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DEEP TILLAGE EFFECTS ON SOIL CARBON STOCKS – EVIDENCE FROM LONG-TERM EXPERIMENTS

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Abstract

In most natural ecosystems, soil carbon is concentrated at the very top of the soil profile and therefore large parts of the soil are not being sufficiently used for carbon storage. Tillage facilitates the translocation of soil organic carbon (SOC) to deeper parts of the soil and thus can enhance soil carbon.

Initial evidence of this came from long-term field observations following deeper tillage in northern Germany. At these sites, the ploughing horizon was extended downwards from 25 cm to 35 cm on average in the 1960s and 70s and was followed by increased SOC stocks. More drastic and deeper tillage (>60 cm depth) is used as a melioration measure to improve the soil's infiltration capacity. Various long-term experiments have shown that deep tillage of this kind increases soil carbon stocks by more than 40 % over the long term. A similar drastic melioration measure is soil flipping of grassland using a digger. Its effect on soil carbon is considerable, increasing total carbon stocks by about 70 % and doubling subsoil carbon stocks. Translocated topsoil carbon appears to be stabilised and preserved in the subsoil, but the reasons for this high stability are still not fully understood.

Additionally, deep tillage decreases the carbon content at the soil surface, which stimulates new C sequestration in the topsoil. After deep ploughing, it takes decades for the topsoil to return to its initial carbon content. Deep tillage turns topsoils into long-term C sinks. Not all soils are suitable for deep tillage and some negative effects of deep tillage on SOC stocks have also been observed (in forests). The results of various long-term experiments indicate that burial of topsoil with tillage can increase total SOC stocks and may thus result in C sequestration.

1. Vertical soil carbon distribution and C sequestration

The distribution of organic carbon (OC) in the soil profile is highly skewed, with a very high OC content in the topsoil and low OC content in the subsoil. This has resulted in more than 50 % of total SOC stocks being stored in the topsoil (Jobbagy & Jackson, 2000). In German agricultural soils, 67 % of total OC stocks are located in topsoils (0-30 cm) (Vos *et al.*, 2019) and only 33 % below a depth of 30 cm (down to 100 cm depth). This unequal distribution of OC is greater in grasslands than in croplands. Thus, large parts of the soil profile in the subsoil are barely being used to store OC. This may be of relevance since SOC stabilisation is mainly *via* adsorption onto mineral surfaces (von Lützow *et al.*, 2006). In subsoils a large proportion of mineral surfaces are OC free and not used for SOC stabilisation. More importantly, environmental conditions in the subsoil reduce OC turnover and thus subsoil preserves OC more effectively than topsoil (Kirschbaum et al., in this conference proceeding). Also mean apparent radiocarbon ages indicate slower OC turnover and high radiocarbon ages with increasing soil depth (Mathieu *et al.*, 2015).

Organic carbon in soils is important for soil fertility, but is also relevant for climate mitigation since globally it is a larger C pool than atmospheric C (as CO_2) and biosphere C (as biomass) combined. Theoretical calculations show that total anthropogenic greenhouse gas emissions could be compensated by an annual increase in the global SOC pool of 4‰. This theoretical concept is the basis of the 4per1000 initiative that was launched in 2015 at COP21 in Paris (Minasny *et al.*, 2017). The 4per1000 initiative promotes the sequestration of SOC for climate mitigation, but at the same time acknowledges SOC's role in soil fertility and thus food security. Climate adaptation can also be achieved with more SOC due to its effects on water storage capacity and infiltration rates for example.

The main obstacle to making better use of subsoils for SOC storage is the slow translocation of OC downwards in the soil profile. Most OC enters the soil *via* leaves and root litter close to the soil surface. Only very small fractions of C input to soil occur at greater depths or are translocated with water leaching or bioturbation. In croplands, the practice of tillage helps to homogenise and distribute OC within the ploughing horizon, but in grasslands tillage is hardly performed at all, which explains the steep OC gradients with soil depth. Full inversion tillage has traditionally been used in Europe for grassland renovation only with possible positive effects on total SOC stocks.

2. Long-term effects of deeper tillage

One way to ensure the input of OC deep into the soil is deeper tillage. In large parts of western Europe deeper tillage was promoted during the 1960s and 70s, leading to a deepening of the ploughing horizon from around 25 cm to around 30 cm today. Field observations before and after the deepening of the ploughing horizon in northern German croplands show that SOC stocks increased by between 2 and 42 % with deeper tillage (Nieder & Richter, 2000).

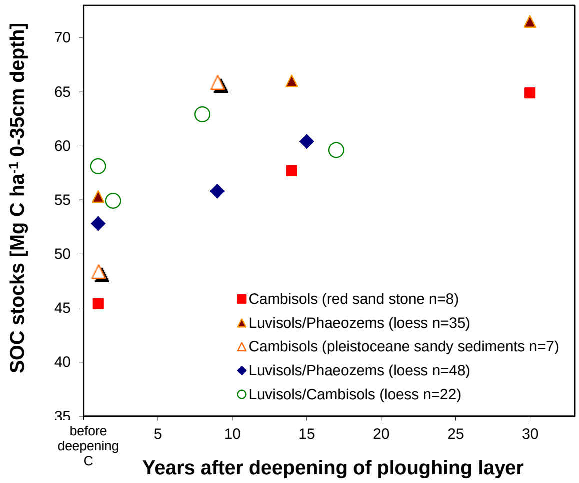

Figure 1: Time series of soil organic carbon (SOC) stocks of five different soil groups after deepening of the ploughing horizon from about 25 cm to about 35 cm depth (Nieder & Richter, 2000)

With deeper tillage the OC content of the ploughing horizons is initially diluted with OC-poor subsoil that is ploughed into the topsoil. However, after a few years, total SOC stocks of the croplands were shown to increase, thus indicating considerable SOC sequestration. However, these results were based on practice field sites and there was no control treatment without deepening of the ploughing horizon. Thus, there might be other reasons for the increased SOC stocks, such as the continuous rise in yield during the same period.

3. Soil carbon increase after deep tillage of croplands

Deep tillage was facilitated by technological developments that started with the invention of the steam engine plough in the 19th century. It was only in the 1940s that tillage deeper than 50 cm was possible in almost all soil types. Deep tillage is defined as a one-time melioration measure to improve soil properties by ploughing deeper than 60 cm depth. This has been done all over the world, particularly on soils with a poor water infiltration capacity due to hard pans. In northern Germany it was particularly popular and today about 10 % of northern German croplands show evidence of deep ploughing. Deep ploughing transfers the topsoil into the subsoil where it is stored as diagonal stripes (Fig. 2).

Deep tillage has long-lasting effects on SOC, with SOC stocks enhanced considerably by on average 43 % in the long term (Alcantara *et al.*, 2016) (Fig. 3). This SOC increase can mainly be attributed to higher subsoil SOC stocks because 43-72 % of the initial SOC was preserved for more than 40 years, assuming no significant C input to these subsoil horizons.

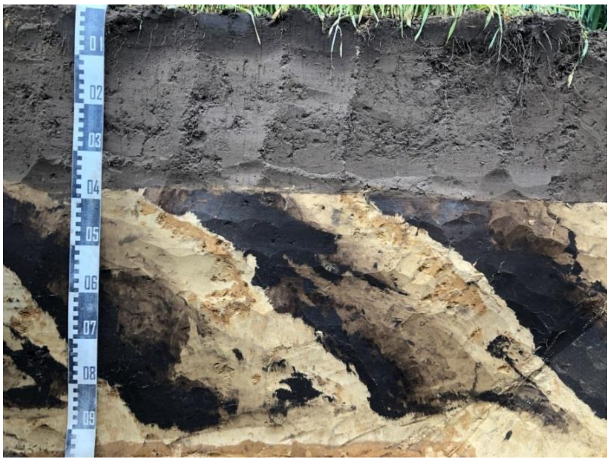

Figure 2: Deep-ploughed sandy cropland in northern Germany 51 years after the deep ploughing event. The diagonal stripes below 35 cm depth are the former topsoil horizons that were translocated into the subsoil with deep ploughing (Essemühle site, Alcantara *et al.* 2016)

A new topsoil that developed after deep ploughing initially had a low OC content since it consisted mainly of OC-poor subsoil material. Surprisingly, the topsoil OC content of deep-ploughed croplands was still 10 to 20 % below that of the reference topsoil that had not been deep ploughed. This shows that SOC accumulation is a long-term process in Central European croplands and may only reach a steady state after many decades, if ever.

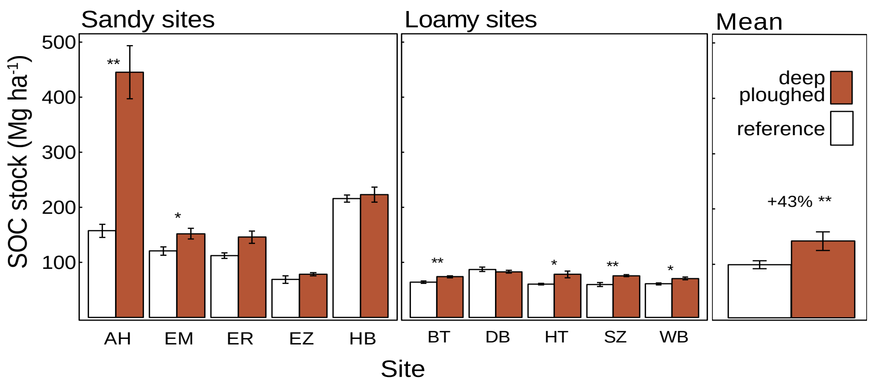

Figure 3: Long-term SOC stock changes due to deep ploughing of sandy and loamy croplands in Germany. Deep ploughing was conducted once on average 45 years before sampling (Alcantara *et al.*, 2016)

In contrast, deep ploughing of forest soils has shown inconsistent effects on SOC stocks. In some deep-ploughed forest soils, OC stocks were even lower than in non-deep-ploughed reference soils (Alcantara *et al.*, 2017). This may be due to a slower C cycling in forests or an absence of nitrogen for organic matter accumulation. Deep ploughing may also have adverse effects on soil structure and fertility. This is particular the case in silty soils that have a vulnerable structure. Thus, deep ploughing for C sequestration can only be recommended if it is conducted under full consideration of the side effects and with the aim of increasing soil fertility and productivity.

4. Deep soil flipping of NZ grassland

In grasslands too, additional OC can be stored with burial of topsoil OC in the subsoil. On the west coast of New Zealand, deep soil flipping of grasslands is performed in order to facilitate better drainage of the soils. This total inversion of the soil profile down to a two-metre depth has been found to significantly increase total SOC stocks by on average 69 % (+179 Mg SOC ha^{-1}) within 20 years of the soil flipping (Schiedung *et al.*, 2019) (Fig. 4).

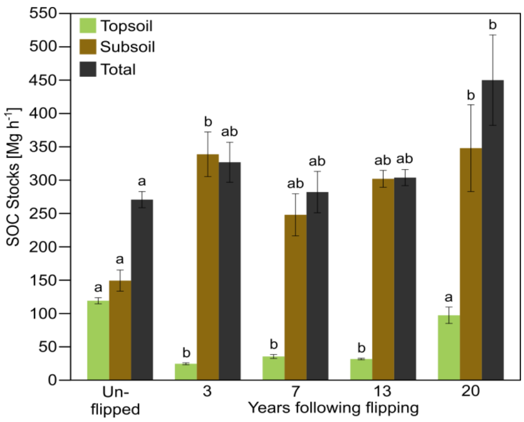

Figure 4: Soil organic carbon stocks in the topsoil (0-30 cm), subsoil (30-150 cm) and total soil (0-150 cm) in a chronosequence of flipped soils on the west coast of New Zealand close to Cape Foulwind (Schiedung *et al.*, 2019)

During this period, continuous OC sequestration was detected in the topsoil with rates of 1.2 to 1.8 Mg C ha^{-1} yr^{-1}. A new topsoil formed with OC stocks similar to the initial OC stocks after 20 years. These grasslands are extremely productive due to high fertilisation rates (>300 kg N yr^{-1}) and high annual precipitation (>2000 mm). Therefore, OC input into the soil from leaves and root litter is high and helps to rapidly build up OC stocks and maintain soil fertility after soil flipping.

The large emissions of methane and other greenhouse gases from these highly productive pasture systems in New Zealand can partly be compensated by C sequestration due to soil flipping. Around 60 years of greenhouse gas emissions can be compensated. Similar to deep ploughing, the soil flipping technique is only recommended for specific soils, *e.g.* hard pans that prevent water infiltration and need to be meliorated.

5. Conclusions

The redistribution of OC in soil profiles by machinery such as ploughs can affect OC turnover and ultimately change SOC stocks. This is in contrast with the traditional perception that tillage enhances microbial activity and OC turnover in soils due to the disruption of aggregates. It is important to acknowledge here that deep tillage is conducted only once or infrequently every 5 to 10 years. For such infrequent tillage events, the positive effect of transferring soil OC deeper into the soil outweighs the possible (mostly unproven) negative effects of tillage. Thus, for selected soils, deeper tillage may be useful for enhancing productivity (on grasslands and croplands) while facilitating C sequestration.

6. Acknowledgments

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