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Long-term effects of tillage systems on soil health of a silt loam in Lower Austria

Marton Toth [a,*], Christine Stumpp [a], Andreas Klik [a], Peter Strauss [b], Bano Mehdi-Schulz [c], Gunther Liebhard [a,b], Stefan Strohmeier [a]

[a] University of Natural Resources and Life Sciences, Vienna, Department of Water, Atmosphere and Environment, Institute of Soil Physics and Rural Water Management, Muthgasse 18, Wien 1190, Austria

[b] Federal Agency for Water Management, Petzenkirchen, Institute for Land and Water Management Research, Pollnbergstrasse 1, Petzenkirchen 3252, Austria

[c] University of Natural Resources and Life Sciences, Vienna, Department of Water, Atmosphere and Environment, Institute of Hydrology and Water Management, Muthgasse 18, Vienna 1190, Austria

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ABSTRACT

Tillage is an essential practice for soil preparation in agriculture that influences a broad variety of soil parameters. However, the long-term implications of tillage on soil health are complex, context specific, and need to be better understood. The aim of our study is to evaluate soil physical, chemical, and biological effects of three different tillage practices: conventional tillage (CT), mulch tillage (MT), and no-till (NT). A long-term experiment in Mistelbach, Lower Austria, was launched in 1994 and comprehensively sampled in 2002 and 2021. To evaluate tillage-impacts over the two decadal monitoring we assessed soil health indicators in the 0–20 cm soil depth (conventional ploughing layer) and below 20 cm. A "Soil Management Assessment Framework" (SMAF) procedure was applied to assess and compare soil quality using the Soil Quality Index (SQI). Considering multiple indicators, we found overall quality improvements in all three tillage-experiments over time. However, particularly the conservation practices (MT and NT) enhanced soil quality, predominately soil organic carbon (SOC) and soil physical indicators (e.g. water holding capacity, coarse pores). The study confirms that SOC in the 0–20 cm layer significantly increased under no-till (46 Mg C ha^{-1}) compared to conventional tillage (26 Mg C ha^{-1}). At the same time aggregate stability and water holding capacity increased under conservation agriculture (MT and NT). The proven positive impacts on soil health will further help to promote agricultural practices that sustain productivity while pushing forward climate change mitigation actions in temperate climate.

1. Introduction

Substantial efforts have been undertaken to enhance traditional tillage systems and to maintain a balance between the raising crop production demand, soil quality, and agro-environmental sustainability. Well-managed soils can develop their functions and interactions between physical, chemical, and biological quality attributes (Vezzani and Mielniczuk, 2009). However, the choice and application of a tillage system are strongly context-specific. Conservation tillage techniques, such as no-till and mulch tillage, can reduce the degrading impacts that could be brought on by intensive agricultural management practices, especially in soils with poor soil structure. Commonly, conservation tillage practices are considered effective when they achieve at least a 30 % surface cover through crops and organic residues (Carter, 2005), which in reality is not always the case (Hösl and Strauss, 2016). Well-covered soil surfaces develop an increased resistance to rainfall erosivity (erosive energy) as the cover shields the soil aggregates from breakdown, detachment and transport, and eventual sealing of pores in sediment cumulation areas (Jury and Horton, 2004). Conservation tillage practices have widely proven mitigation-effects on erosion (Myers and Wagger, 1996; Lenka and Lal, 2013; Gabbasova et al., 2015; Zavalin et al., 2018); particularly organic mulch cover increases soil organic matter and reduces surface runoff (Franzluebbers, 2002). Eventually, conservation tillage can enhance soil moisture, stabilize water permeability, improve the soil structure (such as aggregate stability), and reduce the chance of soil erosion. (Edwards et al., 2000; Adekalu et al., 2006; Mulumba and Lal, 2008; Jordan et al., 2010; Kahlon et al., 2013; Liebelt et al., 2015).

* Corresponding author.
E-mail address: marton.toth@boku.ac.at (M. Toth).

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Conservation tillage practices have an advantage preserving and improving the supporting and regulating soil functions (Busari et al., 2015). However, positive effects on yields seem context-specific and were not always associated with the benefits of conservation tillage practices. Indeed, Howard et al. (1998) and Mbuthia et al. (2015) observed beneficial advantages of NT on soil quality, however the effects on crop yield varied across their target study area in Tennessee. Morrison et al. (2017) found through an experiment in eastern Canada that corn, soybean, and wheat yield, under NT practices, were 20 % lower compared to the conventionally tilled plots. Nevertheless, considering the net-profit, no-till requires fewer working hours, less energy compared to conventional systems. Therefore, reduced and no-tillage practices may economically out-perform conventional approaches under specific conditions (Borin et al., 1997; Uri, 2000; Tabatabaeefar et al., 2009). As a foundation for sustainable production, agricultural management decisions will eventually need to take into account both actual economic competitiveness and the preservation of crucial soil qualities (Andrews et al., 2004; Adhikari and Hartemink, 2016; Çelik et al., 2021). Monitoring (selected) soil quality trends can support the according on-farm decision-making processes.

According to Doran and Zeiss (2000), soil health is the ability of soil to function as a vital living system within ecological and land-use boundaries. Soil health can be determined by several physical, chemical, and biological soil quality indicators (Stott, 2019). However, a broad variety of different soil health indicators applied may yield unclear conclusions due to the variable (positive and negative) trends observed. The Soil Quality Index (SQI) approach combines and evaluates multiple soil health effects (Karlen et al., 1997). The approach allows to holistically assess soil health development rather than focusing on single parameters and trends. The "Soil Management Assessment Framework" (SMAF; Andrews et al., 2004) is used to establish the SQI and assesses how management practises impact soil quality and whether it is improving, maintaining, or degrading (Karlen et al., 2019). According to Karlen et al. (2013), , Cherubin et al., 2019), Gura and Mnkeni (2019), the SMAF has been widely applied in different agro-ecological contexts to examine trends resulting from changes in land use and/or the adoption of new agricultural practises.

In 1994, a field experiment was launched in eastern Austria to examine the effects of different tillage systems on surface runoff, soil erosion, and nutrient and pesticide losses on silt loam in the Pannonian region (Klik and Rosner, 2020). The experiment has been conducted for three decades by the local agricultural school in Mistelbach, Lower Austria, implemented and tested by farming professionals. The field experiment serves as a perfect study site to investigate long-term tillage effects on soil health development while evaluating the feasibility of specific conservation agriculture practices. The specific target of the current study is to compare and to assess the impacts of conventional tillage (CT), mulch tillage (MT), and no-till (NT) on a set of physical, chemical, and biological soil quality indicators. Our approach generally distinguishes between the conventional ploughing layer (upper 0–20 cm) and the deeper soil layer below 20 cm. At the individual parameter level we used twenty indicators to statistically determine the tillage treatments' long-lasting effects (present state), and used fifteen consistent indicators to compare our results with the first monitoring pursued in 2002. We applied the SQI methodology compiling thirteen indicators to inter-compare the different treatments (present state), and the changes over time of each practice individually. Our study's underlying hypothesis is that the adapted soil management (since 1994) affected the soil health states, especially in the upper (0–20 cm) layer. Furthermore, we hypothesize that mulch– and no-tilled soils, through winter crop cover and reduced tillage disturbance, have a beneficial long-lasting impact on soil organic carbon stocks.

2. Materials and Methods

2.1. Site description

The study site is located in Mistelbach, Lower Austria, an important agricultural production area about 40 kilometres north of Vienna (48° 35' 01" N, 16° 35' 16" E, 252 m above sea level) (Fig. 1). The region has a temperate climate (Komissarov and Klik, 2020). Average annual air temperature is 9.8 °C and precipitation is 539 millimetres. 64 % of precipitation falls between April and September. In 2010, according to the Austrian regional statistics, 77 % of Mistelbach's district-land was used for agriculture, which is substantially larger than the average arable land cover of Lower Austria (41 %) (Statistik Austria, 2010) (https://www.statistik.at/blickgem/gemDetail.do?gemnr=31633; accessed April 15, 2023). Mistelbach is located in the Molasse basin, which consists of clay marl, sands, conglomerates, gravels, calcareous sandstones, and freshwater limestone. Above the deposits are thin layers of quaternary sediments, particularly loess and loess clays (Amt der NÖ Landesregierung Abt, 2007). The soil is classified as a Haplic Phaeozem according to the World Reference Base (IUSS Working Group WRB, 2022), or Typic Argiudols using the USDA Soil Taxonomy (Soil Survey Staff, 2022). The soil has a silty loam texture with a slightly alkaline reaction and low organic matter content. The A-horizon is approximately 30–35 cm deep covering the loess-deposit C-horizon. The terrain-slope of the study site is 13.2 %, with a south-eastern and north-western exposure in the valley (exposition 220°) (Klik and Rosner, 2020).

2.2. Tillage and agricultural management

In 1994, a research project started to compare CT, MT and NT systems. Conventional tillage (CT) affects the top approximately 20–25 cm soil depth using a mouldboard plough for inverting the soil typically in spring. This is followed by two tillage treatments of 8 cm depths using a disc harrow; one time applied for seedbed preparation in spring, and one time applied in autumn for straw incorporation after harvest (Fig. 2). Mulch tillage (MT) reaches to 8 cm soil depth using a cultivator for mulching the winter cover crops. No-till (NT) pursues a direct planting of the main crop using the Accord Optima Hard Drive and universal pneumatic seeders applied in the residues of the winter cover crops (Klik and Rosner, 2020; Komissarov and Klik, 2020). On the mulch-tilled (MT) – and no-tilled (NT) experimental plots, there is a layer of crop residues at 5–10 cm on the soil surface. The tillage experiments have been conducted at the valley's south-eastern and north-western slopes (Fig. 1). Each plot is 90 m long and 3 m wide. The crop rotation includes spring – and winter barley (*Hordeum vulgare* spp.), winter wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), sunflower (*Helianthus anuus* L.), and sugar beet (*Beta vulgaris* L.). Between 1994 and 2019, 50 kg ha^{-1} yr^{-1} and 10 kg ha^{-1} yr^{-1} winter cover crops were added to MT and NT plots every second year, respectively. On the MT plots, the mixture contained 12.5 kg sweet pea (*Lathyrus odoratus* L.), 20 kg common vetch (*Vicia lativa* L.), 3 kg buckwheat (*Fagopyrum esculentum* Moench), 7.5 kg Egyptian clover (*Trifolium alexandrinum* L.), 1 kg Persian clover (*Trifolium resupinatum* L.), 5 kg California bluebell (*Phacelia minor* (Harv.) Thell.), 1 kg yellow mustard (*Sinapsis* spp.) and mallow (*Malva* spp.). A mixture of 7 kg California bluebell and 3 kg yellow mustard was applied with NT. Since 2019, 200 kg ha^{-1} yr^{-1} mixture of cover crops has been used both on the MT and NT plots; it contains winter wheat, field pea (*Pisum sativum* subsp. *arvense* (L.)), and broad bean (*Vicia faba* L.) (https://lako.at/versuche/; accessed September 10, 2022). The distance between maize, sunflower, and sugar beet crop rows varies between 0.50 and 0.80 m (Strohmeier et al., 2016), and it varies between 0.15 and 0.20 cm for winter barley and winter wheat (https://lako.at/versuche/; accessed September 10, 2022). The previously conducted conventional tillage (prior to the experiment launched in 1994) had been operated since the 1970 s (Komissarov and Klik, 2020). According

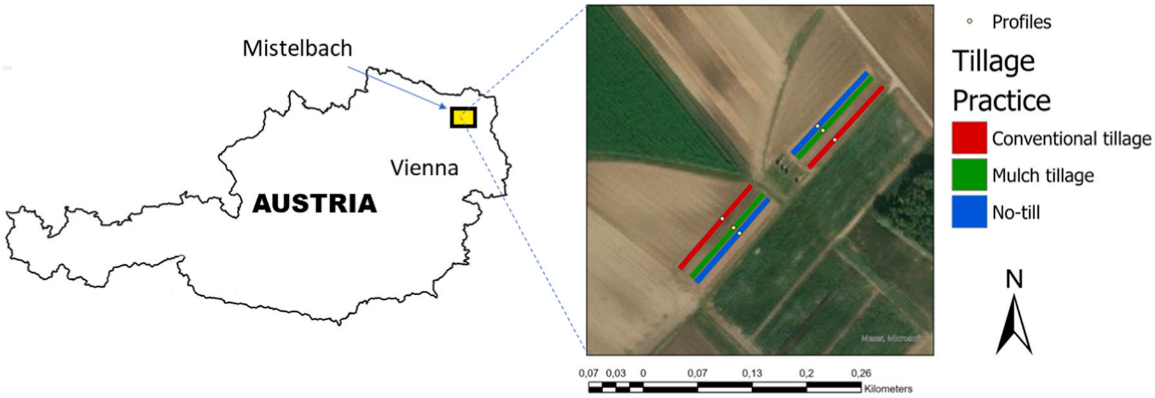

Fig. 1. Location of the Mistelbach in the Austrian map indcluding the long-term experiment site with the conventional tillage, mulch tillage, and no-till parcels and the excavated soil profiles.

Fig. 2. Soil surfaces of three different managements in spring (before seeding) and autumn (after harvest): conventionally tilled (CT) plot after disc harrowing in spring (top left) and after harvest in autumn (bottom left); mulch-tilled (MT) plot with winter-cover crops in spring (top centre) and after harvest in autumn (bottom centre); no-till (NT) plot with winter-cover crops in spring (top right) and after harvest in autumn (bottom right).

to the database of the Agricultural School in Mistelbach (https://lako.at/versuche/; accessed September 10, 2022); in 2021, previous to the monitoring campaign of the present study, sunflower was the main crop. For weed control a non-selective herbicide, 3.75 l ha^{-1} Glyphosate, and selective herbicides, such as active agents of 3 l ha^{-1} Acclonifen, 0.5 l ha^{-1} Haloxyfop-P, and 0.2 l ha^{-1} universal additives were used. Each tillage practice was supplied with the same mineral fertilizer application using 230 kg ha^{-1} calcium-ammonium-nitrate (62.1 kg N ha^{-1}).

2.3. Monitoring and assessment

2.3.1. Soil sampling and soil health parameters

The advanced and present soil sampling was designed to maintain comparability with the comprehensive initial monitoring campaign conducted by Hoffmann (2005) in 2002. Six soil profiles from each tillage system were sampled in two replicates in November 2021 for disturbed and undisturbed soil samples (N=372) (Fig. 1). Undisturbed samples were taken at 0–5, 10–15, 25–30, 50–55, and 70–75 cm soil depths to determine saturated hydraulic conductivity (Ksat), bulk density (BD), and total porosity (TP) (Fig. 3). Undisturbed samples collected at 0–5, 10–15, 25–30, and 50–55 cm were also used to determine water holding capacity (WHC) and coarse pores (CP). Disturbed samples were taken from similar depths to analyse clay and sand contents, particle density (PD), electric conductivity (EC), soil pH (pH), cation exchange capacity (CEC), soil organic carbon (SOC), soil organic matter (SOM), total carbon (Total C), total nitrogen (Total N), C/N ratio (C/N), soil respiration (SR), and dehydrogenase activity (DHY) (2) (Fig. 3). The disturbed samples had been air dried were crushed, then sieved through a 2 mm sieve. Between June and Nov. 2021 samples (N=54) were collected from 0 to 5 cm soil depth for aggregate stability (AS) assessment (Fig. 3). These samples were taken from each tillage practices at three hill slope locations (bottom, middle, and top of the hill slope on the north-western side of the valley). Maximum rooting depths (RD) were obtained from the soil profiles between 0 and 100 cm.

Water holding capacity and coarse pores were evaluated using the pressure plate extractor method (Dane and Hopmans, 2002). Water holding capacity was defined as $\theta_a=\theta_{fc}-\theta_{pwp}$, where θ_a refers to the water holding capacity, θ_{fc} is the volumetric water content at −330 hPa (field capacity), and θ_{pwp} is the volumetric water content at −15, 000 hPa (permanent wilting point). Coarse pores were defined as $\theta_{cp}=\theta_0-\theta_{fc}$, where θ_{cp} refers to the coarse pores, θ_0 - is the water content at 0 hPa (saturation), and θ_{fc} – is the volumetric water content at −330 hPa (field capacity). Bulk density was calculated through the core

Fig. 3. Excavated soil profile in November 2021 with the sampling depths of different soil indicators 1.) sampling depths for the following indicator(s): water holding capacity, coarse pores, particle density, sand – and clay contents, soil pH, electric conductivity, cation exchange capacity, total carbon, total nitrogen, C/N ratio, calcium carbonate, soil organic carbon, soil organic matter, dehydrogenase activity, and soil respiration 2.) sampling depths for the following indicator(s): bulk density, total porosity, saturated hydraulic conductivity, and 3.) following sampling depth for the indicator(s): aggregate stability.

cylinder method according to Grossman and Reinsch (2002); particle density was conducted through the pycnometer method according to Flint and Flint (2002); total porosity was calculated from particle density and bulk density (Flint and Flint, 2002). Saturated hydraulic conductivity (Ksat) was measured using the falling head soil core method (Reynolds and Elrick, 2002). Clay and silt contents were determined with the pipette method (Gee and Or, 2002).

Total carbon and total nitrogen were measured through dry combustion method (Bremner, 1996; Nelson and Sommers, 1996). The C/N ratio was calculated by dividing the total carbon by the total nitrogen. Soil pH and electric conductivity were measured using a conductivity meter (Rhoades, 1996; Thomas, 1996). Calcium carbonate content was measured by pressure calcimeter according to Scheibler (Loeppert and Suarez, 1996). Cation exchange capacity was measured through buffered salt extraction method (Blume et al., 2000).

Regarding the biological indicators, soil organic carbon was calculated as the difference between the total and inorganic carbon (Nelson and Sommers, 1996). Soil organic matter was measured using the Loss-On-Ignition method (Ben-Dor and Banin, 1989). Soil respiration was measured utilizing the CO_2 release method (Öhlinger, 1996), and dehydrogenase activity was measured using the reduction of the triphenyl tetrazolium method (Öhlinger, 1996).

Aggregate stability was determined with the Eijkelkamp wet sieving apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) according to Kemper and Rosenau (1986) methodology using air dried aggregates between 1 and 2 mm.

After the indicators were measured and calculated, they were classified into three assessment-groups: holistic impacts assessment (SQI), management impacts, and temporal impacts (Table 1).

2.3.2. Holistic soil health assessment

Thirteen indicators were selected to evaluate the changes in soil quality over the past two decades and to identify differences through management in 0–20 cm and below 20 cm depths (Table 2). The SQI was assessed using the same soil quality indicators and sampling depths defined during the first monitoring conducted in 2002 (Hoffmann, 2005). The selection of the applied soil quality indicators is based on this previous study, and it aimed to continuously monitor and evaluate the changes in soil quality and on the same soil quality indicators in the future. SQI was assessed in three steps: (1) define and set-up target indicators, (2) interpret the indicators (scoring and weighting), and (3) integrate them into a single SQI value (Andrews et al., 2004; Nakajima et al., 2015).

In a first step (1), soil quality indicators were selected and grouped by functions, corresponding to a previous study pursued at the experimental site (Hoffmann, 2005) (Table 2). In the second step (2), soil quality indicators were converted into score-ranging using "score-ranging curves" (Andrews et al., 2004; Wienhold et al., 2009; Stott et al., 2010)). We used linear standardized scoring functions, where the indicators were classified as "more is better" (such as SOC), "less is better" (such as BD), and "mid-point optimum", such as soil pH (Hussain et al., 1999). Based on the literature, specific weights were assigned to the score values of each indicator (Table 2). For uncertainty assessment and evaluating the impacts of variable weighing, three different weighting indices were generated and their values were presented as G, W1, and W2. 'G' stands for equal weights in each soil quality function; W1 and W2 were given variable weights for soil quality indicators for each productivity, storage, and filter function (Table A.1). The last step (3) was integrating the interpreted indicators into a single soil quality index (*SQI*). The weights were multiplied by each function's score (*SFI*); the respective product was multiplied by the weights of function indices (*wi*) (Eq. 1).

$$SQI = \sum_{i=1}^{n} (wiSFI) \tag{1}$$

We calculated the contribution of single indicators into the SQI. The normalization of each soil quality indicator (*SQIind*) was calculated multiplying the summarized indicator weight (*I*) under the productivity (*p*), storage (*s*), and filter (*f*) functions with the 5 % - median and 95 % percentiles of the indicator (*pct*) (Eq. 2).

$$SQind = I(p, s, f)pct \tag{2}$$

2.3.3. Management impacts

The target was to compare the long-lasting impacts of the three tillage systems on physical, chemical, and biological indicators with various statistical methods in the two defined layers (conventional ploughing layer (0–20 cm) and deeper soil layer (below 20 cm)). Second target was to define statistical relations (correlations) between selected indicators and relative crop yield in the two soil depths-layers. According to Arvidsson et al. (2014), the relative crop yield (%) (RCY) was defined as the dry harvest per m^{-2}, where conventional tillage (100 %) is used as reference. In this part, twenty indicators were applied using the newly measured data from 2021 (Table 1).

2.3.4. Temporal conditions

The target of this assessment was to investigate the change of fifteen selected indicators in the two defined layers (0–20 cm, below 20 cm) since the initial comprehensive sampling pursued in 2002 (Table 1). The comparison was made between the newly measured data from 2021 and the data from first comprehensive sampling in 2002.

Table 1
Classification, and measurement methods of the evaluated physical, chemical, and biological soil quality indicators.

Properties	Indicators	Selected indicators to evaluate the impact of			Method
		a.) SQI	b.) Management	c.) Temporal	
Physical	Water holding capacity	x	x	x	Pressure Plate Extractor
	Bulk density	x	x	x	Core Method
	Total porosity	x	x	x	Calculation from particle and bulk densities
	Coarse pores	x	x	x	Pressure Plate Extractor
	Saturated hydraulic conductivity	x	x	x	Falling Head Soil Core Method
	Maximum rooting depth	x	x	x	Measured maximum rooting depth in the soil profile
	Clay		x		Pipette Method
	Sand		x		Pipette Method
	Aggregate tability	x	x	x	Wet sieving method
Chemical	Total carbon		x	x	Dry Combustion Method
	Total nitrogen	x	x	x	Dry Combustion Method
	C/N ratio	x	x	x	Division of total carbon and total nitrogen
	Calcium carbonate		x	x	Pressure Calcimeter Method according to Scheibler
	Soil pH	x	x	x	Conductance meter method
	Electric conductivity	x	x	x	Conductance meter method
	Cation exchange capacity	x	x	x	Buffered salt extraction method
Biological	Soil organic carbon	x	x	x	Difference between total carbon and inorganic carbon
	Soil organic matter		x	x	Loss-On-Ignition Method
	Soil respiration		x		CO_2 release method
	Dehydrogenase activity		x		Reduction of Triphenyl tetrazolium method

Particle density of the soil was measured as 2.65 g cm-3, and used to calculate the total porosity.

Table 2
Selected soil quality indicators in the 0–20 cm, and below 20 cm depths, their linear standardized scoring functions (SSF) according to the literature, and their classification into productivity, storage, and filter functions.

Soil Quality Indicator (Applied depths)	Acronym	Unit	Linear SSF	LTS	UTS	O	Functions			References
							Productivity	Storage	Filter	
Physical indicators										
Aggregate stability (0–5 cm)	AS	%	More is better	0	30	-		x	x	Karlen et al. (1994a) Mausbach and Seybold (1998), Hussain et al. (1999)
Maximum rooting depth (20–100 cm)	RD	cm	More is better	5	150	-	x			Jaeggli (1986)
Water holding capacity (0–20 cm, 20–55 cm)	WHC	%	More is better	10	30	-	x	x		Karlen et al. (1994a)
Bulk density (0–20 cm, 20–75 cm)	BD	g cm^{-3}	Less is better	1.20	1.45	-	x	x	x	Karlen et al. (1994a), Karlen and Stott (1994)
Total porosity (0–20 cm, 20–75 cm)	TP	%	Optimum	20	80	50		x		Karlen and Stott (1994), Mausbach and Seybold (1998), Hussain et al. (1999)
Saturated hydraulic conductivity (0–20 cm, 20–75 cm)	Ksat	m d^{-1}	More is better	0.01	1	-		x		Bretschneider et al. (1993)
Coarse pores (0–20 cm, 20–55 cm)	CP	%	More is better	3	15	-	x		x	Bodenkunde (1982)
Chemical indicators										
Total Nitrogen (0–20 cm, 20–55 cm)	Total N	Mg ha^{-1}	More is better	0.9	35	12	x	x		Amberger (1996) Gisi (1997)
C/N ratio (0–20 cm20–55 cm)	C/N	-	Optimum	5	30	12			x	Hoffmann (2005)
Soil pH (0–20 cm, 20–55 cm)	pH	-	Optimum	4.5	9.0	6.5	x		x	Karlen et al. (1994a)
Electric conductivity (0–20 cm, 20–55 cm)	EC	μs cm^{-1}	Less is better	2000	8000	-	x			Karlen et al. (1994a)
Cation exchange capacity (0–5 cm)	CEC	mMol kg^{-1}	Less is better	50	150	-			x	Karlen et al. (1994a)
Biological indicators										
Soil Organic Carbon (0–20 cm, 20–55 cm)	SOC	Mg ha^{-1}	More is better	15	90	-	x	x	x	Hussain et al. (1999)

Linear SSF: Linear Standardized Scoring Function, LTS: Lower Threshold, UTS: Upper threshold, O: Optimum threshold.

2.4. Statistical analyses

Statistical analyses were conducted using R software developed by the Rstudio Team in 2020 (http://www.rstudio.com/; accessed August 15, 2022) (RStudio Team, 2020). Shapiro-Wilk test was applied to determine normality of the datasets. The impacts (significance, $p<0.05$) of the long-term management practices on soil health were assessed by two-way ANOVA. Tukey's least significant difference post hoc test was used where the two-way ANOVA showed significant differences ($p<0.05$) to compare the three tillage systems. Pearson correlation was used to assess correlations among the normally distributed soil properties and relative crop yields between 0 and 20 cm and 20–55 cm datasets; the "corrplot" package was used to detect and visualise correlations. Temporal conditions' changes between 2002 and 2021 were assessed by paired t-test and Wilcoxon-test. The "ggplot2", "dplyr", and "ggpubr" packages were used to generate the boxplot graphs for the Soil Quality Indices. Radar graphs were used to illustrate the effects of soil quality indicators in the SMAF.

3. Results

3.1. Holistic soil health assessment

The three functional indices (productivity, storage, and filter) indicate an increase of the soil quality, between 0 and 20 cm; where SQI increased from 0.56 to 0.59 in CT, from 0.60 to 0.68 in MT, and from 0.56 to 0.70 in NT experiments since 2002 respectively (Fig. 4). The productivity, storage and filter functions contributed at a different level in the tested treatments. In the soil depth between 0 and 20 cm the indicators of the productivity function contributed 33 % (CT), 34 % (MT), and 34 % (NT) to the overall soil quality. While, in 2002, the contribution of the productivity function to the SQI was 35 % (CT), 34% (MT), and 34 % (NT). The contribution of the storage function slightly reduced under the three tillage practices compared to 2002; from 32 % to 29 % under CT and MT, and from 33 % to 30 % under NT. The filter function increased from 33 % to 38 % under CT, from 34 % to 37 % under MT, and from 33 % to 36 % under NT (Fig. 5).

Soil quality improved also below 20 cm in all three function indices under the three tillage systems compared to 2002. The largest improvement was evident under NT practice, where the SQI increased from 0.43 to 0.63 (Fig. 4). The productivity function indicators

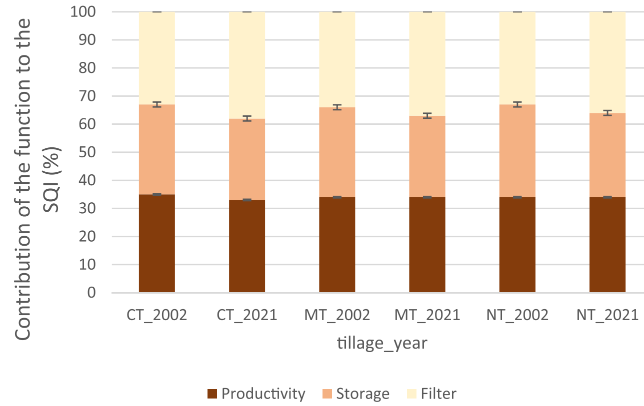

Fig. 5. Contribution (%) of productivity, storage, and filter functions to the soil quality index (SQI) between 0 and 20 cm in the first – and second comprehensive monitoring in 2002 and 2021 under the three applied tillage systems.

dominated the contributed to the SQI below 20 cm soil depth: in 2002, the productivity function contributed 37 % (CT), 38 % (MT), and 43 % (NT) to the SQI. In 2021, they contributed 37 % (CT), 36 % (MT), and 38 % (NT) to the SQI (Fig. 5). Storage function increased from 26 % to 34 % under NT since 2002. The indicators of the filter function have minorly changed since the last monitoring (Fig. 6).

According to the comparison of the soil quality indicators between 0 and 20 cm, 8 out of 12 indicators were remarkably affected by the tillage systems. SOC has increased significantly in MT and NT experiments since 2002, visualized through the radar graphs (Fig. 7). WHC,

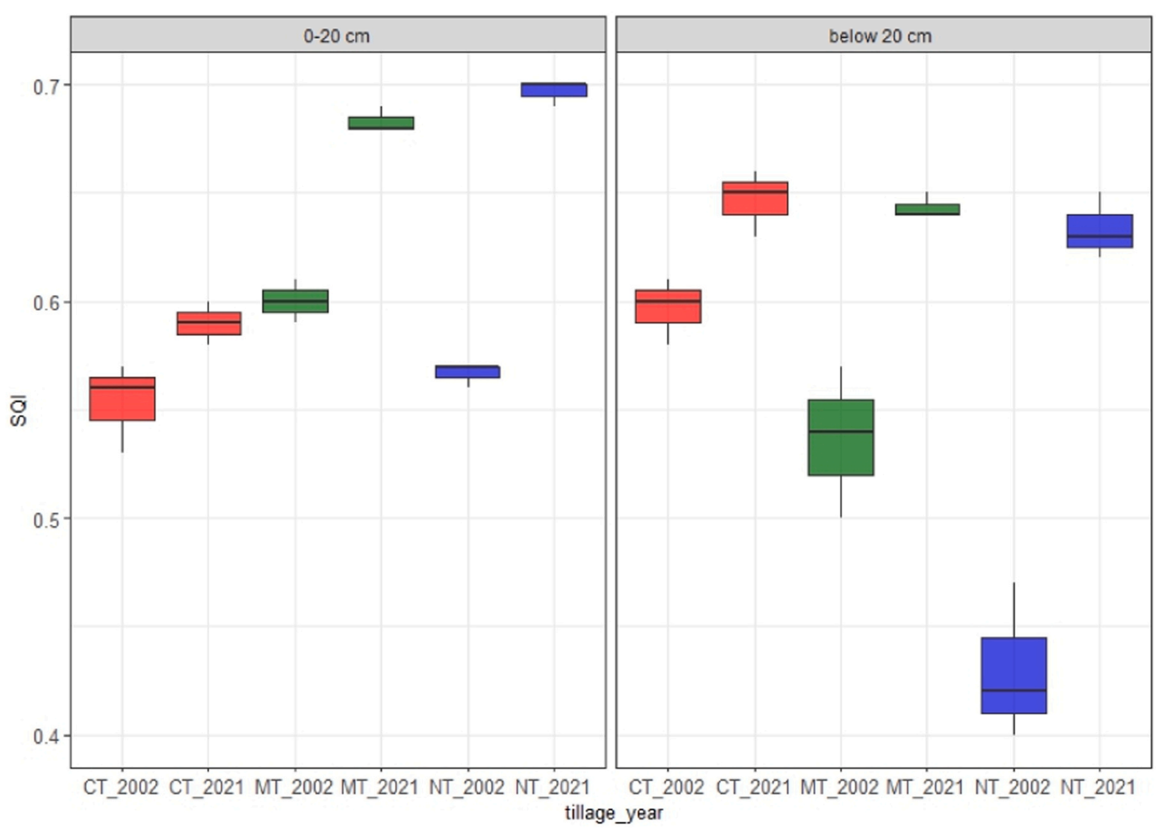

Fig. 4. Calculated Soil Quality Index (SQI) values in 2002 and 2021 between 0 and 20 cm (left), and below 20 cm (right) under the applied tillage systems and the year of monitoring (tillage_year). CT_2002: SQI value onventional tillage (CT) for the first comprehensive sampling in 2002. CT_2021: SQI value under conventional tillage (CT) for the second comprehensive sampling in 2021. MT_2002: SQI value under mulch tillage (MT) for the first comprehensive sampling in 2002. MT_2021: SQI value under mulch tillage (MT) for the second comprehensive sampling in 2021. NT_2002: SQI value under no-till (NT) for the first comprehensive sampling in 2002. NT_2021: SQI value under no-till (NT) for the second comprehensive sampling in 2021.

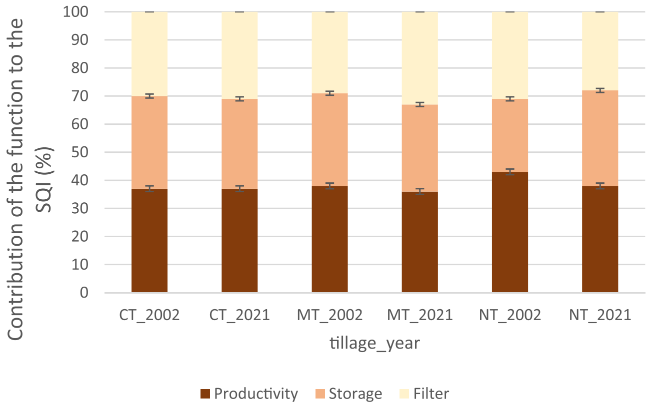

Fig. 6. Contribution (%) of productivity, storage, and filter functions to the soil quality index (SQI) below 20 cm in the first – and second comprehensive monitoring in 2002 and 2021 under the three applied tillage systems.

CP, and Ksat showed noticeable improvement compared to 2002 under MT and NT. From the chemical indicators, CEC showed an increase under the three tillage systems, and Total N showed improvement only under NT. SOC increased under MT and NT below 20 cm. Total N and C/N-ratio increased under CT and MT and remained stable over time in NT experiments. Below 20 cm, we observed significant changes on 3 indicators from the 11 determined indicators (Fig. 7). Long-lasting impacts of tillage methods on the chosen soil quality indicators were compared in the two established depths in accordance with the newly measured data from 2021 on the Fig. 8.

3.2. Management impacts

Tillage affected WHC, BD, and TP values between 0 and 20 cm (Table A.2), also AS between 0 and 5 cm, although not statistically significance. $CaCO_3$ content revealed significant differences among the tillage systems in the two layers. Tukey's test indicated significantly different $CaCO_3$ content between CT and MT and between CT and NT. CT had a relatively large $CaCO_3$ content in the 0–20 cm layer (20.8 %) compared to MT (10.9 %) and NT (9.9 %). Below 20 cm, the $CaCO_3$ content and pH showed significant differences among the tillage systems; tillage also slightly impacted the coarse pores, and C/N ratio values (Table A.3). Despite the minor differences between the pH values of CT (8.2) and NT (8.5), Tukey's also showed significance for pH likewise.

Tillage had a significant impact on SOC contents between 0 and 20 cm. Tukey's test showed that reduced-tilled (MT) and no-tilled (NT) soils had significantly larger SOC content reaching 1.4 % for MT and 1.5 % for NT compared to 0.9 % for CT (Table A.4). The tillage system significantly influenced SOC, which had a positive correlation with the Total N (0.62) and SOM (0.71) in the 0–20 cm depth. SOC also had a negative correlation with the $CaCO_3$ (-0.79) and the relative crop yield data between 1994 and 2021 (-0.73). Relative crop yield also revealed a positive correlation with $CaCO_3$ (0.94) in the 0–20 cm depth. Soil pH significantly differed among the tillage practices below 20 cm; it correlated with the relative crop yield (-0.70) between 20 and 55 cm (Table A.5, Table A.6). Relative crop yield set as 100 % for CT performed at 95 % and 92 % in MT and NT respectively.

3.3. Temporal conditions

Five out of the fifteen indicators changed significantly through conventional tillage in the 0–20 cm depth since 2002; bulk density (from 1.24 to 1.45 g cm^{-3}) increased, while total porosity decreased (from 53.18 % to 45.47 %), and aggregate stability (from 25.04 % to 21.52 %) decreased. The three tillage systems significantly affected Total N and SOC between 0 and 20 cm (Table A.7). Total N increased significantly in all three tillage experiments in the 0–20 cm depth, and the below 20 cm layer. It increased from 0.09% to 0.21% in CT, from 0.09 % to 0.22 % in

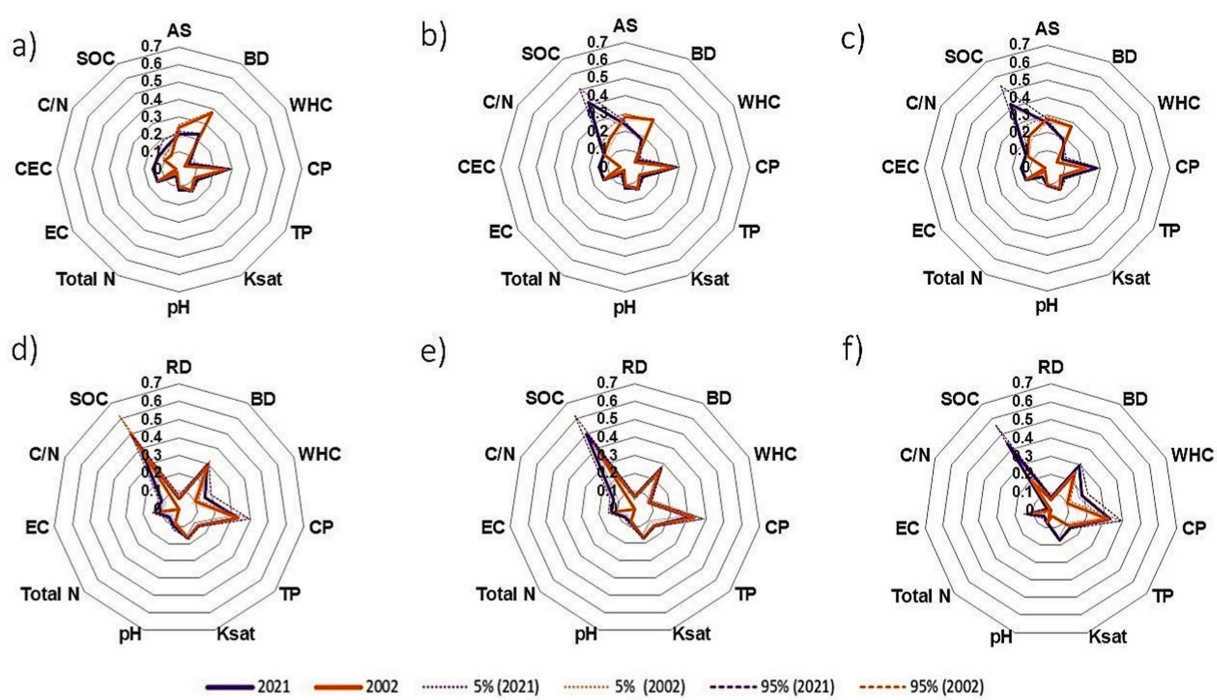

Fig. 7. a-c) comparison of the normalized values of the evaluated soil quality indicators between 0 and 20 cm in 2002 and 2021 with conventional tillage, mulch tillage and no-till, d – e) comparison of the normalized values of the evaluated soil quality indicators below 20 cm in 2002 and 2021 with conventional tillage, mulch tillage, and no-till; where AS – aggregate stability, BD- bulk density, WHC- water holding capacity, CP- coarse pores, TP – total porosity, Ksat – saturated hydraulic conductivity, pH – soil pH, Total N- total nitrogen, EC – electric conductivity, CEC – cation exchange capacity, C/N – C/N ratio, SOC – soil organic carbon, RD – maximum rooting depth; SQI-values, 2002 and 2021: median values, 5 %: 5th percentile, 95 %: 95th percentile.

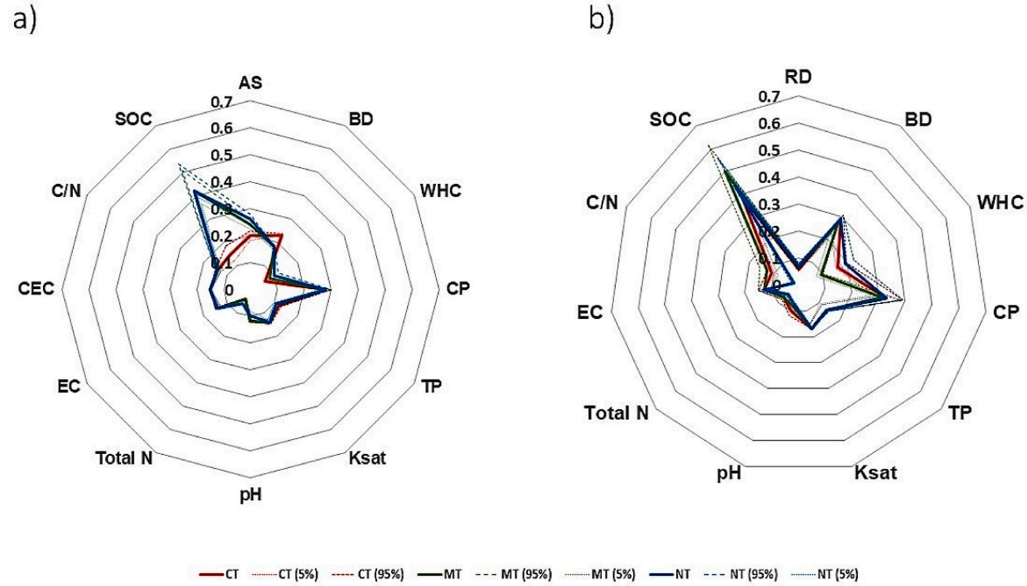

Fig. 8. a) comparison of the normalized values of the evaluated soil quality indicators in 2021 between 0 and 20 cm (left), b) comparison of the normalized values of the soil quality indicators in 2021 below 20 cm (right); where AS – aggregate stability, BD- bulk density, WHC- water holding capacity, CP- coarse pores, TP – total porosity, Ksat – saturated hydraulic conductivity, pH – soil pH, Total N- total nitrogen, EC – electric conductivity, CEC – cation exchange capacity, C/N – C/N ratio, SOC – soil organic carbon, RD – maximum rooting depth; SQI-values, 2002 and 2021: median values, 5 %: 5th percentile, 95 %: 95th percentile.

MT, and from 0.10 % to 0.23 % in NT experiments between 0 and 20 cm. And, it increased from 0.04 % to 0.16 % in CT, from 0.03 to 0.16 in MT, and from 0.04 % to 0.13 % in NT (Table A.8). Accordingly, Total N increased from 2 to 6 Mg N ha^{-1} (CT), from 2 to 7 Mg N ha^{-1} (MT), and from 3 to 7 Mg N ha^{-1} (NT) between 0 and 20 cm. Below 20 cm, the significant increase was from 2 to 8 Mg N ha^{-1} (CT), from 1 to 8 Mg N ha^{-1} (MT), and from 2 to 7 Mg N ha^{-1} (NT). SOC significantly changed under MT and NT. SOC content increased from 1.03 % to 1.43 % under MT and from 1.06 % to 1.51 % under NT between 0 and 20 cm. Accordingly, SOC increased from 28 to 44 Mg C ha^{-1} (MT), 30–46 Mg C ha^{-1} (NT), and 22–26 Mg C ha^{-1} (CT).

4. Discussion

4.1. Holistic soil health assessment

The case study carried out on a silt loam in lower Austria confirms several long-term tillage impacts on soil health. Investigating the long-term impacts on soil health was possible because a study by Hoffmann (2005) applied the same soil quality indicators nearly two decades ago. And, our solid cooperation with the local agricultural school and their accurate management of the plots since 1994 made our study attainable and unique in the Pannonian region. The two-decadal monitoring experiment found that overall soil quality improved in the upper 20 cm soil layers under all three applied tillage practices. Although there is no standard for SQI classification and weighing procedures (Fernandes et al., 2011), the SQI approach can be utilized for interpreting and inter-comparing different soil management practices affected by similar climatic, soil and other local-environmental conditions. Our study showed that the largest soil quality improvement was achieved under NT in the upper soil layer, conducting minimum soil disturbance (direct seeding) and maintaining a dense surface cover. Hussain et al. (1999) reported comparable SQI values after an eight-years tillage experiment in Illinois; their study was carried out with no-till (NT), chisel plough (CP), and mouldboard plough (MP) on a silt loam soil with soybean and corn rotations. Their study reported SQI values of 0.57 for NT in the upper (0–15 cm) soil layer, which was lower than the corresponding value found in our study (0.69). Still, if we evaluate the SQI value after eight years of NT conversion in 2002, our SQI value (0.56) was similar to southern Illinois. Chisel and mouldboard-ploughed soils in Illinois had a lower SQI than our study site's mouldboard ploughed CT practice; SQI was 0.34, 0.23 under CP and MP in southern Illinois, which is lower than both SQI values in 2002 and 2021 found in Lower Austria. Our overall SQI result achieved through NT also matches the findings of Karlen et al. (1994b) on a silt loam soil in Wisconsin. They observed that ploughed (0.48) and chiselled (0.49) soils had lower soil quality compared to no-tilled (0.68) after 12 years. The mean annual precipitation in Illinois and Wisconsin was nearly double as high as in Lower Austria, however, that did apparently not affect the trends of CT versus NT practices using the SQI evaluation method.

In the 0–20 cm soil depth, the crop productivity function slightly decreased from 35% to 33% under CT, which suggests that some indicators were sensitive to the intense tillage procedures applied (such as AS, WHC, and SOC). BD declined under CT treatment since the initial monitoring pursued in 2002, which might be caused by soil erosion, and the relatively low amount of soil organic matter. The storage function of the SQI is mainly based on soil physical indicators sensitive to tillage (such as AS, and WHC) as well as compaction (such as BD). However, the large (approximately 30%) contributions of the crop productivity and water storage functions to the overall SQI suggests that the Mistelbach soils might still store and supply adequate amounts of water and nutrients to sustain the crop production at the study site under the actual conditions.

The environmental filter function's indicators contributed the largest share of the SQI between 0 and 20 cm. It suggests that the chemical indicators (such as pH, EC, and CEC) of the filter function were not sensitive to the continuous tillage and the observed soil compaction. The productivity function's indicators contributed the largest degree to the SQI below 20 cm. However, the contribution of the productivity function to the SQI was less in 2021 than it was in 2002. Although the difference was not significant, it suggests that most of the productivity indicators such as pH, EC, CP, RD, and Total N did not contribute to raising the quality of the soil in the calcareous C-horizon. Others, such as BD showed a decrease even in the deeper layers, which also contributed to this result.

4.2. Management impacts

We particularly observed the beneficial impacts of long-lasting conservation tillage practices (i.e. MT and NT) on SOC between 0 and 20 cm. This is consistent with research from other countries, such as conducted by McVay et al. (2006) observing comparable trends in the topsoil (0–20 cm) among NT and CT practices in five different study sites on silt loam soils under different cropping systems in Kansas. They observed an increase in SOC under NT (35.0 Mg ha^{-1}) compared to CT (41.8 Mg ha^{-1}) between 0 and 20 cm after 17 years of no-till system under wheat-grain sorghum fallow cropping system. Liu et al. (2014) also found significantly increased SOC content after 17 years of NT compared to CT between 0 and 20 cm soil depths on a silt loam soil in Linfen Country northern China, where the mean annual precipitation was approximately 550 mm and winter wheat was the cover crop. After 17 years of treatments, the SOC content was 25.4 Mg ha^{-1} with NT, and 17.7 Mg ha^{-1} with CT. Stockfisch et al. (1999) observed similar trends even in deeper layers in Germany comparable to our study. After utilizing mulch tillage and conventional tillage practices for 20 years in a silt loam soil in Göttingen with maize, winter wheat, and winter barley, they observed 12 g kg^{-1} SOC (CT), and 17.5 g kg^{-1} SOC (MT) between 0 and 20 cm.

In our study, MT and NT practices enhanced aggregate stability which is likely related with the protective surface cover particularly during winter, the reduced soil disturbance, as well as most likely an increased microbial activity (not measured). The relation between SOC and AS under reduced/no tillage is also supported by findings of Tisdall and Oades (1980), Martens (2000), and Kasper et al. (2009).

WHC is not significantly affected by tillage, however, it was higher under NT compared to CT between 0 and 20 cm, especially at the top-layer (0 and 5 cm) due to the covered soil surface. (Table A.2). As claimed by Minasny and McBratney (2017), conservation tillage practices might have a positive influence on WHC due to the high SOC content in the topsoil.

Under CT, mixing of the deeper calcareous layers and the remarkably higher soil erosion may have caused high-carbonate concentrations in the subsoil. Between 1997 and 2003, the recorded soil loss at the experimental site was 33.3 Mg ha^{-1} yr^{-1} under CT, 4.0 Mg ha^{-1} yr^{-1} under MT, and 2.2 Mg ha^{-1} yr^{-1} under NT (Klik and Rosner, 2020). Larger carbonate concentrations under CT are in agreement with the findings of Papiernik et al. (2005) claiming that tillage influences soil erosion which in turn can affect the soil surface's $CaCO_3$ content. The long-term intense tillage caused a continuous decay of the aggregate structure that might have stimulated the leaching of $CaCO_3$ to the deeper layers over the years. Boix-Fayos et al. (2001) concluded that, under certain conditions, macro aggregate stability can be enhanced through carbonates when SOC is low. However, large carbonate concentrations in the silt fraction commonly decrease aggregation (Dimoyiannis et al., 1998) particularly those of micro aggregates (Boix-Fayos et al., 2001; Schrader and Zhang, 1997).

Due to the significant differences among the three tillage systems, SOC and the $CaCO_3$ were the indicators which showed correlations with each other and with the crop yield between 0 and 20 cm. However, these results have to be considered with caution. Homogenic preparation of conventional seedbeds can result in a high success rate (low crop failure) from the point of plant growth compared to no-till seeding practices, where seeds may be planted less favorably due to micro-topographical unsteadiness in the soil. As Mehdi et al. (1999) and Liebhard et al. (2022) pointed out, crop residues may delay crop emergence after seeding on no-till plots. However, despite the lower crop yield in NT experiments, the practice might still be economically viable due to the relatively low use of machinery. For instance, the total net-profit reported between 2011 and 2021 were € 10,497 ha^{-1} (NT), € 10,096 ha^{-1} (MT), and € 10,101 ha^{-1} (CT) (Landwirtschaftliche Fach, 2021) (https://lako.at/versuche/; accessed September 10, 2022). However, economic feasibility changes over time through e.g. changes of agricultural input costs.

Accordingly, the long-term monitoring not only concentrates on the impacts of tillage practices on soil health and soil erosion, but it also investigates the input costs and the total incomes of these practices (https://lako.at/versuche/; accessed September 10, 2022). Therefore, the experimental site will serve as an open living laboratory to jointly test the impact and applicability of conservation agriculture under actual and future conditions.

4.3. Temporal conditions

Among other impacts, frequent tillage and heavy machinery use can lead soil compaction (National Resources Conservation Service USDA, 2008) (https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health/soil-health-assessment ; accessed September 10, 2022). Our study indicated a significant increase in bulk density, and a significant decrease in total porosity under CT between 0 and 20 cm, between the two sampling periods. Severe soil erosion under CT may have also contributed to an increase in bulk density, as eroded fine particles might accumulate and seal finer soil pores. Although bulk density increased significantly, the density remains below a threshold that is considered to restrict root growth in a silt loam (<1.65 g cm^{-3}) (National Resources Conservation Service USDA, 2008) (https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health/soil-health-assessment ; accessed September 10, 2022). However, future climatic trends may lead to increased occurrence of extreme erosion events and lead to more soil pore sealing and crusting effects (Strohmeier et al., 2021). Under NT soil compaction risk seems larger in the deeper layers; high bulk densities suggest a low volume of pore space and a reduced ability to store water (Fernandes et al., 2011). Continous, long-term tillage also contributed to a significant decrease of aggregate stability under CT as also reported by Johnson and Hoyt (1999), and Balesdent et al. (2000). The significant increase of the nitrogen stocks in all depths under the three tillage must be the consequence of the continous nitrogen fertilizing in the last 30 years, combined with the relatively low levels of leaching due to the low amount of annual precipitation.

5. Conclusions

This study broke down and evaluated long-term tillage effects on soil health through parameter specific and holistic assessment procedures, evaluating the effects over time as well as comparing the different practices' impacts after multi-decadal application. The findings of our study support the hypothesis that reduced tillage generally develops soil health over time, especially in the upper soil layers. The experiment showed that soil carbon stocks significantly increased under mulch and no-tillage. No-till also fostered the development of other important soil physical functions and indicators, such as water holding capacity and aggregate stability, in the upper 0–20 cm soil layer. Opposed to that, the long-term continuous (deep)tillage destabilized soil aggregates, decreased the soil structure and resulted in substantial accumulation of $CaCO_3$ in the 0–20 cm depth under CT treatment.

The holistic soil health assessment using SQI showed significantly larger scores and increase over time through NT and MT compared to CT. All three observed tillage treatments showed slight (CT) and notable (MT and NT) overall SQI increase over the two decadal monitoring experiments. But despite the consistent enhancement of the filter functions, the SQI assessment eventually indicated a declining water storage in all treatments and particularly a decreasing crop productivity functionality under CT in the tillage layer (0–20 cm depth), which emerges sustainability concerns to be further looked at.

This research aims at serving as verification and reference to multiple positive impacts of reduced tillage under central European light soil and temperate climate conditions. The study emphasizes the importance of maintaining long-term monitoring initiatives, under welldocumented and continuous management, to investigate the indicated trends approaching towards sustainability thresholds, particularly considering new agricultural regulations and upcoming socio-environmental and climatic challenges.

CRediT authorship contribution statement

Stefan Strohmeier: Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Bano Mehdi-Schulz:** Writing – review & editing, Supervision, Methodology. **Gunther Liebhard:** Writing – review & editing, Supervision, Project administration. **Andreas Klik:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Peter Strauss:** Writing – review & editing, Supervision, Methodology. **Marton Toth:** Writing – review & editing, Writing – original draft, Methodology. **Christine Stumpp:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

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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Appendices.

Appendix 1

Table A.1
Weightings of soil quality indicators within 'G', 'W1', and 'W2' under productivity, storage, and filter functions in the two established depths (0–20 cm, and below 20 cm).

Function (depth)	Function Index	Function weight	Indicator	Indicator weights		
				G	W1	W2
Productivity (0–20 cm)	G	0.33	BD	0.143	0.150	0.125
	W1	0.40	SOC	0.143	0.125	0.200
	W2	0.40	pH	0.143	0.150	0.125
			Total N	0.143	0.150	0.125
			WHC	0.143	0.125	0.175
			EC	0.143	0.150	0.125
			CP	0.143	0.150	0.125
Storage (0–20 cm)	G	0.33	AS	0.143	0.150	0.125
	W1	0.30	TP	0.143	0.150	0.125
	W2	0.30	BD	0.143	0.150	0.125
			Total N	0.143	0.150	0.125
			SOC	0.143	0.125	0.200
			WHC	0.143	0.125	0.175
			Ksat	0.143	0.150	0.125
Filter (0–20 cm)	G	0.33	AS	0.143	0.150	0.125
	W1	0.30	CP	0.143	0.150	0.150
	W2	0.30	SOC	0.143	0.125	0.150
			CEC	0.143	0.150	0.150
			BD	0.143	0.125	0.175
			pH	0.143	0.150	0.125
			C/N	0.143	0.150	0.125
Productivity (below 20 cm)	G	0.33	RD	0.125	0.150	0.100
	W1	0.40	BD	0.125	0.100	0.100
	W2	0.40	SOC	0.125	0.100	0.175
			pH	0.125	0.150	0.100
			Total N	0.125	0.100	0.175
			WHC	0.125	0.100	0.150
			EC	0.125	0.150	0.100
			CP	0.125	0.150	0.100
Storage (below 20 cm)	G	0.33	TP	0.166	0.175	0.125
	W1	0.30	BD	0.166	0.200	0.125
	W2	0.30	Total N	0.166	0.150	0.200
			SOC	0.166	0.150	0.200
			WHC	0.166	0.150	0.200
			Ksat	0.166	0.175	0.150
Filter (below 20 cm)	G	0.33	CP	0.200	0.250	0.175
	W1	0.30	SOC	0.200	0.150	0.250
	W2	0.30	BD	0.200	0.225	0.150

(*continued on next page*)

Table A.1 (*continued*)

Function (depth)	Function Index	Function weight	Indicator		Indicator weights	
			pH	0.200	0.225	0.175
			C/N	0.200	0.150	0.250

AS: aggregate stability, RD: maximum rooting depth, BD: bulk density, CP: coarse pores, TP: total porosity, Ksat: saturated hydraulic conductivity, WHC: water holding capacity, Total N: total nitrogen, C/N: C/N ratio, SOC: soil organic carbon, pH: soil pH, EC: electric conductivity, CEC: cation exchange capacity

Appendix 2

Table A
Mean values and their standard deviations of soil physical indicators from the sampling campaign in 2021. The table contains the mean values from three repetitions, and the results of two-way ANOVA between 0 and 20 cm, and 20 cm below.

Depth/Tillage	Soil physical indicators						
0-5 cm	*BD (g cm^{-3})*	*TP (%)*	*Ksat (m d^{-1})*	*CP (%)*	*WHC (%)*	*Sand (%)*	*Clay (%)*
Conventional tillage	1.32 ± 0.00	50.19 ± 0.01	1.32 ± 1.68	17.87 ± 10.80	15.94 ± 0.18	7.62 ± 2.20	25.98 ± 1.31
Mulch tillage	1.50 ± 0.02	43.59 ± 0.80	8.43 ± 10.03	10.59 ± 2.47	16.03 ± 0.23	7.24 ± 1.42	25.92 ± 0.99
No-till	1.53 ± 0.14	42.20 ± 5.43	1.27 ± 1.59	14.43 ± 6.31	19.26 ± 2.92	8.46 ± 1.59	25.69 ± 0.91
10–15 cm							
Conventional tillage	1.57 ± 0.01	40.76 ± 0.53	3.29 ± 2.58	8.98 ± 6.04	13.62 ± 0.10	8.41 ± 1.46	25.45 ± 0.92
Mulch tillage	1.57 ± 0.01	41.01 ± 0.18	0.79 ± 0.70	5.53 ± 1.41	14.45 ± 4.20	8.81 ± 0.57	26.15 ± 0.67
No-till	1.55 ± 0.01	41.61 ± 0.40	0.66 ± 0.06	15.07 ± 1.14	15.23 ± 2.63	7.34 ± 0.09	26.71 ± 0.91
25–30 cm							
Conventional tillage	1.53 ± 0.06	42.91 ± 2.11	5.05 ± 6.63	19.43 ± 7.09	18.05 ± 2.84	9.07 ± 2.25	25.10 ± 1.13
Mulch tillage	1.56 ± 0.01	1.98 ± 0.08	5.13 ± 6.43	8.81 ± 3.39	14.07 ± 2.72	7.61 ± 0.88	26.37 ± 0.78
No-till	1.48 ± 0.13	45.03 ± 5.10	1.12 ± 0.21	17.88 ± 9.62	17.65 ± 0.47	7.71 ± 1.15	27.32 ± 1.66
50–55 cm							
Conventional tillage	1.43 ± 0.03	46.65± 1.05	0.74 ± 0.66	35.91 ± 3.42	24.64 ± 2.91	6.22 ± 0.39	21.95 ± 0.81
Mulch tillage	1.40 ± 0.01	47.82 ± 0.44	12.01 ± 0.24	20.53 ± 11.84	17.63 ± 2.21	6.25 ± 1.31	22.97 ± 2.55
No-till	1.43 ± 0.06	46.70 ± 2.02	6.38 ± 2.02	33.17 ± 7.48	28.40 ± 6.46	6.48 ± 1.15	19.75 ± 0.25
70–75 cm							
Conventional tillage	1.40 ± 0.09	47.95 ± 3.43	14.93 ± 18.66	-	-	-	-
Mulch tillage	1.48 ± 0.00	44.97 ± 0.26	2.77 ± 2.67	-	-	-	-
No-till	1.45 ± 0.08	45.90 ± 3.16	4.27 ± 5.07	-	-	-	-
Two-way ANOVA 0–20 cm							
Tillage	0.12	0.19	n.a.	0.23	0.35	n.a.	0.80
Depth	0.02*	0.24	n.a.	0.30	0.09	n.a.	0.70
Tillage x Depth	0.07	0.60	n.a.	0.54	0.76	n.a.	0.59
Two-way ANOVA 20–75 cm							
Tillage	0.77	0.34	n.a.	0.11	0.05*	0.73	0.46
Depth	0.07	0.68	n.a.	0.02*	0.01*	0.05*	<0.01**
Tillage x Depth	0.63	0.85	n.a.	0.91	0.39	0.64	0.11

BD: bulk density, TP: total porosity, Ksat: saturated hydraulic conductivity, CP – coarse pores, WHC: water holding capacity, ±: standard deviation, n.a.: not analyzed (data were not normally distributed for Shapiro-Wilk test), *: significant ($0.01<p<0.05$), **: strongly significant ($p<0.01$). Maximum rooting depth (RD) was measured in the soil profiles under conventional tillage (CT), mulch tillage (MT), and no-till (NT), however, the measured values were not significantly different from each other (0–100 cm): 78 cm (CT), 80 cm (MT), 82.5 cm (NT).

Appendix 3

Table A.3
Mean values and their standard deviations of the selected soil chemical indicators from the sampling campaign in 2021. The table contains the mean values of two measurements, and the results of the two-way ANOVA in the 0–20 cm, and 20 cm below depths.

Depth/Tillage	Soil chemical indicators						
0-5 cm	*Total C (%)*	*Total N (%)*	*C/N*	*$CaCO_3$ (%)*	*pH*	*EC (μS cm^{-1})*	*CEC (Mmol kg^{-1})*
Conventional tillage	2.92 ± 0.32	0.22 ± 0.01	13.25 ± 1.44	20.43 ± 1.28	8.03 ± 0.28	196.40 ± 23.48	19.95 ± 1.06
Mulch tillage	3.05 ± 0.47	0.22 ± 0.01	13.53 ± 1.65	10.95 ± 1.53	7.97 ± 0.15	243.20 ± 77.50	20.30 ± 1.70
No-till	3.33 ± 0.27	0.24 ± 0.01	13.87 ± 0.30	10.36 ± 0.49	8.06 ± 0.05	212.00 ± 4.24	19.95 ± 1.63
10–15 cm							
Conventional tillage	2.93 ± 0.30	0.20 ± 0.01	15.04 ± 2.11	21.09 ± 2.20	8.04 ± 0.27	186.85 ± 2.62	20.40 ± 0.99
Mulch tillage	2.94 ± 0.56	0.21 ± 0.04	14.00 ± 0.16	10.80 ± 0.25	8.10 ± 0.14	224.20 ± 69.01	19.30 ± 0.28
No-till	2.71 ± 0.57	0.21 ± 0.01	12.82 ± 1.87	9.44 ± 0.15	8.21 ± 0.01	197.40 ± 27.72	20.00 ± 2.40
25–30 cm							
Conventional tillage	2.87 ± 0.30	0.18 ± 0.00	15.50 ± 1.01	20.87 ± 0.78	8.12 ± 0.18	171.35 ± 4.45	19.55 ± 1.34
Mulch tillage	2.57 ± 0.27	0.18 ± 0.01	13.93 ± 1.98	11.16 ± 0.55	8.23 ± 0.10	165.70 ± 4.67	19.00 ± 0.14
No-till	3.31 ± 0.45	0.16 ± 0.07	23.98 ± 12.76	22.96 ± 0.37	8.44 ± 0.15	143.25 ± 10.96	15.70 ± 1.84
50–55 cm							

(*continued on next page*)

Table A.3 (*continued*)

Depth/Tillage	Soil chemical indicators						
0-5 cm	*Total C (%)*	*Total N (%)*	*C/N*	*$CaCO_3$ (%)*	*pH*	*EC ($\mu S\ cm^{-1}$)*	*CEC (Mmol kg^{-1})*
Conventional tillage	3.45 ± 0.16	0,14 ± 0.00	25.53 ± 0.13	22.02 ± 0.45	8.25 ± 0.14	129.10 ± 9.90	13.55 ± 1.20
Mulch tillage	3.40 ± 0.11	0,15 ± 0.00	23.50 ± 1.93	22.35 ± 0.73	8.40 ± 0.04	140.75 ± 3.46	12.80 ± 0.00
No-till	3.37 ± 0.13	0,11 ± 0.02	31.80 ± 9.40	22.86 ± 0.69	8.56 ± 0.18	141.1 ± 29.84	13.35 ± 0.35
Two-way ANOVA 0–20 cm							
Tillage	n.a.	0.51	0.30	<0.01**	0.69	0.45	n.a.
Depth	n.a.	0.09	0.23	0.85	0.37	0.59	n.a.
Tillage x Depth	n.a.	0.81	0.93	0.68	0.85	0.99	n.a.
Two-way ANOVA 20–55 cm							
Tillage	0.25	0.34	0.19	<0.01**	0.05*	0.54	n.a.
Depth	0.02*	0.04*	0.05*	<0.01**	0.13	0.03*	n.a.
Tillage x Depth	0.19	0.95	0.97	<0.01**	0.97	0.20	n.a.

Total C: total carbon, total N: total nitrogen, C/N: C/N ratio, $CaCO_3$: calcium carbonate, pH: soil pH, EC: electric conductivity, CEC: cation exchange capacity, ±: standard deviation, n.a.: not analysed (data were not normally distributed for Shapiro-Wilk test), *: significant (0.01<p<0.05), **: strongly significant (p<0.01)

Appendix 4

Table A.4
Mean values form two repetitions of the selected biological indicators, and their standard deviations of the selected soil biological indicators from the sampling campaign in 2021. The table contains the results of the two-way ANOVA in the 0–20 cm, and 20 cm below depths.

Depth/Tillage	Soil biological indicators			
0-5 cm	SOC (%)	SOM (%)	DHY (μg TPF g^{-1} 16 h^{-1})	SR (CO_2 100 g TS^{-1} 24 h^{-1})
Conventional tillage	0.87 ± 0.25	6.65 ± 0.22	14.16 ± 4.48	5.15 ± 0.81
Mulch tillage	1.49 ± 0.11	7.10 ± 0.14	54.70 ± 45.79	7.56 ± 3.29
No-till	1.79 ± 0.16	7.85 ± 0.16	15.41 ± 5.93	3.72 ± 0.93
10–15 cm				
Conventional tillage	0.92 ± 0.43	6.56 ± 0.18	9.01 ± 2.04	6.88 ± 5.05
Mulch tillage	1.38 ± 0.20	6.75 ± 0.40	10.55 ± 8.51	2.99 ± 0.82
No-till	1.23 ± 0.08	6.39 ± 0.46	2.50 ± 5.14	2.33 ± 0.95
25–30 cm				
Conventional tillage	0.89 ± 0.44	6.07 ± 0.04	6.12 ± 2.44	2.59 ± 0.07
Mulch tillage	0.95 ± 0.13	5.73 ± 0.21	4.02 ± 1.29	2.41 ± 0.38
No-till	0.93 ± 0.06	5.36 ± 0.00	4.34 ± 0.11	3.16 ± 1.37
50–55 cm				
Conventional tillage	0.61 ± 0.11	4.13 ± 0.58	2.01 ± 0.44	0.81 ± 0.23
Mulch tillage	0.81 ± 0.01	4.08 ± 0.00	1.85 ± 0.21	0.98 ± 0.66
No-till	0.76 ± 0.06	4.22 ± 0.46	-0.29 ± 1.12	1.39 ± 0.54
Two-way ANOVA 0–20 cm				
Tillage	0.01*	0.17	n.a.	0.09
Depth	0.17	0.02*	n.a.	0.02*
Tillage x Depth	0.23	0.06	n.a.	0.58
Two-way ANOVA 20–55 cm				
Tillage	0.65	0.42	n.a.	n.a.
Depth	0.13	<0.01**	n.a.	n.a.
Tillage x Depth	0.87	0.27	n.a.	n.a.

SOC: soil organic carbon, SOM: soil organic matter, DHY: dehydrogenase activity, SR: soil respiration, ±: standard deviation, n.a.: not analysed (data were not normally distributed for Shapiro-Wilk test), *: significant (0.01<p<0.05), **: strongly significant (p<0.01).

Appendix 5

Table A.5
Pearson correlation matrix values among the normally distributed soil indicators and relative crop yield data (RCY) between 0 and 20 cm (p-values in bracket).

	Total N	C/N	SOC	SOM	$CaCO_3$	pH	EC	BD	Clay	TP	CP	WHC	RCY
Total N	-												
C/N	-0.15												
	(0.65)												
SOC	0.62	-0.25											
	(0.03)	(0.43)											
SOM	0.71	-0.11	0.71										
	(0.01)	(0.74)	(0.01)										
$CaCO_3$	-0.38	0.31	-0.79	-0.37									
	(0.23)	(0.32)	(>0.01)	(0.24)									
pH	0.27	-0.43	0.33	0.03	-0.33								
	(0.40)	(0.17)	(0.29)	(0.92)	(0.29)								

(*continued on next page*)

Table A.5 (*continued*)

	Total N	C/N	SOC	SOM	$CaCO_3$	pH	EC	BD	Clay	TP	CP	WHC	RCY
EC	0.61 (0.03)	0.32 (0.31)	0.41 (0.19)	0.28 (0.38)	-0.36 (0.26)	0.11 (0.74)							
BD	-0.29 (0.36)	0.17 (0.60)	0.39 (0.21)	-0.04 (0.89)	-0.41 (0.18)	0.17 (0.60)	0.08 (0.81)						
Clay	-0.26 (0.42)	-0.82 (<0.01)	0.17 (0.59)	-0.29 (0.52)	-0.29 (0.36)	0.39 (0.21)	-0.47 (0.13)	0.19 (0.55)					
TP	0.28 (0.38)	-0.18 (0.58)	-0.40 (0.25)	0.04 (0.91)	0.41 (0.19)	-0.17 (0.61)	-0.09 (0.79)	-1.00 (<0.01)	-0.19 (0.55)				
CP	0.12 (0.71)	0.08 (0.80)	-0.36 (0.25)	-0.00 (1.00)	0.19 (0.56)	-0.44 (0.15)	-0.15 (0.65)	-0.59 (0.04)	-0.36 (0.25)	0.59 (0.04)			
WHC	0.92 (<0.01)	0.04 (0.91)	0.51 (0.89)	0.69 (0.01)	-0.30 (0.34)	0.10 (0.75)	0.44 (0.15)	-0.31 (0.33)	-0.43 (0.17)	0.30 (0.35)	0.36 (0.24)		
RCY	-0.35 (0.26)	0.26 (0.41)	-0.73 (<0.01)	-0.39 (0.21)	0.94 (<0.01)	-0.25 (0.44)	-0.21 (0.52)	-0.44 (0.17)	-0.25 (0.44)	0.42 (0.17)	0.02 (0.95)	-0.39 (0.21)	-

Total N: total nitrogen (%), C/N: C/N ratio, SOC: soil organic carbon (%), SOM: soil organic matter (%), $CaCO_3$: calcium carbonate (%), pH: soil pH, EC: electric conductivity ($\mu S\ cm^{-1}$*), BD: bulk density (*$g\ cm^{-3}$*), Clay: clay content (%), TP: total porosity (%), CP: coarse pores (%), WHC: water holding water capacity (%), RCY: relative crop yield (%). RCY data was used as an average value under CT (100%), MT (95%), and NT (92%) between 1994 and 2021.*

Appendix 6

Table A.6
Pearson correlation matrix values among the normally distributed soil indicators and relative crop yield data (RCY) between 20 and 55 cm (p-values in bracket).

	Total N	C/N	SOC	SOM	$CaCO_3$	pH	EC	BD	Clay	TP	CP	WHC	RCY
Total N	-												
CN	-0.97 (<0.01)												
SOC	0.42 (0.17)	-0.44 (0.14)											
SOM	0.63 (0.03)	-0.56 (0.06)	0.49 (0.10)										
$CaCO_3$	-0.48 (0.11)	0.56 (0.06)	-0.26 (0.42)	-0.49 (0.10)									
pH	-0.72 (<0.01)	0.76 (<0.01)	0.01 (0.98)	-0.47 (0.12)	0.37 (0.24)								
EC	0.73 (<0.01)	-0.81 (<0.01)	0.54 (0.07)	0.68 (0.02)	-0.48 (0.11)	-0.59 (0.04)							
BD	0.76 (<0.01)	-0.70 (0.01)	0.56 (0.06)	0.76 (<0.01)	-0.58 (0.05)	-0.42 (0.17)	0.59 (0.04)						
Clay	0.54 (0.07)	-0.50 (0.10)	0.55 (0.07)	0.69 (0.01)	-0.41 (0.19)	0.24 (0.46)	0.41 (0.19)	0.43 (0.16)					
TP	-0.76 (<0.01)	0.71 (0.01)	-0.56 (0.06)	-0.75 (<0.01)	0.58 (0.05)	0.44 (0.16)	-0.60 (0.04)	-1.00 (<0.01)	-0.43 (0.17)				
CP	-0.75 (<0.01)	0.73 (<0.01)	-0.68 (0.01)	-0.55 (0.07)	0.55 (0.06)	0.32 (0.32)	-0.64 (0.03)	-0.57 (0.52)	-0.59 (0.04)	0.58 (0.05)			
WHC	-0.68 (0.02)	0.72 (<0.01)	-0.63 (0.03)	-0.53 (0.08)	0.48 (0.11)	0.48 (0.11)	-0.64 (0.03)	-0.37 (0.24)	-0.73 (<0.01)	0.37 (0.23)	0.85 (<0.01)		
RCY	0.28 (0.38)	-0.34 (0.28)	-0.24 (0.46)	0.15 (0.64)	-0.06 (0.87)	-0.70 (0.01)	0.16 (0.63)	0.14 (0.66)	-0.03 (0.93)	-0.15 (0.64)	0.16 (0.63)	-0.05 (0.89)	-

Total N: total nitrogen (%), C/N: C/N ratio, SOC: soil organic carbon (%), SOM: soil organic matter (%), $CaCO_3$: calcium carbonate (%), pH: soil pH, EC: electric conductivity ($\mu S\ cm^{-1}$*), BD: bulk density (*$g\ cm^{-3}$*), Clay: clay content (%), TP: total porosity (%), CP: coarse pores (%), WHC: water holding capacity (%), RCY: relative crop yield (%). RCY data was used as an average value under CT (100%), MT (95%), and NT (92%) between 1994 and 2021.*

Appendix 7

Table A.7
Temporal effects of the tillage systems since the last monitoring (2002) in the 0–20 cm depth.

Tillage	Soil physical indicators					
	BD ($g\ cm^{-3}$)	TP (%)	Ksat ($m\ d^{-1}$)	AS (%)	CP (%)	WHC (%)
CT	*	*	ns	*	ns	ns
MT	ns	ns	ns	ns	ns	ns
NT	ns	ns	ns	ns	ns	ns
	Soil chemical indicators					
	pH	EC ($\mu S\ cm^{-1}$)	Total N (%)	Total C (%)	$CaCO_3$ (%)	C/N
CT	ns	*	**	ns	ns	ns
MT	ns	ns	**	ns	ns	ns
NT	ns	*	**	ns	ns	*
	Soil biological indicators					
	SOC (%)	SOM (%)				
CT	ns	*				
MT	*	*				
NT	**	*				

Paired t-test / Wilcoxon test results between the measured data of the two monitoring (2002–2021), where CT: conventional tillage, MT: mulch tillage, NT: no-till, BD: bulk density, TP: total porosity, Ksat: saturated hydraulic conductivity, AS: aggregate stability, CP: coarse pores, WHC: water holding capacity, pH: soil pH, EC: electric conductivity, Total N: total nitrogen, Total C: total carbon, $CaCO_3$: calcium carbonate, C/N: C/N ratio, SOC: soil organic carbon, SOM: soil organic matter, ns: not significant ($p>0.05$), *: significant ($p<0.05$), **: strongly significant ($p<0.01$). The 2002 data is cited from Johanna Hoffmann's dissertation: "Auswirkung unterschiedlicher Bodenberarbeitungssysteme auf die Bodengesundheit" (2005).

Appendix 8

Table A.8
Temporal effects of the tillage systems since the last monitoring (2002) below 20 cm.

Tillage	Soil physical indicators					
	BD (g cm^{-3})	TP (%)	Ksat (m d^{-1})	CP (%)	WHC (%)	RD (cm)
CT	ns	ns	ns	ns	ns	ns
MT	ns	ns	*	ns	ns	ns
NT	ns	ns	*	ns	*	ns
	Soil chemical indicators					
	pH	EC (µS cm^{-1})	Total N (%)	Total C (%)	$CaCO_3$ (%)	C/N
CT	**	ns	**	ns	ns	ns
MT	*	ns	**	ns	ns	ns
NT	ns	ns	*	ns	ns	ns
	Soil biological indicators					
	SOC (%)	SOM (%)				
CT	ns	ns				
MT	ns	ns				
NT	ns	ns				

Paired t-test / Wilcoxon test results between the measured data of the two monitoring (2002–2021), where CT: conventional tillage, MT: mulch tillage, NT: no-till, BD: bulk density, TP: total porosity, Ksat: saturated hydraulic conductivity, CP: coarse pores, WHC: water holding capacity, RD: maximum rooting depth, pH: soil pH, EC: electric conductivity, Total N: total nitrogen, Total C: total carbon, $CaCO_3$: calcium carbonate, C/N: C/N ratio, SOC: soil organic carbon, SOM: soil organic matter, ns: not significant ($p>0.05$), *: significant ($p<0.05$), **: strongly significant ($p<0.01$). The 2002 data is cited from Johanna Hoffmann's dissertation: "Auswirkung unterschiedlicher Bodenberarbeitungssysteme auf die Bodengesundheit" (2005).

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