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RESEARCH ARTICLE

# Benchmarking carbon sequestration potentials in arable soils by on-farm research on innovative pioneer farms

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**Abstract**
*Purpose* Tackling the global carbon deficit through soil organic carbon (SOC) sequestration in agricultural systems has been a focal point in recent years. However, we still lack a comprehensive understanding of actual on-farm SOC sequestration potentials in order to derive effective strategies.
*Methods* Therefore, we chose 21 study sites in North-Eastern Austria covering a wide range of relevant arable soil types and determined SOC pool sizes (0–35 cm soil depth) in pioneer versus conventional management systems in relation to permanently covered reference soils. We evaluated physico-chemical predictors of SOC stocks and SOC quality differences between systems using Fourier-transform infrared (FTIR) spectroscopy.
*Results* Compared to conventional farming systems, SOC stocks were 14.3 Mg ha$^{-1}$ or 15.7% higher in pioneer farming systems, equaling a SOC sequestration rate of 0.56 Mg ha$^{-1}$ yr$^{-1}$. Reference soils however showed approximately 30 and 50% higher SOC stocks than pioneer and conventional farming systems, respectively. Nitrogen and dissolved organic carbon stocks showed similar patterns. While pioneer systems could close the SOC storage deficit in coarse-textured soils, SOC stocks in medium- and fine-textured soils were still 30–40% lower compared to the reference soils. SOC quality, as inferred by FTIR spectra, differed between land-use systems, yet to a lesser extent between cropping systems.
*Conclusions* Innovative pioneer management alleviates SOC storage. Actual realized on-farm storage potentials are rather similar to estimated SOC sequestration potentials derived from field experiments and models. The SOC sequestration potential is governed by soil physico-chemical parameters. More on-farm approaches are necessary to evaluate close-to-reality SOC sequestration potentials in pioneer agroecosystems.

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**Keywords** Conservation agriculture · Pioneer farms · Sequestration potential · Soil organic carbon · Soil organic carbon deficit · Soil organic carbon quality

**Abbreviations**

| | |
|---|---|
| C | carbon |
| CEC | cation exchange capacity |
| DOC | dissolved organic carbon |
| EC | electric conductivity |
| FTIR | Fourier-transform infrared spectroscopy |
| N | nitrogen |
| SOC | soil organic carbon |
| TN | total nitrogen |

## Introduction

Soils constitute the largest terrestrial carbon (C) sink with approximately 1,500-1,800 Pg stored in the first 100 cm (Batjes 1996; Jobbágy and Jackson 2000; Sanderman et al. 2017), thus exceeding the C present in vegetation and the atmosphere by a large margin (Smith 2012). Historically, human-driven land-use change has substantially reduced global soil organic C (SOC) stocks, with the largest losses being ascribed to cropland conversion and agricultural intensification in the second half of the 20th century (Guo and Gifford 2002; Sanderman et al. 2017). Since soils represent such a large C stock and have the potential for long-term C sequestration, they strongly regulate global C source-sink dynamics (Bloom et al. 2016) and may thus play a key role in future efforts to mitigate and tackle current climate change challenges.

Lately, soils have been in the spotlight of political and governmental interests, since SOC sequestration was pointed out a potential greenhouse gas removal strategy (Lal et al. 2018; Minasny et al. 2017) and an essential measure to maintain ecosystem functioning (Wiesmeier et al. 2019). For example, the 4 per mille initiative was launched at the COP21 by UNFCC in 2015 with the ambition to increase global SOC stocks by 4‰ in order to balance annual global net atmospheric $CO_2$ increments. The 2019 IPCC report pointed out the urgent need of adapting arable land management to cope with climate change (Shukla et al. 2019), since climate change related yield losses pose a major future threat (Iizumi and Ramankutty 2016). And just recently, the European Union has advanced its strategic targets for soil management (Mission Soil Health), aiming for the following targets for C and nitrogen (N): (i) current C concentration losses on cultivated land – which are estimated at approximately 0.5% per year – are reversed to an increase by 0.1–0.4% per year; (ii) reducing fertilizer use by at least 20%; and (iii) reduce N losses by at least 50%. Thus, the restoration of C deficits in agricultural soils has become a primary goal (Bossio et al. 2020).

SOC sequestration as well as negative environmental impacts of current agricultural land-use – including SOC loss – can be mitigated by the implementation of conservation management techniques, such as the extension of soil coverage by living plant canopies and/or mulch, the reduction of mechanical disturbance (through minimum or no-tillage approaches) or the increase of crop diversity via improved rotations including cover and inter crops (Hobbs et al. 2008). Long-term experimental (LTE) observations as well as recent advances in modelling have clearly pointed towards this potential across multiple biomes (Chambers et al. 2016; Körschens et al. 2013; Minasny et al. 2017; Tao et al. 2019; Valkama et al. 2020). SOC sequestration potentials of commonly applied soil conservation practices (i.e., diversified crop rotation, residue and tillage management, contour farming, strip cropping or cover crops) reported by Chambers et al. (2016) ranged between 0.07 and 0.27 Mg $ha^{-1}$ $yr^{-1}$ measured over the course of 10 years after implementation in North American croplands. In a recent meta-analysis, Bai et al. (2019) could show that cover crops and conservation tillage enhanced SOC storage by a total of 20 and 13%, respectively, in long-term experiments (> 20 years). They further evidenced environmental controls on certain measures; for example, while soil texture shaped SOC storage potential of conservation tillage, mean annual temperature significantly affected SOC sequestration rates from cover crops. On the contrary, Xiao et al. (2021) estimated SOC increases under conservation tillage to be close to zero and probably attributed to associated measures such as residue retention. However, several studies acknowledged that the combined implementation of measures, i.e. system change as usually practiced in agriculture where several elements are changed at once, is among the approaches with the highest SOC sequestration potential (Bai et al. 2019; Xu et al. 2020). As evident from the studies outlined above, deriving specific estimates for SOC sequestration potentials for agricultural soils is challenging.

Adding to this multifactorial complexity, the full SOC sequestration potential is hardly achieved as major environmental, practical, political and socio-economic challenges arise with a shift towards sustainable management practices (Amundson and Biardeau 2018), further hampering our ability to estimate SOC sequestration potentials. Although higher SOC storage through conservation agriculture offers theoretical benefits for better yield under environmental stresses (Zhao et al. 2017), yield penalties have – although strongly context-dependent – also been identified (Pittelkow et al. 2015), constituting a potential obstacle for wider implementation. Obviously, there is a natural, soil texture-dependent limit for SOC sequestration to each specific soil, since the stabilization of organic compounds is mainly due to their sorption onto charged mineral surfaces (Hassink 1997; Six et al. 2002). Moreover, there are climatic constraints for the implementation of certain conservation management practices.

The 4 per mille initiative suggested that an annual 4 per mille increase in SOC could intercept annual anthropogenic greenhouse gas emissions from fossil carbon. Bruni et al. (2021) calculated that annual C inputs to European agricultural systems would have to increase by approximately 43% – or 0.66 Mg C $ha^{-1}$ $yr^{-1}$ – in order to reach this goal. Using a similar modelling approach under climate change scenarios, Riggers et al. (2021) projected that in 2099, C inputs would need to be 51–93% (i.e., 1.3–2.3 Mg $ha^{-1}$ $yr^{-1}$) higher as compared to current inputs just to preserve current SOC stocks. Although reports claim that annual 4 per mille sequestration rates can be reached under best management practices (Minasny et al. 2017), it is certainly undisputable that this would require substantial changes in agricultural practices. The socio-economic framework further shapes the practical feasibility of SOC sequestration at various scales (Amundson and Biardeau 2018; Stockmann et al. 2013). Even with large monetary and political effort, it is highly unlikely that every farmer will change their long-established management schemes; and those farmers willing to change will not apply the maximum amount of possible measures.

Thus, the transition from scientific evidence on SOC sequestration potentials of conservation agriculture towards effective gains at the farming system scale poses a major challenge of high relevance. Clearly, this requires on-farm approaches to evaluate close-to-reality SOC sequestration potentials in systems that have the chance to be practically adapted as they emerge out of practice. To date, this constitutes a critical knowledge gap.

Against this background, this study investigates actual on-farm SOC sequestration potentials based on multiple pairwise comparisons between conventional and highly innovative 'pioneer' farming systems across a large range of relevant arable soil types in North-Eastern Austria. These pioneer farming systems have the self-imposed aim of increasing SOC and soil health. In order to evaluate the potential of pioneer farming systems to close potential SOC storage deficits, an adjacent, permanently covered reference soil considered as SOC saturation threshold was analyzed in addition (Crews and Rumsey 2017). We match current SOC stock measurements with historical data to evaluate the long-term SOC sequestration dynamics and determine soil physico-chemical predictors of SOC stocks. We further evaluate whether a shift from standard to pioneer farming management is accompanied by changes in SOC quality using Fourier-transform infrared (FTIR) spectroscopy. Thus, we hypothesize that (i) pioneer management systems show increased SOC stocks as compared to standard management systems, yet may not entirely close the SOC storage deficit as compared to reference soil systems; (ii) soil physico-chemical parameters significantly influence SOC stocks, and thus the realized potential varies with soil type and nutrient status; and (iii) the quality of SOC changes with the conversion from standard to pioneer management.

## Materials and methods

### Site description

Twenty-one sites in North-Eastern Austria covering a wide range of relevant arable soil types were chosen for this study (Fig. 1, Supplementary Information 1). The research sites are characterized by a temperate continental climate, with mean annual precipitation ranging from 537 to 703 mm, and mean annual temperature ranging from 7.9 to 11.0 °C. Each investigation site is comprised of (i) a pioneer agro-ecosystem with high-level soil conservation practices (from now

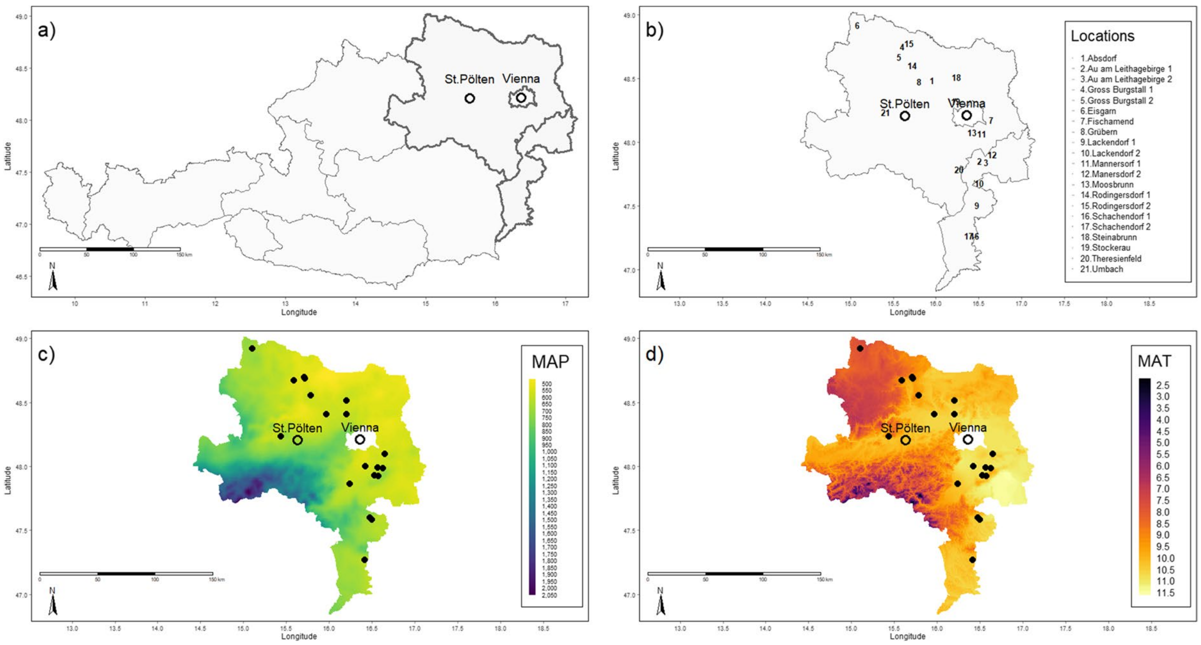


**Fig. 1** Map of sampling site locations in North-Eastern Austria (**a**, **b**). Mean annual precipitation (**c**) and mean annual temperature (**d**) data (obtained from CRU) from 1981–2020

on referred to as ‘pioneer farming’), (ii) a standard cropping system managed according to prevailing good agricultural practices (i.e., regular ploughing at 20–25 cm soil depth, no cover cropping, predominantly mineral fertilization, use of pesticides; from now on referred to as ‘standard farming’) and (iii) a reference ecosystem under permanent vegetation (i.e., field grass and hedge margins, no forests; from now on referred to as ‘reference system’). Pioneer farming systems selected for this study have changed their management more than nine years (⌀ 26 years) ago with an operational target of increasing SOC and biological activity by differently combining measures such as high rotation diversity, multi-species cover crop mixtures, minimum tillage and organic fertilization. They may be considered highly innovative in their farming approach. We also conducted interviews with pioneer farmers in order to obtain information on their management practices and crop yields. In particular, we obtained the following information: time since first measure applied, intercropping yes/no and since when if yes, reduced tillage yes/no and since when if yes, fertilization regime (type of fertilizer used), and type of crops cultivated and approximate yields for the last five years. A detailed description of the main measures applied at each pioneer farming site is given in Supplementary Information 2.

## Experimental setup and soil sampling

Management systems at each site are located at small distance (< 200 m) to ensure pedologically equivalent characteristics. Soil samples were taken from June-August 2021 using a soil auger (⌀ 7 cm) at three different soil depths: 0–5, 5–20 and 20–35 cm. For standard and pioneer farming systems, four soil samples were taken within a square of 5 × 5 m, while reference systems were sampled along a 10–15 m linear transect. The four obtained soil samples were subsequently pooled to form a composite sample. Immediately after sampling, the pooled soil samples were sieved (to pass 2 mm) in the field and stored in cooling boxes. Soil samples taken on each respective day were taken to the laboratory, where approximately 300 g of the soil were immediately frozen at -21 °C, while the rest was air-dried. A total of 189 soil samples were obtained and treated in this manner (21 sites x 3 management systems x 3 depths). For the determination of soil bulk density, one additional undisturbed soil core was taken at each management system at a soil depth of 15 cm using a metal cylinder (⌀ 8 cm, height 5 cm).

## Soil physical and chemical analyses

Soil particle size distribution, oxalate-extractable Al- and Fe-oxides as well as cation exchange capacity (CEC) were measured on composite samples for each site and management system (n = 63). Therefore, equal amounts of air-dried soil from each soil depth were pooled and subsequently analyzed. All other analyses were conducted on all 189 samples.

Soil pH and EC were determined in a 10:1 (w/w) mixture of purified water (18.2 MΩ; total organic carbon ≤ 2 ppb) and air-dried soil (ÖNORM L 1083) using a inoLab Multi 9620 IDS electrode.

Total C and N were analyzed on a C/N elemental analyzer (Thermo Fischer Scientific, MA, USA) using total combustion on air-dried and ball-milled soil samples. The inorganic C content was determined using the Scheibler method (ÖNORM L 1084). Subsequently, the SOC concentration was calculated as the difference between total and inorganic C.

For the determination of DOC, 5 g of dry soil were mixed with 50 ml purified water and left standing overnight. The next day, the suspension was shaken for 2 h with an overhead shaker and filtered through a 0.45 µm membrane filter. After a centrifugation step (15,000 rpm for 10 min), the supernatant was measured using a UV-VIS diode array spectrophotometer (Agilent 8453, Agilent Technologies, CA, USA) at 254 nm wavelength. The DOC concentration was determined according to Brandstetter et al. (1996).

Ammonium oxalate-extractable Al and Fe were determined according to Schwertmann (1964). Therefore, 2 g of dry soil were mixed with 100 ml of an ammonium oxalate solution (pH 3), shaken overnight in the dark and then filtered. Extracted Fe was measured by flame atomic-absorption spectroscopy (Perkin Elmer 2100), while extracted Al was measured by inductively coupled plasma optical emission spectroscopy (Perkin Elmer Optima 8300, Perkin Elmer, MA, USA).

CEC was measured according to ÖNORM L 1086. Briefly, 5 g of air-dried soil were mixed with 100 ml of a 0.1 M $BaCl_2$ solution and settled overnight. The next day, the suspension was shaken for two hours on an overhead shaker and filtered. Exchangeable cations (Ca, K, Mg, Na) were determined by flame atomic-absorption spectrometry (Perkin Elmer 2100, Perkin Elmer, MA, USA), and CEC was calculated as the sum of exchangeable cations (in $mmol_c\ kg^{-1}$).

Bulk density was evaluated according to ÖNORM B 4414. Therefore, the undisturbed soil cores taken were oven dried (105 °C, 24 h), subsequently sieved to pass 2 mm, and the amount of dry soil per 250 $cm^3$ volume was determined.

Particle size distribution was determined on air-dried soil samples with a combined sieve and pipette method according to Soil Survey Staff (2004) after organic matter removal with $H_2O_2$ and dispersion with $Na_4P_2O_7$. Sand, silt and clay contents (in %) were later on used to categorize soils into the three main texture classes according to the USDA soil classification system, i.e. coarse-, medium- and fine-textured soils.

Aggregate stability was determined by wet sieving (ÖNORM L 1082). Briefly, soil aggregates with a diameter of 1000–2000 µm were dipped on a 250 µm sieve. Here, 4 g of soil (EW) were used. The mass of stable aggregates after dipping ($m_K$) and the mass of sand after chemical dispersion of the remaining aggregates ($m_A$) is determined. These parameters are used to calculate the relative amount of stabile aggregates (%SAS):

$$\%SAS = \frac{m_K - m_A}{EW - m_A}$$

To investigate functional groups of soil components, Fourier-Transform infrared (FTIR) spectroscopy was carried out. FTIR spectra were obtained in the attenuated total reflectance mode with an optical diamond crystal (Tensor 27 SN 1683; Bruker ®). Soil samples were scanned from $4000-400\ cm^{-1}$ at a rate of 24 scans per sample and a resolution of 4 $cm^{-1}$ against ambient air as a background. Replicate spectra of each sample were vector-normalized and averaged using the Bruker software OPUS © (version 7.2).

## Long-term SOC data derived from soil surveys

In Austria, a systematic survey of agricultural soils has been initiated in 1970 within an ongoing long-term soil mapping programme on the scale of 1:10,000. Surveyors inspect soil profiles visually and stratify the mapping region based on expert judgement. SOC concentrations were measured with potassium dichromate titration (Walkley and Black 1934) and corrected for correspondence with results from the dry-combustion method. The bulk density of soils was estimated from reference data for agricultural soils. Moreover, the Austrian Federal Ministry of Finances started collecting soil data in 1970 and established a database with 441 representative soil profiles aiming to evaluate their natural productivity. For each reference soil profile, a representative SOC stock was derived from proxy functions with soil texture as most relevant input parameter, thus allowing the estimation of SOC stocks in the first 35 cm of soil. Vector data inferring SOC stocks derived from these surveys from 1970 were compared with our measured SOC stocks in order to evaluate long-term SOC changes. For more information we refer to Baumgarten et al. (2021).

## Statistics

We pre-evaluated whether management systems differed in soil texture. A one-way ANOVA revealed that neither clay (n = 63, $F_{2,60}$=0.16, p = 0.852) nor silt (n = 63, $F_{2,60}$=0.14, p = 0.869) and sand (n = 63, $F_{2,60}$=0.23, p = 0.795) contents differed between management systems within site. Variance homogeneity was evaluated using Welch and Brown-Forsythe tests, while normal distribution of data was evaluated using Kolmogorov-Smirnov and Shapiro-Wilk tests. In case of variance heterogeneity and non-normal distribution, data were log-transformed prior to statistical analyses.

A multivariate analysis of covariance (MANCOVA) was performed to investigate differences in soil SOC, TN and DOC stocks as well as the soil SOC:TN ratio, the DOC:SOC ratio and aggregate stability between management systems. Management (i.e., standard farming systems, pioneer farming systems and reference soil systems) was used as a fixed factor, and site and soil depth were treated as covariates. We used a SS type III model to test for significant management effects (with site as nested variable) as well as significant interactions with soil depth. To evaluate the statistical significance of the overall model, the Wilks´ lambda distributions (λ) and derived F- and p-values for main and interaction effects are stated. Post-hoc Tukey tests using a Šidák correction for multiple pairwise comparisons were used to evaluate significant differences between management systems.

We used paired sample t-tests with a Bonferroni correction for multiple pairwise comparisons to evaluate significant differences between surveyed and measured SOC stocks in standard and pioneer farming systems, respectively. The same approach was used to determine differences in the SOC:clay ratio between management systems at 0–5, 5–20 and 20–35 cm soil depth.

Due to uneven group sizes, one-way ANOVA and post-hoc Tukey tests based on a trimmed mean were used to evaluate SOC stock (on a Mg $ha^{-1}$ $cm^{-1}$ base) differences between management systems within the three main USDA texture classes.

We used linear regression analyzes and Spearman correlation coefficients to evaluate the relationship between SOC and soil physico-chemical parameters across all management systems (n = 189). We consider regressions with an $R^2 > 0.3$ as relevant relationships. In order to determine the most significant predictors of SOC stocks among the physico-chemical parameters tested, we applied categorical regression analysis with optimal scaling using alternating least squares. A ridge regularization and 0.632 bootstrap for estimation of the prediction error was carried out. Sand content was automatically excluded as variable from the categorical regression analysis due to multicollinearity effects. Moreover, we excluded N stocks since this factor usually correlates with C stocks without any predictive power. SOC, TN and DOC stocks were recalculated on a cm base (i.e., Mg $ha^{-1}$ $cm^{-1}$) to account for different sampling depths.

We also conducted a categorical principal component analysis (PCA) with the different management systems as categories, and soil chemical (pH, EC, CEC, SOC, TN, DOC, oxalate-extractable oxides) and physical (clay content, silt content, aggregate stability) parameters as explanatory variables. Nutrient stocks at each soil depth (0–5, 5–20 and 20–35 cm depth) were re-calculated on a centimetre base (Mg $ha^{-1}$ $cm^{-1}$) to account for uneven sampling depths. We used a Varimax transformation and Kaiser normalization of components.

We refer to significant differences at the $p < 0.05$ level. Statistical analyses and figures were conducted in SPSS 26 and Sigma Plot 14.

FTIR spectra were also evaluated using PCA; once with a broad spectral range and once on spectral areas focusing on organic molecular compounds avoiding the effect of inorganic compounds – especially of calcite. Band regions were selected at 3700 – 2600 $cm^{-1}$ and 1700 – 1400 $cm^{-1}$ (Tatzber et al. 2007). PCA with broad spectral range was rotated using a Varimax transformation and Kaiser normalization of components. PCA was conducted using Unscrambler X 11.0 (Camo ®).

## Results

Overall, management system significantly affected soil chemical and physical characteristics (Wilks´ $\lambda = 0$, $F_{378,702} = 6.547$, $p < 0.001$), and soil depth was also a significant factor in interaction with management system (Wilks´ $\lambda = 0.256$, $F_{36,495} = 5.007$, $p < 0.001$; Table 1). Moreover, soil management had a highly significant effect on all analyzed parameters ($p < 0.001$). Significant interactions between soil management and depth were also given for all parameters except of the DOC:SOC ratio (p = 0.629).

In the first 35 cm of soil, SOC contents in pioneer farming systems were – with 105.3 ± 11.5 Mg $ha^{-1}$ – 15.7% higher as compared to stocks in standard farming systems (91 ± 10.4 Mg $ha^{-1}$; $p < 0.05$; Fig. 2a). In comparison, soils from reference systems had a mean SOC content of 139.2 ± 15.2 Mg $ha^{-1}$ and where thus 53.9 and 32.9% higher as compared to SOC contents in standard and pioneer farming systems, respectively ($p < 0.05$; Fig. 2a). In line with patterns observed for SOC, TN stocks were highest in the reference soil systems with 10.8 ± 1.2 Mg $ha^{-1}$ ($p < 0.05$; Fig. 2b); total N contents were on average 30.6% lower in the standard farming systems (6.7 ± 0.9 Mg $ha^{-1}$) and 24.3% lower in the pioneer farming systems (8.3 ± 1.1 Mg $ha^{-1}$). The lowest DOC contents with 0.77 ± 0.03 Mg $ha^{-1}$ soil were found under standard farming management (Fig. 2c). DOC contents of pioneer farming and reference soil systems were significantly higher in comparison ($p < 0.05$); with 0.97 ± 0.03 and 1.34 ± 0.03 Mg $ha^{-1}$ soil, respectively. The SOC:TN ratio in the standard farming system (14.4 ± 0.56) was found to be significantly higher as compared to the reference soil systems (13.34 ± 0.47), while the SOC:TN ratio in the pioneer farming system (13.61 ± 0.45) was indifferent from both (Fig. 2c). On the contrary, no significant difference between management systems was found for the DOC:SOC ratio (Fig. 2e). Aggregate stability was on average 49% in the standard farming system and 55% in the pioneer farming system, which corresponds to an 12.9% increase ($p < 0.05$; Fig. 2f). In the reference soil, the average aggregate stability was with 73% approximately 49.8 and 32.7% significantly higher as compared to standard and pioneer farming systems, respectively ($p < 0.05$).

Nutrient stock changes between management systems showed similar trends across all soil depths, yet changes were most pronounced in the top soil layer at 0–5 cm depth (Fig. 3a-f). While pioneer systems had 28% higher SOC stocks at 0–5 cm soil depth as compared to standard farming systems, this difference diminished to 16 and 11% at 5–20 and 20–35 cm soil depth, respectively (Fig. 3a). The same was true for TN and DOC contents, where pioneer systems showed approximately 35% higher contents at 0–5 cm soil depth and 20–25% higher contents at 5–20 and 20–35 cm soil depth (Fig. 3b-c). As for the aggregate stability, a similar difference of approximately 15% between pioneer and standard farming system was recorded at 0–5 and 5–20 cm soil depth, while the difference at 20–35 cm has reduced to 7% (Fig. 3f).

We compared C stock data from a survey conducted in 1970 by experts with our measured data in 2021 (Fig. 4). C stocks of the standard farming systems increased by 22.5% – from 72.9 ± 8.4 to 89.3 ± 11.0 Mg $ha^{-1}$ – in the top 35 cm of soil over the 50-year period, yet the difference was not significant (p = 0.091). On the other hand, C stocks of the pioneer farming system increased significantly by 37.8% over the same time period (p = 0.001); from 74.9 ± 8.7 to 103.2 ± 12.0 Mg $ha^{-1}$.

Linear regression analyses revealed significant positive relationships between SOC stocks and TN, DOC, aggregate stability, and EC ($R^2 > 0.3$; Fig. 5a-d), while relationships between SOC and silt content, clay content, soil pH, CEC and extractable oxides were not significant ($R^2 < 0.3$; Supplementary Information 3). A multiple categorical regression analysis revealed significant physico-chemical predictors of SOC stocks ($F = 47.259$, $p < 0.001$, $R^2 = 0.69$; Table 2). DOC, EC and CEC were significant positive predictors among the tested soil chemical parameters, while aggregate stability and clay content were the most dominant soil physical predictors. Moreover, aggregate stability positively predicted SOC stocks,

**Table 1** Test statistics of the MANCOVA analysis to evaluate the effect soil management (standard farming, pioneer farming, reference system), site and soil depth on nutrient stocks (SOC, TN and DOC), elemental ratios (SOC:TN and DOC:SOC) and aggregate stability

| Overall model | | | | | | |
|---|---|---|---|---|---|---|
| | Wilks´ Lambda | *F*-value | Df | *P*-value | | |
| Management (Site) | 0 | 6.547 | 378,702 | < 0.001 | | |
| Management x Depth | 0.256 | 5.007 | 36,495 | < 0.001 | | |
| Individual parameters | | | | | | |
| | Parameter | Type III sum of squares | Df | Mean square | *F*-value | *P*-value |
| Management (Site) | SOC | 7.253 | 63 | 0.115 | 24.511 | < 0.001 |
| | DOC | 3.307 | 63 | 0.052 | 2.972 | < 0.001 |
| | TN | 9.812 | 63 | 0.156 | 21.572 | < 0.001 |
| | SOC:TN | 907.962 | 63 | 14.412 | 5.122 | < 0.001 |
| | DOC:SOC | 0.003 | 63 | 5.348E-5 | 6.83 | < 0.001 |
| | Aggregate stability | 5.827 | 63 | 0.092 | 21.304 | < 0.001 |
| Management x Depth | SOC | 0.798 | 6 | 0.133 | 28.297 | < 0.001 |
| | DOC | 0.944 | 6 | 0.157 | 8.908 | < 0.001 |
| | TN | 1.205 | 6 | 0.201 | 27.909 | < 0.001 |
| | SOC:TN | 61.88 | 6 | 10.313 | 3.665 | 0.002 |
| | DOC:SOC | 3.412E-5 | 6 | 5.687E-6 | 0.726 | 0.629 |
| | Aggregate stability | 0.335 | 6 | 0.056 | 12.864 | < 0.001 |

Test statistics of the full model as well as of individual parameters are given separately

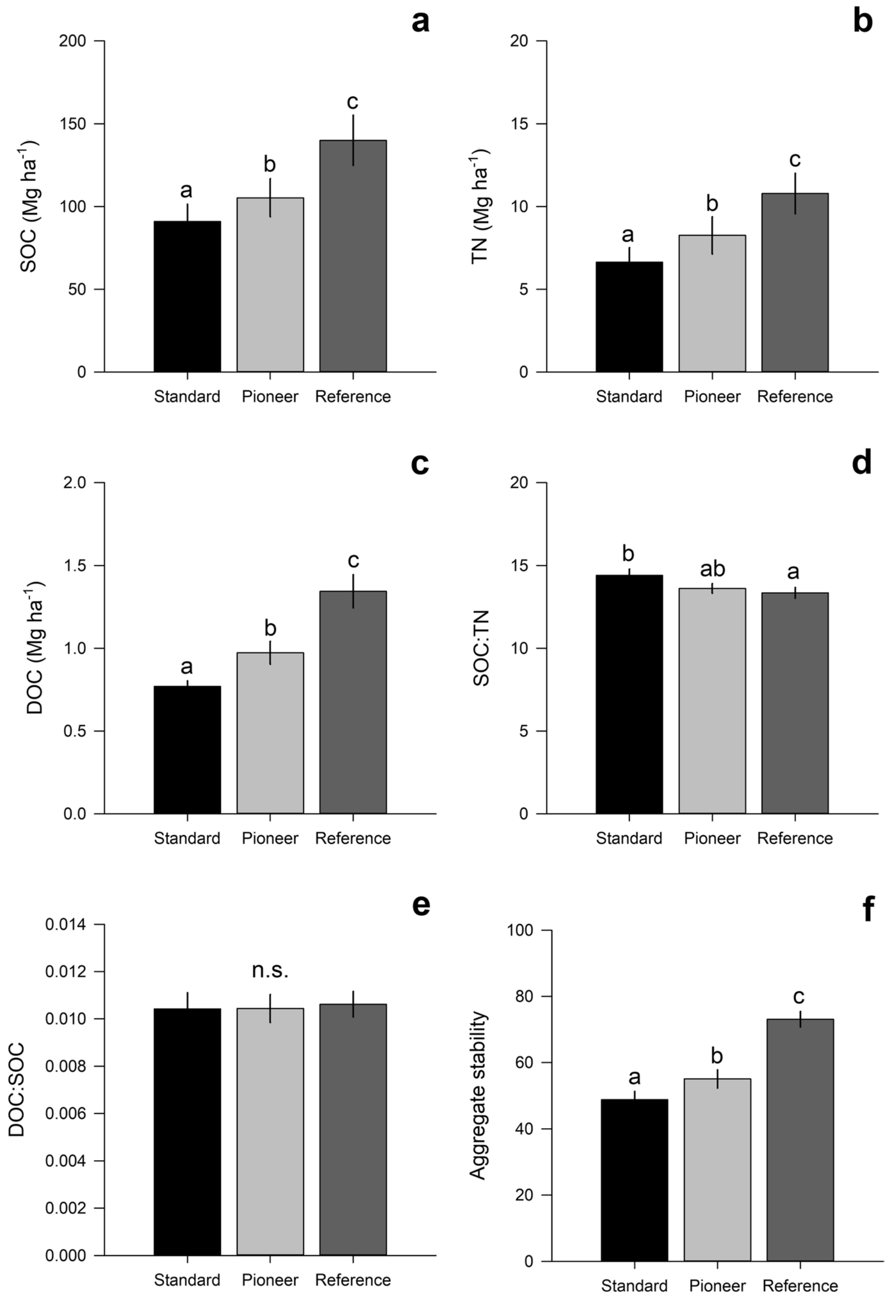


**Fig. 2** **a** SOC, **b** TN and **c** DOC stocks (in Mg ha$^{-1}$) as well as the (**d**) SOC:TN ratio, the (**e**) DOC:SOC ratio and (**f**) soil aggregate stability of standard farming, pioneer farming and reference systems. Stocks were summed across all three soil depths (0–5, 5–20 and 20–35 cm), while the mean is presented for ratios and aggregate stability. Different letters above bars indicate significant differences between management systems ($p < 0.05$) as derived from post-hoc Tukey tests within the MANCOVA analysis (n.s., not significant)

while the silt content negatively predicted SOC stocks.

We evaluated management differences in SOC stocks between different texture classes (Fig. 6a). Overall, we found significantly lower SOC stocks in medium textured soils as compared to coarse and fine textured soils (F = 15.186, $p < 0.001$; data not shown). In soils with a coarse texture, SOC stocks from pioneer farming systems approximated those from reference soils, and SOC contents in standard farming systems were significantly lower ($p < 0.05$; Fig. 6a). In medium- and fine-textured soils, SOC stocks in reference soils were significantly higher as compared to standard and pioneer farming systems ($p < 0.05$), which were indifferent from each other. SOC:clay ratios were evaluated and showed significant

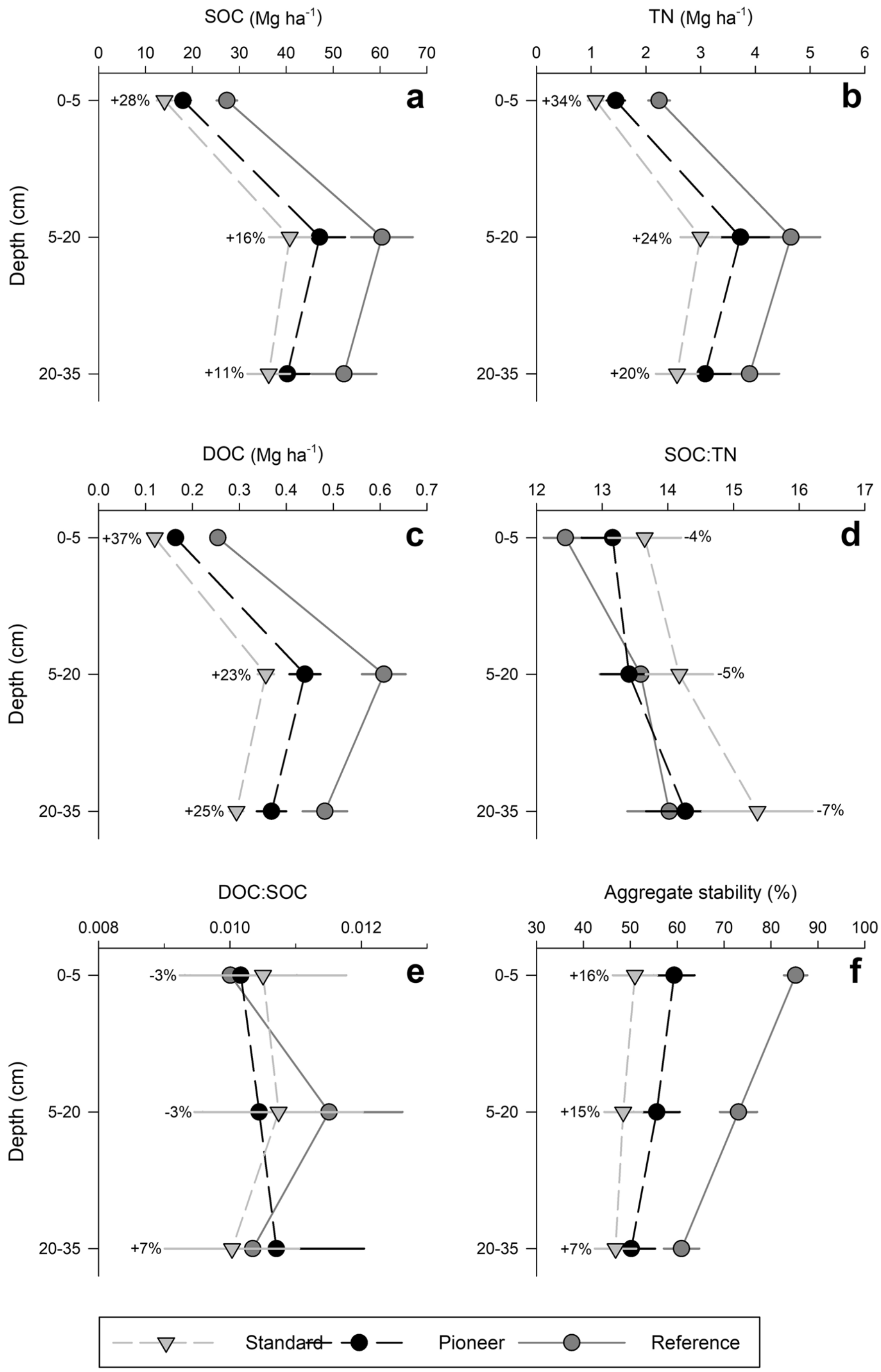


**Fig. 3** **a** SOC, **b** TN and **c** DOC stocks (in Mg $ha^{-1}$) as well as the (**d**) SOC:TN ratio, the (**e**) DOC:SOC ratio and (**f**) soil aggregate stability of standard farming, pioneer farming and reference systems at three soil depths (0–5, 5–20 and 20–35 cm). Shown is the mean ± SE, and percent values indicate the difference between standard and pioneer farming systems

differences between all three management systems ($p < 0.01$; Fig. 6b). Standard and pioneer farming systems showed SOC:clay ratios of 0.091 ± 0.01 and 0.11 ± 0.01, respectively, while reference systems exhibited highest SOC:clay ratios with 0.18 ± 0.01. Large variations between sites were observed; across 21 sites, ratios ranged from 0.03 to 0.23, 0.04–0.38 and 0.04–0.45 in standard farming, pioneer farming and reference systems, respectively. Lowest values were generally found with increasing soil depth.

The conducted PCA showed that DOC, SOC, TN and aggregate stability clearly separated the dataset

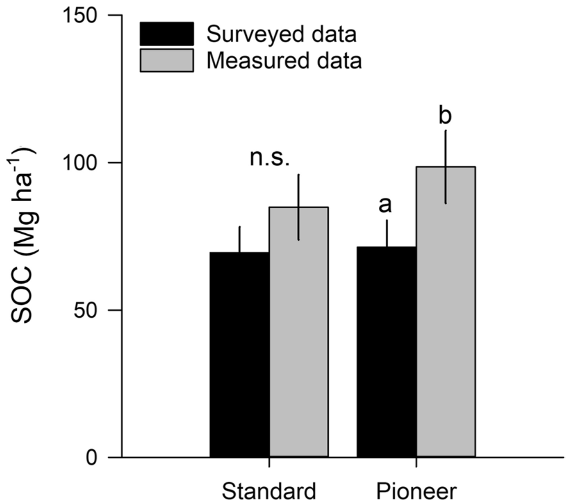


**Fig. 4** Comparison of soil SOC stocks (in Mg ha$^{-1}$) of the first 35 cm from standard and pioneer farms as surveyed in 1970 and measured in 2021. Different letters indicate significant differences ($p < 0.05$) between surveyed and measured stocks as revealed by paired-sample t-test (n.s., not significant)

along the first PCA axis (Supplementary Information 4). The silt content also loaded on the first PCA axis, yet opposite to the afore-mentioned parameters. On the other hand, site parameters such as clay content, CEC, pH and EC strongly loaded on the second PCA axis. Oxalate-extractable Al- and Fe-oxide contents were weak predictors. Altogether, the separation of the dataset was rather equally strong along both PCA axes, with a 34.43 and 31.16% of the variation in the dataset explained by the first and second axis, respectively.

The site scores of the PCA based on the broad range in the FTIR spectrum revealed a separation between sites along the first and second principal component (Fig. 7); in particular, the sites Au am Leithagebirge, Eisgarn, Steinabrunn and Theresienfeld separated well along the first component (Fig. 7a). The second principal component is influenced partly by several band regions around 1798 cm$^{-1}$, 1425 cm$^{-1}$, 872 cm$^{-1}$, 712 cm$^{-1}$ (Fig. 7c), but also by a broad band with a maximum around 1030 cm$^{-1}$ with two small side peaks at 1086 and 1140 cm$^{-1}$. Negative loadings were found for the band regions 3650 – 2600 cm$^{-1}$ and from 1700 – 1520 cm$^{-1}$ (Fig. 7c). We observed a separation between land-use systems (i.e., reference soil versus both cropping systems), while the separation between agricultural systems was less pronounced (Fig. 7b). The loading plot displays that both band regions 3650 – 2600 cm$^{-1}$ and 1700 – 1520 cm$^{-1}$ were responsible for the observed shift in land-use systems (Fig. 7d).

## Discussion

Sustainable agricultural management poses a great potential for SOC sequestration (Paustian et al. 2016). Across 21 pair-wise comparisons, pioneer farms store 15.7% – or 14.3 Mg ha$^{-1}$ – more SOC in the top 35 cm of soil compared to standard farms (Fig. 2a). This magnitude is impressive given the fact that agri-environmental measures to sustain SOC stocks have been widely implemented in Austrian agro-ecosystems since 25 years (Baumgarten et al. 2011; Dersch and Böhm 2001), and thus cropland management towards the conservation of SOC is prevalent (Baumgarten et al. 2021).

From our compiled data, we were able to calculate annual SOC gains. Across all 21 sites, the mean annual SOC sequestration rate was 0.56 ± 0.38 Mg ha$^{-1}$ yr$^{-1}$, which is remarkable and close to the projected increase of 0.66 Mg C ha$^{-1}$ yr$^{-1}$ that is required to reach the 4 per mille target (Bruni et al. 2021); the discrepancy between our measured SOC sequestration potential and requirements under future climate scenarios is however still large (Riggers et al. 2021). Our results are also in line with European and global scale studies that evaluated sequestration rates of sustainable management practices (Dersch and Böhm 2001; Gattinger et al. 2012; Lugato et al. 2014; Rodrigues et al. 2021). On a global scale, Gattinger et al. (2012) estimated that organic farming practices can additionally sequester 0.45 ± 0.21 Mg ha$^{-1}$ yr$^{-1}$ as compared to non-organic farming systems. An early study from Freibauer et al. (2004) on the potential of agricultural measures to increase SOC in European croplands came to a similar result. In comparison, recent annual sequestration estimates of sustainable soil management measures (such as crop residue incorporation, cover cropping or reduced tillage) for European countries were in the range of 0.05–0.20 Mg ha$^{-1}$ yr$^{-1}$ (Lugato et al. 2014; Rodrigues et al. 2021), and thus well below that of global projections. SOC sequestration potentials estimated from LTEs in Austria agree well with our calculations, where

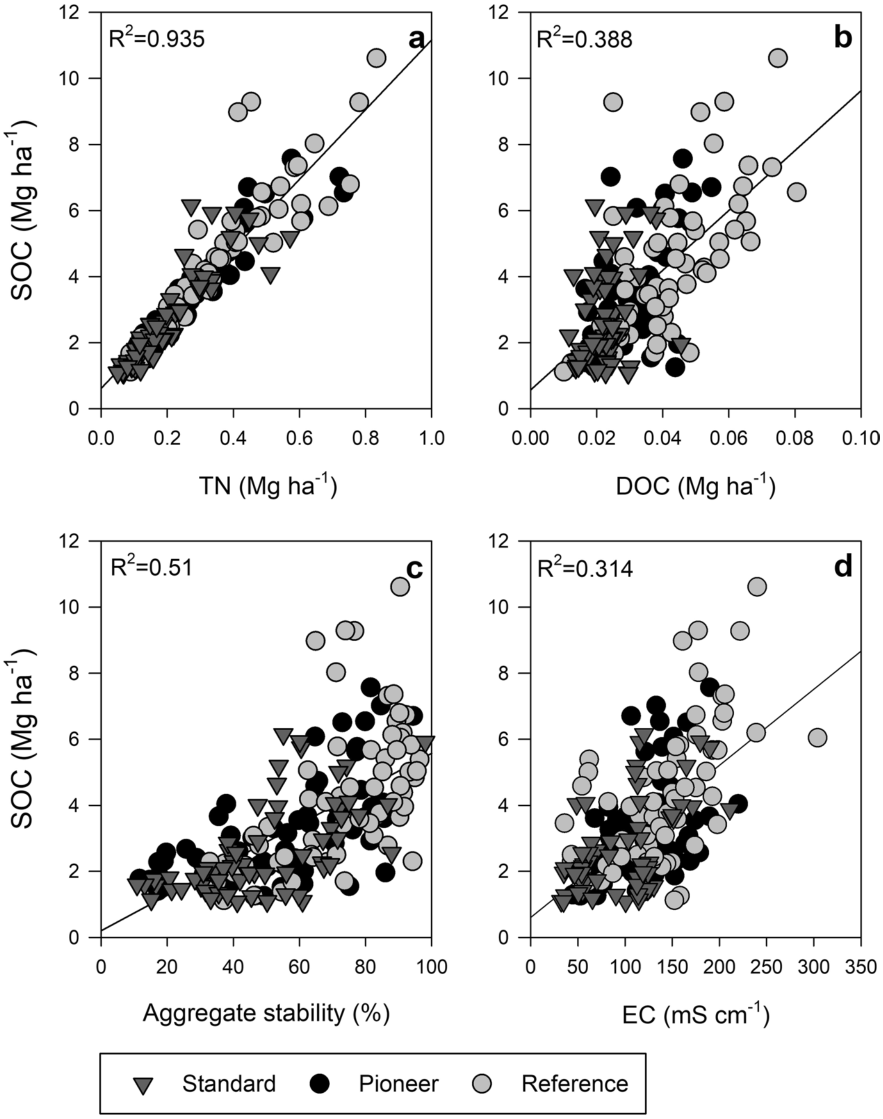


**Fig. 5** The relationship between SOC stocks (in Mg $ha^{-1}$ $cm^{-1}$) and soil physico-chemical parameters across all management systems (standard farming system, pioneer farming system and reference system) and depths as revealed by linear regression analyses and Spearman correlation coefficients. SOC, TN and DOC stocks were recalculated on a cm base (i.e., Mg $ha^{-1}$ $cm^{-1}$) for comparability

**Table 2** Results of a categorical regression analysis on the prediction of SOC stocks through soil physicochemical parameters

| | | *F*-value | *p*-value | Direction |
|---|---|---|---|---|
| Soil chemical parameters | pH | 1.887 | 0.171 | |
| | EC | 78.013 | < 0.001 | (+) |
| | CEC | 52.286 | < 0.001 | (+) |
| | Oxalate-extractable oxides | 0.258 | 0.612 | |
| | DOC stocks (kg $m^{-2}$) | 66.132 | < 0.001 | (+) |
| Soil physical parameters | Aggregate stability (%) | 91.353 | < 0.001 | (+) |
| | Clay content (%) | 0.575 | 0.449 | |
| | Silt content (%) | 42.133 | < 0.001 | (-) |

Given are *F*- and *p*-values as well as the direction of the relationship for significant predictors ($p < 0.05$)

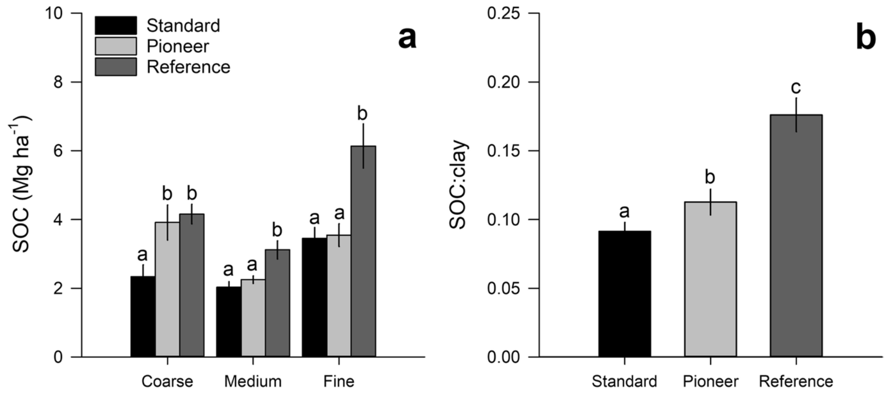


**Fig. 6** **a** SOC stocks (in Mg ha$^{-1}$ cm$^{-1}$) of standard farming, pioneer farming and reference soil systems in coarse-, medium- and fine-grained soils. **b** The SOC:clay ratio of standard farming, pioneer farming and reference soil systems at 0–5, 5–20 and 20–35 cm soil depth. Different letters indicate significant differences ($p < 0.05$) between management systems

measures such as reduced tillage, farmyard manure application and crop residue incorporation increased SOC stocks by approximately 0.2–0.4 Mg ha$^{-1}$ yr$^{-1}$, respectively, under controlled experimental settings (Dersch and Böhm 2001). A comprehensive survey on cropland SOC changes over a 30-year period has recently been conducted in Switzerland (Dupla et al. 2021). While annual SOC stocks remained equal or decreased from 1993 to 2007, they recognized a considerable increase from 2007 to present. The authors attributed the observed SOC increase to imposed agri-environmental measures such as cover cropping and minimum rotations of four crops that the government made mandatory by law.

Comparing surveyed SOC stock data from 1970 with our measured data allows a valuable evaluation of long-term SOC sequestration dynamics and potentials (Fig. 4). Pioneer farming systems stored an additional 28.3 Mg ha$^{-1}$ over a 50-year period, which equals an annual SOC sequestration rate of 0.56 Mg ha$^{-1}$ yr$^{-1}$; SOC stock changes in standard farming systems on the other hand did not increase significantly over this timespan. This clearly demonstrates that conservation agricultural practices facilitate SOC storage over long time periods.

Comparing SOC sequestration potentials between studies is difficult due to great methodological heterogeneity. For example, long-term experiments often focus on single management measures under controlled and often optimized conditions. While this approach is important to disentangle the sequestration power of single measures, it does not reflect on-farm situations, where several different measures at various timescales are commonly applied together. Moreover, SOC sequestration potentials derived from modelling approaches are generally estimated using data from LTEs. While such efforts are clearly needed to advance our understanding about management-related SOC dynamics, they commonly neglect socio-economic, institutional and political barriers, which are of utmost importance for a successful long-term implementation of sustainable farming measures (Amundson and Biardeau 2018). Taking all these considerations into account, the realistic achievable potential was suggested to be approximately 10–20% of the biological potential (Cannell 2003; Freibauer et al. 2004; Smith et al. 2005). In this regard, our observed on-farm annual SOC sequestration rates are quite remarkable. Clearly, the pioneer farming sites that were considered for this study are operated by farmers who must be considered the pinnacle of sustainable agri-environmental innovation in North-Eastern Austria. Therefore, the benchmark pioneer farming systems in this study may represent an upper limit of what is achievable.

According to interviews held with the participating farmers, the application of sustainable agricultural measures was not at the expense of crop yield; an argument often held against conservation agricultural practices (Pittelkow et al. 2015). This was verified using regional yield data from the Austrian Federal Ministry of Agriculture, Regions and Tourism. Average yields for wheat (5.79 compared to 5.20 t ha$^{-1}$) and rapeseed (3.87 compared to 3.14 t ha$^{-1}$) were above the regional average, silage maize (48.9 compared to 48.7 t ha$^{-1}$) and barley (5.79 compared to 5.84 t ha$^{-1}$) were similar, and grain maize (9.28 compared to 10.36 t ha$^{-1}$) yields were below average crop yields. This is in line with observations showing that sustainable management measures such as no tillage, residue incorporation

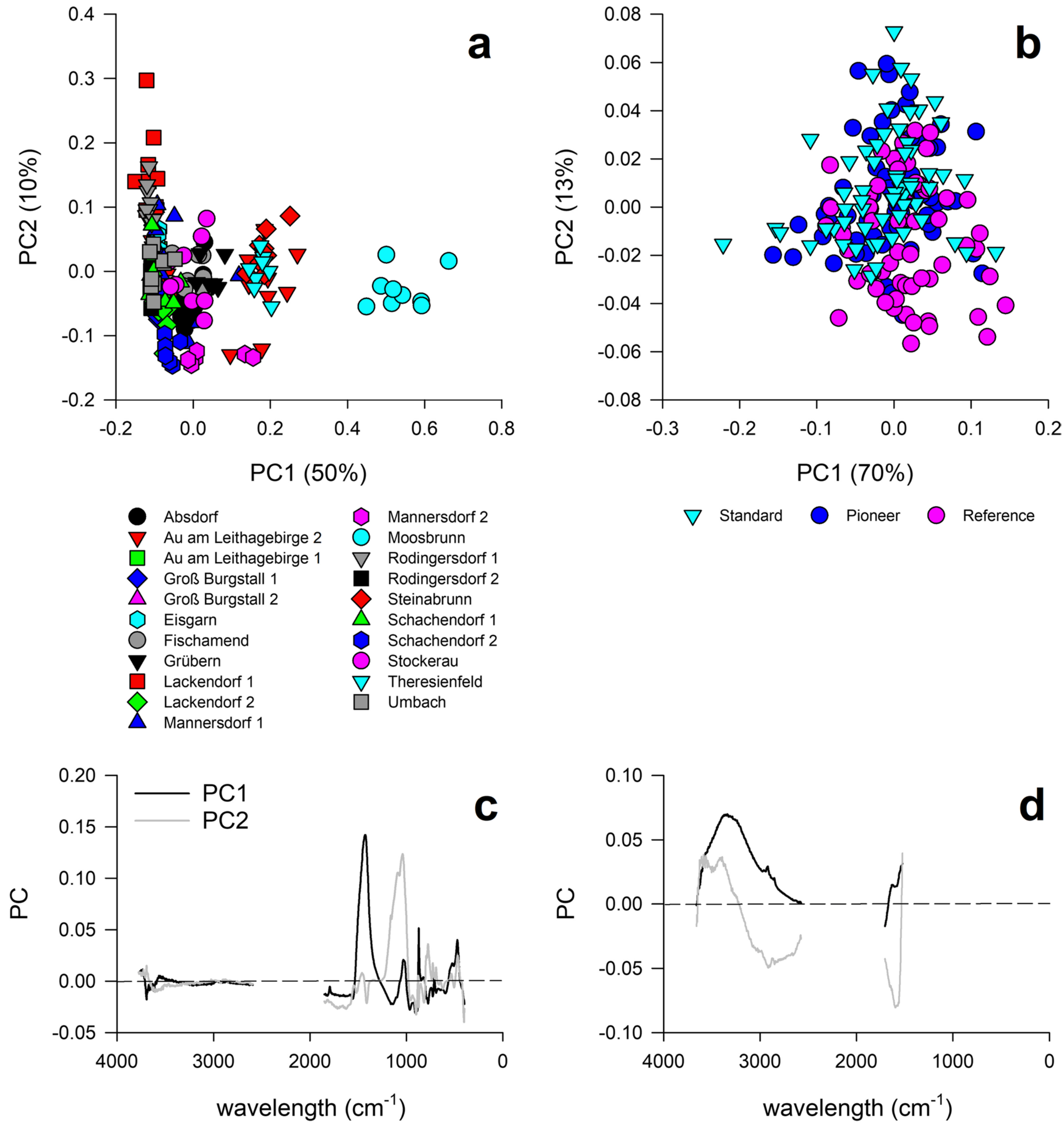


**Fig. 7** Site score (**a**) and treatment score (**b**) as well as loading (**c**, **d**) plots of two principal component analyses based on FTIR spectra of standard farming, pioneer farming and reference soils across a broad (**a**, **c**) and a reduced (**b**, **d**) spectral range. Black and grey lines in (**c**, **d**) refer to loadings of the first and second principal components, respectively. The reduced spectral range mainly refers to organic bands

or crop rotation do not compensate crop yields in drier regions (Sun et al. 2020).

It has often been argued that SOC increases in reduced tillage systems are limited to the topsoil, and thus simply a redistribution of SOC from deeper soil layers towards the topsoil occurs (Powlson et al. 2014). We did not detect such a shift; our data rather show that SOC stocks were also increased – if slightly less though – at a soil depth of 35 cm (Fig. 3a). However, we cannot rule out a potential depletion of SOC stocks at deeper soil layers (Angers and Eriksen-Hamel 2008). N contents in pioneer farming systems followed the trajectory of SOC stocks and increased by 1.6 Mg $ha^{-1}$ $yr^{-1}$ in the top 35 cm (Figs. 2b and 3b). A potential N dilemma for SOC sequestration has been proposed by Van Groenigen et al. (2017), arguing that the build-up of SOC would require substantial N inputs, either by fertilization or the cultivation of leguminous crops. Our data actually show that pioneer farming systems, compared to standard farming systems, sequestered more N than SOC, with N increases of 34, 24 and 20% at 0–5, 5–20 and 20–35 cm soil depth, respectively (Fig. 3b); on the other hand, SOC increased by 28, 16 and 11%, respectively (Fig. 3a). This was also reflected in the slightly decreased SOC:TN ratio (Figs. 2c and 3c). Based on interviews with farmers, we know that cover cropping has been implemented on all 21 sites for (on average) more than 23 years. Moreover, organic fertilization is widely applied on more than half of our analyzed 21 sites, while mineral fertilization is applied on five sites. Thus, we argue that N inputs via fertilization and cover cropping provides sufficient N to effectively build up SOC.

Our data also indicated that SOC contents are strongly linked to soil physico-chemical parameters (Figs. 5 and 6a). A categorical regression analyses evidenced that CEC, EC and DOC were the strongest positive soil chemical predictors of SOC, while aggregate stability and silt content were significant soil physical predictors (Table 2). The positive influence of CEC on SOC through the electrostatic bridging between mineral surfaces and SOC compounds is well documented and further underlines the importance of bivalent cations for soil organic matter stabilization (Stewart et al. 2008; von Lützow et al. 2008). DOC refers to simple C compounds that can easily be metabolized by soil microorganisms (Sokol and Bradford 2019; Sokol et al. 2019). Thus, DOC constititutes a significant C fraction suggested to fuel the in-vivo turnover of the soil microbial biomass (Liang et al. 2017), and thus SOC sequestration and stabilization (Buckeridge et al. 2022). Overall, soil aggregate stability was the strongest predictor of SOC stocks (Table 2). Soil aggregation is considered to be a key process of SOC preservation, since soil aggregates physically protect SOC from mineralization (Abiven et al. 2009; Six et al. 2004) and reduce microbial activity through reduced oxygen diffusion into aggregates (Mikutta et al. 2006). The physical stabilization of SOC in soil macro- and micro-aggregates can be significantly impaired by soil management (Wiesmeier et al. 2019). In particular, negative effects of intensive tillage due to physical disruption have frequently been reported (Grandy and Robertson 2006; Six et al. 1999, 2004). On the other hand, sustainable agricultural practices such as reduced tillage, cover cropping or organic fertilization facilitated soil aggregation (Blanco-Canqui and Ruis 2020; Karami et al. 2012; Sithole et al. 2019). This is supported by our results, since pioneer farming systems showed a significantly higher aggregate stability across the whole soil profile (Figs. 2f and 3f). Thus, soil aggregation might constitute a key link to long-term SOC stabilization (Mustafa et al. 2020).

The clay content is considered a key factor in SOC storage due to its sorption capacity within soil aggregates and onto mineral surfaces (Dungait et al. 2012; Getahun et al. 2016; Verheijen et al. 2005). Based on the concept that potential SOC saturation is a function of clay content, the ratio of SOC to clay content has been proposed as a good indicator of soil structural quality and health (Dexter et al. 2008; Johannes et al. 2017). Prout et al. (2021) suggested SOC:clay ratios of 0.125, 0.1, 0.077 to indicate optimal, reasonable and low structural soil quality, respectively. The mean SOC:clay ratio in our pioneer farming systems was 0.11, suggesting an overall good structural quality (Fig. 6b). SOC:clay ratios in the standard systems were – with a mean value of 0.09 – below the proposed aim for good soil management (Johannes et al. 2017). In comparison, the SOC:clay ratio obtained for standard farming systems is comparatively high for conventional farming systems (Guillaume et al. 2022) and further underlines the already well managed state of agricultural soils in Austria (Baumgarten et al. 2021). The mean SOC:clay ratio of $0.18 \pm 0.01$ obtained for our reference soils might thus constitute the obtainable limit.

At some point however, SOC sequestration through sustainable management measures might reach a steady-state equilibrium. This saturation point is attributed to the limited capacity of soils to stabilize SOC onto mineral surfaces, particularly silt and clay particles (Hassink 1997; Six et al. 2002; Stewart et al. 2007). Investigations of agricultural soils in France and Germany evidenced that sandy soils showed a high degree of SOC saturation, while the opposite was true for fine-textured soils (Angers et al. 2011; Wiesmeier et al. 2014). Using a natural, undisturbed reference soils instead of the estimating SOC saturation as a function of fine particles (Hassink 1997), our data clearly show that pioneer farming systems reached a SOC saturation point in coarse-textured soils (Fig. 6a); SOC contents in the standard farming systems on the other hand were still approximately half of that of both the pioneer farming and the reference system. As for medium- and fine-textured soils, both farming systems showed SOC deficits of approximately 1 and 2.5 Mg ha$^{-1}$ in medium- and fine-textured soils, respectively, as compared to undisturbed reference systems. This discrepancy can be attributed to the disruption of soil macroaggregates and the subsequent mineralization of the released SOC caused by soil tillage (Post and Kwon 2000; Six et al. 2000). Further studies need to investigate how the observed SOC deficit in medium- and fine-textured soils can be tackled with agri-environmental measures, since the SOC sequestration potential was far from exhausted in these soils.

Against our expectation, FTIR analyses showed no clear separation of standard and pioneer farming systems (Fig. 7b). Considering a wide spectral range, a separation of the various study sites became obvious (Fig. 7a). Band regions assigned to calcite (1798 cm$^{-1}$, 1425 cm$^{-1}$, 872 cm$^{-1}$ and 712 cm$^{-1}$; Smidt et al. 2010), to lignin (1030 cm$^{-1}$, 1086 cm$^{-1}$ and 1140 cm$^{-1}$; Schwanninger et al. 2004) and to various OH vibrations found in inorganic (clay minerals, hydroxides) and organic compounds such as cellulose (band regions 3650 – 2600 cm$^{-1}$ and 1700 – 1250 cm$^{-1}$; Schwanninger et al. 2004; Tinti et al. 2015) were mainly responsible for the separation between sites (Fig. 7c). Alpiphatic C-H bands which have their maxima at 2920 and 2850 cm$^{-1}$ may have also contributed to the separation (Tatzber et al. 2007). Overall, clay minerals played only a minor role in any separation. Spectra across a narrow range that are suggested to indicate functional SOC groups could only extend the group of reference soils from both cropping systems but only with a huge overlap (Fig. 7b). The loading plots showed that both the band regions 3650 – 2600 cm$^{-1}$ and 1700 – 1520 cm$^{-1}$ were responsible for the shift in land-use systems (Fig. 7d), which could be assigned to a higher content of organic matter, especially of rather stable organic fraction (Meissl et al. 2007, 2008). We can interpret these outcomes as follows: evolution, degradation and transformation of SOC takes place with a certain dependency of land-use. Different farming activities, however, change the molecular pattern of SOC not quickly and deeply enough to become visible in FTIR spectra of bulk samples, at least not at the sites chosen in this study.

Within the search for meaningful carbon farming targets, the on-farm research from this study, building on advanced pioneer farming systems, provides a novel solution in line with Barré et al. (2017): the highest reachable carbon stock should be derived from within a given land-use (e.g. mean top 10%) rather than using saturation-deficit approaches calibrated via other land-use datasets such as grassland topsoils (e.g. Hassink 1997; Wenzel et al. 2022). Larger-scale assessment of C-stocks on pioneer farms could be an efficient approach to estimate such soil type specific benchmarks (Amelung et al. 2020). Following an inverse modelling strategy (e.g. Martin et al. 2021), the pairwise (i.e. standard vs. pioneer) datasets of this study combined with general soil information (e.g. texture) might also allow spatial upscaling and estimation of biomass input needs to achieve given regional/national carbon goals.

Finally, our study also provides a successful example of science-practice integration in view of implementing the European Mission Soil Health, aiming to establish a network of lighthouse farms accompanied by research (EC 2021). Both, carbon indicators as well as evaluation strategies used in this study proved effective means to advance in this strategy of farming system innovation for better climate change mitigation and adaptation.

## Conclusions

This study demonstrated substantial on-farm SOC sequestration potentials of agricultural croplands through highly innovative soil management across a wide range of arable soil types in North-Eastern Austria. On average, pioneer farming systems stored 14.3 Mg ha$^{-1}$ or 15.7% more SOC as compared to standard farming systems. This equals a sequestration rate of 0.56 Mg ha$^{-1}$ yr$^{-1}$, which is rather close to the projected SOC increments needed to intercept annual anthropogenic greenhouse gas emissions. Clearly, more on-farm studies are needed to estimate

SOC sequestration potentials across multiple biomes. Aggregate stability as well as nutrient availability (i.e., available DOC and cations) strongly predicted SOC stocks across all management systems, suggesting a strong physico-chemical control over SOC dynamics beyond agricultural management. Pioneer farming – yet not standard farming – could close the SOC saturation deficit in coarse-textured soils. This was not the case in medium- and fine-textured soils, where SOC stocks of both farming systems showed a substantial deficit to the reference systems. We therefore suggest that the definition of attainable climate change mitigation targets for carbon farming requires on-farm soil-health monitoring networks on innovative lighthouse farms to derive site-specific SOC sequestration benchmarks for agriculture.

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**Data availability** Data are available upon request from the corresponding author.

**Declarations**

**Competing interests** The authors have no competing interests to declare.



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