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RESEARCH ARTICLE

Vineyard cover crop management strategies and their effect on soil properties across Europe

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Abstract

Vineyard soils are often of inherently poor quality with low organic carbon content. Management can improve soil properties and thus soil fertility. In European wine-growing regions, a broad range of inter-row management strategies evolved based on specific local site conditions and the varying effects of management intensities on soil, water balance, yield and grape quality. Accordingly, there is a need to investigate the effects of locally common cover crop management strategies and tillage intensity on soil organic carbon content and soil physical parameters. In this study, we investigated the impact of the most common inter-row management practices in Austria, France, Romania and Spain. In all countries, we compared paired sites. Each site with cover crops and inter-row management of low intensity was compared with one site with (temporarily) bare soil and high management intensity. All studied sites with cover crops and low management intensity, except those in Spain, had higher organic carbon contents than the paired more intensively managed vineyards. However, the highly water-limited Spanish vineyards with

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temporary cover crops had lower organic carbon contents than the paired sites with bare soil. Sites with more organic carbon had better results for bulk density, percolation stability (PS), hydraulic conductivity and available soil water, with soil hydraulic parameters being less pronounced than others. Country comparison of inter-row weed control systems showed that PS was particularly low in sampled vineyards in Romania and Spain, where weed control is based on intensive mechanical tillage. Alternating management systems with tillage every second inter-row showed a decrease in soil structure compared with permanent green cover. Thus, inter-row management with cover crops and reduced tillage increases soil organic carbon content and improves soil structure compared with bare soil management. If local constraints, such as water scarcity, do not allow year-round planting, alternating inter-row management with several years of alternating periods may be an option to mitigate those adverse effects. However, negative impact on the soil structure occurs with the very first tillage operation, whereas negative effects on the carbon balance only appear after long-term use of tillage.

KEYWORDS

alternating management, inter-row management, management intensity, soil cover, soil organic carbon, soil physical properties, tillage, vineyard soil quality

1 | INTRODUCTION

Soils with good quality and fertility, which fulfil the necessary soil functions for plant growth, are fundamental for sustainable plant production. With all efforts to further increase productivity to meet growing food demand (Van Dijk et al., 2021), soil management strategies must be adapted to preserve soil fertility and essential soil functions (Rojas et al., 2016). Soil fertility and the provision of soil functions depend on the condition of soil properties, which are strongly impacted by their use and management (Adhikari & Hartemink, 2016). It has been shown that conservation farming, including conservation tillage, cover crops and residue management, improves soil properties and sustains crop productivity (Blanco & Lal, 2023). Particularly, aggregate stability is higher because not only organic binding agents aggregate soil particles in clusters, but also other soil physical properties such as macroporosity, infiltration capability and soil water retention improve in the absence of mechanical soil disturbance and the effects of cover crops (Blanco-Canqui & Ruis, 2018, 2020). Any long-term improvement of agricultural soil functions is linked to improving soil structure. With conventional intense soil management, the temporary increase of pore space by mechanical soil loosening is cancelled by the post-tillage settlement (Sandin et al., 2017). In contrast, management in the sense of conservation agriculture with an interplay

Highlights

- Locally evolved inter-row vineyard management may often be improved regarding soil quality impacts
- Low-intensity management with cover crops improves soil structure more than hydraulic parameters
- Temporary cover cropping due to water limitation showed no positive effects on soil properties
- Alternating low-intensity inter-row management is a feasible alternative to permanent green cover

between plants, microbes and primary mineral and organic soil constituents forms a soil structure with well-connected stable biopores (Bodner et al., 2021, 2023; Vogel et al., 2022; Xiong et al., 2022). The modulation of soil physico-chemical properties and microbial communities has an impact on soil structure and further on soil functionality (Legrand et al., 2018). Conservation agriculture promotes microbial diversity (Wang et al., 2017), which does not necessarily mean that the functioning of the ecosystem is impaired due to functional redundancy in the soil microbial community (Loreau, 2004). However, conservation agriculture, in particular the reduction

of tillage, tends to promote taxonomic and functional diversity of soil life (Legrand et al., 2018). Nevertheless, the operated management systems for annual and perennial crop production have grown historically based on local possibilities and limitations.

Among the perennial cropping systems, vineyard cultivation is an important land use with economic, cultural and ecological significance worldwide (Christ & Burritt, 2013). The European Union is the world's main wine producer and accounts for the largest vine (*Vitis vinifera*) cultivation areas, with a predominant production in the Mediterranean region (Cardell et al., 2019). Accordingly, the impact of the applied vineyard management systems on maintaining soil functions and the provision of key ecosystem services in these production areas is substantial. The implementation of sustainable management in vineyards limits soil degradation processes and promotes the enrichment of soil organic carbon (Brunori et al., 2016). However, in vineyard management, the effect of commonly applied management systems on soil quality, especially on soil physical parameters, and the added value of conservation systems compared with conventional systems are not always clear, as has been found for French and Spanish vineyard regions (Gómez et al., 2014; Salomé et al., 2016). A general reason for the lack of improvement of soil quality and especially soil structure through reduced tillage intensity management is the insufficient effect of pore formation by plant roots and edaphic fauna (Wardak et al., 2022). In contrast to permanently vegetated systems, root growth and soil fauna activity is insufficient to compensate for the reduction of mechanical soil loosening (Bodner et al., 2023; Schlüter et al., 2018). This is especially applicable to vineyard management and water-limited vine production regions, where farmers cut back on the use of permanent cover crops out of concern for competing water use (Celette et al., 2008; Monteiro & Lopes, 2007; Ruiz-Colmenero et al., 2013). Careful cover crop management is needed to prevent soil erosion during heavy rainfall events on the one hand and to limit the additional water demand of cover crops on the other hand (Capó-Bauçà et al., 2019; Lopes, 2016; Novara et al., 2021). This implies different designs of cover crop management (Medrano et al., 2015). Accordingly, the range of management intensity has varying effects on soil parameters, depending on the timing, duration and implementation of soil cover and related soil management (Garcia et al., 2018; Poeplau & Don, 2015). Furthermore, management intensity is thought of differently in different wine-growing regions. In the French case study region, high management intensity usually means bare soil surface due to herbicide application without mechanical soil disturbance. Accordingly, the effects on soil physical parameters may be different from those of

bare soils obtained by mechanical tillage, often applied in other European wine regions.

Since water scarcity is an issue that significantly affects production and management in most European wine-growing regions, careful soil and cover crop management is a relevant issue not only for the well-studied Mediterranean region. In addition, farmers across Europe face further challenges related to management intensity, comprising competition for nutrients, additional costs and more difficult pest control (Stipešević & Kladičko, 2005). Particularly vineyards are often characterized by inherently shallow soils with poor organic carbon contents and located on steep and erosion-prone slopes (Coll et al., 2011; Garcia et al., 2018; Salomé et al., 2016). For instance, vineyards have the lowest soil organic carbon contents among all agriculturally used areas in Austria (Gerzabek et al., 2005). Nonetheless, vineyard management differs widely in each wine-growing region due to the downsides of low-intensity management (Zehetner et al., 2015). Accordingly, there is a need to investigate which management strategies with various intensities make a difference to soil quality and soil structure parameters to improve local soil ecosystem services in European vineyards.

To test whether cover crop management across Europe would result in similar effects on soil quality with a focus on soil physical properties, we compare different inter-row management strategies that are prevailing in four different European wine-growing regions. There we compare the effects of commonly used “high-intensity” versus “low-intensity” strategies of tillage and soil cover management and evaluate the differences in each wine-growing region. We hypothesize that the comparison across the different regions will reveal a different extent of impact of the different management systems on soil physical properties within and between the tested regions.

The impacts on soil physical properties and organic carbon content are, however, only one aspect of the vineyard ecosystem. In our framework project, we aimed to comprehensively analyse the effects of the commonly applied management systems across European vineyards. This includes aspects such as soil biota, plant species richness and composition, functional traits and cultural ecosystem services (Biddoccu et al., 2020; Buchholz et al., 2017; Fiera et al., 2020; Guzmán et al., 2019; Hall et al., 2020; Hervé et al., 2018; Judt et al., 2019; Kratschmer et al., 2019; Liebhard et al., 2024; Pflingstmann et al., 2019; Popescu et al., 2019; Winter et al., 2018). All these aspects were investigated in the same vineyards and are intended to provide a better understanding of the vineyard ecosystem.

2 | MATERIALS AND METHODS

2.1 | Area of study

The field measurements were made in four wine-growing regions in Austria (AT), France (FR), Romania (RO) and Spain (ES) (Figure 1).

Table 1 gives an overview of the regional characteristics.

2.2 | Vineyard management

Pairs of low and high management intensity systems were selected with a premise of similar soil and climatic conditions. Generally, low-intensity systems are characterized by low-intensity of vegetation cover management in the vineyard inter-rows. High-intensity systems are defined by frequent removal of the vegetation cover either mechanically or chemically. Depending on local conditions, of various inter-row practices have been established, ranging from intensive, frequent tillage with bare soil to permanent vegetation cover without any tillage management. An example of the significant heterogeneity of possible management practices is a system, where only every second inter-row is kept clear. We assigned these gradations to “low” or “high” depending on local standard practices (Table 2). However, since the

range of management intensity varies between countries, the terms “low” and “high” are to be considered in relation to local standards. In addition, in some cases, unique features of management have to be considered, for example, organic management with many but only shallow tillage operations (e.g., weeding harrow).

2.3 | Studied vineyards

We sampled 78 vineyards in the four countries. These vineyards were chosen as site pairs. We defined site pairs as two vineyards that are close to each other and have similar geological and hydrological (pre-)conditions. Of these two vineyards, one is managed with high intensity and the other with low intensity. Only site pairs with similar soil structures were selected to compare management effects on soil structure parameters (Table S1). Furthermore, only vineyards that had been cultivated consistently for at least the last five years before sampling were selected. In addition to the pairwise analyses in which we limited our selection to test pairs with the same soil conditions, we also examined the effects of management intensity at all 78 sites. Information on vineyard management was acquired from questionnaires and personal interviews with the farmers, as shown in Table S2. The information was simplified to give a comparable overview.



FIGURE 1 Location of the four investigated European wine-growing regions.

TABLE 1 Characterization of the four vineyard regions with mean annual temperature (°C) and mean annual rainfall (mm), for 1996–2015, predominant soil types (IUSS Working Group WRB, 2022) and predominant soil texture classes (Soil Science Division Staff, 2017).

Country	Wine region	Temperature	Annual rainfall	Soil type	Soil texture class
AT	Carnuntum and Leithaberg	10.6	600	Calcic Phaeozems	Loamy Sand and silt Loam
FR	Coteaux du Layon	12.7	610	Chromic and Calcaric Cambisols, partly leptic or hypereutric	Clay Loam to sandy Loam, loamy Sand
RO	Târnave, Transylvania	9.8	660	Eutric Cambisols, Calcaric Cambisols	Silty Clay, clay Loam to sandy Loam
ES	Montilla-Moriles	17.0	600	Calcaric Cambisols, Calcaric Luvisol	Clay Loam to silty clay Loam, silty Clay

TABLE 2 Soil and cover management systems for each country with intensity, description of management system and management type.

Country	Intensity	Management description	Management type
AT	Low	Permanent vegetation cover in all inter-rows, mulched, predominantly with commercial cover crop seed mixtures	Permanent, mulched
	High	Alternating tillage of every second inter-row. Bare and covered inter-rows change every 2–4 years	Alternating, mechanical
FR	Low	Permanent vegetation cover in all inter-rows, mulched	Permanent, mulched
		Almost permanent vegetation cover with the cultivation of every second inter-row once a year if needed. Inter-rows change every year	Permanent, chemical
	High	Alternating bare soil/vegetation cover of every second inter-row by herbicide use. Management changes every year	Alternating, chemical
RO	Low	Bare soil management with frequent chemical weed control and, in very few cases, individual mechanical tillage use	Bare soil, mech./chem
		No tillage with “permanent” grass cover, cover crop in every inter-row chopped several times a year	Permanent, mulched
	High	Alternating mechanical tillage of every second inter-row, bare and covered inter-rows change every year	Alternating, mechanical
ES	Low	Bare soil management with frequent tillage (including milling) and predominantly mechanical weed control	Bare soil, mechanical
		Permanent cover crop management, commonly controlled by mulching in early spring and biyearly tillage	Permanent, mulched
	High	Temporary cover crop management in winter season, removed mechanically or chemically in early March	Temporal, mech./chem.
		Bare soil management with frequent tillage (commonly cultivator) and complementary chemical weed control	Bare soil, mechanical

2.4 | Soil sampling and analysis

The sampling in all vineyard regions took place in 2015 and 2016. In each vineyard, 16 undisturbed soil cores from the topsoil (3–8 cm soil depth) were collected. Samples were taken at representative field locations in the middle of each inter-row. Table 3 shows the measured

parameters, the applied method and the number of replications per plot.

First, normal distribution for the measured parameters at each site was tested using the Shapiro–Wilk test. Accordingly, outliers were removed (<3% of measure values). Subsequently, the equality of means for the paired low- and high-intensity vineyards was tested using

TABLE 3 Measured soil property or cover crop parameter, analysis method and quantity of samples (n) per plot.

Soil property	Analysis method	n
Texture	Particle size distribution through sieving and sedimentation, ISO 11277	8
CaCO ₃	Carbonate content with the Volumetric method, ISO 10693	8
pH	pH, ISO 10390	8
Bulk Density (BD)	Dry bulk density, ISO 11272	16
Total organic carbon (TOC)	Organic and total carbon after dry combustion, ISO 10694	8
Total organic carbon (TOC)**	Organic carbon by dry combustion, ÖNORM L 1080	8*
Percolation Stability (PS)	Percolated Water after 10 min, according to Auerwald (1995)	8
Macroaggregate stability	Macroaggregate stability, according to Barthès & Roose (2002)	4*
Saturated Hydraulic Conductivity (k_{sat})	k_{sat} with the Falling Head Soil Core Method after Reynolds et al., 2002	16
Unsaturated Hydraulic Conductivity	Water-retention characteristic with Wind's evaporation method, ISO 11275	4
Pore Size Distribution—Moisture Tension	Water-retention characteristics according to ISO 11274	4
Decomposition rate and Stabilization factor	Decomposition based on the Tea Bag Index, according to Keuskamp et al. (2013)	11*
Maximum plant biomass	Maximum dry biomass from four 1m ² subplots and four sampling dates	4*
Maximum vegetation ground cover	Average max. ground cover from all subplots, according to Londo (1976)	4*

*Only for selected countries.

**Check measurements for selected samples.

the two-sample t-test for independent samples. The non-parametric two-sample Welch test was used for site pairs where the variances could not be assumed to be equal according to the F-test. Additionally, the means of the paired low- and high-intensity vineyards grouped by country were tested for equality using the Mann-Whitney U test since not all summarized country data are normally distributed.

2.5 | Numeric modelling of the effects of changed soil hydraulic properties

The effect of changes in soil hydraulic properties in the topsoil was assessed in addition to measurements with numeric simulations using the HYDRUS-1D software package. We calculated soil water fluxes based on the van Genuchten–Mualem single porosity model with soil hydraulic properties (Table S3) determined from the water-retention curve according to Wind's evaporation method (HYPROP, METER Group, Inc. USA). The effects of management on soil hydraulic properties were estimated using design rainfalls. Three design rainfalls with increasing intensity were chosen using long-term time series from the Carnuntum and Leithaberg wine regions (ehyd.gv.at). The duration level was selected as 15-min rainfall in each case, and the return periods were chosen as 1, 5 and 100 years, corresponding to total rainfall amounts of 11.3, 20.0 and 37.8 mm. More detailed information on

the HYDRUS-1D calculation and the design rainfall events is given in the Supplementary Information section.

3 | RESULTS

3.1 | Total organic carbon

Most vineyards managed with low-intensity and cover crops in Austria, France and Romania had an increase in total organic carbon (TOC). In contrast, the investigated low-intensity vineyards in Spain showed no difference or even lower TOC (Table S4, Figure 2). The unexpected deviation was verified by control measurements with an alternative dry combustion method according to ÖNORM L 1080 to measure organic carbon. The control measurements confirmed the deviating effect of low intense management, including temporally limited cover crops in Spain.

The Spanish vineyards had, on average, a maximum above-ground dry biomass of approx. 149 g m⁻² in the low-intensity temporary grassed inter-rows and a dry biomass of 40 g m⁻² in the bare soil managed inter-rows, which meant approx. 48.5 and 30.7% maximum coverage rates. The Austrian vineyards had, on average, a dry biomass of approx. 185 g m⁻² in the permanently grassed inter-rows and a dry biomass of 173 g m⁻² in the prior tilled inter-rows, meaning maximum coverage rates of approx. 88.0 and 79.0%.

3.2 | Bulk density and percolation stability

The pairwise comparison of bulk densities in the topsoil layer shows that most vineyards with low management intensity and cover crops in Austrian, French and Romanian vineyards were less compacted than in the vineyards managed with high intensity. In Spanish vineyards, this was the opposite. Two sampled paired sites had higher compaction in sites with less management intensity and temporary cover crops, whereas two Spanish pair sites did not differ (Table S4). Looking at all pair sites broken down by country, there were differences in all countries, but with little statistical power (Figure 3). It should be considered that samples were taken between the wheel tracks in the inter-rows.

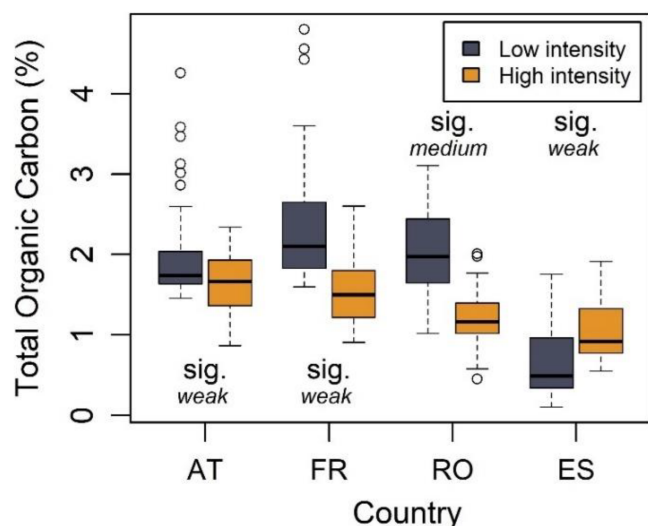
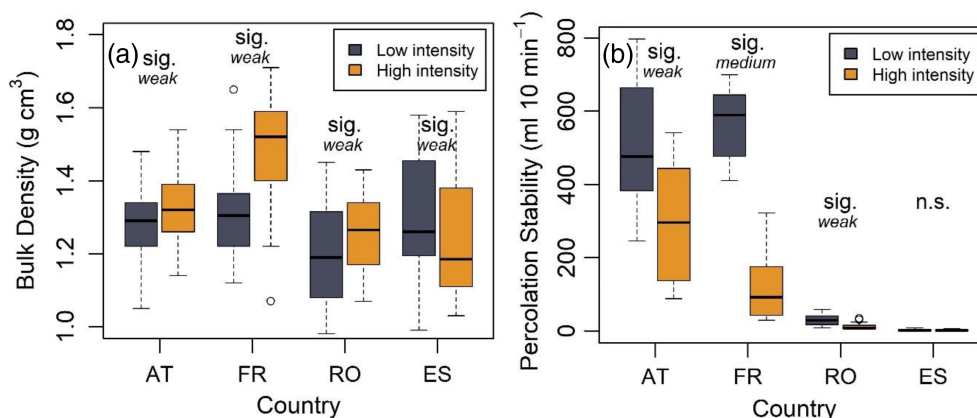


FIGURE 2 Total organic carbon (TOC) based on soil surface samples for the low and high management intensity sites grouped by country. Mean value comparison of low- and high-intensity management sites with Mann-Whitney- U test, statistical power given as effect size (<0.3 weak; 0.3–0.5 medium, >0.5 high).

FIGURE 3 Bulk Density (a) and Percolation Stability (b) based on soil surface samples for the low and high management intensity sites grouped by country. Mean value comparison with Mann-Whitney U test, statistical power given as effect size (<0.3 weak; 0.3–0.5 medium, >0.5 high).



The differences in structural stability are more pronounced for the parameter of percolation stability (PS) (Figure 3b). The comparison of country data shows a large difference between the soils and management systems, especially with regard to mechanical soil disturbance. The highest values for PS were measured from samples from low-intensity management with cover crops in Austrian and French vineyards. Permanent cover crops and the complete absence of mechanical tillage characterize these. In contrast, even regular or alternating weed control in every second inter-row using a cultivator (Austria) or primarily herbicides and occasionally blades (France) resulted in a substantial reduction in PS.

Comparing the relation between Bulk Density (Figure 4a) and Percolation Stability (Figure 4b) with the TOC content illustrates the dependence of the structural parameters on the TOC. The increase of TOC in both countries correlates similarly with a decrease in BD (Figure 4a). The increase of PS with increasing TOC is very different, though (Figure 4b). In mechanically undisturbed soils, the PS increases significantly, whereas the accumulation of humus in regularly mechanically disturbed soil leads to a small increase in PS.

3.3 | Soil hydraulic properties

The effects on saturated hydraulic conductivity (k_{sat}) and available water content (AWC) are limited (Table 4). In the investigated Austrian vineyards, the differences between low- and high-intensity management are too small to determine a difference in (k_{sat}) and AWC. The effects of different management intensities in the Romanian and Spanish vineyards are also unclear, with hydraulic conductivity being higher at low management intensity than at high intensity in two of four vineyard pair sites. The most significant

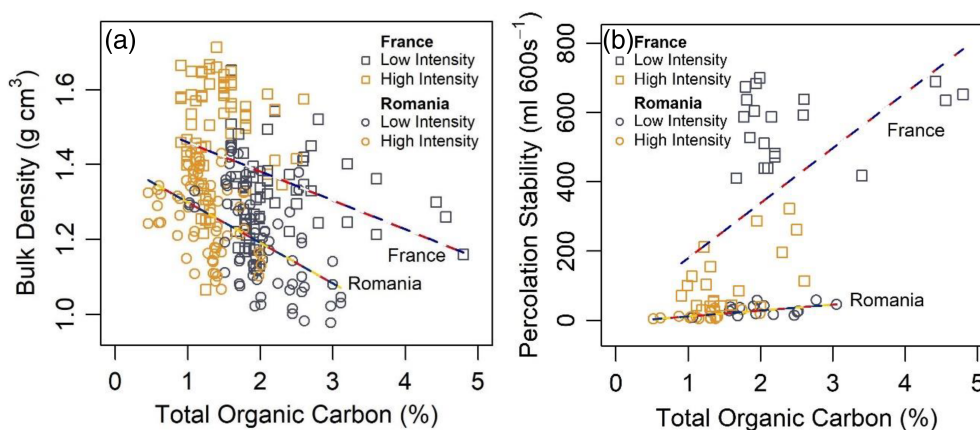


FIGURE 4 Scatter plot of Bulk Density (a) in g cm^{-3} and Percolation Stability (b) in $\text{ml } 10 \text{ min}^{-1}$ against total organic carbon (TOC) in % based on soil surface samples for the low management intensity and high management intensity sites. For clarity, point data and linear regression lines are only shown for France and Romania. Figures with data from all four countries are given in the Supplementary Information, Figure S1. Quality measure R^2 for BD/PS: France 0.12/0.34, Romania 0.28/0.42.

improvement due to low management intensity was observed in the French vineyards.

With differences in the hydraulic parameters being small, we further show the effects of the different soil hydraulic parameters due to low- and high-intensity management during heavy precipitation events. Table 5 shows the results of a numerical model comparing the effects of design rainfalls with various intensities on infiltration capacity, water storage and percolation in the topsoil.

Regarding water storage two days after the design rainfall events, the water content is higher for Austria and Romania and lower for France and Spain, with lower management intensity and the use of cover crops. In all simulations, the higher water content after two days is primarily due to the higher water content at the start of the rainfall, which results from the different hydraulic parameters and the setting of initial soil water conditions to -330 hPa . Compared with the differences in the initial water contents, the losses due to percolation are comparatively low.

4 | DISCUSSION

4.1 | Total organic carbon

Most vineyards managed with low-intensity and cover crops had an increase in TOC, except the vineyards in Spain, which showed no difference or even lower TOC. An increase in organic carbon content in the soil surface due to the long-term reduction of tillage and use of cover crops was expected (Crystal-Ornelas et al., 2021; Page et al., 2020; Zehetner et al., 2015). This raises the question

why this effect did not occur in Spanish vineyards or was even opposite. In general, soil texture is the main factor regarding the sensitivity of carbon content to changes in soil management. This means soils with coarse textures are more responsive to a system change to less tillage intensity and use of cover crops than soils with fine textures (Rosinger et al., 2023). In contrast, soils with fine texture have a higher TOC storage capacity than soils with coarse texture (Rosinger et al., 2022). While the maximum organic carbon storage capacity is irrelevant for the studied poor-quality vineyard soils, selecting sites with similar texture excludes the influence of soil texture on carbon sequestration and carbon storage (Table S1). A comparison of TOC and clay contents for different management intensities shows that insufficient clay mineral docking stations did not restrict sites with low organic carbon content to build clay-humus complexes (scatter plot available in the supplementary information, Figure S2). Differences in the sorption of soil organic carbon and the stabilizing effect of calcium ions in interaction with aluminium or iron (Rowley et al., 2018) were similarly excluded as reasons for differences in carbon sequestration due to the same chemical soil conditions. Besides texture, inherent chemical soil properties influence the soil organic carbon budget and the formation of clay-humus complexes. Calcium ions in interaction with aluminium or iron have a stabilizing effect and influence the sorption of soil organic carbon (Rowley et al., 2018). However, this factor was similarly excluded due to the same chemical soil conditions as reasons for differences in carbon sequestration. Consequently, the difference must have been caused by differences in tillage, cover crop management, fertilization, soil biota composition or climatic conditions.

TABLE 4 Soil hydraulic properties: Country, pair site number, management intensity, means and standard deviations of Saturated Hydraulic Conductivity (k_{sat}) in m d^{-1} ; Available Water Content (AWC) between 330 and 15,000 hPa in volume percent.

Country	Pair site	Intensity	k_{sat}	AWC
AT	1	Low	13.48 ± 2.61	11.83 ± 0.22
		High	13.46 ± 6.47	12.04 ± 1.01
	2	Low	12.82 ± 3.56	14.53 ± 1.65
		High	17.00 ± 7.84	15.34 ± 0.70
	3	Low	10.15 ± 9.59	17.46 ± 0.83
		High	13.48 ± 6.13	18.27 ± 0.63
	4	Low	16.08 ± 9.47	17.2 ± 1.12
		High	07.42 ± 6.59	16.03 ± 0.90
	5	Low	26.78 ± 13.14	17.18 ± 0.41
		High	24.83 ± 13.45	17.58 ± 1.97
FR	6	Low	02.12 ± 0.62	19.34 ± 3.15
		High	01.18 ± 0.45	14.36 ± 1.01
	7	Low	05.48 ± 2.25	16.8 ± 2.05
		High	01.37 ± 1.81	13.96 ± 0.78
	8	Low	16.97 ± 6.28	16.19 ± 1.88
		High	00.53 ± 0.47	14.38 ± 0.71
	9	Low	17.62 ± 6.26	16.51 ± 2.05
		High	16.92 ± 5.32	13.49 ± 1.32
	10	Low	19.26 ± 3.11	15.00 ± 0.82
		High	14.48 ± 2.99	13.98 ± 0.79
RO	11	Low	18.39 ± 13.75	10.80 ± 0.80
		High	08.29 ± 6.67	10.10 ± 2.44
	12	Low	07.65 ± 0.81	12.89 ± 0.79
		High	00.03 ± 0.02	17.92 ± 1.07
	13	Low	07.30 ± 7.21	16.74 ± 2.34
		High	05.78 ± 4.33	14.33 ± 0.26
	14	Low	07.00 ± 7.85	15.91 ± 0.98
		High	13.70 ± 9.71	12.51 ± 0.68
ES	15	Low	04.03 ± 1.87	15.98 ± 1.62
		High	05.32 ± 3.54	14.31 ± 1.17
	16	Low	11.80 ± 10.81	20.46 ± 3.17
		High	13.47 ± 2.27	17.67 ± 0.82
	17	Low	18.62 ± 14.42	15.02 ± 2.96
		High	04.55 ± 3.05	16.64 ± 1.87
	18	Low	01.63 ± 0.69	06.4 ± 1.53
		High	00.59 ± 0.34	10.66 ± 0.54

Note: Significance of the difference based on the two-sample *t*-test or Welch test for independent samples. Significant differences are indicated with bold font.

In general, conventional tillage in Mediterranean vineyards depletes the organic carbon stocks drastically compared with undisturbed land. Novara et al. (2013) measured a decrease in TOC of 32% due to regular tillage. They found that the depletion of organic carbon was primarily due to the loss of the largest aggregates, which

was attributed to tillage (An et al., 2010) and a decrease of plant residue inputs (Dorodnikov et al., 2011). Soil aggregation would be the most effective way to protect organic carbon from mineralisation by reducing accessibility of microbes to the particulate organic matter (Lützwow et al., 2006). However, the high mineralisation

Duration level		15 min		15 min		15 min		60 min	
Return periods		1 year		5 years		100 years		100 years	
CO	INT	STO	PER	STO	PER	STO	PER	STO	PER
AT	Low	35.0	02.6	36.4	13.9	36.5	27.7	36.6	51.7
	High	23.0	04.9	23.3	17.3	23.4	31.1	23.4	55.2
FR	Low	22.7	04.4	23.3	16.5	23.3	30.3	23.4	54.3
	High	29.1	06.1	29.5	18.4	29.5	32.2	29.5	56.3
RO	Low	43.6	07.0	43.6	19.7	43.7	33.5	43.7	57.5
	High	33.8	07.7	33.9	20.4	33.9	34.2	33.9	58.3
ES	Low	19.3	07.3	19.5	19.9	19.5	33.7	19.5	57.8
	High	25.8	04.6	26.2	16.9	26.3	30.7	26.3	54.7

Note: Evaluation for four design rainfalls with duration levels of 15 or 60 min and return periods of 1, 5 and 100 years, meaning 11.3, 20.0, 37.8 and 61.9 mm rainfall. Calculation shows no surface flow for any scenario, storage (STO) in topsoil and percolation (PER) below the topsoil layer at a soil depth of 15 cm two days after the rain event given in mm.

TABLE 5 Simulating the effects of changes in soil hydraulic properties in the study countries (CO) due to different soil management intensity (INT) for a single rainfall event.

rates due to high aeration and susceptibility of the organic carbon stock to microbial activity exceed potential local organic carbon regeneration rates (Novara et al., 2013). Thus, the Mediterranean region with its semiarid climate presents difficult conditions for humus formation and conservation (Díaz-Martínez et al., 2024; García & Hernández, 1996). However, reducing management intensity is reported to still cause an increase of TOC in comparable soils of arid areas (López-Fando & Pardo, 2011; Sombrero & De Benito, 2010). Furthermore, Belmonte et al. (2016) showed that permanent vegetation cover in vineyards that was comparable with the Spanish vineyards in terms of poor soil quality and climate positively affected soil organic carbon content. There, even individual soil disturbances had minor effects on the long-term increase of TOC.

Thus, the differences were assumed to be caused by the differing management in combination with the semiarid climate. Autret et al. (2016) concluded from their investigations that the potential to sequester and store organic carbon in the soil was higher through organic carbon input through cover crops than through the effects of reduced soil disturbance in low-intensity systems. Consequently, the lack of a positive effect of reduced tillage and intermediate cover cropping in the sampled Spanish vineyards is explained by an interaction of unfavourable factors. This means the combination of difficult conditions for soil life and high mineralisation rates in these climatic conditions and an insufficient duration and cover of vegetation in the inter-rows. Looking at the investigated Spanish vineyards, the above-ground biomass of the Spanish vineyards had a maximum of approx. 149 g m^{-2} in the low-intensity temporary grassed inter-rows and a dry biomass of 40 g m^{-2}

in the bare soil managed inter-rows. For comparison, the Austrian vineyards had a biomass of approx. 185 g m^{-2} in the permanently grassed inter-rows and a biomass of 173 g m^{-2} in the prior tilled inter-rows of alternating management. Also, the degree of maximum ground cover differed according to the maximum biomass (Spain 48.5 and 30.7%, Austria 88.0 and 79.0%). Furthermore, the Austrian wine growers predominantly used commercial seed mixtures according to the agri-environmental soil mitigation measures for soil amelioration, to mitigate soil erosion and to increase soil fertility and biodiversity (Hudek et al., 2022). In addition to the quantity of the cover crop biomass, the execution of cover cropping varied, with operational differences between all sites. At pair 15, the low-intensity vineyard inter-rows were managed with grass cover that was regularly cut in early spring and additionally managed with a cultivator biyearly. This was the only Spanish pair site where TOC values were similar in both vineyards, with low-intensity and high-intensity management. In pairs 16–18, the low-intensity vineyard inter-rows were covered with catch crops only temporarily. The low-intensity site 16 had barley as a cover crop, used as forage or incorporated with additional farmyard manure approx. 30 cm into the soil profile. However, any downward displacement of organic material into deeper soil layers could not be detected by sampling the top soil layer. The low-intensity sites in pair sites 17 and 18 used spontaneous vegetation as cover crops, whereas at site 17, the cover crop vegetation was still influenced by a commercial mix of cereals, crucifers and legumes from seeding seven years ago. In addition to the removal of biomass and incorporation into deeper soil layers, another reason for the lower TOC in the investigated low-intensity managed sites compared with

their paired high-intensity managed sites in Spain may be priming (Sun et al., 2019). Low-intensity managed sites to build up humus more often included the addition of organic fertilizers (Table S2). Fertilization by adding easily decomposable organic matter such as manure, however, promoted microbial activity that may have consumed more carbon than supplied by the manure, leading in total to humus depletion. In addition, a change in the composition of microbial community due to tillage may also have affected the carbon cycle (Nielsen et al., 2011). The loss of functional groups such as the C-cycling micro-organisms during conventional tillage may have reduced mineralisation processes.

4.2 | Bulk density and percolation stability

The pairwise comparison of bulk densities shows that most vineyards (except the ones in Spain) with low management intensity and cover crops were less compacted than in the vineyards managed with high intensity. However, in relation to benchmarks (USDA Soil Quality Institute, 1998), there was hardly any problematically high compaction, regardless of which system was implemented. According to Blanco-Canqui and Ruis (2018, 2020), most sites with long-term low-intensity or even no tillage using cover crops are more resistant to compaction. The deviation of the Spanish data is attributed to the lack of success in humus formation (Table S4, Figure 2). Without the increased formation of stable soil aggregates in undisturbed soils, compaction tends to be higher than in mechanically loosened soils. Additionally, the temporary cover crops do not have the necessary intensity to loosen the soil comparably with mechanical cultivation. Besides the decisive, direct effect of soil management, an unfavourable TOC/clay ratio also contributes to a lack of soil stability in the sampled Spanish vineyards. According to Feller and Beare (1997), soils with high clay content require a correspondingly high organic carbon content to achieve the same aggregate stability as soils with lower clay content. Johannes et al. (2017) confirmed such a correlation. They identified a TOC/clay ratio of 1/10 as a cut-off point between good and medium structural quality, with ratios smaller than 1/13 indicating a probably poor structural state. Accordingly, Romanian and Spanish vineyard soils, which have higher clay contents than Austria and France, have consistently lower TOC/clay ratios than 1/13 and poor soil structure.

The differences in PS are even more pronounced than in bulk density (Figure 3). The highest values for PS were measured in Austrian and French vineyards with

permanent cover crops and the complete absence of mechanical tillage. Even minor use of mechanical weed removal resulted in a substantial reduction in PS. Considering TOC is the single most important soil property parameter correlating with PS (Mbagwu & Auerswald, 1999), the PS differences between low- and high-intensity managed vineyard pairs correspond to the differences of TOC for Austria and France. In contrast to the measurements in Austria and France, the measurements in Romania and Spain are in a different range. All vineyard soil samples in Romania and Spain imply significant signs of soil degradation. The measured PS values were far below the threshold of 150 mL per 10 minutes (Mbagwu & Auerswald, 1999). While any differences in soil structure and soil type must be taken into account, it is clear that the systems based on intensive mechanical tillage in Romania and Spain damage the soil structure much more than low tillage with a cultivator every few years (Austria) or weed removal using primarily herbicides (France). Similarly, the parameter macroaggregate stability shows a severe degradation in the Spanish low-intensity ($193 \pm 124 \text{ g kg}^{-1}$) and high-intensity ($142 \pm 54 \text{ g kg}^{-1}$) vineyards. The threshold value of 300 g kg^{-1} indicates the structure loss (Barthès & Roose, 2002). Apart from the system difference in weed removal, soil biota, texture and particularly clay mineralogy may be a reason for the low PS in Romania and Spain. Feller and Beare (1997) found that soils with higher clay needed larger TOC contents to reach similar aggregate stability. In line with this observation, the Romanian and Spanish sites have more clayey soils compared with the investigated Austrian and French sites. However, the site pairs (e.g., 12 in Romania and 18 in Spain) with clay contents lower than Austrian and French sites do not differ from other sites with higher clay proportions in Romania and Spain and relativize the influence of texture in this context.

In French and Romanian vineyards, the low-intensity management with cover crops caused an increase in TOC in comparison with the high-intensity management with tillage or herbicides. Comparing the relation between BD and PS with the TOC (Figure 4) illustrates their dependence on the TOC. The increase of TOC in both countries correlates similarly with a decrease in BD. This relation (France: $y = -0.077 x + 1.537$, $R^2 = 0.12$; Romania: $y = -0.108 x + 1.408$, $R^2 = 0.28$) also corresponds to the relation determined with pedotransfer functions and coefficients (Dexter et al., 2008), derived from the French RMQS database (France: $y = -0.106 x + 1.476$, $R^2 = 0.99$; Romania: $y = -0.124 x + 1.509$, $R^2 = 0.99$). In contrast to this similar relation regarding BD, the PS increases significantly in mechanically undisturbed soils, whereas the accumulation of humus in regularly

mechanically disturbed soil leads only to a smaller increase in PS. The difference is attributed to the intensive soil disturbance that damages the soil structure by breaking and exposing the soil aggregates. As a result, the soil organic matter previously preserved in the aggregates is unprotected to be metabolized by soil life. Although the aggregate stability in the mechanically disturbed Romanian vineyard soils hardly increases, the TOC is similar to those in the mechanically undisturbed French vineyard soils. Thus, we assume that the root exudates, which contribute many times more effectively to the formation of stable clay-humus complexes than plant residues (Rasse et al., 2005; Sokol et al., 2019), are particularly affected by mechanical tillage. This assumption is also supported by the findings of Zehetner et al. (2015) who found the highest dissolved organic carbon levels in the topsoil of their analysed vineyards with dense cover crop root mats in the topsoil and without tillage. Another consequence of tillage and cover crop management is the modulation of soil biota, which also has an impact on soil aggregation. Bacteria contribute to both macro- and microaggregation (Lehmann et al., 2017). Fungi, which are less sensitive to (mechanical) disturbances (Legrand et al., 2018), have a particular impact on macroaggregation (Lehmann et al., 2017). Tillage and cover crops particularly impact bacteria and fungi, which appear to be even more important for soil aggregation than soil animals (Lehmann et al., 2017). Conservation agriculture increases species richness and evenness (Legrand et al., 2018) and thus strengthens aggregate stability. Accordingly, the cultivation of the Spanish inter-rows based on mechanical tillage additionally promotes the continuous decomposition of humus and destruction of the soil aggregates with hardly measurable PS values.

4.3 | Soil hydraulic properties

Considering that decisions regarding inter-row management largely depend on available water and aims to optimize soil structure and soil water balance for the vines, the effects on saturated hydraulic conductivity and AWC are limited (Table 4). Whereas cover crop and tillage management cause significant differences in evaporation and transpiration processes (Liebhard et al., 2022), various management intensities showed divergent effects on hydraulic parameters and the water storage capacity of the soil.

In the investigated vineyards, the impact of low- and high-intensity management on k_{sat} and AWC is generally small (Table 4). The most significant improvement in soil hydraulic parameters due to low management intensity was observed in the French vineyards. A comparison of

structural and soil hydraulic parameters (Tables S4 and 4) shows that the differences in PS are much more pronounced than in the hydraulic parameters, especially in the AWC, which is based on measurements of unsaturated hydraulic conductivity. We conclude that the PS parameter is more meaningful here, as it reflects better the relevant processes during precipitation events on dry soil.

Because the differences in the hydraulic parameters are small, we looked at the effects of management during heavy precipitation events (Table 5). Considering that the design rainfall events are comparatively low, as the areas are not characterized by heavy erosive precipitation (Johannsen et al., 2022), the calculation showed that even extreme precipitation events ($T = 100$ years) can infiltrate without ponding or surface runoff. This estimate is based on parameters from undisturbed soil samples and simulation with a soil physical model for simulating water in variably saturated media. Thus, the risk of soil erosion should not be entirely neglected, considering possible soil surface sealing and crusting during splash erosion (Zambon et al., 2020). Consequently, maintaining the infiltration capacity and protecting the soil surface using cover crops (Gómez et al., 2011; Hösl & Strauss, 2016; Klik et al., 1998) may still be essential in the investigated vineyards in case of indication of erosion effects. Regarding percolation below the surface layer, low-intensity management with cover crops had a minor water loss to deeper soil layers in Austrian, French and Romanian vineyards with low management intensity and cover crops compared with their high-intensity managed pair site counterparts. As with most other soil parameters, the effect in Spanish vineyards regarding percolation was reversed with lower percolation at higher management intensity.

Regarding water storage capacity, it is noticeable that, according to the simulation, low-intensity managed vineyards in France store less water after heavy rain events despite their significantly higher potential to store water (AWC, Table 4). Again, the effect of higher saturated hydraulic conductivity (Table 4) did not cause more percolation and was smaller than the effect of the higher initial soil water content in intensively managed vineyards (Table 5). The opposite behaviour is compared with Austrian and Romanian vineyard site pairs in the simulation because the van Genuchten parameter n , which describes the pore size distribution, is higher in French vineyard pairs with low management intensity than with high management intensity (Table 1). By implication, water storage during dryer periods, which is more decisive and essential for farmers, becomes more effective with decreasing water content in low-intensity management compared with high-intensity management.

4.4 | Impact of commonly applied management systems in the investigated countries

A comparison of the effects of the management systems typically applied in Austria, France, Romania and Spain requires caution regarding the terminology used. This is vital, since unclear definitions and different use of soil and management-related terms potentially lead to misconceptions and hinder the implementation of research results into practice (Weninger et al., 2024). The inter-row management intensity primarily relates to the application of cover crops and the frequency of management (e.g., tillage, herbicide application or mulching). This is related to the intensity and frequency of soil disturbance. Yet, it strongly depends on local strategies, as intensive inter-row vegetation management in France is mainly based on herbicide use. In contrast, inter-row management in Spain and Romania is based on tillage. Also, Austria's "high-intensity" inter-row management is based on tillage, yet the tillage of every second inter-row implies several years without any soil disturbance. In addition to these differences in management systems, differences in supposedly clear designations must also be considered, as "permanent grass cover" typically means mulching one to five times a year in Austria. In contrast, in the investigated Romanian vineyards, it meant chopping the cover crop five times a year. Similarly, tillage intensity ranges from ploughing with subsequent milling (e.g., Romania) to shallow cultivating (e.g., Austria). Considering this different terminology, the effects of the most common inter-row management practices in the investigated regions on soil properties, soil protection and soil formation can be compared.

Concerning the protection and formation of the soil structure, local management systems show significant differences in aggregate formation and soil degradation. Concerning erosion processes, long-lasting soil cover and avoidance of intense soil disturbance with heavy machinery are major factors for erosion control (Klik & Eitzinger, 2010). This all the more as vineyards are often steep and have erosion-prone slopes. Regarding humus decomposition, organic carbon is protected against microbial degradation as long as it is enclosed in soil aggregates or associated with clay minerals (Dynarski et al., 2020; Lehmann & Kleber, 2015; Perdrial et al., 2010). Accordingly, the low-intensity inter-row management sites in Austria, France and Romania have a trend of higher TOC, PS, k_{sat} and AWC compared with the sites with higher inter-row management intensity. Based on the alternating management variants in Austria and Romania, it can be seen that the difference between bare soil management and alternating system (Romania)

is more significant than that between the alternating system and permanent vegetation cover (Austria). The biomass produced in the inter-rows also increases the TOC content in Romanian vineyards. Not even the alternating mechanical tillage that breaks up the aggregates and exposes the soil organic matter prevented humus accumulation in Romanian vineyards. However, aggregate stability suffers greatly from tillage in Romanian and Spanish vineyards. In Spanish vineyards, the temporary vegetation cover during the winter season did not improve the soil quality. Temporary vegetation in Spanish vineyards did not cause an increase in TOC or PS or decrease BD compared with bare soil management. Obviously, the intensity of cover crops was insufficient to accumulate humus, form aggregates and loosen the soil to compensate for the reduced tillage operations. Our results are in line with other studies investigating the effects of the local management systems in Spanish wine regions on soil parameters (Gómez, 2017; Gómez et al., 2014). They show an indistinct impact of management systems and considerable variability between farms with similar management practices. The variability is attributed to a certain extent to differences in the duration and intensity of the cover crop vegetation. Therefore, managing cover crops to gain a positive effect on organic carbon and soil physical parameters is a challenge in the semi-continental Mediterranean climate with long, dry and hot summers. However, long-lasting permanent grass management without any soil disturbance has already shown the long-term recovery capacity of cover crops in a Mediterranean area (Belmonte et al., 2016). Under these conditions, the first increases in TOC and aggregate stability become apparent only after a few years.

In addition to protecting the soil from degradation, soil management must also aim to maintain active soil life. The metabolites of plants and microorganisms form mineral-associated organic matter and contribute to the formation of particulate organic matter. Thus, soil structure is improved (Sokol et al., 2019). While microorganisms respire the carbon in the humus, increasingly in fallow soils of intensive farming systems, cover crops within low-intensity management systems counteract humus decomposition by supplying the soil microbiome with food. Accordingly, the TOC content and soil structure parameters in the permanently covered inter-rows were higher than in vineyard soils with disturbed soil life. Soil life in Spanish vineyards is often exposed to stress, even in low-intensity managed vineyards. One reason is that the temporary cover crop does not guarantee a continuous food supply from root exudates. Directly after the removal of cover crops in early March, microbial activity is supposed to reach its maximum due to rising soil

temperatures and water availability from fall and winter precipitation. Even with similar annual precipitation as in comparable wine-growing regions (Table 1), soil life is exposed to greater stress. The stress of soil organisms increases due to high soil temperatures and increasing drought in the semi-continental Mediterranean climate with long, hot, dry summers. In addition, efforts to build up humus in the low-intensity management variant could be counterproductive and lead to priming (Sun et al., 2019). In this case, applying readily available organic matter and nutrients (Table S2) promotes microbial respiration, which exploits the soil organic carbon after the applied fertilizer is exhausted.

A speciality of viticulture is alternating soil cover management. According to the farmers who operate this system, it results from their efforts to optimize the balance between higher water losses and pest pressure through inter-row greening and soil decomposition in bare inter-row management. The Romanian system with yearly alternating mechanical tillage of every second inter-row leads to higher TOC contents compared with predominantly mechanical bare soil management (Figure 2). Accordingly, the BD is lower with higher TOC. However, the effect on PS and soil hydraulic properties is not significant. This indistinguishability is attributed to the still frequent tillage operations with aggregate-destroying machinery, even in the low-intensity management, which regularly sets back biological pore formation. Alternating tillage in Austria has longer alternation times, is less intensive and uses more conserving equipment for the soil. The difference between “high-intensity” management with alternating inter-row management and “low-intensity” management with permanent vegetation cover in all inter-rows is for many measured parameters still significant. Consequently, the moderate intensification in this way does not preserve soil structure similarly to permanent green cover. Yet, all considered parameters are still far from threshold values, indicating problematic soil degradation. The effect of the Austrian alternating inter-row management system on the investigated soil parameters matches the results found by Belmonte et al. (2016). They showed that the soil recovery capacity of permanent greening becomes apparent only through long-lasting green cover management. This means soil recovery effects appear earliest after three years, measured by increasing organic matter and aggregates. With alternating intervals of 2–4 years in the Austrian system, the positive effects of inter-row greening are just becoming measurable when the next tillage period starts on that inter-row. Whereas a single tillage operation already affects the soil aggregates, organic matter reacts slower. Thus, an “almost permanent” cover crop with once-a-year tillage of every second

inter-row, as in one investigated French vineyard, hardly reduces organic matter. An alternation with long-term tilling periods such as in Austria leads to lower TOC (Table S4, Figure 2) through less addition of organic matter counteracting mineralisation processes. Furthermore, the missing organic carbon, particularly in the mineral-associated carbon pool, limits formation of stable aggregates (Belmonte et al., 2016) and thus does not counteract aggregate destruction by tillage.

According to the interviews with farmers of the studied sites, a transition from intensive tillage-based management to more soil conserving systems is often hampered by fear of additional water loss, pests and diseases. However, from a soil physical point of view, the management system should constantly be tested regarding a change towards permanent green cover. Moreover, comparing results of sites with herbicide-based weed management with tillage-based sites shows better PS without mechanical soil disturbance, indicating better soil structure. Consequently, if a transition to permanent green cover is not possible, weed removal should be tested to change towards non-mechanical weed control. The interviews with the farmers revealed various reasons for mechanical tillage. This included spider control by removing their habitat in cover crops and residues. In particular for Spanish sites, traditional plantations in a globet system (each vine trained to a stake) without trellises do not allow herbicide applications due to the location of “green plant parts” absorbing the phytotoxic active ingredient too close to the soil surface. In addition, herbicide use in vineyards may harm water quality and other biodiversity and is not appreciated by consumers. Furthermore, national agri-environmental programmes support farmers if they do not use any herbicides in Austria. However, modern and economic trellis-based vineyard systems should constantly strive for optimisation in low-impact and all-season ground-covering inter-row management.

5 | CONCLUSIONS

We investigated the effects of common vineyard inter-row management practices in Austria, France, Romania and Spain by comparing paired vineyards, each one vineyard with cover crops and low tillage intensity with one vineyard with bare soil and high tillage intensity. Regarding organic carbon content, almost all sites with lower tillage intensity and cover crops showed a long-term increase compared with more intensively managed vineyard soils. Only in the highly water-limited Spanish vineyards, temporary cover crops controlled with low-intensity tillage did not improve soil organic carbon.

We assume that the adverse effects of mechanical weed control are even greater under these climatic conditions and that temporary (short term) cover crops are insufficient to compensate for this. Where low-intensity management with cover crops increased the TOC, better values were also measured for bulk density and PS and to a lesser extent for hydraulic conductivity and available soil water. It was found that PS was particularly low in Romania and Spain, where weed control is based on intensive tillage. Accordingly, alternating tillage in every second inter-row with a change of inter-rows every 2–4 years, common in Austria, showed only slight degradation compared with permanent green cover management. In contrast, the yearly alternating intensive tillage of every second inter-row in Romania leads to poorer physical soil quality parameters. In Austria, France and Romania, positive effects of year-round green cover on organic carbon content and soil physical parameters were observed. No positive effects of the short-term temporary cover crops were observed in intensively tilled Spanish inter-row soils. To verify the considerations made, it would be interesting for future studies to investigate the temporal course of plant excretion, microbial activity and decomposition rates, which could more accurately reveal the associated changes in aggregate stability and allow an evaluation of selected management effects.

AUTHOR CONTRIBUTIONS

Gunther Liebhard: Visualization; writing – review and editing; validation; writing – original draft; data curation; methodology; investigation; formal analysis; software. **Gema Guzmán:** Investigation; writing – review and editing; validation; project administration. **José A. Gómez:** Investigation; writing – review and editing; validation. **Silvia Winter:** Investigation; funding acquisition; writing – review and editing; validation. **Johann G. Zaller:** Investigation; writing – review and editing; validation; data curation. **Thomas Bauer:** Conceptualization; investigation; methodology; writing – review and editing; project administration; resources. **Annegret Nicolai:** Investigation; writing – review and editing. **Daniel Cluzeau:** Investigation. **Daniela Popescu:** Investigation; writing – review and editing. **Claudiu-Ioan Bunea:** Investigation. **Peter Strauss:** Conceptualization; investigation; resources; supervision; project administration; writing – review and editing; writing – original draft; funding acquisition; methodology.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at <https://zenodo.org/doi/10.5281/zenodo.11612780>.

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