) that have received the same management and external inputs rather than manipulation experiments, which ensure some real-world relevance. However, practices evolution such as mechanization and increased usage of amendments and fertilizers may compensate for the yield loss as a result of continued erosion (Gregorich et al., 1998; Doetterl et al., 2016). Therefore, SOC content and crop productivity evolution may be partially decoupled whereby, without soil depth constraints, soil erosion does not substantially affect productivity. Erosion may still be an important driver for SOC losses in eroding landscapes (Meersmans et al., 2009; Bakker et al., 2007; Fenton et al., 2005). In intensively managed systems, fertilizer applications compensate for erosion-induced nutrient losses and that nutrient loss (i.e. topsoil limitation) may not be the most important effect of erosion whereas rooting space and water availability are more likely to be key issues as soil depth limitation constitutes a physical limit which could not easily be overcome by agricultural practices adaptations. On the other hand, our range of functional forms allowed for a representation of a wide variety of cases. In our simulations, we did not consider the increase in productivity that did occur during the last decades, however, it should be noted that this study focussed on the impact of erosion, relative to non-eroding conditions (e.g. Van Oost et al., 2005). Nevertheless, the simulated C loss and soil-atmosphere fluxes could be overestimated as higher C inputs allow for higher C stocks and this will reduce C losses.

4.2 Impact on SOC losses

Our results showed that the erosion effect on crop productivity increased SOC losses by 3 % to 17 % relative to CTL. This relative increase depends primarily on the cumulative amount of soil truncation and the functional form of the relationship between erosion and productivity. The model evaluation showed that, for both CTL~~ and FB scenarios~~, model predictions were close to the observations for sites ~~having experienced~~that are characterized by relatively small soil truncation (i.e. short cultivation period or low erosion rates) (Fig. 4). ~~The ~~FB ~~scenario~~ resulted in an overall better prediction because it was able to predict the large relative SOC losses for the ~~cases~~environments where intensive erosion took place. However, the addition of the ~~feedback~~erosion-induced productivity decline in the model led to contrasting results. On the one hand, ~~and in line with the sensitivity analysis and the feedback nature, ~~SOC losses were higher for sites where ~~yields were~~productivity was more sensitive to erosion ~~due do nutrient depletion~~(concave or ~~soil thinning when compared to the CTL scenario. The FB scenario~~linear erosion-crop productivity relationships). FB showed an increase in the model performance when SOC losses were important (~~e.g. USA, Denmark, Belgium 1) (~~Table 2, Fig. 4). ~~In contrast,~~

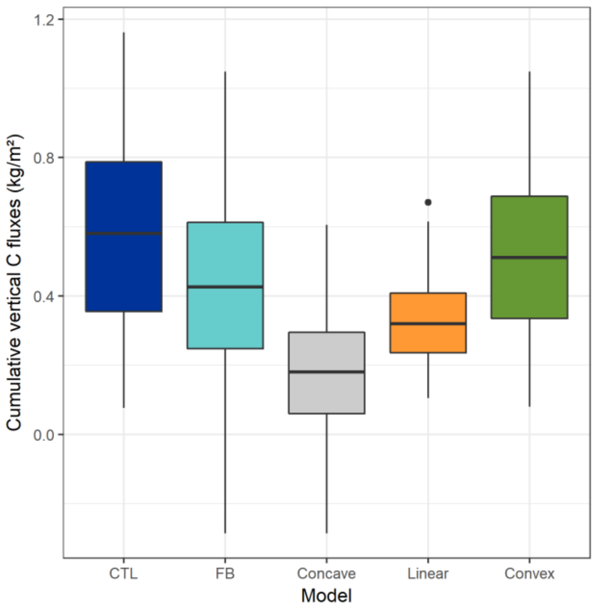


Figure 7 – Comparison the ~~predictive power~~cumulative vertical C fluxes (kg C m^{-2}) between CTL (grey) and FB (colours) after 200 years of transient simulations. Positive values indicate a net flux from the ~~model was smaller~~atmosphere to the soil. Green, blue, light blue and orange represent respectively FB results, concave relationship, linear relationship and convex relationship. Statistics for ~~sites with low SOC losses (e.g. Belgium 2, Spain 2, UK).~~ the concave relationship, linear relationship and physical relationship are performed on subsets of FB results dataset. Boxes represent the interquartile range and whiskers the 5 % to 95 % range of the distribution.

On the other hand, ~~adding~~linear and convex yield ~~feedbacks related to water availability and physical hindrance~~evolution in response to soil erosion had little effect on the model results (Fig. 4). ~~Model validation, however, indicated that results with and without the erosion feedback on yields were~~The differences between FB and CTL model simulations were relatively similar~~. Despite the increased SOC losses, both aggregated statistics and ranges for similar erosion rates did not exhibits clear differences between the scenarios expect~~ except for (i) ~~nutrient-limited~~ environments characterized by a concave relationship between crop productivity and soil erosion (B < 0.9) and under moderate to high erosion ~~rate~~rates or (ii) ~~a~~ when erosion rates are simply very high~~ erosion rates cases.~~ . Based on the results of the FAST analysis (Table 3), -where the strong impact of cumulative soil truncation and the ~~feedback nature on SOC losses and fluxes was highlighted~~form of the erosion-productivity relationship were identified, we argue that the small differences between ~~the scenarios in the model validation~~FB and CTL are mainly ~~due~~related to the short ~~timescale~~periods during which the~~ selected~~ sites have been ~~eroding~~exposed to agricultural erosion.

~~Longer timescale simulations~~

The use of longer simulation periods (200 years) ~~improved the understanding of~~ further exemplified the link between erosion-~~yield~~crop productivity and SOC losses~~ and ~~/vertical fluxes. The sensitivity analysis highlighted a strong influence of the soil erosion rate and yield reduction rate while ~~exhibiting a weak link between SOC response (SOC stock loss and vertical carbon fluxes) and the initial SOC content or the profile~~C profile shape, as determined by the clay content, the mineralization rate and the root depth distribution ~~(Table 2). Furthermore, differences between the CTL and FB scenarios as well as between the feedbacks nature were larger than those observed in the validation. The addition of the feedback had the most impact for higher erosion rate ,the high sensitivity settings and, to a lesser extent, the physical hindrance. Nutrient depletion had the largest impact owing to their immediate response to~~

~~erosion and lead to potentially high losses. In contrast, water availability constraints are~~ were less ~~distinguishable from the CTL scenario, except in the cases where B is close to 1 and total soil truncation is high (~~influential (Table 3).

Table ~~3, Fig~~ **4**~~).~~ – Relative SOC loss and cumulative C fluxes (kg C m^{-2}) after 200 years of transient simulations for CTL and FBs. Results are given for the whole FB and for the sub-sets of FB corresponding to the concave relationship, the linear relationship and the convex relationship.

	Relative SOC loss			Cumulative vertical C fluxes (kg C m^{-2})		
	Range	Mean	Standard deviation	Range	Mean	Standard deviation
CTL	0.02 – 0.57	0.31	0.14	0.06 – 1.17	0.59	0.25
FB	0.05 – 0.74	0.37	0.17	- 0.29 – 1.05	0.41	0.21
Concave	0.05 – 0.74	0.43	0.18	- 0.29 – 0.61	0.17	0.18
Linear	0.04 – 0.67	0.35	0.16	0.1 – 0.67	0.32	0.12
Convex	0.02 – 0.65	0.34	0.16	0.08 – 1.05	0.52	0.22

~~The observed timescale dependency of predictions performance of respective model scenarios can be explained by the non-linear evolution of the SOC content of a profile exposed to erosion. Without feedback~~

When the effect of erosion on productivity is not accounted for, the SOC stock follows a non-linear evolution over time that can be divided into two phases. Given the exponential form of the SOC depth profile, a quick initial decrease of the SOC content is followed by a stabilization of SOC content to a steady state level due to an equilibrium between the C input, C uptake from the atmosphere, the lateral export and the C mineralization (Bouchoms et al~~,~~., 2017~~, Kirkels et al., 2014~~; Kuhn et al., 2009; Liu et al., 2003). Under continuous erosion, the rate of C export from a profile is decreasing over time owing to the differential SOC distribution between subsoil and topsoil (~~Kirkels et al., 2014;~~Kuhn et al., 2009; Liu et al., 2003). Hence, the fast initial decrease of the SOC stock is linked to the erosion of a SOC-rich topsoil, whereby a small sediment flux may carry a relatively large amount of SOC (Kirkels et al., 2014). In the later stages of the transient simulation, i.e. where the SOC-poor subsoil is exposed to erosion, the SOC loss is smaller for a similar amount of soil truncation ~~(Kirkels et al., 2014). At this stage,~~(Kirkels et al., 2014), the impact of the erosion-~~yield feedback~~crop productivity effect becomes more important and drives the SOC stock decline. Depending on the erosion rate, the first phase ~~can~~could last for several decades before a steady state ~~could be reach. High sensitivity feedbacks~~is reached. The impact of declining productivity on ~~SOC input such as nutrient depletion and physical hindrance tends~~the SOC losses depended on the form of the response: concave or linear responses to ~~increase~~soil erosion tended to amplify the SOC losses in the first ~~phase~~decades while the effect of ~~low sensitivity effect~~ the convex relationship may be partially masked ~~until~~in the first decade and become more stringent only in the later stages of the ~~above-described SOC loss processes~~transient simulations when compared to C losses evolution without an effect of erosion on productivity.

4.~~2~~3 SOC dynamics in eroding landscape: discussion of the addition of erosion-yield ~~feedback~~relationship on the vertical C ~~balance~~fluxes

In eroding landscapes, several studies have highlighted that a fraction of the erosional SOC loss is replaced by new ~~photosynthate~~photosynthates, thereby creating a local atmospheric carbon sink (Harden et al., 1999; Berhe et al., 2007; Van Oost et al., 2007a). Although much ~~weaker~~smaller than the C release rate from land cover conversion or SOC lateral export, this ~~so-called dynamic replacement~~erosion-induced atmospheric sink term operates on long time scales and can be sustained as long as (i) new C-depleted subsoil material is exposed to the surface and (ii) new C inputs, mainly from plants, are available (Doetterl et al., 2016;~~Kirkels~~ Wang et al., ~~2014~~2017; Naipal et al., 2018). Both conditions can be questioned here, particularly for landscapes having experienced intense cultivation, and hence erosion, for several centuries. ~~We do not address the first one here as it not the main focus of this study. As for the second one, when not including the feedback between erosion and yield, one assumes a constant C input to the soil and the absence of soil resource limitations (e.g. water, nutrients, rooting depth).~~The first condition requires deep soils without depth limiting factors. The second condition requires continued C inputs via roots and plant residues.

In their meta-~~data~~ analysis, Bakker et al. (2004) highlighted that deeply truncated soils exhibit a large reduction in crop productivity. Our simulation results showed ~~-~~that reducing C input in response to long-term erosion actually decreased the SOC stocks by 5 % to 74~~% in~~ % for the sites where intense ~~eroding cases~~erosion takes place (Fig. 5) ~~while producing results in line~~and were consistent with observed SOC losses (see above and Fig. 4). As Harden et al. (1999) and Doetterl et al. (2016) reported, taking into account the erosion ~~feedback~~effect on productivity leads to a better estimation of the C budget and particularly the dynamic replacement, which ~~could~~is likely to be overestimated when ignoring the erosion-yield ~~feedback~~relationship, particularly when considering longer timescales. Our study supports these ~~assumptions, finding that, compared to~~assertions: when comparing FB and CTL, the ~~CTL scenario,~~ cumulative vertical C ~~balance~~fluxes decreased on average by 15 % to 71 % after 200 years depending on the ~~feedback~~relationship nature between erosion and productivity (Fig. 6 and Fig. 7). Simulations pointed out that intense sustained erosion coupled combined with a strong reduction in soil C input can turn the soil into a net C source for the atmosphere when the soil C input becomes smaller than the mineralization rate due to decreasing productivity.

~~Simulations pointed out that intense sustained erosion coupled with sufficient C input reduction can turn the soil profiles into a net C source for the atmosphere when the C input to the soil profile become smaller than the mineralization rate, due to the decreasing yields. FAST analysis (Table 2) indicates that most of the uncertainty in our simulations is related to the combination of yield reduction strength, erosion rate and mineralization rate, which stressed the importance of (i) accurate SOC profile calibration and linking erosion and vegetation.~~

~~Although the model provided estimations of vertical carbon fluxes, which were of the correct order of magnitude and represented the relative differences between the sites well, there is an overall underestimation of the net vertical balance. Although we derived the functional form of the feedbacks from Bakker et al (2004), yields reduction effects on SOC and vertical carbon fluxes as presented in Fig. 5 should be carefully interpreted. SOC content and cumulative vertical fluxes seem to be much more sensitive to high sensitivity relationships (B~~

~~< 0.9) than threshold ones (convex, B > 1.1), although this observation is a direct consequence of the equation nature. With only the exponent varying, the yield reduction functions intersect only when the soil truncation is zero or equals 1 meter; it can be questioned to what extent this assumption is representative of real environmental situations. Furthermore, the investigated soil truncation range (60cm) was not sufficient to pass the threshold of yield degradation in convex cases (B > 1.1). The observations on which the feedback relationships were based, were produced by the comparative plots methods, which although better at representing the erosion effect on crop yields than desurfacing or transect methods, may not be as accurate as local on-site evaluations (Bakker et al, 2004). Furthermore, the assumption of a linear decrease of C input in response to yield may not be accurate in some cases. Particularly, in shallow soils environment, plants tend to adapt their root morphology and increase their root density in response to limited rooting-depth, leading to a slower decline of both C inputs and C stocks over time (Bardgett et al., 2014;Jin et al., 2017), Kosmas et al, 2001). It can be argued that a better fit of the equation to specific conditions would improve the prediction power of the model particularly in the context of nutrient depletion situations where our model overestimated the losses and underestimated the C uptake for low rates of soil truncation. Furthermore, it should be noted that agricultural practices have changed drastically during the last 60 years. Mechanization and intense usage of amendments and fertilizers tend to counterbalance the yield loss consecutive to long term erosion (Gregorich et al., 1998;Doetterl et al., 2016;Kirkels et al., 2014). Therefore, SOC content and yield evolution may have been partially decoupled whereby, without soil depth constraints, soil erosion has not altered the yields while still driving the SOC losses in eroding landscapes (Meersmans et al., 2009;Bakker et al., 2007;Fenton et al., 2005).~~

~~5 Conclusion~~

~~Based on~~

5. Conclusion

Using results from a meta-~~data~~ analysis, we ~~extracted three main~~used different functional relationships linking soil truncation and crop ~~yields discretized by the value of the exponent: two non-linear relationships corresponding to a high-sensitivity to erosion (i.e. nutrient depletion), a low-sensitivity threshold behavior (i.e. water availability) and a linear relationship representing soil thinning~~productivity. We implemented the effect of soil erosion~~-yield feedback~~ on crop productivity in a simple but depth-explicit model of SOC dynamics. The integration of the erosion-yield ~~feedback~~relationship allowed us to represent the effect of erosion on SOC evolution through a decrease of ~~the~~soil C ~~input~~inputs due to reduced ~~yields~~productivity as well as from ~~the~~ lateral SOC export. ~~We performed a model validation based on 10 sites across Europe and USA. Taking into account the uncertainties linked to environmental conditions~~By confronting model simulations with observational data, our results point out that introducing ~~the~~ erosion ~~constraint~~constraints on ~~yields~~soil C input improves estimates of SOC losses, compared to a model ~~setting without the feedback provided that~~approach where the effect of erosion on productivity is not included, if (i) soil truncation is substantial and (ii) the erosion-yield ~~link~~relationship is accurately ~~calibrated to the~~ representing local conditions. ~~These finding were further supported by the long-term~~

A sensitivity analysis~~, which pointed~~ showed that the ~~importance of ~~erosion rate~~ (i.e. cumulative soil truncation), the strength~~, the form of the erosion~~ feedback on yield-~~productivity relation and the depth attenuation of the SOC mineralization rate ~~depth-distribution as~~are the ~~main source of variability of~~key factors controlling SOC losses and ~~cumulative vertical carbon fluxes~~soil-atmosphere C exchange. Long-term simulations showed that both ~~the ~~SOC content and the cumulative ~~vertical~~soil-atmosphere C ~~fluxes~~exchange were largely influenced by soil truncation and ~~yield~~productivity decrease due to erosion. The inclusion of the erosion~~ yield feedback~~ effect on crop productivity in the model ~~leads~~lead to higher SOC losses ~~or ~~(an additional SOC loss of ~~5% to 74% of the initial SOC content,~~37 % ± 17 %, relative to ~~the case in which~~simulations where no feedbacks are ~~assumed. Furthermore, not taking the feedback into account could lead to a 15% to 71~~considered) and less C uptake on eroding sites. (30 % ± 25 % overestimation~~ of the net C uptake at sites of erosion after 200 years of soil erosion. The approach is~~). The results are thus particularly relevant for ~~long~~longer-term ~~simulations while stressing~~assessments and they stress the need for an integrated landscape modelling to better ~~constraint~~constrain the ~~final~~overall SOC budget. Although fertilizer application may compensate for erosional nutrient losses, our simulations show that erosion-induced reduction in soil C inputs may be relevant for the soil C budget, particularly when rooting depth and water availability are limiting factors.

~~Competing interests~~

~~The authors declare that they have no conflict of interest.~~

~~Ackowledgements~~

~~This research was funded by the Belgian Science Policy Office (BELSPO) in the framework of the Inter University Attraction Pole project (P7-24): SOGLO – The Soil system under global change.~~

6. References

Andren, O., and Katterer, T.: ICBM: The introductory carbon balance model for exploration of soil carbon balances, Ecological Applications, 7, 1226-1236, 1997.

Bakker, M. M., Govers, G., and Rounsevell, M. D. A.: The crop productivity–erosion relationship: an analysis based on experimental work, CATENA, 57, 55-76, http://dx.doi.org/10.1016/j.catena.2003.07.002, 2004.

Bakker, M. M., Govers, G., Jones, R. A., and Rounsevell, M. D. A.: The Effect of Soil Erosion on Europe’s Crop Yields, Ecosystems, 10, 1209-1219, 10.1007/s10021-007-9090-3, 2007.

Bardgett, R. D., Mommer, L., and De Vries, F. T.: Going underground: root traits as drivers of ecosystem processes, Trends Ecol Evol, 29, 692-699, 10.1016/j.tree.2014.10.006, 2014.

Bardgett, R. D., and van der Putten, W. H.: Belowground biodiversity and ecosystem functioning, Nature, 515, 505-511, 10.1038/nature13855, 2014.

Berhe, A. A., Harte, J., Harden, J. W., and Torn, M. S.: The significance of the erosion-induced terrestrial carbon sink, Bioscience, 57, 337-346, 2007.

Beven K.: Toward integrated envrionmental models of everywhere uncertainty, data, and modelling as a learning process, Hydrology & Earth System Sciences 11(1), 460-467, 2007.

Billings, S.A., Buddemeier, R.W., Richter, D.D., Van Oost, K. and Bohling, G.,: A simple method for estimating the influence of eroding soil profiles on atmospheric CO2. Global Biogeochem. Cycles, 24, 2010.

Bouchoms, S., Wang, Z., Vanacker, V., Doetterl, S., Van Oost, K.: Modelling long-term soil organic carbon dynamics under the impact of land cover change and soil redistribution, Catena, 151, 63-73, 2017.

Chappell, A., Sanderman, J., Thomas, M., Read, A., and Leslie, C.: The dynamics of soil redistribution and the implications for soil organic carbon accounting in agricultural south-eastern Australia, Global Change Biology, 18, 2081-2088, 10.1111/j.1365-2486.2012.02682.x, 2012.

Chappell, A., Baldock, J., and Sanderman, J.: The global significance of omitting soil erosion from soil organic carbon cycling schemes, Nature Climate Change, 10.1038/nclimate2829, 2015.

Crowther, T. W., Todd-Brown, K. E., Rowe, C. W., Wieder, W. R., Carey, J. C., Machmuller, M. B., Snoek, B. L., Fang, S., Zhou, G., Allison, S. D., Blair, J. M., Bridgham, S. D., Burton, A. J., Carrillo, Y., Reich, P. B., Clark, J. S., Classen, A. T., Dijkstra, F. A., Elberling, B., Emmett, B. A., Estiarte, M., Frey, S. D., Guo, J., Harte, J., Jiang, L., Johnson, B. R., Kroel-Dulay, G., Larsen, K. S., Laudon, H., Lavallee, J. M., Luo, Y., Lupascu, M., Ma, L. N., Marhan, S., Michelsen, A., Mohan, J., Niu, S., Pendall, E., Penuelas, J., Pfeifer-Meister, L., Poll, C., Reinsch, S., Reynolds, L. L., Schmidt, I. K., Sistla, S., Sokol, N. W., Templer, P. H., Treseder, K. K., Welker, J. M., and Bradford, M. A.: Quantifying global soil carbon losses in response to warming, Nature, 540, 104-108, 10.1038/nature20150, 2016.

Cukier, R. I., Fortuin, C. M., Shuler, K. E., Petschek, A. G., and Schaibly, J. H.: Study of the sensitivity of coupled reaction systems to uncertainties in rate coefficients. I Theory, The Journal of Chemical Physics, 59, 3873-3878, doi:http://dx.doi.org/10.1063/1.1680571, 1973.

Cukier, R. I., Schaibly, J. H., and Shuler, K. E.: Study of the sensitivity of coupled reaction systems to uncertainties in rate coefficients. III. Analysis of the approximations, The Journal of Chemical Physics, 63, 1140-1149, doi:http://dx.doi.org/10.1063/1.431440, 1975.

den Biggelaar, C., Lal~~,~~., R., Wiebe, K., Breneman, V., and Sparks, D. L.: The Global Impact f Soil Erosion n Productivity: I: Absolute and Relative Erosion-induced Yield Losses, in: Advances in Agronomy, Academic Press, 1-48, 2003.

Dialynas, Y. G., S. Bastola, R. L. Bras, S. A. Billings, D. Markewitz, and D. d B. Richter: Topographic variability and the influence of soil erosion on the carbon cycle, Global Biogeochem. Cycles, 30, 644–660, 10.1002/2015GB005302, 2016.

Dlugoß, V., Fiener, P., Van Oost, K. and Schneider, K.: Model based analysis of lateral and vertical soil carbon fluxes induced by soil redistribution processes in a small agricultural catchment. Earth Surface Processes and Landforms, 37(2): 193-208, 2012.

Doetterl, S., Berhe, A. A., Nadeu, E., Wang, Z., Sommer, M., and Fiener, P.: Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes, Earth-Science Reviews, 154, 102-122, 10.1016/j.earscirev.2015.12.005, 2016.

Farina, R., Seddaiu, G., Orsini, R., Steglich, E., Roggero, P. P., and Francaviglia, R.: Soil carbon dynamics and crop productivity as influenced by climate change in a rainfed cereal system under contrasting tillage using EPIC, Soil and Tillage Research, 112, 36-46, 10.1016/j.still.2010.11.002, 2011.

Fenton, T., Kazemi, M., and Lauterbachbarrett, M.: Erosional impact on organic matter content and productivity of selected Iowa soils, Soil and Tillage Research, 81, 163-171, 10.1016/j.still.2004.09.005, 2005.

Gregorich, E. G., Greer, K. J., Anderson, D. W., and Liang, B. C.: Carbon distribution and losses: erosion and deposition effects, Soil & Tillage Research, 47, 291-302, 1998.

Fiener, P., Dlugoss V. and Van Oost, K.: Erosion-induced carbon redistribution, burial and mineralisation — Is the episodic nature of erosion processes important? CATENA, 133(0): 282-292, 2015.

Harden, J. W., Sharpe, J. M., Parton, W. J., Ojima, D. S., Fries, T. L., Huntington, T. G., and Dabney, S. M.: Dynamic replacement and loss of soil carbon on eroding cropland, Global Biogeochem. Cycles, 13, 885-901, 1999.

Heckrath, G., Djurhuus, J., Quine, T. A., Van Oost, K., Govers, G., and Zhang, Y.: Tillage Erosion and Its Effect on Soil Properties and Crop Yield in Denmark, J. Environ. Qual., 34, 312-324, doi: 10.2134/jeq2005.0312, 2005.

Hiederer, R., and Köchy, M.: Global soil organic carbon estimates and the harmonized world soil database, EUR, 79, 25225, 2011.

Hoffmann, T., Glatzel, S., and Dikau, R.: A carbon storage perspective on alluvial sediment storage in the Rhine catchment, Geomorphology, 108, 127-137, 2009.

Houghton, R. A.: Balancing the global carbon budget, Annual Review of Earth and Planetary Sciences, 35, 313-347, doi:10.1146/annurev.earth.35.031306.140057, 2007.

Izaurralde, R., Williams, J., McGill, W., and Rosenberg, N.: Simulating soil carbon dynamics, erosion and tillage with EPIC, First National Conference on Carbon Sequestration sponsored by the US Department of Energy-National Energy Technology Laboratory, 2001, 14-17,

Izaurralde, R. C., Williams, J. R., Post, W. M., Thomson, A. M., McGill, W. B., Owens, L. B., and Lal., R.: Long-term modeling of soil C erosion and sequestration at the small watershed scale, Climatic Change, 80, 73-90, 2007.

Jin, K., White, P. J., Whalley, W. R., Shen, J., and Shi, L.: Shaping an Optimal Soil by Root-Soil Interaction, Trends Plant Sci, 22, 823-829, 10.1016/j.tplants.2017.07.008, 2017.

~~Kaplan, J. O., Krumhardt, K. M., Ellis, E. C., Ruddiman, W. F., Lemmen, C., and Klein Goldewijk, K.: Holocene carbon emissions as a result of anthropogenic land cover change, The Holocene, 10.1177/0959683610386983, 2010.~~

~~Kaplan, J. O., Krumhardt, K. M., and Zimmermann, N. E.: The effects of land use and climate change on the carbon cycle of Europe over the past 500 years, Global Change Biology, 18, 902-914, 10.1111/j.1365-2486.2011.02580.x, 2012.~~

Kirkels, F. M. S. A., Cammeraat, L. H., and Kuhn, N. J.: The fate of soil organic carbon upon erosion, transport and deposition in agricultural landscapes — A review of different concepts, Geomorphology, 226, 94-105, http://dx.doi.org/10.1016/j.geomorph.2014.07.023, 2014.

Kosmas, C., Gerontidis, S., Marathianou, M., Detsis, B., Zafiriou, T., Nan Muysen, W., Govers, G., Quine, T., and Vanoost, K.: The effects of tillage displaced soil on soil properties and wheat biomass, Soil and Tillage Research, 58, 31-44, doi: 10.1016/S0167-1987(00)00175-6, 2001.

Kuhn, N. J., Hoffmann, T., Schwanghart, W., and Dotterweich, M.: Agricultural soil erosion and global carbon cycle: controversy over?, Earth Surface Processes and Landforms, 34, 1033-1038, 2009.

Lal~~,~~., R.: Soil erosion and the global carbon budget, Environ. Int., 29, 437-450, 2003.

~~Lal, R.: Soil carbon sequestration impacts on global climate change and food security, Science, 304, 1623-1627, 2004.~~

Larney, F. J., Li, L., Janzen, H. H., Angers, D. A., Olson, B. M., and Zvomuya, F.: Soil quality attributes, soil resilience, and legacy effects following topsoil removal and one-time amendments, Canadian Journal of Soil Science, 96, 177-190, 10.1139/cjss-2015-0089, 2016.

Liu, S., Bliss, N., Sundquist, E., and Huntington, T. G.: Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition, Global Biogeochem. Cycles, 17, 1074,~~ doi:~~ 10.1029/2002gb002010, 2003.

Lugato E., Paustian K., Panagos P., Jones A. and Borelli P.: Quantifying the erosion effect on current carbon budget of European agricultural soils at high spatial resolution, Global Change Biology, 22(5), 1976-1984, doi: 10.1111/gcb.13198, 2016.

Manies, K.L., Harden, J.W., Kramer, L. and Parton, W.J.: Carbon dynamics within agricultural and native sites in the loess region of western Iowa. Global Change Biology, 7(5): 545-555, 2001.

Meersmans, J., Van Wesemael, B., De Ridder, F., Fallas Dotti, M., De Baets, S., and Van Molle, M.: Changes in organic carbon distribution with depth in agricultural soils in northern Belgium, 1960â�“2006, Global Change Biology, 15, 2739-2750, 10.1111/j.1365-2486.2009.01855.x, 2009.

~~Minasny, B., Finke, P., Stockmann, U., Vanwalleghem, T., and McBratney, A. B.: Resolving the integral connection between pedogenesis and landscape evolution, Earth-Science Reviews, 150, 102-120, 10.1016/j.earscirev.2015.07.004, 2015.~~

Montgomery, D. R.: Soil erosion and agricultural sustainability, Proceedings of the National Academy of Sciences of the United States of America, 104, 13268-13272, DOI 10.1073/pnas.0611508104, 2007.

Nadeu, E., Gobin, A., Fiener, P., van Wesemael, B., and van Oost, K.: Modelling the impact of agricultural management on soil carbon stocks at the regional scale: the role of lateral fluxes, Global Change Biology, n/a-n/a, 10.1111/gcb.12889, 2015.

Naipal., V., Ciais, P., Wang, Y., Lauerwald, R., Guenet, B., and Van Oost, K.: Global soil organic carbon removal by water erosion under climate change and land use change during 1850-2005 AD, Biogeosciences Discussions, 1-33, 10.5194/bg-2017-527, 2018.

PARTON, W. J.: The CENTURY model., *Evaluation of soil organic matter models*. Springer, Berlin, Heidelberg, p. 283-291, 1996.

Quine, T. A., and Zhang, Y.: An investigation of spatial variation in soil erosion, soil properties, and crop production within an agricultural field in Devon, United Kingdom, Journal of Soil and Water Conservation, 57, 55-65, 2002.

~~Quinton, J. N., Govers, G., Van Oost, K., and Bardgett, R. D.: The impact of agricultural soil erosion on biogeochemical cycling, Nature Geosci, 3, 311-314, http://www.nature.com/ngeo/journal/v3/n5/suppinfo/ngeo838_S1.html, 2010.~~

Ritchie, J. C., and McHenry, J. R.: Application of Radioactive Fallout Cesium-137 for Measuring Soil Erosion and Sediment Accumulation Rates and Patterns: A Review, Journal of Environmental Quality, 19, 215-233, 10.2134/jeq1990.00472425001900020006x, 1990.

Ritchie, J. C., McCarty, G. W., Venteris, E. R., and Kaspar, T. C.: Soil and soil organic carbon redistribution on the landscape, Geomorphology, 89, 163-171, 2007.

Rosenbloom, N.A., Harden, J.W., Neff, J.C. and Schimel, D.S.:Geomorphic control of landscape carbon accumulation. Journal of Geophysical Research-Biogeosciences, 111(G1): G01004, 2006.

Stallard, R. F.: Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial~~,~~., Global Biogeochem. Cycles, 12, 231-257, 1998.

~~Starr, G. C., Lal, R., Malone, R., Hothem, D., Owens, L., and Kimble, J.: Modeling soil carbon transported by water erosion processes, Land Degradation & Development, 11, 83-91, 2000.~~

Van Oost, K., Govers, G., Quine, T. A., Heckrath, G., Olesen, J. E., De Gryze, S., and Merckx, R.: Landscape-scale modeling of carbon cycling under the impact of soil redistribution: The role of tillage erosion, Global Biogeochem. Cycles, 19, doi: 10.1029/2005gb002471, 2005a.

Van Oost, K., Van Muysen, W., Govers, G., Deckers, J., and Quine, T. A.: From water to tillage erosion dominated landform evolution, Geomorphology, 72, 193-203, 2005b.

Van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W., Heckrath, G., Kosmas, C., Giraldez, J. V., da Silva, J. R., and Merckx, R.: The impact of agricultural soil erosion on the global carbon cycle, Science, 318, 626-629, 10.1126/science.1145724, 2007a.

Van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W., Heckrath, G., Kosmas, C., Giraldez, J. V., da Silva, J. R. M., and Merckx, R.: The impact of agricultural soil erosion on the global carbon cycle, Science, 318, 626-629, 2007b.

Vanacker, V., Bellin, N., Molina, A., and Kubik, P. W.: Erosion regulation as a function of human disturbances to vegetation cover: a conceptual model, Landscape Ecology, 29, 293-309, 10.1007/s10980-013-9956-z, 2013.

Vanwalleghem, T., Stockmann, U., Minasny, B. and McBratney, A.B.: A quantitative model for integrating landscape evolution and soil formation. Journal of Geophysical Research: Earth Surface, 118(2): 331-347, 2013.

Wang, X., Cammeraat, E. L. H., Cerli, C., and Kalbitz, K.: Soil aggregation and the stabilization of organic carbon as affected by erosion and deposition, Soil Biology and Biochemistry, 72, 55-65, http://dx.doi.org/10.1016/j.soilbio.2014.01.018, ~~2014a~~2014.

Wang, Z., ~~Van Oost, K., Lang, A., Quine~~Hoffmann, T., ~~Clymans, W., Merckx, R., Notebaert, B., and~~ Six, J., Kaplan, J. O., Govers, G~~.: The fate~~., Doetterl, S., and Van Oost, K.: Human-induced erosion has offset one-third of ~~buried~~carbon emissions from land cover change, Nature Climate Change, 7, 345-349, 10.1038/nclimate3263, 2017.

Wilken, F., Sommer, M., Van Oost, K., Bens, O. and Fiener, P.: Process-oriented modelling to identify main drivers of erosion-induced carbon fluxes. Soil, 3(2): 83-94, 2017.

Yoo, K., Amundson, R., Heimsath, A.M. and Dietrich, W.E.: Spatial patterns of soil organic carbon ~~in colluvial soils: a long-term perspective, Biogeosciences, 11, 873-883, 10.5194/bg-11-873-2014, 2014b.~~on hillslopes: Integrating geomorphic processes and the biological C cycle. Geoderma, 130(1-2): 47-65, 2006.