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On-farm soil organic carbon sequestration potentials are dominated by site effects, not by management practices

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ABSTRACT

Although conservation agriculture practices evidently facilitate the build-up of soil organic carbon (SOC), the sequestration potential of arable soils is strongly mediated by edaphic attributes; so far, their interplay is not well understood. Deciphering these drivers is however important to correctly estimate SOC storage potentials in arable soils and to derive effective strategies for the implementation of successful measures. By using an on-farm approach, we conducted a pairwise comparison of 21 conventional and highly innovative 'pioneer' farms across a wide range of arable soil types and evaluated the leverage of site attributes and management practices such as crop diversity, reduced tillage, organic fertilization, cover cropping and inter cropping on the SOC sequestration potential.

While most pioneer management practices proved beneficial for the sequestration of SOC – particularly cover cropping and crop diversity – our results clearly show that soil texture was the most significant shaping factor. Coarse-textured soils had a significantly higher potential for SOC accrual compared to medium- and fine-textured soils. The initial SOC content also had a significant effect on prevalent sequestration potentials. Based on the fact of a clear predominance of natural site conditions over management impacts in enhancing SOC storage of arable soils, we call for a critical discussion of carbon farming schemes. As similar efforts and costs of implementing carbon farming measures will have distinctive carbon gains, dependent on environmental constraints beyond farmers' influence, we advocate for strategies harmonizing both activity- and results-based approaches to maximize the ecological effectiveness and the spatial dissemination of soil health innovations. Carbon farming schemes thus need reconsideration within the state-of-the-art scientific framework of carbon saturation behaviour in order to properly account for biophysical constraints when formulating soil-related climate change mitigation policies.

The sequestration of organic carbon (C) into arable soils is increasingly gaining attention of political and governmental stakeholders due to its potential leverage in removing greenhouse gases from the atmosphere (Amelung et al., 2020; Lal et al., 2018). This seems particularly important in the context of predicted climate change scenarios (Shukla et al., 2019), although several studies illustrated a limited capacity of soil organic C (SOC) sequestration into arable soils to mitigate climate change (Amundson and Biardeau, 2018; Freibauer et al., 2004; Smith et al., 2005). In order to derive effective strategies on an institutional level for the potentially successful sequestration of SOC, we require a better understanding of the factors driving but also impairing SOC storage.

Although the positive effect of single measures such as reduced tillage, diverse crop rotations or cover cropping has been established through long-term experimental observations (Bai et al., 2019; Xiao et al., 2021), studies based on on-farm approaches that evaluate the

Abbreviations: C, Carbon; SOC, Soil Organic Carbon; LMM, Linear Mixed Modeling.

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effectiveness of conservation agriculture practices to sequester SOC in relation to edaphic conditions such as soil texture or the initial SOC content are limited.

Recently, we investigated actual on-farm SOC sequestration potentials based on a pairwise comparison of 21 conventional and highly innovative 'pioneer' farming systems at three soil depths (0–5, 5–20 and 20–35 cm) across a large range of relevant arable soil types in North-Eastern Austria (Rosinger et al., 2022). These pioneer farms have the paramount aim of increasing SOC and improving soil health by applying different combinations of high-level soil conservation practices such as high rotation diversity, multi-species cover crop mixtures, minimum tillage or organic fertilization. Over a mean (conversion) period of 26 years, pioneer farms sequestered an additional 14.3 Mg C ha^{-1} or 15.7% more in the top 35 cm of soil as compared to conventional farming systems. This study further demonstrated that soil texture and physico-chemical attributes shaped the SOC sequestration potential.

In this study, we intersect SOC stocks from our previous study with detailed information on pioneer management routines in order to evaluate the leverage of single conservation agriculture practices to sequester SOC in relation to inherent edaphic properties. Therefore, we conducted comprehensive interviews with the pioneer farmers to obtain detailed information on their management practices from the last six years. In particular, we inquired about their soil tillage, crop rotation, as well as cover and inter cropping regimes, the type and amount of fertilizer they applied (organic fertilizers applied by pioneer farmers were exclusively produced on-farm, with the exception of two arable organic farms using small amounts of externally-produced compost), as well as the year of transition to conservation agriculture management and the first management measures taken (see Supplementary Material 1). Subsequently, we applied linear mixed modeling (LMM) in order to evaluate the effect of site conditions (i.e., soil texture class and the initial SOC content) and agricultural management practices (crop diversity, tillage intensity, organic fertilization, inter cropping, and cover cropping) on the SOC sequestration potential in arable soils (see Supplementary Material 1).

Overall, soil texture was the strongest predictor of SOC stock differences between pioneer and standard farming systems (Table 1). In particular, pioneer farming conducted on coarse-textured soils sequestered significantly more SOC – approximately 35.4 Mg ha^{-1} – than on fine- and medium-textured soils in the top 35 cm (Fig. 1a). Therefore, although fine-textured soils have in general a higher SOC storage capacity (Rosinger et al., 2022; Wiesmeier et al., 2019), SOC stocks in sandy soils are more responsive to a system change towards conservation agriculture. The initial SOC content (Wald Z = 5.562, $p < 0.001$) also had a strong leverage on SOC differences between pioneer and standard farming systems.

Among the tested management variables, cover cropping and crop diversity had a significant effect on SOC sequestration potentials (Table 1), which is well in line with literature (Bai et al., 2019; Garland et al., 2021; Maiga et al., 2019). Furthermore, in a recent on-farm study conducted in Switzerland, Dupla et al. (2022) showed a positive effect of organic matter inputs and cover crop intensity on SOC changes over a 10-year period, while tillage intensity and the SOC:clay ratio were related to a decrease in SOC contents.

Table 1
Type III Tests of Fixed Effects.

Parameter	*Df*	*F-value*	*p-value*
Intercept	1,45	4.463	0.040
Soil texture	2,45	19.725	<0.001
Crop diversity	2,45	6.458	0.003
Tillage intensity	2,45	1.600	0.213
C input	2,45	1.202	0.310
Inter cropping	4,45	1.762	0.153
Cover cropping	5,45	2.884	0.024

AIC: 125.440, BIC: 172.589.

Pioneer farms where cover crops are routinely cultivated could sequester an additional 14.8 Mg ha^{-1} in the top 35 cm of soil as compared to pioneer farms without the application of cover crops (Fig. 1f); this corresponds well with projected SOC stock increases through cover crops over this time period (Poeplau and Don, 2015; Seitz et al., 2022). Highly diverse crop rotations (i.e., 5–6 different crops in the last six years) led to an additional sequestration of 31.3 Mg ha^{-1}, while a low crop diversity (i.e., three different crops in the last six years) actually decreased SOC accrual slightly below levels obtained from standard farming systems. Tillage intensity, inter cropping and C fertilization via organic manures were weak predictors of SOC sequestration potentials within the confines of our dataset ($p > 0.05$). Several *meta*-studies indeed point to a limited/variable role of tillage intensity for SOC sequestration when considered as a sole factor beyond its relation to other system variables such as residue management or cover cropping (Haddaway et al., 2017; Li et al., 2020). The same was true for nitrogen ($F = 0.498$, $p = 0.484$), phosphorus ($F = 1.876$, $p = 0.177$) and potassium ($F = 1.758$, $p = 0.184$) fertilization (see Supplementary Material 2), as revealed by a-priori model selection. While fertilization influences SOC stocks directly via higher C input as well as indirectly via reduced priming (Kirkby et al., 2014), the limited effect in our on-farm study is related to a relatively narrow variation in nutrient inputs with farmers following recommendations according to the prevailing legal framework. Moreover, the time since conversion to conservation agriculture had no significant effect within our dataset ($F = 0.356$, $p = 0.703$; see Supplementary Material 2). This is somewhat surprising, yet could be owed to the large number of soil types sampled in this study and the resulting overarching effect of soil texture: time of SOC stocks to reach a new steady-state after management change is strongly texture dependent, i.e., longer for fine-textured soils and shorter for coarse-textured soils (Sanderman and Baldock, 2010).

Since differently-textured soils do display a distinct SOC saturation (Rosinger et al., 2022; Wiesmeier et al., 2019), storage targets and result-based carbon payment schemes need to be formulated carefully. Clearly, the fact that soil texture is a stronger predictor for SOC sequestration potentials as compared to conservation farming practices is an important finding and points to the need of texture- or soil type-specific targets (e.g. top 10% for a given pedoclimatic condition under a given land-use; Barré et al., 2017) when institutionalizing C sequestration targets (Oldfield et al., 2022). Carbon crediting based on measured SOC stock increases over time will differently reward similar measures with thus similar costs (e.g. diverse cover crops) due to the unavoidable influence of natural site conditions (mainly texture as shown here) beyond farmers' management influence. Furthermore, and in line with the saturation behaviour of SOC (Stewart et al., 2007), our results evidenced the limited SOC accrual with higher initial SOC stock. Beyond site, also carbon management history influences expectable gains; i.e., past achievements, e.g. via long-term implementation of conservation measures, would lead to lower SOC accrual and thus lower returns from carbon trading for first-moving pioneer farmers (COWI, 2021).

From a farmer's perspective, this dependency on texture and management history poses a fairness and equal treatment challenge of result-based carbon farming schemes. A fairness problem, however, could also be claimed from the perspective of buyers of carbon credits (either private or public) for schemes that provide activity-based payments to encourage climate change mitigation or other environmental benefits. In this case, similar funding compensating for implemented management measures would equally reward dissimilar ecosystem services as landholders would receive the same payment irrespective of the actual amount of C sequestered.

This fairness dilemma thus adds additional complexity to other well-known carbon farming challenges such as additionality, permanence, leakage and transparency (Paul et al., 2023). These challenges interlink pedological (e.g. relative change of stable pools to ensure permanence of sequestration, minimum detectable difference or direct leakage through

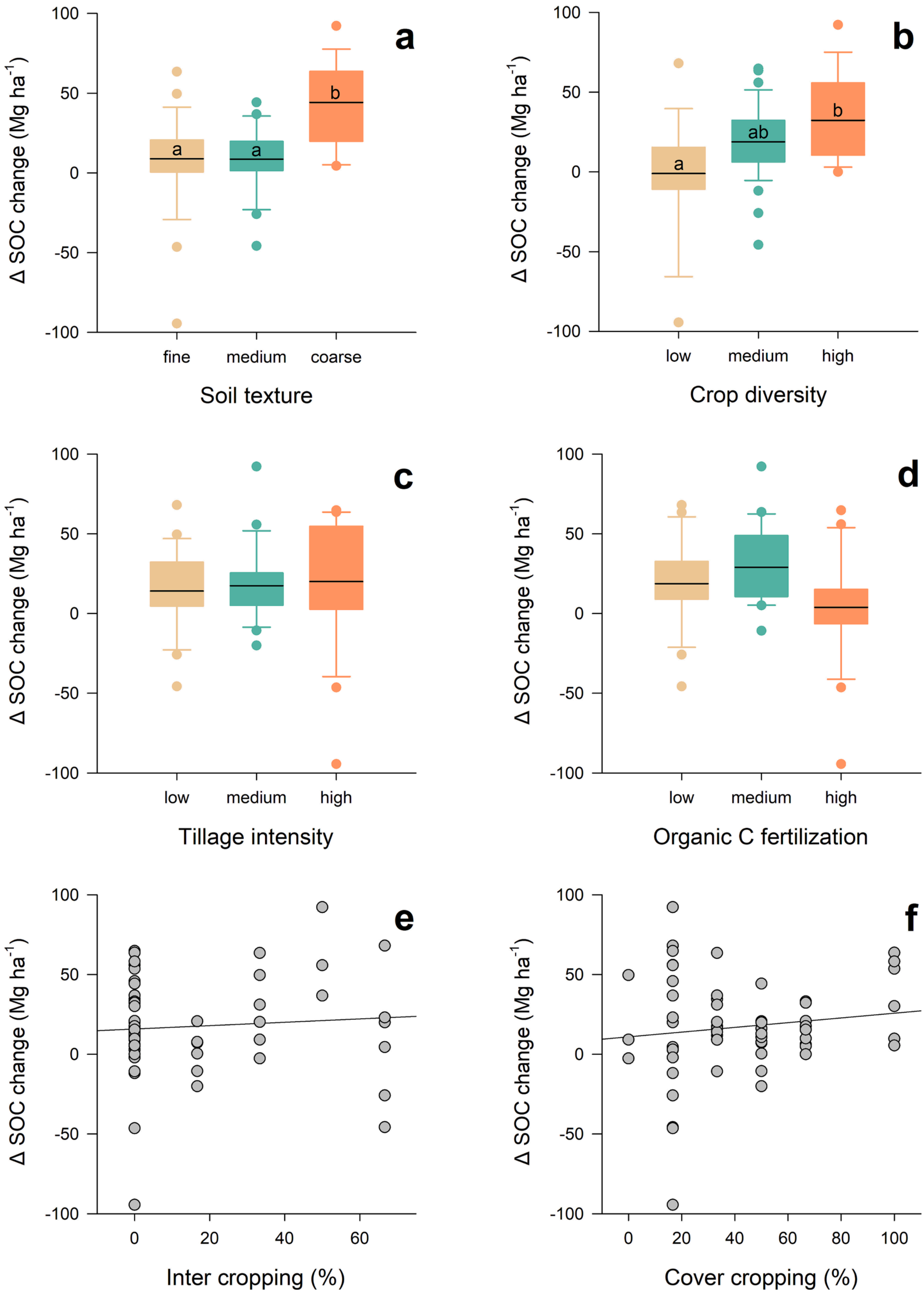

Fig. 1. The effect of (a) soil texture, (b) crop diversity, (c) tillage intensity, (d) C addition through organic fertilization, (e) inter cropping and (f) cover cropping on the difference in SOC stocks (in Mg ha^{-1}) between pioneer and standard farming systems in the first 35 cm of soil. The box plots in (a-d) summarize the results from 63 samples (21 sites × 3 soil depths). Boxes indicate the first and third quartile, the band is the mean of all values and the whiskers show the 10th–90th percentile. Different letters in the boxplot indicate significant differences ($p < 0.05$) between categories. Categories obtained for (b) crop diversity, (c) tillage intensity and (d) organic fertilization are based on the 33rd and 66th percentile.

N_2O offsets; see Berthelin et al., 2022; Deluz et al., 2020; Guenet et al., 2021) and agronomic (e.g. additional nitrogen demand or indirect leakage due to extensification and impacts on global food production; see Hasegawa et al., 2018; Van Groenigen et al., 2017) uncertainties of C sequestration potentials with socio-economic and political barriers of adoption and governance (e.g. Demenois et al., 2020; Thamo and Pannell, 2016).

Arable land is at focus of current C sequestration strategies due to high expected gains from restoring past losses (Sanderman et al., 2017). Global farmland tenure (about 86 % estimated at private ownership according to FAOSTAT agricultural census 2010 data) is an important factor for designing effective climate change policies (Murken and Gornott, 2022) including considerations of farmers' motivations for adoption. Kragt et al. (2017) and Amundson and Biardeau (2018) reported a limited participation of farmers in C sequestration incentives for Australia and the USA, concluding that (i) the positive perception of farmers towards soil health is mostly linked to yield stabilization under increasingly variable weather and predicted trends under climate change and (ii) that the most effective approach to change management for improving soil health (including C sequestration) is farmer-to-farmer extension (see also e.g. Skaalsveen et al., 2020 on no-till adoption).

Considering C sequestration goals within these economic, social and political objectives and interests, we advocate for strategies harmonizing activity- and results-based approaches to maximize both effective ecological impact and wide-spread adoption of soil health innovations. The upcoming EU-Mission Soil Health concept of Lighthouse Farms might provide a promising model for such an integration of activity-based farming system innovation with scientifically evidenced soil health advances (Bouma and Veerman, 2022). Following this approach, future carbon farming schemes might credit farmers' innovation beyond 'common practice' (additionality) for a clearly-defined soil health goal (e.g. enhanced C sequestration), compensating additional expenses as well as inherent potential yield penalties within the innovation process, while a data-driven impact assessment ensures to buyers of carbon credits (i.e., public or private bodies) objective verification of obtainable results within a defined time period by these best-practices. Thereby, effective farmer-based innovation and dissemination of conservation agriculture practices could be fostered along with scientific advances in capturing the key levers and bottlenecks for managing soil health.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2023.116466.

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