Reply to Reviewer 1

Summary:
This study investigates the effect of simulated bioturbation by wild boar on forest soil carbon stocks and on soil C stability. Bioturbation was simulated by artificial soil disturbance down to the mineral soil. Total soil carbon stocks did not change after six years of regular soil disturbance. However, a major part of the litter layer carbon was incorporated into the mineral soil due to bioturbation. Accordingly, litter layer carbon stocks decreased and mineral soil carbon stocks increased following bioturbation. Moreover, mineral-associated carbon increased due to soil disturbance. The authors suggest that mineral soils were not carbon saturated and have an unused capacity to stabilize and store more carbon. In conclusion, the authors claim that wild boar bioturbation may enhance (speed up) carbon stabilization in the mineral soil.

General comments:
Overall, I think this is a very nice study. Wild boar populations are increasing across Europe and their effects on soil carbon dynamics are still not fully understood. The manuscript is well written, the study design and measurements are sound and the results are interpreted in a good way. However, I have a number of concerns regarding the sampling procedure, the statistical analysis, and some of the figures. Please, find my specific comments in the following. I think after a revision the manuscript will make a valuable contribution to the research field and should be considered for publication in Biogeosciences.

Specific comments:
Title:
In my opinion, it should be added to the title that wild boar bioturbation was actually simulated.
Reply: We agree and changed the title accordingly. However, please keep in mind that bioturbation comprise reworking of soils by any creatures (including humans) and plants. Thus, we always changed “wild boar bioturbation” into “simulated wild boar bioturbation”. However, the term “bioturbation” was not always changed into “simulated bioturbation”.

Abstract:
P 1, L 7: Please rephrase ‘can help’.
Reply: Rephrased accordingly to “can facilitate the incorporation of litter-derived carbon”

P 1, L 9: Add that wild boar bioturbation was simulated.
Reply: We added that bioturbation was simulated

P 1, L 17: Please rephrase ‘can help’.
Reply: Rephrased to “Wild boar may speed up this process with their grubbing activity.”

Introduction:
P 1, L 30: I suggest either to replace ‘the main process’ by ‘a major process’ or to add an appropriate reference to that statement.

Reply: We changed this accordingly

P 3, L 2: Please add the references of the studies which have investigated wild boar effects on soil carbon stocks.
Reply: We added the references to Wirthner, 2011 and Mohr and Topp, 2001 here.

P 3, L 11: Add that the effects of 'simulated' wild boar grubbing were investigated.

Reply: "Simulated" was added.

Materials and Methods
P 3, L 16, 17: I think there should be an 'a' before mean annual temperature and moisture.
Reply: Was added accordingly.

P 4, L 14-19: It took me a while to understand the idea behind mass equivalent sampling, and why you applied it in this study. However, I'm still not sure if I properly understand it and I'm therefore a bit concerned if this procedure might affect the results. By sampling the same amount of soil per horizon and pit, I have the feeling you could underestimate potential C losses from bioturbation. For example, in the theoretical case, 50% of the LF horizon organic matter stocks would have been mineralized due to bioturbation, this sampling procedure would artificially 'refill' the missing amount of organic matter with organic matter from the next horizon (i.e. O horizon). Now, the O horizon is (artificially) smaller, but will be 'refilled' with soil from the next layer, and so on. At some point, material from a deeper layer which has not been sampled at the reference plot would be sampled to 'refill' the missing amount of organic matter. Thus, the actual amount of lost C would be underestimated. I might be completely wrong, but then I suggest to elaborate more in detail on the sampling procedure.

Reply: We agree that the sampling procedure is not easy to understand. Therefore, we included the figure for illustration and we revised this paragraph where necessary to make more clear. However, the general concept was developed by Ellert and Bettany 1995 and before also by Jenkinson (see also Wendt and Hauser 2013, EJSS). In most cases it is recommend applying a mass correction to the obtained soil data set. However, sampling directly in a mass corrected way is the preferable method to correct for differences in soil mass. The "refilling" of missing soil mass the reviewer are referring to, is done with subsoil material that is C poor. Thus, the sampling procedure can hardly bias results in a way outlined by the reviewer: If O horizon material (around 500 g/kg Corg) would be lost due to bioturbation, it would be replaced by subsoil material with 2.5 g/kg Corg in an equivalent soil mass sampling. Thus, a 10.00 % loss of O material would result in a 9.95% C-loss with the refilling from subsoil material. This is practically the same C-loss and the error is far below the precision that can be achieved with any soil sampling. We agree, that sampling the soil treatments is never completely without bias but, as explained above, the sampling procedure will not bias the results in a way that our interpretation is not valid anymore. In contrast, the disturbance due to the simulated bioturbation does not allow to recognize any organic layers and thus does not allow classical sampling methods.

P 5, L 1-2: Was there only one composite sample per site, treatment and soil horizon? Please clarify.
Reply: We added that it was one composite sample per site and treatment.

P 5, L 14: Which statistical test did you use? What was you level of significance? How, did you account for nesting within sites? Please clarify.

Reply: We added the missing information (mixed linear model (lme) accounting for site and area as nested random factors (α=0.05))

Results

P 5, L 17: Again, please indicate that bioturbation was simulated (here and elsewhere in the text).

Reply: We added "simulated"

P 5, L 18: Fig. 2a not 2A.

Reply: Was corrected accordingly.

P 5, L 23: In my opinion it is not necessary to show the results of the individual plots. Thus I would suggest to move Fig. 3 to the supplements.

Reply: We agree and shift this figure to a supplement as Fig. S1.

P 6, L 4: Instead of showing the individual plots (Fig. 3) I suggest to add a figure showing the bioturbation effect separate for the forest types.

Reply: As suggested, we added a new figure 3 showing the bioturbation effects for the three forest types.

P 6, L 8-10: This should be part of the discussion.

Reply: We revised this to "This was related to greater thickness of the forest floor and a larger proportion of mineral soil SOC in deciduous and coniferous forest reference plots than in mixed forest plots." and would argue that this is still a result and no interpretation.

P 6, L 14: It is stated earlier that fractions were determined on composite samples only. How did you do statistics on that? Please clarify.

Reply: Statistics was conducted not a site level but taking all sites and both areas into account (see above).

P6, L 15: Clarify that 'treatment effects' were similar among forest types. In the present form I first thought that e.g. POM fractions were similar among forest types.

Reply: We corrected this accordingly.

P 6, L 19: is 'total stocks of MOM' correct? Or should it be MOM fraction? This reads a bit confusing. I would also suggest to refer to Fig. 4a here.

Reply: Thank you for noticing. We rephrased to "MOM fraction" and referred to Fig 4a and 4b.

P 6, L 23-24: Please add the forest floor POM/SOM proportion and stocks to Figure 4.

Reply: A fractionation of SOM into POM and MOM for the forest floor is technically not possible due to the very low fraction of minerals in the forest floor. We will add this in the figure legend. It can be approximated that almost all SOM in the forest floor is POM.

Although this results are included in Fig. 5, I think it would be more clear if you add it to Fig. 4.

Reply: See above.

P 7, L 4: Was there no mineral surface C in the forest floor of the reference plots? Did you measure it? Please clarify.
Reply: The forest floor had a carbon content of almost 50% with is equal to almost pure organic matter. With the applied fractionation procedure it was not possible to fractionate this material with almost no minerals.

Discussion:
P 8, L 30: I guess it should be Fig. 2b not 1b.
Reply: Thank you for noticing. It was corrected.

P 9, L 10: Please cross-check figure reference.
Reply: Thank you for noticing. It was corrected.

Conclusion
P 10, L 16: Please, add that wild boar activity was simulated.
Reply: Was added.

To put your results into a bigger context, I suggest to add some information/thoughts about potential long-term consequences.
Reply: We added the following sentence: "On long-term this may even lead to enhanced SOC stocks due to an increased fraction of stabilised SOC. Soil disturbance with mixing and bioturbation were previously assumed to enhance SOC mineralisation and cause SOC losses. This could not be confirmed in our study and calls for a new perception. Soil mixing with bioturbation or anthropogenic with machinery lead to a more even distribution of SOC in the soil profile and may result in enhanced SOC stocks on long-term."

Figures:
Figure 2: In the case horizons showed significant differences between treatments please indicate that by adding significance stars to the figure.
Reply: We included the information on the significance between the horizons in the figure captions since it is difficult to visualize between the bars: "Significant differences were found in 0-5 cm depth and in the combined forest floor (L+O layer)."

Figure 3: This figure should be moved to the supplements. Instead replace it with a barchart for each forest type. Add significance stars to the figure.
Reply: This figure illustrates the variability between the plots, but we agree and shifted it to the supplement. A new figure with the forest types was added.

Figure 7: In the case horizons showed significant differences between treatments, please indicate that by adding significance stars to the figure. What happened to L+O of the reference plots?

Reply: This figure refers to the MOM-fraction. There was no mineral fraction in the L+O-horizon in the reference plots and therefore this fraction could not be analysed for the reference treatment.

Reply to reviewer 2

General comments:
Axel Don et al. have submitted an original, well written and very interesting draft to BG. They investigated the effect of wild boar bioturbation on soil organic carbon (SOC) dynamics in a 6 year study in two forests of Germany (focusing on coniferous plots in one forest and coniferous + deciduous plots in the second forest), both on acidic and sandy soils.
The experimental design is nice and sound, the authors have manually simulated wild boar bioturbation (each year, which is a high frequency). They discuss in a clear way the advantages and limitations of the chosen design. Yet, I think that in many sentences of the manuscript and also in the draft title, the fact that wild boar were not part of the game should be more clearly stated (see below my specific comment 1 on this topic).
Reply: We very much appreciate all comments and suggestions from the reviewer and took all of them into account. We agree and added “simulated” wherever wild boar bioturbation is mentioned.

SOC dynamics is studied in paired-plots (control vs. bioturbation) by focusing on SOC stocks (using equivalent soil mass for litter + 0-5/5-10/10/15 cm soil layers) and SOC physical fractionation to separate particulate SOC from mineral associated SOC (0-5/5-10 cm soil layers + C content of the mineral fraction of the O layer of bioturbed plots). The results show that SOC stocks were not affected by bioturbation but that the fate of litter SOC was affected by bioturbation: 1/ a part remains in the litter (as litter), 2/ a part is incorporated as particulate/light organic matter in the mineral topsoil layer, 3/ a part remains in the litter layer, but is associated to minerals.
The authors finally state that the part of the litter SOC that has been associated to minerals (in the litter layer) has been "stabilised" by bioturbation. I suggest that this statement on carbon "stabilisation" should be avoided. We indeed lack evidences regarding the residence time of mineral-associated SOC above the topsoil (i.e. in the litter layer; see below my specific comment 2 on this topic).
Reply: See reply below.

Specific comments:
1/ Wild boars were not involved in this study :)
I suggest to state more clearly in the title and in the text that bioturbation by wild boar was simulated. - "Simulated wild boar bioturbation..." for the title. - in the text this could be done for instance p5 line 17 "[simulated] wild boar bioturbation" and in many other sentences of the draft.
Reply: We agree and added “simulated” wherever wild boar bioturbation is mentioned.

2/ Mineral-associated C in the litter layer (above-ground) cannot be called "stabilised" C
First, I would like to remind that in (mineral) soils, a large part of mineral-associated SOC is not stabilised. This has been clearly shown in e.g. long term bare fallows trials where the fine soil fraction looses SOC at a relatively high rate. So transfering litter SOC to the mineral-associated SOC fraction does not mechanistically imply that all of it has been stabilised. A part of it may be stabilised if this transfer would have taken place in the mineral soil layer (i.e. below the soil surface). Indeed the mean residence time of mineral-associated SOC is generally higher that the one of the particulate organic

matter SOC in mineral soil layers. But here the bioturbation transfer of SOC from litter to
the mineral-associated C fraction occurred in the litter layer (i.e. above the soil surface),
where there is no evidence that this above-ground mineral-associated C would have a
slower turnover than litter C from the F/H O layers. This should be acknowledged in the manuscript.

Reply: We will add in the material and method section to define the term “stabilised” by adding the following sentence: We refer to SOC associated with minerals (MOM) as stabilised SOC since its turnover is slower compared to non-mineral associated POM. “Stabilised” does not mean “inert” but only refers to the fact that organic compounds attached to mineral surfaces are more difficult for microorganisms to use as substrate. There is a large number of studies showing that under different environmental conditions (also in aquatic systems) the mineral association of organic compounds reduces its turnover (e.g. Eusterhues et al. 2003 Organic Geochemistry, Six et al. 2002, Plant and Soil, Kleber et al. 2007 Biogeochemistry, von Lützow et al. 2006, European Journal Soil Science). Bioturbation leads to a complete mixture of organic layer and mineral soil and it is not possible to distinguish both compartments anymore. Moreover, in forests with intensive bioturbation (by earthworm) only temporarily forest floor can be found and litter is incorporated into the mineral soil. This is a similar situation like in the investigated plots with simulated bioturbation. Thus, from an ecological and biogeochemistry point of view there is no reason to assume that attachment of organic compounds will not lead to stabilisation in the sense to decreased turnover.

- The title of the manuscript should be changed, avoiding the confusing term (and not
properly measured for litter layers) "stability". The expression "increases mineral C
loading" should be preferred and would better represent the findings of the study.

Reply: We do not agree that the term “increased mineral C loading” will be more clear and easy to understand compared to “increases the stability of forest soil carbon”. Here we only refer to a gradient change in stability/turnover. Thus, this is not misleading but reflects the fact that more SOC is incorporated into the mineral soil making it less prone to disturbances such as forest fires and also more SOC is mineral associated (see above).

- The title of section 2.2 should be changed. Stability of SOC was not assessed, but
"SOC distribution in physical soil fractions".

Reply: We changed the title accordingly into “Distribution of organic carbon in physical soil fractions”

- The title of section 2.3 should be changed to "Associating C on minerals with bioturbation".

Reply: We propose to delete this heading and include the section into the previous one with an introductory sentence.

- The title of section 3.2 should be changed to "Contact [...] facilitates the association
of litter C with minerals in the litter layer"

Reply: We revised the heading and deleted the word “soil” in order to emphasis the transitional character of the new compartment in which litter layer and mineral soil is mixed together. However, as explained above, we do not see any reason to assume that mineral association of organic carbon does not lead to slower turnover and thus higher C stability. We propose as new heading “Contact between litter layer carbon and minerals facilitates carbon stabilisation”.

- The abstract/conclusion should be re-written: bioturbation has a positive effect on "C

association to minerals" or on "mineral C loading in the litter layer", not on C stability,
we do not know of this C is "more stabilised", it is more linked to minerals, and research
on the turnover of mineral-associated C in the litter layer is therefore needed.
Reply: See reply above.

3/ The effect of wild boar on plant biodiversity and forest ecosystem C cycle is questionable
In the introduction section, the authors insist on the "mainly positive effects in forests" (p2 line 15) of wild boar bioturbation. However, other studies are questioning this statement,
presenting the effect of ungulate populations as :
- "jeopardiz[ing] forest regeneration process"
- "detrimental to the peculiarity of forest plant communities"
- leading to "lanscape-level biotic homogeneization" (see e.g. Boulanger et al., 2017 in Global Change Biology)

If forest regeneration process is actually jeopardized by wild boar invasions, then the
fate of the global ecosystem C stock and cycle is not clear... This should be acknowledged
in the manuscript.
Reply: We acknowledge that the effects of wild boar on biogeochemical processes and forest ecology are not fully understood and may also be negative.
Reply: We agree that studies on wild boar effects are not uniform in their results. Therefore, we included a sentence acknowledging that wild boar may also have negative effects: "However, other studies also found negative wild boar effects on forest regeneration or understory biodiversity (Siemann et al., 2009; Barrios-Garcia and Ballari, 2012)". Since Boulanger et al., 2017 did not find any effect of wild boar on species richness for any vegetation layer, we refrain from citing this paper as example for negative wild boar effects.

4/ No positive grubbing effect on total SOC stocks were found
Please correct this mistake at p8 lines 9-10
Reply: We corrected this and changed it to: "supporting our finding of no SOC loss with bioturbation".

Technical corrections:
p1 l26: "an[d]" ?
Reply: Thank you for noticing. We corrected this.

p5 l17: "due [to] six"
Reply: Thank you for noticing. We corrected this.

p7 l2: "significant[ly]

Reply: Changed accordingly.

p8 l20: please replace "mainly" with "only"
Reply: Changed accordingly.

p9 l16: please reverse "forest floor" and "mineral soil" : "mineral soil" : mineral soil mixed into the
forest floor almost doubled the C load (not the opposite)
Reply: Changed accordingly.

~~Bioturbation by~~Simulated wild boar bioturbation increases the stability of forest soil carbon

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Abstract. Most forest soils are characterised by a steep carbon gradient from the forest floor to the mineral soil, indicating that carbon is prevented from entry into the soil. Bioturbation can ~~help incorporate~~facilitate the incorporation of litter-derived carbon into the mineral soil. Wild boar are effective at mixing and grubbing in the soil and wild boar populations are increasing in many parts of the world. In a six-year field study, we investigated the effect of simulated wild boar bioturbation on the stocks and stability of soil organic carbon in two forest areas. Regular bioturbation mimicking grubbing by wild boar was performed artificially in 23 plots and the organic layer and mineral soil down to 15 cm depth were then sampled. No significant changes in soil organic carbon stocks were detected in the bioturbation plots compared with non-disturbed reference plots. However, around 50% of forest floor carbon was transferred with bioturbation to mineral soil carbon and the stock of stabilised mineral-associated carbon increased by 28%. Thus, a large proportion of the labile carbon in the forest floor was transformed into more stable carbon. Carbon saturation of mineral surfaces was not detected, but carbon loading per unit mineral surface increased by on average 66% in the forest floor due to bioturbation. This indicates that mineral forest soils have non-used capacity to stabilise and store carbon. Transfer of aboveground litter into the mineral soil is the only rate-limiting process. Wild boar ~~can help to~~may speed up this process with their grubbing activity.

1 Introduction

The stability of soil organic carbon (SOC) strongly depends on its association with soil minerals (Lehmann and Kleber, 2015; von Lützow et al., 2006). Organic carbon (C) that enters forest soil as aboveground litter is retained in an organic layer, with little opportunity for long-term stabilisation. Carbon in the organic layer is vulnerable to disturbances such as wildfire, windthrow or forest clear-cutting, since it is present in non-stabilised organic matter and exposed at the soil surface (Zakharova et al., 2014; Jandl et al., 2007). The organic layer in German forests stores on average 19 Mg C ha-1, which may reduce the available amount of SOC that enters the mineral soil below ~~an~~and can be stabilised (Grüneberg et al., 2014). Translocation of organic layer C into the mineral soil is necessary for its stabilisation, but incorporation of dissolved organic matter (DOM) and particulate organic matter (POM) from the forest floor into the mineral soil is slow, as demonstrated by studies using isotope techniques (Fröberg et al., 2007a;Hagedorn et al., 2004;Arai et al., 2007). Besides downward movement of dissolved organic matter, bioturbation is ~~the main~~a major process that brings organic matter from the forest floor into the mineral soil. Bioturbation by earthworms has been found to be very effective in translocating litter C from the surface to mineral soil (Don et al., 2008). The invasion of European earthworms into some North American forests has led to complete disappearance of the forest floor due to bioturbation, but most of this forest floor C was found in the underlying mineral soil (Alban and Berry, 1994). Most earthworms are restricted to non-sandy, non-acidic soils (Curry, 2004), while bioturbation by other animals such as termites, small rodents and ants can be found in many soils irrespective of soil texture (Wilkinson et al., 2009). However, wild boar (*Sus scrofa*), also called feral pigs or wild pigs, are most important for bioturbation in forests. This species is native to Eurasia, but has dispersed over all continents except Antarctica due to its adaptability, high reproduction rate and secretive nature (Barrios-Garcia and Ballari, 2012). Wild boar is thus one of the most widely distributed species of mammal in the world. After almost becoming completely extinct in many parts of Europe, such as Great Britain, Scandinavia, Russia and large parts of Germany, by the beginning of the 20th century, wild boar populations have experienced a tremendous increase globally in recent decades, re-invading large parts of their former territory and beyond. The number of hunted wild boars has increased by over 10-fold in Germany, from 50 000 animals in 1950 to more than 600 000 animals today (Arnold et al., 2015). The wild boar populations in France, Italy, Eastern Europe, North America and Asia are also increasing, most likely due to climate warming and changes in agricultural management providing more food, high reproduction rates and adaptation to a wide variety of habitats (Geisser and Reyer, 2005). Moreover, increased frequency of fructification of deciduous forest trees, such as beech and oak, has helped to increase food availability for wild boars and insufficient game management (Servanty et al., 2009). Wild boar can negatively affect agricultural land by destroying grassland vegetation cover and feeding on crops such as maize. In contrast, wild boar may have many positive effects in forests, e.g. by encouraging natural regeneration of trees that require mineral soils for germination (Bruinderink and Hazebroek, 1996), enhancing tree growth by grubbing (Lacki and Lancia, 1986), spreading plant seeds and fungi (zoochory), suppressing some pest (invertebrate) species and removing carrion. However, other studies also found negative wild boar effects on forest regeneration or understory biodiversity tbilised

(Siemann et al., 2009;Barrios-Garcia and Ballari, 2012). The vast majority of ecological studies on wild boar agree on the significant impact of the species on plant and animal communities and the ecosystem. However, there is a surprising lack of quantitative data on the environmental impact of wild boar (Massei and Genov, 2004).

Wild boar are effective soil disturbers, since they can easily rifle with their snout to 5 to 15 cm depth in the soil, an activity called grubbing or rooting (Kotanen, 1995). Thus, the forest floor becomes mixed with the mineral soil (Singer et al., 1984). Wild boar are omnivorous and obtain a considerable proportion of their diet by grubbing in the soil, seeking for food such as acorns or other fruits from forest trees, bulbs, annelids, molluscs and mushrooms. However, soil disturbance through bioturbation or tillage is reported to cause SOC losses via enhanced organic matter mineralisation (Franzluebbers, 1999; Kristensen et al., 2000). By breaking up aggregates and aerating the soil, microbial SOC turnover may be stimulated. Disturbance by tillage of native sward in North American prairie grassland causes rapid SOC loss (Mann, 1986). Soil disturbance by bioturbation through wild boar grubbing may have a significant impact on SOC and nutrient cycling in forest ecosystems, since in temperate forests most nutrients and SOC are stored in the forest floor and the upper mineral soil (Wirthner, 2011). However, the impact of these large mammals on forest SOC and nutrient cycling and stocks has largely been neglected. Disturbance by tillage, harvesting, storm damage, fire, drought or insects is frequently mentioned in forest soil inventories and studied (Overby et al., 2003; Nave et al., 2010), but wild boar disturbance is generally not reported (Schulp et al., 2008). While numerous studies demonstrated the influence of forest management and disturbances on SOC stocks, such as tree species selection (Vesterdal et al., 2013), thinning (Jurgensen et al., 2012), harvesting (Nave et al., 2010) and liming (Melvin et al., 2013), wild boar disturbance effects have rarely been investigated~~.~~ (Wirthner, 2011, Mohr and Topp, 2001).

Mixing of soil horizons and incorporation of energy-rich organic material into the mineral soil can stimulate microbial activity and respiration, and therefore may enhance decomposition (Mallik and Hu, 1997; Risch et al., 2010). Thus, the labile organic C of the forest floor may be lost with invasion and further expansion of wild boar populations, with negative consequences for forest SOC stocks and side-effects for the global C cycle and climate change. Detection of wild boar effects on SOC is difficult, due to the large inherent spatial variability of forest floor and mineral soil SOC stocks and the additional variability caused by wild boar grubbing (Wirthner, 2011). A dedicated experimental design and sufficiently large samples are required to quantify changes in SOC due to bioturbation. In addition, reference sites that have definitely never been grubbed by wild boar in the past are required. The aim of this study was to quantify the effect of simulated wild boar bioturbation on SOC stocks and the degree of stabilisation of SOC in coniferous and deciduous forests. The consequences of wild boar grubbing on organic matter stocks in forests were quantified.

2 Material and Methods

~~1~~2.2 Study sites

Two study areas were selected and a total of 24 research plots scattered within these areas were established. The first area is located 3 km north-west of the city of Braunschweig (coordinates: 52°17’N, 10°26’E), in a region with a mean annual temperature of 8.8°C and a mean annual precipitation of 620 mm. The soil is this area is a Lamellic Luvisol developed on periglacial loess and sand deposits with a moder organic layer. The forest in the area is diverse, comprising deciduous forest dominated by beech and oak, coniferous forest dominated by spruce and Douglas fir and mixed forest. The second area is located close to the city of Eberswalde, around 50 km north-east of Berlin (52°52’N, 13°49’E). Mean annual temperature in this area is 8.9°C and mean annual precipitation is only 520 mm. The soil is a Dystric Cambisol derived from Pleistocene sand deposits with a moder organic layer. The forests in this area are pure pine. Both study areas were fenced in order to exclude wild boar and these fences were successful throughout the study period in the Eberswalde area and in the early part of the period in the Braunschweig area, where wild boar have recently invaded the forests. However, regular inspection revealed no impact or disturbance by wild boar in the study plots.

~~1.3 Research~~2.3 Treatments at the research plots

In the Braunschweig area, 18 study plots (six in deciduous forest, six in mixed forest and six in coniferous forest) were established and marked in early spring 2011. Due to a windthrow event, one coniferous plot was lost. At the same time, six research plots, all in coniferous forest, were established in the Eberswalde area. The plots at both sites consisted of two subplots, each measuring 2 m by 4 m, located directly adjacent to each other and positioned at sufficient distance from trees or other objects, such as ditches or the forest edge that could influence the forest floor or soil. One subplot was used to simulate bioturbation by wild boars, using poles with one end shaped to represent a wild boar tusk (hoes were also used in Eberswalde plots due to very dense grass sward). This bioturbation activity was conducted manually by 2-3 people, who plunged the tool through the forest floor and the upper mineral soil for 10-20 minutes per plot, to mimic the action of wild boar tusks. The resulting bioturbation pattern was random and the results very visually similar to forest soil patches disturbed by wild boar. With this treatment we mimicked bioturbation by wild boar but not removal of material on which wild boar are feeding on. Also the admixture of dung from wild boar is not included. This allows distinguishing the bioturbation effect from other effects of wild boar grubbing. The bioturbation treatment was performed once per year, always in spring, for a period of six years, in order to examine longer-term effects of bioturbation on forest soils. The second subplot in each plot was left undisturbed and served as a reference plot.

~~1~~2.4 Soil sampling

Soil sampling was conducted in late summer 2016 in both areas. In order to obtain representative soil material, very large samples were collected, using a 25 cm x 25 cm metal frame, with three replicates per subplot (only two replicates in the Eberswalde area, since all six plots were in close proximity). In the reference subplots, two organic layers of the forest floor (L-layer and O-layer) and three depth increments in the mineral soil (0-5 cm, 5-10 cm, 10-15 cm) were sampled. In order to make the sampling in the disturbed plots comparable in those plots, we sampled mass equivalent as proposed by Ellert and Bettany (1995) (Fig. 1). For each plot, we used the mean weight of the three replicates of the organic layer (combined sample L- and O-layers) and the three mineral soil depth increments determined in the field in order to sample equal masses (Fig. 1). By sampling equal masses instead of equal depth increments, we accounted directly for the changes in bulk density due to wild boar grubbing. We assumed that the moisture content was similar in the reference plot and the disturbed plot, but corrected deviations from this assumption afterwards in the dataset in order to calculate mass-corrected SOC stocks based on dry matter. The sampling of forest floor layers and mineral soil from the same spot (metal frame) ensures that deviations in separation of forest floor and mineral soil do not affect estimates of total SOC stocks (Don et al., 2012). In total, 567 samples were obtained, with a mean weight per sample of 3.8 kg for the mineral soil and 0.6 kg for the organic layer samples (Fig. 1).

~~1~~2.5 Sample preparation and analysis

All samples were dried at 60°C and organic layer samples were cut (<1 mm) and homogenised in an electric mill. Mineral soil samples were sieved through a 2-mm mesh and a subsample was finely milled for further analysis. For each sample, dry fine soil mass was determined gravimetrically and the C and nitrogen (N) concentration was measured using dry combustion (TrueMac, Leco, USA). Using these parameters, it was possible to calculate SOC stocks according to Poeplau et al. (2017). Inorganic C was not present in any of the samples. For composite samples of all sites in the Braunschweig area and sites 1 and 4 of the Eberswalde area, pH was determined in 1 M KCl solution with a soil:solution ratio of 1:5. Soil texture classes in composite mineral soil samples (5-10 cm depth) were estimated for each plot using the texture-by-feel technique (Vos et al., 2016).

In order to characterise the degree of stabilisation of SOC, density fractionation was performed for one composite mineral soil samples of 0-5 cm depth and 5-10 cm depth derived from a mixture of all field replicates~~.~~ per site and treatment. Using the protocol from Golchin et al. (1995), SOC was divided into three fractions: free particulate organic matter (fPOM), occluded particulate organic matter (oPOM) and mineral-associated organic matter (MOM). In addition, mineral-associated C on minerals mixed into the organic layer by bioturbation was determined, using a similar protocol. In brief, 4 g (0-5 cm depth samples) or 13 g (5-10 cm depth samples) of soil were suspended in a 1.6 g cm^{-3} polytungstate solution (soil:solution ratio 1:10). After ultra-sonication of the samples, minerals were centrifuged and floating particulate organic matter was removed, washed with deionised water and dried at 70°C. We refer to SOC associated with minerals (MOM) as stabilised SOC since its turnover is slower compared to non-mineral associated POM.

~~1~~2.5 Statistical analysis

The recovery rate of soil mass and C content in the fractionation procedure was calculated by adding up the C content of the individual fractions and comparing the total with the original C content at the start of the fractionation.

Statistical analysis was performed using the software R version 3.3.0 (R Core Team, 2016). The differences in SOC stocks were analysed using mixed linear models (package nlme, function lme) accounting for site and area as nested random factors (α=0.05). Tukey's honest significant difference post-hoc test was applied. Descriptive statistics (including means and standard deviations) were calculated for the C stocks in each area, in plots and in individual layers in each plot, and for the C stock distribution among the different soil fractions.

2 Results

2.1 Soil organic carbon stocks in forest floor and mineral soil after bioturbation

The SOC stocks in the forest floor and the mineral soil (0-15 cm depth) did not change significantly due to six years of the simulated wild boar bioturbation ~~treatment~~ (Fig. ~~2A~~2a). Total C stocks in the forest floor and mineral soil (0-15 cm depth) were 75±10 Mg ha^{-1} (mean ± standard error) in the wild boar plots and 77±9 Mg ha^{-1} in the undisturbed reference plots. However, the proportion of mineral SOC stocks increased by 26 % and, correspondingly, forest floor C stocks decreased by 40 % due to bioturbation. Without bioturbation, 51 % of total SOC (down to 15 cm depth) was stored in the forest floor and 49 % in the mineral soil. With wild boar bioturbation, SOC was redistributed, leaving only 29 % of total C in the forest floor and 71 % in the mineral soil. In 22 out of 23 plots, the mineral SOC stock was increased by bioturbation (Fig. ~~3).~~3 and Fig. S1 in supplemental material). However, the variability of SOC between the different plots was large also within the same region and forest type. The C gradient after bioturbation was less steep, with an average SOC content of 16 % in the organic layer compared with 33-49 % in the organic layers of the non-disturbed reference sites (Fig. 2b). Thus,~~ wild boar~~ mixing of mineral soil into the forest floor decreased the C content in the forest floor but increased the C content in the upper mineral soil. However, the wild boar bioturbation treatment was shallow: Below 5 cm depth,~~ wild boar~~ effects on SOC were minor and no effect could be detected below 10 cm depth. Thus, our sampling was sufficiently deep to capture all ~~wild boar~~ bioturbation effects.

Differences in undisturbed SOC stocks between coniferous, mixed and deciduous forest were small and non-significant, with a difference of +3 %, -5 % and -0.2 %, respectively, compared with the average SOC stocks in all plots. In all three forest types, forest floor C stocks were reduced via bioturbation, by 37 % in coniferous forest, 46 % in mixed forest and 37 % in deciduous forest~~.~~ (Fig. 3). In deciduous and coniferous forest,~~ wild boar~~ bioturbation effect on the forest floor was lower than in mixed forest. This was attributable to greater thickness of the forest floor and a larger proportion of mineral soil SOC in deciduous and coniferous forest reference plots than in mixed forest plots. Overall, the reduction in forest floor C stocks due to wild boar bioturbation treatment was lower in the Eberswalde area (-25 %) than in the Braunschweig area (-45 %). However, changes in mineral soil C were greatest in Eberswalde, with SOC stocks doubling in the 0-5 cm depth layer. Plots in Eberswalde were covered with a grass sward that formed a dense root layer and this resulted in a particularly steep C gradient and prevents the incorporation of aboveground litter into the mineral soil.

2.2 ~~Stability~~Distribution of ~~soil~~organic carbon ~~after~~in physical soil fractions

Simulated bioturbation significantly changed the distribution between forest floor SOC and mineral soil SOC, as described above, and also changed the degree of stabilisation of SOC in the mineral soil. The proportion of particulate organic matter (fPOM and oPOM) increased significantly (p=0.04), from on average 52 to 60 % (Fig. ~~4a).~~4a) in all forest types. This relative increase in POM proportion was higher in the uppermost mineral soil layer (0-5 cm) than at 5-10 cm depth. Differences of the treatment effects between forest types were small and non-significant, with a slightly higher increase in the POM fraction in coniferous ~~reference~~ forests (+59 %) than in mixed and deciduous forests (+45 % and +49 %, respectively~~) in the Braunschweig area.~~).

However, even though the ~~proportion~~fraction of MOM on total ~~stocks of MOM~~SOC decreased with bioturbation, the MOM stocks in the mineral soil did not change (Fig. 4a and 4b). This was due to the absolute increase in mineral soil SOC stocks with bioturbation. This increase in mineral soil SOC stocks (0-10 cm depth) can be attributed mainly to an increase in POM stocks with an increase by 58 % for fPOM and 43 % more oPOM. The MOM stocks did not change significantly in the mineral soil, but increased by 27 % in the total soil due to additional MOM in the forest floor. Minerals were mixed into the forest floor with bioturbation, resulting in a mineral-associated SOC stock of 5 Mg ha^{-1} (Fig. 5). Thus, bioturbation did not cause detectable C-losses but transferred floor C into the mineral soil where it is stored mainly as POM (Fig. 5). Within the six-year study period, we did not detect significant physical stabilisation of this transferred C in the mineral soil.

The quality of SOM, as indicated by the C/N ratio, changed with bioturbation, with decreased C/N ratio in the forest floor (Fig. 6). The ratio decreased from 38 to 28 in coniferous forest (average for total forest floor), from 31 to 23 in deciduous forest and from 34 to 22 in mixed forest, indicating a higher fraction of transformed SOM in the disturbed forest floor. Mineral soil C/N ratio was only slightly affected by bioturbation (Fig. 6). This is in contrast to the large shift in fractions in the mineral soil, with a doubling of POM stocks.

~~2.3 Stabilising carbon on minerals with bioturbation~~

~~We found no significant additional adsorption of SOC on mineral surfaces due to bioturbation in the mineral soil, but there was significant adsorption in the forest floor. Minerals mixed into the forest floor in the Braunschweig plots were enhanced with C by 76% after bioturbation, from 24.2 g kg^{-1} in the reference upper mineral soil to 42.7 g C kg^{-1} in the forest floor (Fig. 7). The increase was lower in the Eberswalde plots, with 29 % more C in the heavy fraction of the forest floor material. mineral soil C were greatest in Eberswalde, with SOC stocks doubling in the 0-5 cm depth layer. Plots in Eberswalde were covered with a grass sward that formed a dense root layer and this resulted in a particularly steep C gradient and prevents the incorporation of aboveground litter into the mineral soil.~~

~~2.4 Stability of soil carbon after bioturbation~~

~~Bioturbation significantly changed the distribution between forest floor SOC and mineral soil SOC, as described above, and also changed the degree of stabilisation of SOC in the mineral soil. The proportion of particulate organic matter (fPOM and oPOM) increased significantly (p=0.04), from on average 52 to 60 % (Fig. 4a). This relative increase in POM proportion was higher in the uppermost mineral soil layer (0-5 cm) than at 5-10 cm depth. Differences between forest types were small and non-significant, with a slightly higher POM fraction in coniferous reference forests (+59 %) than in mixed and deciduous forests (+45 % and +49 %, respectively) in the Braunschweig area.~~

~~However, even though the proportion of total stocks of MOM decreased with bioturbation, the MOM stocks in the mineral soil did not change (Fig. 4b). This was due to the absolute increase in mineral soil SOC stocks with bioturbation. This increase in mineral soil SOC stocks (0-10 cm depth) can be attributed mainly to an increase in POM stocks with an increase by 58 % for fPOM and 43 % more oPOM. The MOM stocks did not change significantly in the mineral soil, but increased by 27 % in the total soil due to additional MOM in the forest floor. Minerals were mixed into the forest floor with bioturbation, resulting in a mineral-associated SOC stock of 5 Mg ha^{-1} (Fig. 5). Thus, bioturbation did not cause detectable C-losses but transferred floor C into the mineral soil where it is stored mainly as POM (Fig. 5). Within the six-year study period, we did not detect significant physical stabilisation of this transferred C in the mineral soil.~~

~~The quality of SOM, as indicated by the C/N ratio, changed with bioturbation, with decreased C/N ratio in the forest floor (Fig. 6). The ratio decreased from 38 to 28 in coniferous forest (average for total forest floor), from 31 to 23 in deciduous forest and from 34 to 22 in mixed forest, indicating a higher fraction of transformed SOM in the disturbed forest floor. Mineral soil C/N ratio was only slightly affected by~~

~~bioturbation (Fig. 6). This is in contrast to the large shift in fractions in the mineral soil, with a doubling of POM stocks.~~

~~2.5 Stabilising carbon on minerals with bioturbation~~

~~We found significant~~

The sandy texture of the investigated sites restricted the available mineral surfaces for SOC association and stabilisation. However, the amount of SOC per mineral surface area was changed with the simulated bioturbation. We found significantly more adsorption of carbon on mineral surfaces due to bioturbation in the forest floor but no additional of SOC at mineral surfaces in the mineral soil. Minerals mixed into the forest floor in the Braunschweig plots were enhanced with C by 76% after bioturbation, from 24.2 g kg^{-1} in the reference upper mineral soil to 42.7 g C kg^{-1} in the forest floor (Fig. 7). The increase was lower in the Eberswalde plots, with 29 % more C in the heavy fraction of the forest floor material.

3 Discussion

3.1 Disturbance by bioturbation does not reduce SOC stocks

Physical disturbance of soil, e.g. with tillage, is reported to enhance microbial activity and respiration and thus lead to SOC losses (Sapkota, 2012; Franzluebbers, 1999; Kristensen et al., 2000). However, in a six-year study mimicking soil disturbance with wild boar grubbing in different forest types, we found no changes in total SOC stocks due to bioturbation, but detected redistribution of SOC from the forest floor to the mineral soil (Fig. 2). Similar results have been obtained for earthworm bioturbation, e.g. invasion of earthworms into North American forests has been found to cause rapid incorporation of the forest floor into the mineral soil, without considerable SOC losses (Bohlen et al., 2004). In a study re-sampling six soil pits in northern USA hardwood forest (Tennessee/South Carolina) after invasion of wild boar, Singer et al. (1985) found that the forest layer mass was reduced by 60 % but with no change in organic matter content in the A-horizon. However, conclusions on changes in total SOC stocks could not be drawn in that study. Similarly, a Swiss study found that forest floor C was reduced by 40 % due to wild boar grubbing, but that total SOC stocks down to 30 cm depth were not significantly affected (Wirthner, 2011). However, in that study the reference sites may have been grubbed by wild boars some years before sampling, although old grubbing patterns were not detected. A 14% loss of forest floor C has been found in a forest in the Netherlands, but total SOC stocks including the mineral soil are not reported (Schulp et al., 2008). The sampling design and methods in previous studies may not have been suitable for detecting SOC stock changes in disturbed soils. Studies that only report SOC content and no stocks, or only sample the forest floor, cannot be used to follow the fate of SOC after wild boar grubbing (Bruinderink and Hazebroek, 1996; Mohr et al., 2005;Moody and Jones, 2000). Lower SOC content in the forest floor does not necessarily mean that SOC is lost, since mixing mineral soil into the forest floor can decrease SOC content without decreasing forest floor SOC stocks. Missing bulk density data and insufficiently shallow and small-scale sampling may also prevent appropriate conclusions being drawn from existing wild boar studies. The most difficult task, however, is separation of the forest floor from the mineral soil during sampling. Only combined sampling of both forest floor and mineral soil, as conducted in our study, can ensure that SOC stocks are determined correctly (Don et al., 2012).

Our results also seem to contradict findings by Risch et al. (2010), who estimated an additional CO_2 source from Swiss forests due to wild boar grubbing of 50-98 Gg CO_2 per year. However, those values are based on soil respiration flux measurements ~~with several methodological flaws. For example~~that cannot be directly converted into SOC losses, since autotrophic CO_2 respiration could not be separated from heterotrophic respiration~~, higher~~. Higher CO_2 respiration on grubbed plots ~~may easily~~can be explained by the reported higher fine root density in grubbed plots, which was probably a consequence of the reported more dense ground vegetation. Thus, soil respiration measurements alone cannot be used to estimate SOC changes and to calculate the potential climate impact of wild boar grubbing. In an experiment on Hawaii, SOC stocks in the 0-10 cm layer were 12 % higher in plots with wild boars than in plots from which wild boar had been excluded for 7 to 19 years, supporting our finding of ~~positive grubbing effects on total~~no SOC ~~stocks~~loss with bioturbation (Long et al., 2017).

Our results also question the claim that tillage or disturbance causes SOC losses. Tillage in comparison with no tillage always results in incorporation of crop residues into the mineral soil. Thus, all field studies comparing conventional tillage and no tillage report changes in the depth distribution of SOC, but many studies also report no changes in total SOC stocks (Baker et al., 2007; Hermle et al., 2008;Govaerts et al., 2009). Our study showed that organic matter can be mixed and disturbed without C losses. As a consequence, the general effect of soil disturbance on SOC turnover and stocks may have to be re-evaluated. Any possible SOC loss due to enhanced mineralisation after soil disturbance may also be easily compensated for by the additional SOC that is stabilised. Bioturbation~~ by wild boar~~ brings together organic matter (from forest floor) and mineral particles such as phyllosilicates or oxides, which are essential in stabilising organic matter (Marschner et al., 2008;Eusterhues et al., 2003;Kaiser et al., 2002). In the present study, six years of frequent simulated bioturbation increased MOM by 28 %, but mainly in the forest floor (Fig. 5). Conversion of POM to stabilised MOM in the mineral soil may require longer time scales, and was thus not detectable.

The treatment mimicking bioturbation by wild boar ~~mainly~~only affected the upper mineral soil to 10 cm depth, but not below. This is the critical interface, with a large C-gradient between forest floor and mineral soil ranging from on average 33 % in the O-layer to 6 % in the upper mineral soil (Fig. 1b). Thus, C-input with forest aboveground litter becomes trapped in the organic layer and, without bioturbation, there may be no C flux, apart from dissolved organic carbon, into the mineral soil that could contribute to building up SOC stocks (Fröberg et al., 2007b; Arai et al., 2007). The shallow bioturbation caused by wild boar can break up this C-flux barrier between forest floor and mineral soil and facilitate incorporation of aboveground-derived litter into the mineral soil. Consequently, we found that the C-gradient was clearly less steep in the bioturbation plots than in the undisturbed reference plots (Fig. ~~1b~~2b).

3.2 Contact between ~~organic~~litter layer carbon and minerals facilitates ~~soil~~ carbon stabilisation

Mixing forest floor carbon into the mineral soil by wild boar grubbing may enhance SOC stabilisation by adsorption onto mineral surfaces. However, we did not detect an increase in the mineral-associated fraction of SOC in the mineral soil within the six-year study period (Fig. 5). Nevertheless, the minerals mixed into the forest floor adsorbed SOC, building up a new pool of stabilised SOC in the forest floor. Beside wild boar grubbing, more biological activity seems to be required to transform POM into stabilised MOM. The sandy soils with low pH investigated in this study (Table 1) may not provide sufficiently good conditions to facilitate this biological transformation in the given time frame.

Mineral soil is reported to store a limited amount of SOC stabilised as mineral-associated carbon (Six et al., 2002). The capacity of a soil to stabilise SOC largely depends on its mineralogy and texture, with clayey soils being able to store much more SOC in stabilised form due to their larger specific mineral surface area (Hassink et al., 1997). The soils in the present study are characterised by low specific mineral surface area due to their low clay content. In the reference plots, 48% of total SOC was stabilised on mineral surfaces. However, the mineral-associated SOC content almost doubled within a short distance in the mineral soil (from 0-5 to 5-10 cm depth, see Fig. ~~4b~~7), which indicates that, at least below 5 cm depth, the mineral surfaces are not carbon saturated. Thus, for SOC stabilisation the important issue is whether carbon reaches these mineral surfaces, rather than whether mineral surfaces are saturated or not.

The mixing of minerals and forest floor indicates that there is unexploited potential to adsorb and stabilise SOC on mineral surfaces. We found that ~~forest floor~~mineral soil mixed into the ~~mineral soil~~forest floor almost doubled the C load (Fig. 7). Thus after bioturbation, 66 % more SOC per unit mineral surface was stabilised in the forest floor than in the upper mineral soil. This is surprising, since the soil at both study sites is sandy, with low specific surface area. However, in the extreme situation of minerals being surrounded by organic matter in the forest floor, more SOC becomes attached and thus stabilised onto mineral surfaces. Thus, the mineral surfaces seem to be not limiting for SOC stabilisation but sufficient SOC is required in close vicinity to the mineral surfaces. In general, around one-third of the forest floor C was stabilised in the wild boar bioturbation treatment (Fig. 5). This SOC most likely originated from the forest floor and not from the mineral soil, as indicated by higher C/N ratio (18.3) compared with MOM in the mineral soil (C/N ratio 17.8). Moreover, the stock and the CN ratio of MOM in the mineral soil remained unaffected by the bioturbation treatment (C/N ratio 17.8 in reference plots and bioturbation plots).

3.3 Areal extent of grubbing and vegetation feedbacks

The area affected by wild boar grubbing can be extensive, with between 13 and 80 % of the soil surface affected in different forests inhabited by wild boar (Genov, 1981; Howe et al., 1981; Risch et al., 2010). From 27 to 54 % of Swiss deciduous forest area have been found to be disturbed by wild boar (Risch et al., 2010). In a study on a 70 km long forest-agriculture transect in southern Sweden, 1 to 6 % soil was found to be grubbed by wild boar each year, but with large inter-annual variability (Welander, 2000). Similar results have been reported for Californian meadows, with wild boar grubbing an average of 7% of the study area annually (Krotanen 1995). Thus, the bioturbation frequency applied in the present study does not represent the average bioturbation frequency, but wild boar grubbing hotspots. Severely grubbed areas may extend for a hectare or more, but are typically composed of many small patches of a few square metres (Vallentine 1990, Krotanen 1995). Some patches may be preferentially grubbed compared with others, but the evidence on this is inconclusive. However, wild boar seem to prefer deciduous forest and damp soil over coniferous forest and grassland soil and dry soil (Welander, 2000). This is probably due to greater availability of feedstuffs such as acorns and beechnuts in deciduous forests and soil fauna in damp soil. With the global increase in populations of wild boar, forest soils are being increasingly grubbed, so wild boar-disturbed forest soils are now the rule rather than the exception.

The rather detrimental direct effects of wild boar grubbing on forest ground vegetation (e.g. mechanical damage, uprooting) can result in reduced plant cover. However, it is mainly the ground vegetation that is affected, and not the tree layer. In a Swiss study, the height of saplings (< 1 m) and plant species diversity did not differ between grubbed and non-grubbed plots (Wirthner, 2011). In the present study, we found temporarily enhanced ground vegetation at some plots in the Braunschweig area during the first years, with presence of the nitrophilous species Impatience parviflora indicating enhanced nitrogen availability (data not shown). Since all forests investigated were dominated by the tree layer, no significant effects of our wild boar bioturbation treatment on litter input to the soil were expected. Thus, the observed effects of the wild boar bioturbation treatment on SOC are due to the physical disruption, rather than other processes.

~~Areal extent of grubbing and vegetation feedbacks~~

4 Conclusions

Wild boar is an invasive species in many parts of the world~~, following introduction by European settlers or later. Wild boar can negatively affect agricultural land by destroying grassland vegetation cover~~ and ~~feeding on crops such as maize. In contrast,~~their grubbing activities can be extensive. The simulated wild boar ~~may have mainly positive effects in forests, e.g. by encouraging natural regeneration~~disturbance caused a significant redistribution of ~~trees that require mineral soils for germination (Bruinderink and Hazebroek, 1996), enhancing tree growth by grubbing (Lacki and Lancia, 1986), spreading plant seeds and fungi (zoochory), suppressing some pest (invertebrate) species and removing carrion. In addition, we provide~~SOC in the investigated forest plots with decreasing the organic layer. We provided strong experimental evidence of positive effects of a wild boar bioturbation treatment on SOC stability, whereby SOC in the forest floor is retained and transferred into the mineral soil without C-losses. ~~Conversion~~Bioturbation does not cause SOC losses due to ~~mineral soil SOC can contribute~~enhanced mineralisation, but in contrast helped to transform labile SOC into more stabilised SOC. On long-term ~~C storage and improvement~~this may even lead to enhanced SOC stocks due to an increased fraction of ~~soil heath and productivity~~stabilised SOC. Soil disturbance with mixing and bioturbation were previously assumed to enhance SOC mineralisation and cause SOC losses. This could not be confirmed in our study and calls for a new perception. Soil mixing with bioturbation or anthropogenic with machinery lead to a more even distribution of SOC in the soil profile and may result in enhanced SOC stocks on long-term.

Author contributions

AD designed the experiment and AD and EG carried them out. All authors contributed to soil sampling and data interpretation. CH performed most soil analysis and CV performed the statistics. AD prepared the manuscript with contributions from all co-authors.

Acknowledgements

We thank Zohra Afshar, Viridiana Alcántara, Anita Bauer, Frank Hegewald, Angelica Jaconi, Christopher Poeplau, Annelie Säurich, Florian Schneider and Patrick Wordell-Dietrich for support during field sampling and during sample preparation in the laboratory, and Ines Backwinkel from the Central Laboratory of the Thünen Institute of Climate-Smart Agriculture for element analyses.

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Table1: Forest type, soil texture and soil pH in the plots at the Braunschweig (n=17) and Eberswalde (n=6) experimental sites.

Area	Plot no.	Forest type	Soil texture			pH
			Sand (%)	Silt (%)	Clay (%)	
Braunschweig	1	Deciduous	63	33	4	3.3
	2	Coniferous	51	45	4	2.9
	3	Coniferous	31	65	4	3.5
	4	Coniferous	51	45	4	3.2
	5	Mixed	31	65	4	3.1
	6	Deciduous	51	45	4	3.1
	7	Deciduous		NA		NA
	9	Coniferous	51	45	4	2.9
	10	Mixed	51	45	4	3.6
	11	Deciduous	51	45	4	3.1
	12	Coniferous	31	65	4	3.1
	13	Mixed	65	33	4	3.2
	14	Deciduous	51	45	4	3.0
	15	Mixed	31	65	4	3.1
	16	Mixed	51	45	4	3.0
	17	Deciduous	51	45	4	3.6
	18	Mixed	31	65	4	3.0
Eberswalde	1	Coniferous	80	17	3	3.1
	2	Coniferous		NA		NA
	3	Coniferous		NA		NA
	4	Coniferous	92	5	3	3.1
	5	Coniferous		NA		NA
	6	Coniferous		NA		NA

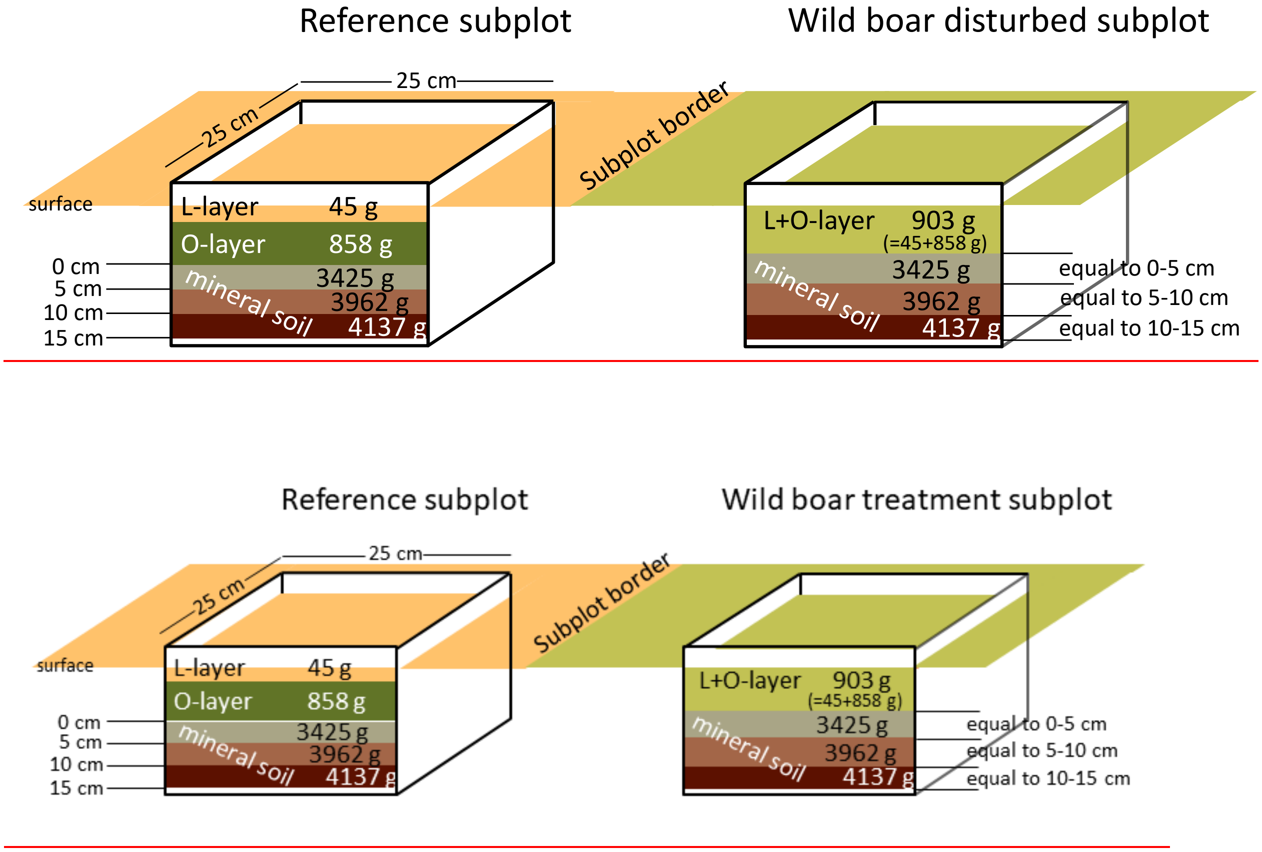


Figure 2: Equal mass sampling of forest floor (L- and O-layer) and mineral soil (0-15 cm depth). Weights refer to the mean weight of the different layers and soil depth increments as obtained in the field.

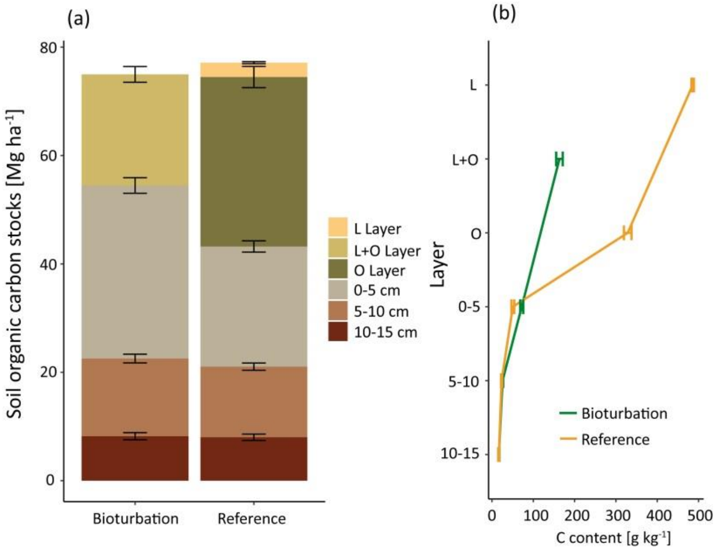
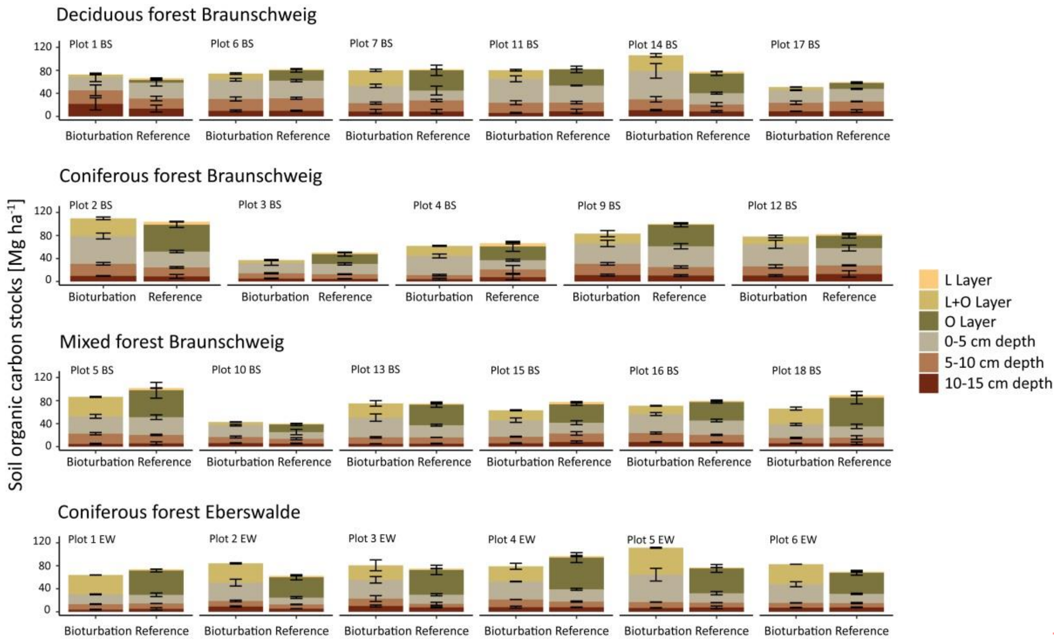


Figure 2: (a) Mean soil organic carbon (SOC) stock [Mg ha^{-1}] distribution ~~and~~, significant differences were found in 0-5 cm depth and in the combined forest floor (L+O layer). (b) SOC content [g kg^{-1}] in different layers and soil depth increments for plots in the treatment mimicking wild boar grubbing (Bioturbation) and in the undisturbed control sub-plots (Reference).



~~**Figure 3: Soil organic carbon (SOC) stocks [Mg ha^{-1}] in different layers in all 23 plots in the experimental areas Braunschweig (BS) and Eberswalde (EW).**~~

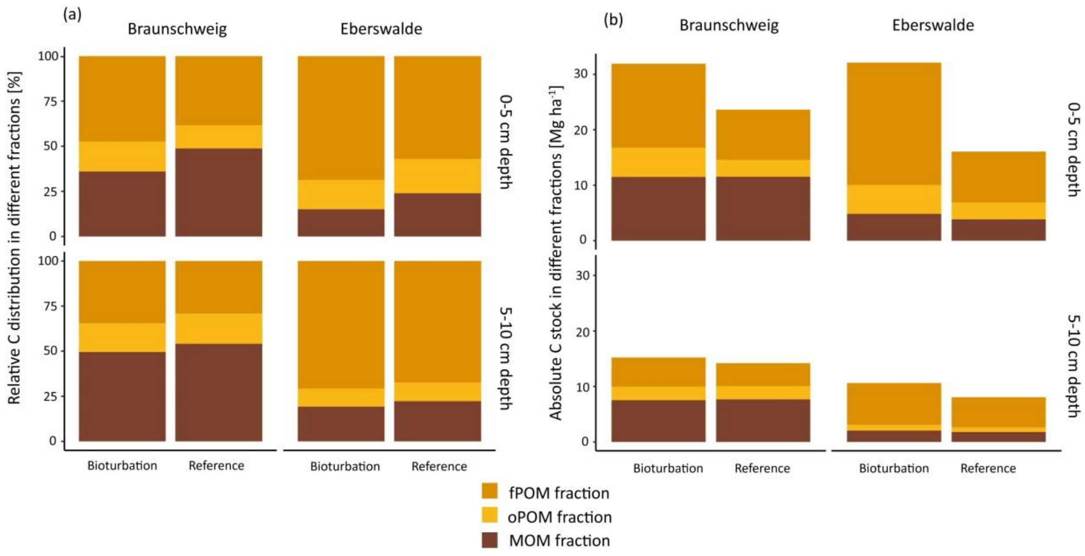
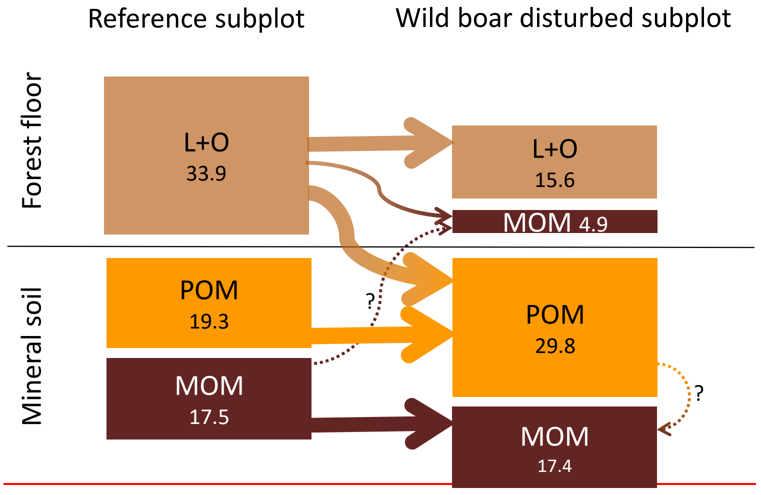


Figure 4: (a) Relative and (b) absolute (b) distribution of soil organic carbon (SOC) fractions in the upper two mineral soil depth layers at the Braunschweig and Eberswalde experimental area after bioturbation and at reference sites. The fractionation procedure was technically not possible to apply for forest floor samples since they consist of almost 100% POM.



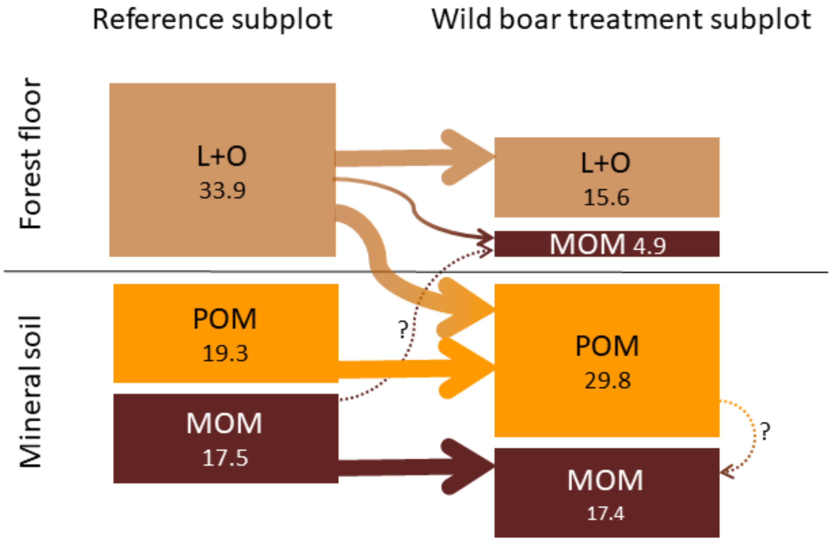


Figure 5: Changes in different soil organic carbon (SOC) pools in the forest floor (L- and O- horizons) and the underlying mineral soil (0-10 cm depth) due to bioturbation. Average carbon stocks for all 23 plots [Mg SOC ha^{-1}]. POM = particulate organic matter, MOM = mineral-associated organic matter.

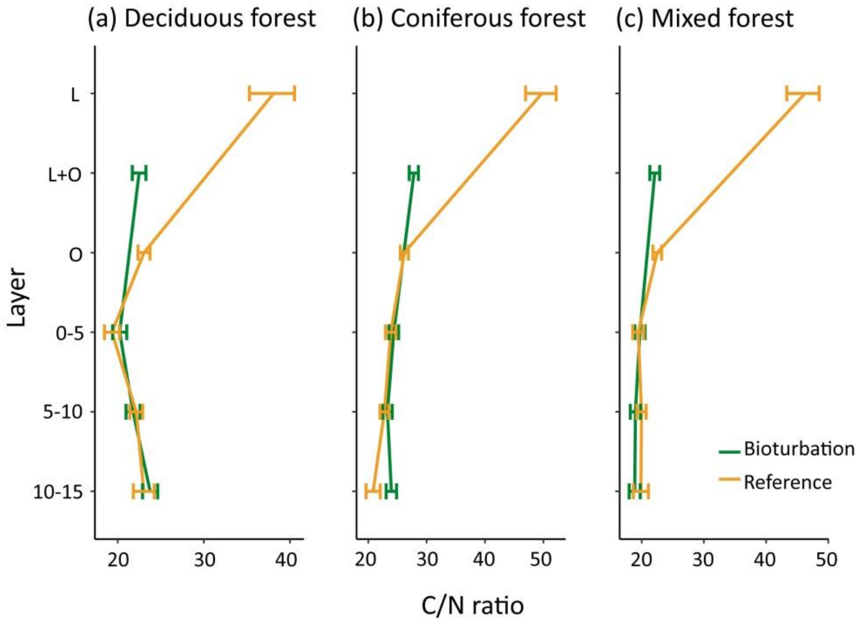


Figure 6: Mean carbon:nitrogen (C/N) ratio of organic matter in different forest floor layers and mineral soil layers in disturbed and reference plots in deciduous (N=6), coniferous (N=11) and mixed forest (N=6). Bars indicate standard error.

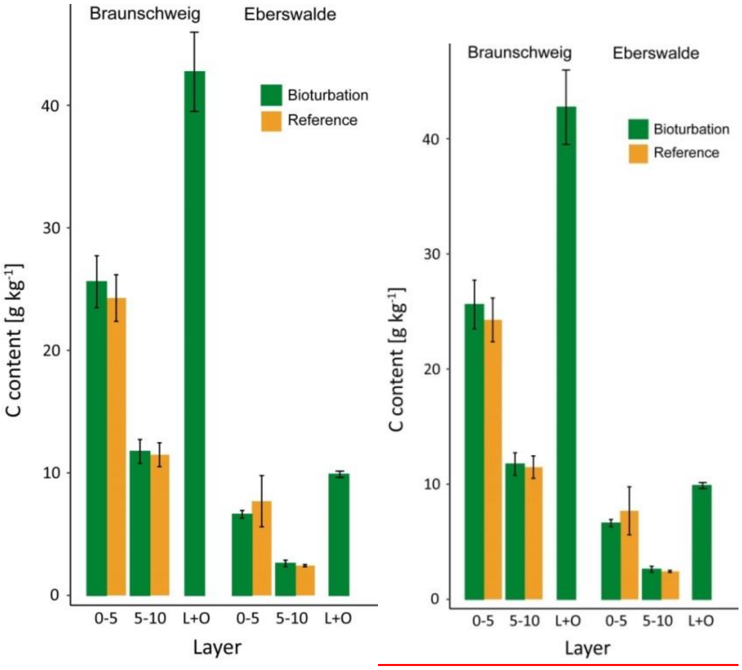


Figure 7: Mean carbon (C) content of the heavy fraction in different soil depth increments at the Braunschweig and Eberswalde experimental areas. Bars denote standard error. The differences found between reference and bioturbation sites were not significant.