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Investigating the Impacts of Tillage and Cover Crop Management on Soil Compaction in Long-Term Agricultural Production Sites Using a Home-Built Dynamic Penetrometer

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ABSTRACT

Agricultural management produces soil compaction depending on intensity of use, specific management and soil properties. We used an adapted, home-built dynamic penetrometer to evaluate 20 long-term sites of arable land, tree orchards, vineyards and grassland in Europe and China, each with different tillage and cover crop strategies. To ensure comparable results across all sites, we pre-tested different penetrometer settings in the laboratory to cover all local conditions and provided Standard Operating Procedures. The laboratory tests showed that different settings in terms of falling hammer height and cone angle produced replicable results, and that narrow plough pans (3 cm) could be detected, even though their density was underestimated by 50%. The pre-tests also demonstrated the dependence of the measurements on soil water content and texture, even under preset conditions close to field capacity. Consequently, the effects of different management practices were only compared directly for each site individually. The field study showed that tillage had a greater effect on penetration resistance than different cover crop systems and intensity. The majority of the more intensively tilled fields showed penetration resistance that was up to 3 MPa lower, at least partially, up to the ploughing depth compared to less intensively tilled fields. However, in only 27% of the fields, the no-till or reduced-till management led to an SPR greater than 2.5 MPa, indicating harmful compaction, compared to conventional management. The effects of cover crops on soil compaction were unclear with differences observed between different mixtures at only one site. Nevertheless, unlike bare soil, cover crops increased penetration resistance in the tillage horizon and reduced infiltration capacity in 75% of the fields investigated. Trends depending on management practices varied due to local soil properties.

We therefore recommend farmers to include penetrometer measurements in their routine to recognize soil compaction in time and apply tailored mitigation strategies.

1 | Introduction

Soil compaction is a reduction in total soil volume accompanied by a change in soil structure. This occurs when the compressive loads acting on the soil surface exceed its inherent stability. Then, bonds of aggregating agents that hold soil particles together break into structural units, leading to a reorientation of soil particles into a configuration with a higher bulk density (Cassel 2019). As consequences of soil compaction, root activities and soil functions are restricted.

The susceptibility of soil compaction depends on several soil properties impacting the cohesive forces between soil particles. These include soil texture, structure, and water content and, to a lesser extent, pH, cation-exchange capacity, and the abundance of organic matter, iron oxides and aluminium hydroxides (de Moraes et al. 2014; Shah et al. 2017). Furthermore, soil management history and pre-consolidation loads influence the soil's physical structure, strength, and reaction to mechanical stress (Casagrande 1936; Dawidowski and Koolen 1994). In general, coarse textured and dry soils are less prone to soil compaction due to their stiff matrices, interlocking, and frictional resistance to deformation (Hillel 2003; Snider and Miller 1985). Accordingly, the application of moderate surface pressure to dry soils causes elastic deformation that leaves only superficial traces. In contrast, clay soils and soils with a high amount of exchangeable calcium are susceptible to compaction damage (Kozlowski 1999), particularly under wet conditions (Soane and van Ouwerkerk 1994). Soil penetration resistance (SPR), which is related to bulk density, increases as soil water potential decreases (Lipiec et al. 2002; da Silva et al. 2016; Souza et al. 2021), because moisture films reduce interparticle bonds and thereby decrease friction (Kozlowski 1999). Plastically deformed and severely compacted soils do not recover naturally for decades (Kozlowski 1999) and can hardly be rehabilitated by management actions. The soil structure can be loosened by means of tillage, but damage to the soil structure cannot be remedied in the short term and restoration requires at least several years.

Preventive measures and sustainable soil management systems include the consideration of soil conditions during management and conserving soil structure, stabilizing tillage techniques which increase the inherent soil stability (Busari et al. 2015). Other measures include traffic control such as reducing vehicle weight and adapting tire pressure (Hamza and Anderson 2005). In the long term, promoting a good and active network of filamentous roots and fungal hyphae improves soil structure (Dabney et al. 2001; Hudek et al. 2022), and increases soil organic matter. In particular, the buildup of organic carbon reduces compactibility by increasing elasticity, structure stability and resistance to deformation of soils (Jensen et al. 2019; Liebhard et al. 2025). The positive effect of increased organic carbon content is already obvious with a small increase in organic material (Soane 1990), and is even more pronounced at high water contents than under dry conditions (Kozlowski 1999).

Soil compaction becomes harmful when it impedes root growth and disturbs soil functions. An increase in compaction impairs the dynamics of water in terms of its conductivity, retention and infiltration capacity, thereby affecting runoff and ponding processes (Alaoui et al. 2018; Biddoccu et al. 2017). Also, plant roots are progressively restricted in their ability to penetrate the soil and grow (Mason et al. 1988). Naturally, plants differ in their ability to penetrate compacted soils, as they have different potential turgor pressures (Whalley et al. 1995), root diameters, and disposition to deflect (Clark et al. 2003). Parameters that reach a threshold that may indicate severe structural damage in soils and a decrease in root and plant growth include air and water conductivity and capacity, and bulk density or SPR (Beylich et al. 2010; Lebert et al. 2006; Shah et al. 2017). For arable soils, threshold values for SPR were identified for various soils and crops, for example, at 2.5 MPa (Bengough and Mullins 1990; Boone 1986; Håkansson and Voorhees 2020; Pabin et al. 1991; Taylor 1971), 3.0 MPa (Horn and Fleige 2009; Kaiser et al. 2009) and 3.5 MPa (Buchter et al. 2004; Roque et al. 2003).

The objectives of agricultural management in terms of soil compaction are to loosen the soil, to prepare the seedbed, and to provide all the soil functions necessary for plant growth. However, unsuitable management can lead to phenomena such as plough horizons, subsoil compaction, or even the collapse of the soil structure in the tillage horizon. Conservation farming systems pursue the strategy of improving the soil structure by improving the soil biology and thus naturally providing a stable and sufficiently permeable soil (Holland 2004). However, inappropriate management or insufficient biological activity may not build up sufficient resistance to natural consolidation and stress caused by management.

Our goal is to support the practical detection of the type and severity of soil compaction as basis for tailored countermeasures and to contribute to the understanding of how different land use and management practices affect soil compaction. To this end, we created a simple, slim, cost-effective, home-built dynamic penetrometer that can be used to measure SPR profiles and evaluate the effects of management practices on compaction. Skilled farmers can build this penetrometer themselves and use it with a provided online evaluation tool to support site-specific management decisions. We tested the consistency and reproducibility of dynamic penetrometer measurements in the laboratory under various settings in terms of falling hammer height and cone angle. We then used the penetrometers to evaluate 20 sites in China and across Europe. At selected sites, we measured additional parameters, such as infiltration capacity, to contextualize the soil compaction data into soil functions. At each site, most of which are long-term, different management systems involving various tillage and cover crop strategies are applied under otherwise identical (soil) conditions. Thus, the aim of this work is to evaluate the long-term impact of tillage and cover crop management on soil compaction across the soil profile, taking into account local conditions.

2 | Materials and Methods

2.1 | Soil Penetration Resistance (SPR) Based on Dynamic Penetrometer Measurements

The determination of SPR profiles by use of dynamic penetrometers is based on the Energy-Work theorem (Halliday and Resnick 1963; Al-Sammarraie and Krlmaz 2023). Kinetic energy of a falling hammer is transferred to the penetrometer, causing it to penetrate the soil. Assuming an inelastic impact between the hammer and the anvil of the penetrometer, with conservation of linear momentum and negligible loss during the collision, the applied energy is transmitted to the soil. Therefore, the work done by the soil to stop the penetrometer tip corresponds to the kinetic energy applied by the falling hammer. Consequently, soil penetration resistance (R_s in N) is calculated as the soil's work to stop the movement of the penetrometer (W_s in J) divided by the penetration distance (P_d in m) as follows:

$$R_s = \frac{W_s}{P_d}$$

(Herrick and Jones 2002). The soil's work to stop the penetrometer movement, considering a loss of kinetic energy when the hammer impacts the anvil (Herrick 2005; Minasny and McBratney 2005) and the hammer and the penetrometer frame move together into the soil is calculated as

$$W_s = m_h g h \frac{m_h}{(m_h + m_f)}$$

where m_h is the mass of the falling hammer in kg, g is the gravity-acceleration constant of approx. 9.81 ms^{-2}, h is the hammer falling height in m, and m_f is the mass of the penetrometer frame (without sliding ruler) in kg.

2.1.1 | Dynamic Penetrometer

Figure 1 shows the design of the simple, cost-effective, home-built dynamic penetrometer that was used. It consists of a cone, a bottom shaft with a sliding measuring device (not shown), and a top shaft with a strike plate, a slide-hammer, an adjustable rubber band for setting the hammer fall height and a sliding handle between two rubber bands. The design is based on the American Society of Agricultural Engineers standards and further developments by Herrick and Jones (2002), with some adaptations for our requirements. Compared to previous standards, adaptations include chamfers for easier removal from the ground without tilting, rubber bands that do not loosen due to vibrations caused by hammer blows, sliding handles that reduce operator-caused friction, a sliding ruler, anvil and hammer with the same diameter, and a slimmer rod for a lower frame-to-hammer weight ratio and reduced risk of shaft friction. The default cone is manufactured based on the American Society of Agricultural and Biological Engineers (2006) standard for soil cone penetrometers as a removable 30° hardened steel cone with a radiused 20.27-mm-diameter base. As agricultural soil penetrometer studies are most commonly performed with cone angles from 30° to 60° (Serafim et al. 2008), an alternative cone according to the Nederland Standards (NNI 1996) with a cone angle of 60° and a radiused 20.60-mm-diameter base was provided to simplify a direct comparison with respective experiments, national standards, and literature. Vertical penetration was ensured by checks using a spirit level or water bubble on the distance measuring device. The penetration distance of each hammer blow is measured using a sliding measuring device that rests on a reference plate positioned at the soil surface and the marks at the bottom shaft. Alternatively, the distance can be measured using an electronic measuring device (measurement accuracy <1 mm), which is held to the underside of the anvil and measures to the reference plate.

2.1.2 | Data Analysis

Individual measured SPR profiles show a progression of uniform values from the initial depth to the final depth of each hammer blow. For multiple replicates, the profiles were averaged in mm increments. Uncertainties for the measured SPR profiles were calculated and presented as 95% confidence intervals. Subsequently, both the averaged SPR values and the confidence interval values were further averaged to cm increments for the output.

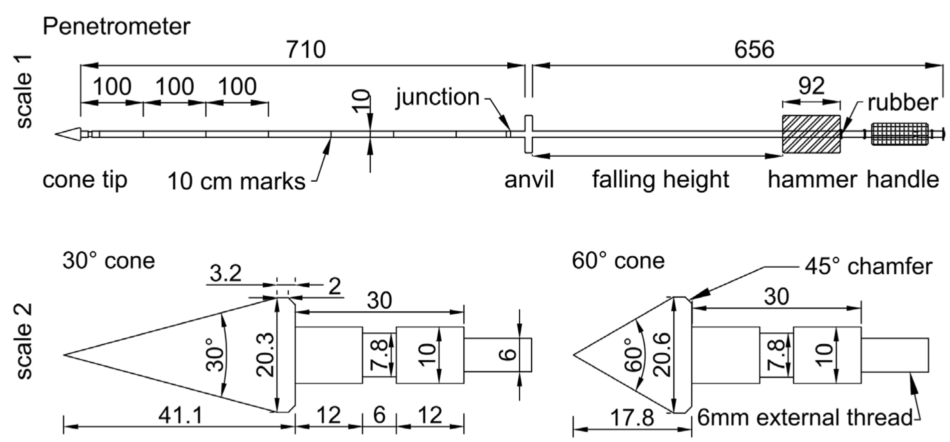

FIGURE 1 | Dynamic penetrometer. Penetrometer frame (top) with selectable cone (bottom). Dimensions are given in mm.

2.1.3 | Testing Sensitivity and Possible Systematic Errors

According to the selected Energy-Work theorem method (the work done by the soil to stop the penetrometer tip corresponds to the applied kinetic energy of the falling hammer) only the base area and not the surface roughness or the angle of the cone affects the penetration resistance. In addition, the penetrometer weight and the drop height of the hammer are included in the calculation via the applied energy, whereby it is not taken into account whether a changed penetration speed also influences the deformation behaviour of the soil. In order to exclude a systematic error due to different cone inclination and drop height, different cone angles (30°/60°) and hammer drop heights (30 cm, 40 cm) were tested in the laboratory with soil columns of 55 cm length containing layers with different bulk densities (0–15 cm at 1.2 $g\,cm^{-3}$, 15–18 cm at 1.9 $g\,cm^{-3}$, 18–30 cm at 1.3 $g\,cm^{-3}$, 30–55 cm at 1.75 $g\,cm^{-3}$). This sequence of soil layers with varying bulk densities was intended to represent a mechanically loosened topsoil, a thin plough pan, a loose layer beneath that, and a compacted subsoil at the very bottom. Two soils from arable land were saturated to correspond to field capacity (pF 1.8) for each compaction level. Soil 1 had a sand/silt/clay content of 11.2/70.4/18.4%, an organic carbon content of 1.6%, an aggregate stability of 18.3% (measured according to Barthès and Roose 2002), a $CaCO_3$ content of 10.3% and a pH of 7.7. Soil 2 had a texture composition of 14.0/60.2/25.8%, an organic carbon content of 1.5%, an aggregate stability of 41.4%, a $CaCO_3$ content of 3.9% and a pH of 7.7. The soils were compacted manually in individual transparent acrylic layer rings with a diameter of 29 cm. The individual rings were stacked on top of each other to form two towers, each 55 cm high, made from soil 1 and soil 2, respectively. The transparent cylinder wall allowed visual checks for border effects. The different settings were measured with 6 repetitions. Differences of means were tested by use of the unpaired two-samples *t*-test. As preconditions, normal distributions were checked using the Shapiro–Wilk test, equal variances of the two groups were checked using the *F*-test. The programming language R was used for these tests.

2.2 | Field Measurement Campaign

2.2.1 | Study Sites

We measured the SPR in soil profiles from sites with mostly long-term agricultural management across Europe and in the Shaanxi Provence in the People's Republic of China (Figure 2). Those sites were selected because at each site different tillage and/or cover crop management systems were applied consistently for many years, enabling long- and short-term management effects to be compared. Basic information on the sites is given in Table 1.

Soil penetration resistance was measured at four vineyard sites (1–4) in European wine-growing regions (1. Leithaberg, Austria; 2. Balaton wine region, Hungary; 3. Rocchetta Ligure, Italy; 4. Montilla-Moriles, Spain) and at five orchard sites (5–9) in apple-growing regions of the United Kingdom and China. In addition, measurements were taken at four sites with only arable land (10–15) in Central Europe and China, three sites with arable land, fallow land and grassland (16–18) in Bulgaria and Italy, and two sites with grassland (19–20) in Bulgaria and the UK.

2.2.2 | Measuring the Effects of Different Long-Term Management

For the field campaign, every operator was trained according to a preset Standard Operating Procedure which included preparation and measurement (Supporting Information S1). At each site, two to five different management systems were compared (Table 2). In order to uniformly take into account the influence of the water content and the matric potential in the measurement and to make the measurements comparable, the penetration resistance was carried out under conditions close to field capacity. Target ranges were derived from the respective local soil texture according to Allen et al. (1998). Volumetric soil water contents were measured at the beginning of the sampling and measuring campaign (Supporting Information S2, Table SM1). If the measured soil water content did not correspond to field capacity, the operators were instructed to saturate the area of interest

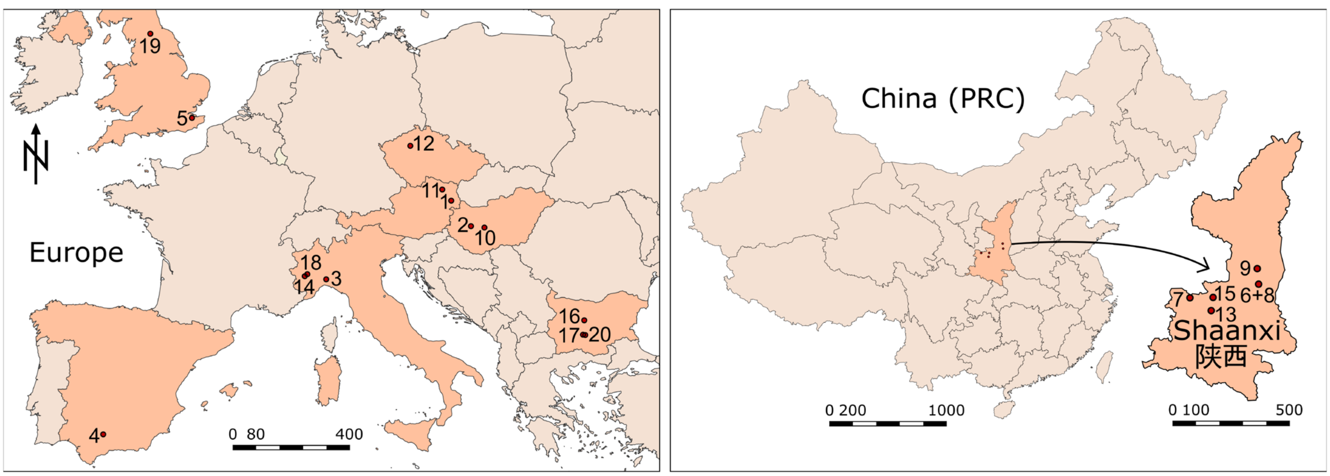

FIGURE 2 | Location of sites in Europe (left) and in the Shaanxi Provence in the People's Republic of China (right). Numbers correspond to sites reported in Table 1.

TABLE 1 | Measurement sites basic information.

ID	Location	Climate	Soil texture	Main crop	Site established
1	Donnerskirchen, Austria	Pannonian	Silty loam	Vineyard	1986
2	Balatoncsicsó, Hungary	Pannonian	Silty loam	Vineyard	2000
3	Rocchetta Ligure, Italy	Mediterranean	Loam	Vineyard	2017
4	La Partera, Spain	Mediterranean	Sandy loam	Vineyard	2011
5	Chesley, Kent, United Kingdom	Atlantic	Silty loam, Loam	Apple orchard	2013
6	Baishui, China	Temperate Continental Monsoon	Silty clay loam	Apple orchard	2015
7	Qianyang, China	Temperate Continental Monsoon	Silty Clay Loam	Apple orchard	2017
8	Baishui, China	Temperate Continental Monsoon	Silt loam, Silty clay loam	Apple orchard	2017
9	Luochuan, China	Temperate Continental Monsoon	Silty Clay, Silty clay loam	Apple orchard	2017
10	Nagyhörcsök, Hungary	Pannonian	Silt	Arable	2023
11	Hollabrunn, Austria	Pannonian	Silty loam	Arable	2005
12	Řisuty, Czech Republic	Humid continental	Sandy loam	Arable	2011
13	Yangling, China	Temperate Continental Monsoon	Silty clay loam	Arable	2019
14	Villafranca Piemonte, Italy	Mediterranean	Sandy loam, Loam	Arable	2020
15	Yongshou, China	Temperate Continental Monsoon	Silty clay Loam	Arable	2015
16	Troyan, Bulgaria	Humid continental	Sandy loam	Arable + Fallow + Grassland	1990
17	Tsalapitsa, Plovdiv, Bulgaria	Humid continental	Sandy clay	Arable + Fallow	2022
18	Tetto Frati, Italy	Continental	Silty loam	Grassland	1992
19	Colt Park, United Kingdom	Humid temperate oceanic climate	Sandy loam	Grassland	1989
20	Plovdiv, Bulgaria	Humid continental	Sandy clay	Grassland	2019

beforehand and wait 2 days until conditions of field capacity were reached, as set out in our Standard Operating Procedures. However, as the measurements were taken in spring or autumn when the soil water content had recovered, this procedure was not necessary at any of the measurement sites. Consequently, all measurements were done consistently across all sites and management variants. The uniformity of soil water conditions across the profile was checked visually and using TDR probes in the soil profile pits. Measurements in soils with different management systems at the same location were carried out on the same day. In order to measure reproducible profiles, the local measurement team was recommended to perform at least 3–5 measurement repetitions per system; the actual number of measurement repetitions was determined based on local possibilities and conditions. Up to 12 measurement repetitions were carried out for individual treatments in order to obtain meaningful profiles with narrow confidence intervals. In fields with tillage operations, penetration resistance was measured at least 1 month after the tillage operation to allow natural soil consolidation and to measure the long-term effect rather than just the short-term soil loosening.

In addition, soil organic carbon, infiltration capacity and bulk density were measured at selected sites (1–6, 11–15, 18). We compared the effects of different management systems by testing the different mean values using a one-way analysis of variance (ANOVA). If the null hypothesis of equality of means across groups was rejected for $\alpha = 0.05$, post hoc paired t-tests with Bonferroni adjustment were conducted by use of the programming language R in program RStudio (Posit Software, PBC, Boston, MA, USA).

TABLE 2 | Description of differences in management for each long-term experiment site and number of penetration resistance measurement replicates (*n*).

ID	Location	Main crop	*n*	Management				
				1	2	3	4	5
1	Donnerskirchen	Vineyard, conventional management	12	No-till, permanent spontaneous vegetation cover mowed once a year	Reduced till, permanent multi species mixture cover	Reduced till, alternating interrow spontaneous vegetation cover	—	—
2	Balatoncsicsó	Vineyard, organic management	5	No-till, permanent Multi species local seed cover	No-till, temporary multi species cover crop mixture	Disking, no cover crop	—	—
3	Rocchetta Ligure	Vineyard, organic management	12	Alternating[a], autumn-till, permanent seeded Conventional multi species cover crop	Alternating[a], no-till, temporary Spontaneous multi species cover crop	Minimum till, no cover	—	—
4	La Partera	Vineyard, conventional management	4	Tilled, temporary sown multi species cover crop	Tilled, no cover crop	—	—	—
5	Chesley, Kent	Apple orchard, conventional management, minimum tillage	12	Permanent wildflower multi species cover	Permanent wildflower multi species cover	—	—	—
6	Baishui	Apple orchard	3	Minimum till, spontaneous multispecies vegetation	Minimum till, white clover cover crop	—	—	—
7	Qianyang	Apple orchard	11	No-till, tall fescue-based vegetation or ryegrass and clover cover	No-till, spontaneous vegetation	Ploughed twice a year, no cover crop	—	—
8	Baishui	Apple orchard	9	No-till, permanent multi-species vegetation cover	No-till, natural vegetation	Ploughed once a year, natural vegetation or commercial species mix	Ploughed twice a year, spontaneous vegetation	Ploughed twice a year, no cover crop
9	Luochuan	Apple orchard	9	No-till, permanent clover cover	Ploughed once a year, no cover	Ploughed twice a year, no cover	Ploughed 3 times a year, no cover	—
10	Nagy-hörcsök	Arable	7	No-tillage, cover crop	Minimum tillage, cover crop	Ploughed, no cover crop	—	—

(Continues)

TABLE 2 | (Continued)

ID	Location	Main crop	*n*	Management 1	Management 2	Management 3	Management 4	Management 5
11	Hollabrunn	Arable, conventional management	12	No-tillage, commercial cover crop mix	Reduced tillage with cultivator, cover crop mix	Ploughed, no cover crop	—	—
12	Řisuty	Arable, conventional management	5	shallow stubble tillage, temporary cover crop	PLOUGHED, temporary cover crop	Ploughed, without cover crop	—	—
13	Yangling	Arable, conventional management	3	No-till, no cover crop	Ploughed, no cover crop	—	—	—
14	Villafranca Piemonte	Arable, conventional management	12	Ploughed, temporary ryegrass cover crop	Ploughed, temporary vetch cover crop	Ploughed, no planted cover crop	—	—
15	Yongshou	Arable, conventional management	8	Green bean cover crop	Black kidney bean cover	Buckwheat cover	Gaodan grass cover	No cover crop
16	Troyan	Arable + Fallow + Grassland	3	Fallow land, no management	Grassland, mowed	Extensive alfalfa cultivation	ploughed arable land, no cover crop	—
17	Tsalapitsa, Plovdiv	Arable + Fallow	3	Fallow land	Ploughed stubble, no cover crop	—	—	—
18	Tetto Frati	Arable + Grassland, intensive management	12	Grassland, permanent spontaneous cover	Grassland - crop rotation with maize every 3–5 years, alfalfa cover	Grassland -crop rotation with maize every 3 years, spontaneous cover	—	—
19	Colt Park[b]	Grassland, hay meadow, grazed	9	Unfertilised	Fertilized 25 kg ha^{-1} 20:10:10 NPK	Seed addition (1990–1992)	—	—
20	Plovdiv	Grassland	3	Fallow land	Disked grassland	—	—	—

[a]3 The inter-row management of management 1 and 2 alternates in time and space between cover crop and temporary green cover. The two management systems are identical, but are shifted by one year. The tillage and cover crop management described here refers to the year prior to measurements being taken. The specifics of the management are described in the Supporting Information S3.
[b]The grassland at the Colt Park site was managed through spring grazing by sheep at a stocking rate of 6.9 sheep per ha, followed by hay cutting in July and autumn grazing by cattle at a stocking rate of 0.9 cattle per ha.

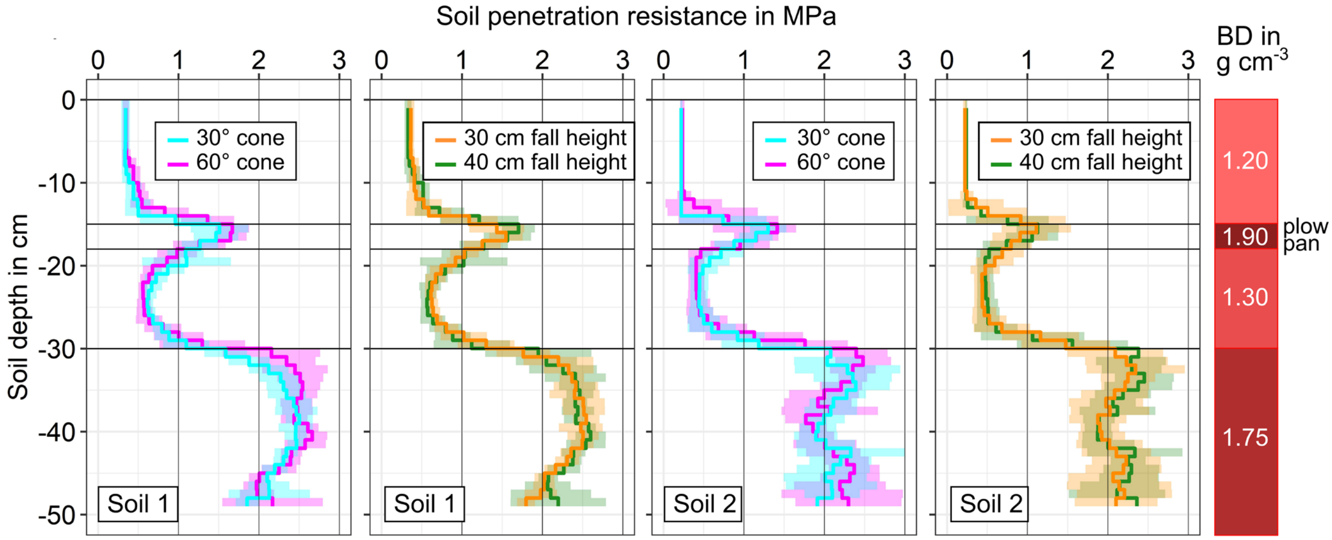

FIGURE 3 | Penetration resistance profiles for two different silt loam soils obtained from laboratory measurements using a dynamic penetrometer. The soil profile was compacted manually (0–15 cm: 1.2 g cm^{-3}, 15–18 cm: 1.9 g cm^{-3}, 18–30 cm: 1.3 g cm^{-3}, 30–55 cm: 1.75 g cm^{-3}). Comparison between 30° (cyan) and 60° (magenta) cones and between 30 cm (orange) and 40 cm (green) fall height ($n=6$ for each profile). Confidence intervals ($\alpha=0.05$) are shown in pale colour.

3 | Results

3.1 | Evaluation of the Reproducibility of Dynamic Penetrometer Measurements With Different Settings

Figure 3 shows SPR profiles from the laboratory experiments with artificially constructed soil columns and different penetrometer settings. For both soils, the two penetration resistance profiles compared (cone shapes with 30° and 60° and hammer fall heights of 30 cm and 40 cm) resulted in similar SPR profiles. The comparisons between the different settings showed in most sections no differences. The only deviations were measured in the comparison between 30° and 60° cones in soil 1. There, the averages of the topsoil section from 0 to 15 cm ($p=0.004$) and of the deepest section from 30 to 50 cm ($p=0.03$) were different. The comparisons between different hammer fall heights showed no significant differences for all sections and both soils. The experiments with layers of similar bulk density revealed different soil penetration resistance values for different soils, though. The SPR values were about 15% higher for soil 1 than for soil 2 for both settings.

3.2 | Evaluation of the Effects of Management on Soil Compaction

3.2.1 | Vineyard and Orchard

The SPR profiles of the inter-rows in the vineyard and orchard sites are shown in Figure 4. All four vineyard sites (1–4) differed in cover crop management and three vineyard sites (1–3) differed in soil management. At the Donnerskirchen site (1), the averaged SPR profiles differed in the topsoil as they were partly outside the 95% confidence intervals of the other SPR profiles in the top 30 cm. The lowest compaction was measured in the no-till vineyard with a surface cover that grew spontaneously. Compaction in the vineyards with minimum tillage management was higher, with a higher maximum of SPR in the vineyard with yearly applied cover crops compared to the vineyard where cover crop is alternating every 2–4 years. At the Balatoncsicsó site (2), the SPR profile for minimum-tillage and the no-till with permanent vegetation is similar except for differences in the top 15 cm of soil. The no-till variant with temporal cover crop had higher compaction across the soil profile down to 40 cm, with a maximum of 3.5 MPa close to the surface. At the Rocchetta Ligure site (3), the SPR profiles of the no-till variant with a spontaneous cover crop and the minimum tillage without a cover crop were similar throughout the profile. The SPR profile of the management system involving autumn tillage prior to the sampling season and a commercial cover crop mix this year differed from the other two management systems within the top 20 cm. As the management of the first two systems, which include cover crops, is identical, with alternating management in space and time but a 1-year shift, the different SPR profiles reveal the temporal variation and impact of tillage. At the La Partera site (4), the vineyard with a cover crop mix was compacted in the inter-rows. In contrast, management without cover crops had loose soil down to 30 cm soil depth. Even though the 95% confidence intervals spanned a range of mostly more than 1 MPa on both sides, the differences due to cover crop management are significant. The difference cannot be explained by different water contents during measurement, which were similar at 32.8% volumetric water content (with cover crop) and 34.4% (without cover crop). However, the temporary cover crop, which comprised different plant species, failed to develop properly in terms of its size, aerial biomass, root biomass or soil coverage. The reasons for this poor development are unclear but are thought to be due to the soil's high carbonate content and the browsing by hares and *Ocnogyna baetica*. Thus, the differences in SPR are directly attributed to the different intensity of annual mechanical soil loosening between the different treatments, which is one superficial tillage pass for seedbed preparation before sowing the cover crop and two to three cultivator passes to eliminate weeds in the bare soil management.

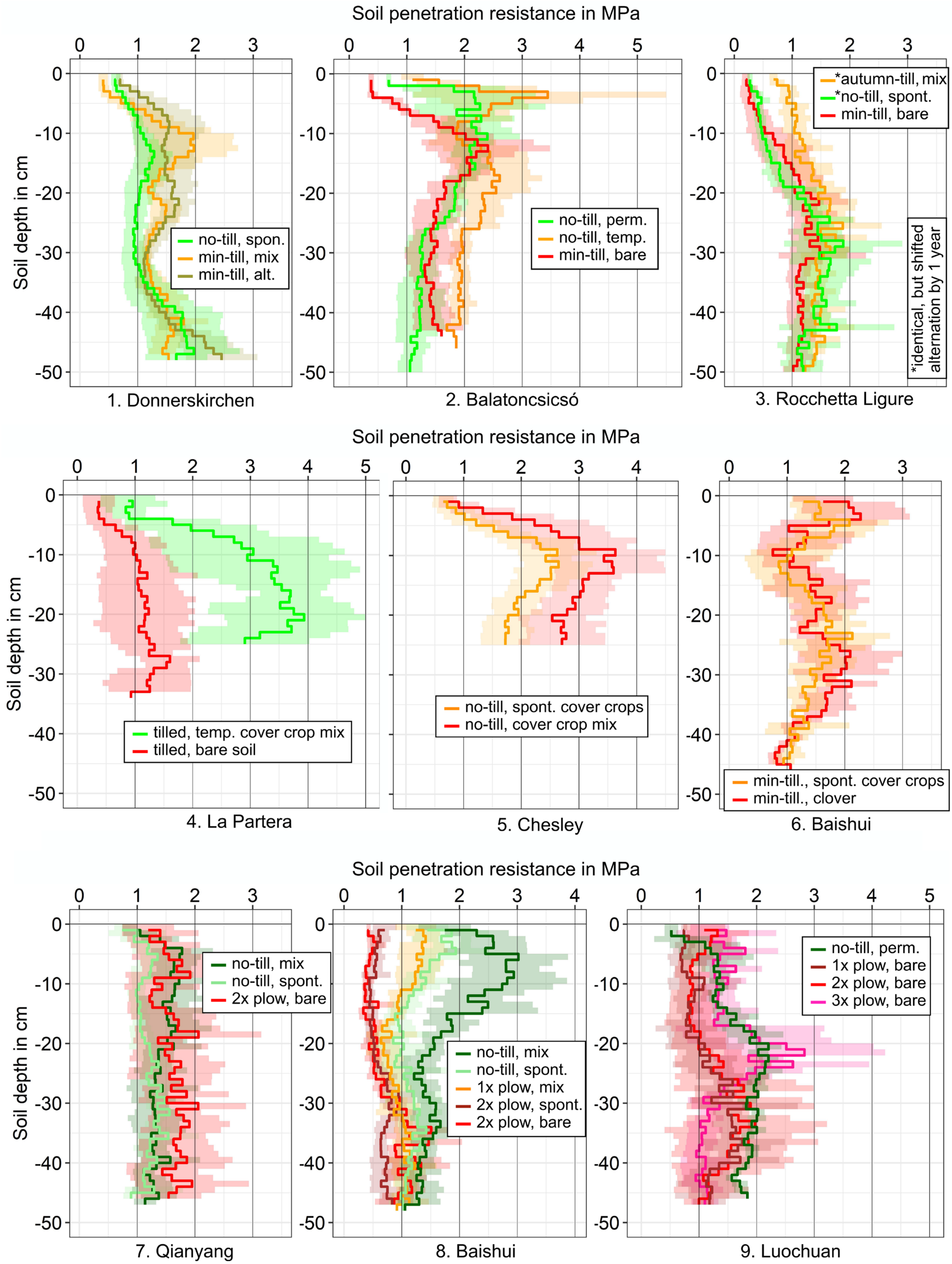

FIGURE 4 | Penetration Resistance over the soil profile for measured vineyard (1–4) and apple orchard (5–9) sites. Averaged penetration resistance in cm steps using a dynamic penetrometer ($n_1 = 12$, $n_2 = 5$, $n_3 = 12$, $n_4 = 4$, $n_5 = 12$, $n_6 = 3$, $n_7 = 11$, $n_8 = 9$, $n_9 = 9$). The legends provide differences in soil and cover crop management. Confidence intervals ($\alpha = 0.05$) are given in light colour.

Of the apple orchard sites (5–9), two sites (5, 6) differed only in cover crop management and three sites (7–9) differed additionally in soil management. The two sites with different cover crop management (5,6) showed different sensitivity to different cover crop management. At the Chesley site (5), soil compaction was higher in one of the no-till orchards with different cover crop mixes (Supporting Information S4). The orchard with the spontaneous cover crop vegetation had a maximum penetration resistance of about 2.5 MPa. The other orchard with a seeded wildflower cover crop mix had a maximum at about 3.5 MPa in the similar soil depth. At the Baishui site (6), the two minimum tillage orchards with different cover crops—spontaneous multi-species cover and white clover cover crop monoculture—had similar SPR over a large part of the soil profile. Only in the top 5 cm, the averaged SPR profile of the white clover cover was higher than the upper confidence interval of the SPR profile of the field with spontaneous cover. The apple orchards in Qianyang (7), Baishui (8), and in Luochuan (9) differed both in cover crop and soil management. At the site in Qianyang (7), the ploughed orchards without cover crops and the orchards without tillage and cover crops did not differ in most sections of the profile. The averaged SPR profile of the to-till variant with spontaneous cover crops exhibited lower penetration resistance values in some sections than the averaged SPR profiles of the other variants, but the upper confidence intervals were only rarely below the lower confidence intervals of the other variants. In contrast, in Baishui (8), the management variants differed according to management intensity. The lowest compaction was measured in the most intensively managed orchards, with or without cover crops, which were ploughed twice a year. The orchard with a cover crop mixture ploughed once a year had higher compaction down to a ploughing depth of 20 cm. Its SPR profile was similar to that of the no-till orchard with spontaneous cover crop vegetation. The second no-till system with ryegrass or clover as cover crops had twice the SPR down to 20 cm depth. Thus, the higher compaction in the cover crop mix compared to the spontaneous vegetation is more pronounced in Baishui (8) than in Qianyang (7). At the Luochuan site (9), no-till management with permanent vegetation was compared to bare soil management with 1–3 ploughs per year. No-till management caused the most uniform SPR profile with a maximum at approx. 2.0 MPa. In the tilled orchards, the more frequently ploughed orchards had higher penetration resistance values than the less frequently ploughed orchards down to the ploughing depth of about 20 cm. The orchard ploughed three times a year has its maximum SPR at the plough depth, which already indicates the formation of a plough pan (Figure 4).

3.2.2 | Arable Soil and Grassland

SPR profiles based on measurements at arable and grassland sites are shown in Figure 5. Four measured sites (10–15) are arable land, three sites (16–18) allow comparison of arable and grassland management, and two sites (19–20) are grassland.

At the Nagyhörcsök site (10), no-tillage management resulted in less compaction than both the minimum and conventional tillage systems at the plough horizon. Below this, the SPR curves were similar down to 40 cm soil depth. At the site in Hollabrunn (11), management with ploughing and bare soil management caused the lowest compaction in the ploughing horizon and the highest compaction below compared to the other systems. The no-tillage with cover crop management had the opposite effect with highest penetration resistance in the topsoil and lowest compaction below 30 cm soil depth compared to the other systems. The variant with tillage but without ploughing produced a SPR profile with values between the other variants throughout the measured soil profile. At the conventionally managed fields in Řisuty (12), both ploughed fields (with or without temporary cover crop) had similar penetration resistance profiles with loose soil in the ploughing horizon in about 20 cm soil depth. Similarly, shallow tillage management led to a penetration resistance below 2 MPa in its respective tillage depth of about 10 cm. Below the maximum tillage depths, SPR values were converging in all fields. At the Yangling site (13), soil compaction was higher under no-till than under conventional management in the top 20 cm. However, even under no-till, there was no problematic surface soil compaction. Below 20 cm, the degree of soil compaction was similar. At the site in Villafranca (14), all three compared fields are ploughed; two of them have different cover crop mixtures and one is kept bare after the main crops. All three penetration resistance profiles are similar with loose soil in the ploughing horizon and an increase below. At the Yongshou site (15), management of the main crops was the same, and only cover crops varied, which did not affect the SPR profiles differently.

At the sites in Troyan (16) and Tsalapitsa (17), arable fields, fallow land, and grassland were measured. At both sites, the different management practices resulted in different profiles in the tillage horizon, with mostly similar compaction in the deepest measured depths around 30 cm. The effects of management were similar at both sites. Ploughing resulted in a loose soil in the tillage horizon and a strong increase below. Fallow land had a loose topsoil (< 0.5 MPa) down to 10 cm soil depth, a steady increase below, and a plateau with the same penetration resistance as at 30 cm soil depth. Particularly at the Troyan site (16), grassland and alfalfa had a higher SPR in the topsoil; however, no harmful compaction was reached in the mechanically undisturbed soils. Similar SPR profiles were measured in arable areas and fallow land in Tsalapitsa (17). At the Tetto Frati site (18), all differently managed grassland indicated soil compaction. The broad range of confidence intervals hampers differentiation, yet the mean SPR profiles of fields with crop rotation every 3 years indicate lower compaction than with permanent grassland management (only mowing, no grazing) in the top 10 centimetres. At the Colt Park (19) and Plovdiv (20) sites, the different cover crop management systems did not cause a difference in SPR at most soil depths.

3.2.3 | Soil Organic Carbon Contents at Different Management Systems

As the management systems at most sites have differed over many years (Table 2), the soil structure and, in some cases, the organic carbon content are different at several sites (Table 3). Still, at 15 sites, no significant differences in soil organic carbon contents were found. At two sites, the organic carbon levels differed in the topsoil (site 9) or the subsoil (site 6). At three sites, organic carbon levels differed across the soil profile (sites 8, 11

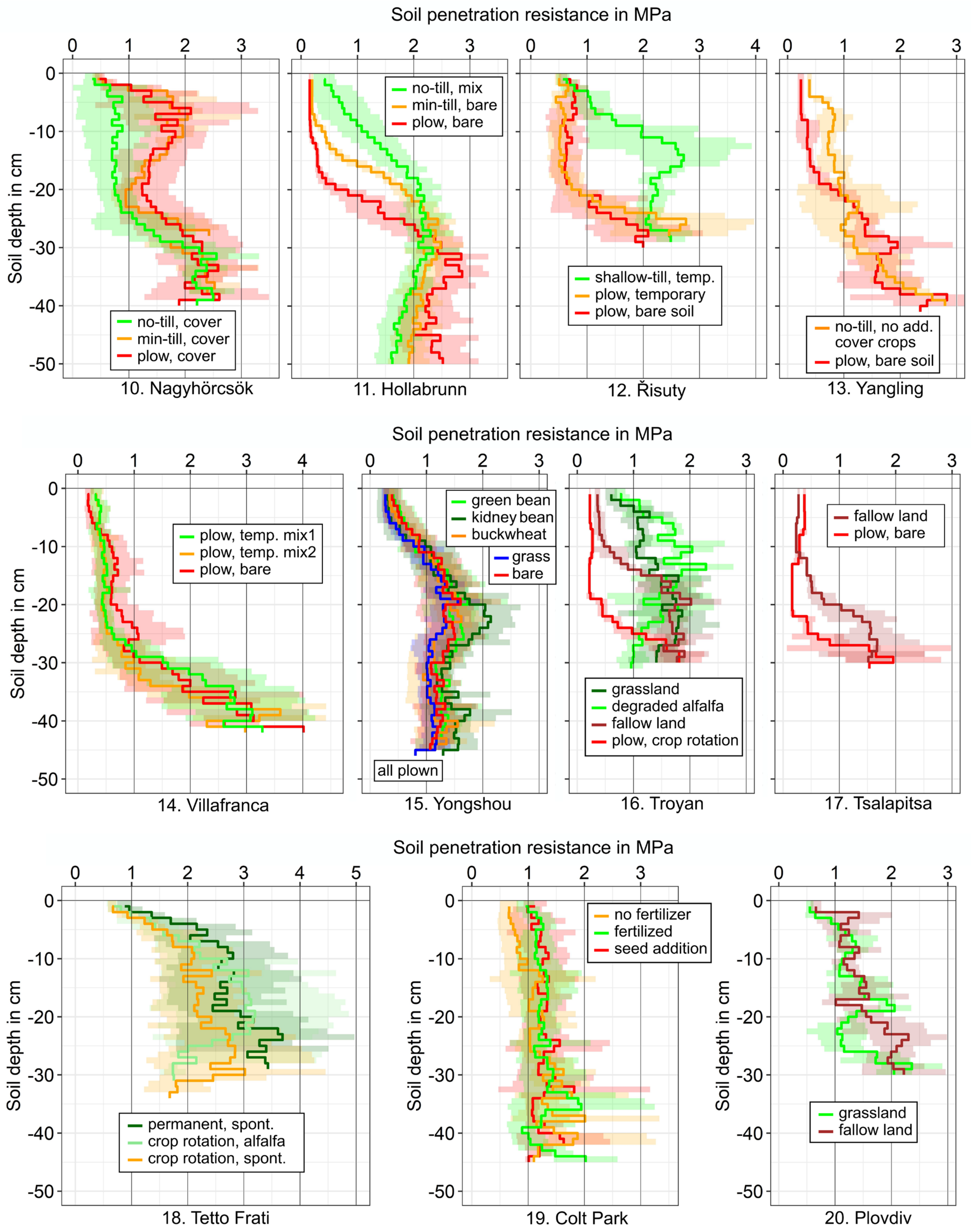

FIGURE 5 | Penetration Resistance over the soil profile for all measured sites of arable land (10–15), arable land and grassland (16–18), and grassland (19–20). Averaged penetration resistance in cm steps using a dynamic penetrometer ($n_{10}=7$, $n_{11}=12$, $n_{12}=5$, $n_{13}=3$, $n_{14}=12$, $n_{15}=8$, $n_{16}=3$, $n_{17}=3$, $n_{18}=12$, $n_{19}=9$, $n_{20}=3$). The legends provide differences in soil and cover crop management. Confidence intervals ($\alpha=0.05$) are given in light colour.

and 18) due to the management system. Significant differences were therefore only measured in apple orchards and arable land; in vineyards and grassland, differences were not significant.

3.2.4 | Bulk Density and Infiltration Capacity

Soil surface infiltration capacity and bulk density measurements were made at selected sites (Table 4). The measurements of the bulk density only showed significant differences at a few sites (2, 3, 11). Considering even the order of minor differences, bulk density and SPR measurements at individual sites (1, 11, 12, 14) consistently showed the effects of the management systems. For the majority of the sites (2–6, 18), however, the effects on the compaction status were inconsistent and not even in order of management intensity.

For infiltration capacity, the significance of the differences was also only given for some individual sites (1, 4, 11, 18) and not for others (2, 3, 5, 6, 10, 14). Considering again even the order of minor differences, the correlation with SPR in the top 20 cm was also only evident for a few sites (2, 4, 6, 11, 17). A higher SPR near the surface did not imply a lower infiltration capacity (1). Compared with the management systems (Table 2), the infiltration capacity was more dependent on cover crop management. More intensive use of cover crops—which was often related to lower tillage intensity—tended to decrease infiltration capacity (1, 4, 11). The opposite effect was found only at site 18.

4 | Discussion

4.1 | Evaluation of the Dynamic Penetrometer Use

Our results from field measurements confirmed that SPR does not necessarily correlate with bulk density measurements only (Table 4, Figures 4 and 5). In addition to the actual compaction status, SPR measurements were also influenced by other soil properties and conditions during the measurement such as water content and tension, texture, soil type (de Moraes et al. 2014; Vaz et al. 2011), and the root network. To minimize the influence of the water content on SPR, similar soil water tensions (field capacity) were aimed as target conditions for the measurement for all management systems; this allows the comparison of data for individual field sites but does not allow for direct comparison of the actual SPR values for different field sites with different soil textures and thus different water contents at field capacity. As the measuring method and instruments also influence the measured SPR profiles, the uncertainties were minimized by following our Standard Operating Procedures for dynamic penetrometers. It is reported that dynamic penetrometers may overestimate SPR in highly compacted soils compared to those measured by static penetrometers, provided the latter can be used as a reference (Minasny 2012). However, the overestimation due to energy loss arising from strikes particularly affects SPRs from approximately 2.5 MPa, where harmful compaction has already been identified (Minasny 2012). Nevertheless, due to their simple and robust design, dynamic penetrometers are subject to fewer sources of error and external influences than static penetrometers. Static penetrometers are dependent on settings and the operator, particularly with regard to standard manually-operated models. Additionally, static penetrometers, which are pressed into the soil at a constant pressure or rate, provide a parameter called cone index, which depends on the cone and the penetration rate (Herrick and Jones 2002; de Moraes et al. 2014).

Results of numerical analyses and experiments on the impact of cone angle and cone diameter on penetration resistance imply that the simplified assumptions based on the energy-work theorem do not accurately account for the deformation behaviour of the soil (Esmailzade et al. 2022; Nowatzki and Karafiath 1972). However, our laboratory tests showed that the different hammer fall heights (30 cm/40 cm) and cone shapes (30°/60° cone) did not affect the measured SPR profiles in most sections. The only differences measured on one soil were due to slightly shifted SPR profiles at the transitions between different bulk densities. Two averaged sections had a different mean value and the averaged curves were outside the other confidence intervals near the transitions. No differences were measured at the plough pans. However, the laboratory tests showed that the influence of the soil properties on the measured values should not be neglected. Although the two soils tested were both silt loams and the individual layers were packed with the same bulk densities, differences in SPR were observed. In soil 1 (11.2% sand, 70.4% silt, 18.4% clay) maximum SPR of about 1.05 (±0.26) MPa was measured in the 3 cm compacted layer representing a plough pan. Soil 2 (14.0% sand, 60.2% silt, 25.8% clay) had a higher maximum SPR of about 1.47 (±0.15) MPa. Higher values were also measured for the other layers but with smaller differences. Across the soil column profile, the measured SPRs in soil 2 were about 15% higher than in soil 1. On the one hand, the differences are attributed to inhomogeneities in the manual layer-by-layer compaction. On the other hand, the differences in grain size distribution are also a factor as it influences the soil stability (cohesion and angle of internal friction) and water content. Although the soils are of the same texture class, the volumetric water content (VWC) at field capacity (pF of 1.8) was almost 2% higher in soil 1 (38.8% VWC) as compared to soil 2 (37% VWC). In general, the water content is a sensitive factor that must always be considered. Even for a single soil tested, setting a specific volumetric water content at different soil bulk densities results in different gravimetric water contents and, more importantly, in different matrix potentials. This results in different ratios between the solid and liquid phases, as well as altered pore pressure and capillary forces, which affect the stability of the soil structure and the friction and soil displacement processes differently. At a low bulk density (e.g., 1.2 $g\,cm^{-3}$), the gravimetric water content is about one and a half times higher (0.31–0.32 $g\,g^{-1}$) than that of the high-density layers (0.20 $g\,g^{-1}$ at 1.9 $g\,cm^{-3}$), with the respective differences in matric potentials and corresponding effects on the frictional resistances.

We have presented the measurements read to millimetre accuracy in cm increments, which has proven to be practical. Averaging to larger increments reduces variations and sizes of confidence intervals. However, larger averaging steps are unsuitable for the detection of plough pans, which are often

TABLE 3 | Organic carbon (OC) for each management at long-term experiment sites.

ID	Location	Sampling depth	Soil organic carbon by management				ANOVA	*t*-test
			1	2	3	4		
1	Donners-kirchen	0–20 cm	2.47 (0.96)	2.34 (0.70)	2.81 (1.02)	—	0.757	—
		20–40 cm	1.07 (0.09)	1.14 (0.18)	1.15 (0.12)	—	0.676	—
2	Balaton-csicsó	0–10 cm	2.92 (0.70)	3.17 (0.59)	1.92 (0.81)	—	0.075	—
		10–20 cm	2.75 (0.13)	3.33 (0.29)	2.15 (1.13)	—	0.100	—
3	Rocchetta Ligure	0–12 cm	2.83 (0.16)	3.04 (0.46)	3.05 (0.47)	—	0.693	—
		12–25 cm	2.50 (0.24)	3.04 (0.32)	2.73 (0.28)	—	0.067	—
4	La Partera	0–20 cm	0.80 (0.08)	0.87 (0.06)	—	—	0.237	—
		20–40 cm	0.73 (0.11)	0.84 (0.06)	—	—	0.136	—
5	Chesley, Kent	0–15 cm	2.97 (0.53)	3.19 (0.34)	—	—	0.504	—
		15–30 cm	1.84 (0.26)	2.04 (0.19)	—	—	0.254	—
6	Baishui	0–20 cm	2.65 (0.06)	2.60 (0.25)	—	—	0.765	—
		20–30 cm	**2.44** (0.16)	**1.99** (0.04)	—	—	**0.010**	**0.010**
7	Qianyang	0–20 cm	1.61 (0.64)	1.02 (0.16)	1.22 (0.41)		0.127	—
		20–60 cm	0.63 (0.06)	0.68 (0.08)	0.70 (0.14)		0.591	—
8	Baishui[a]	0–20 cm	**1.64** (0.13)	**1.31** (0.23)	**1.66** (0.47)	**0.83** (0.17)	**0.003**	1/2: **0.050**, 1/4: **0.000**, 1/5: **0.008**, 2/4: **0.015**, 3/4: **0.016**
		20–60 cm	**0.76** (0.09)	**0.67** (0.10)	**0.68** (0.08)	**0.73** (0.24)	**0.002**	1/5: **0.016**, 2/5: **0.007**, 3/5: **0.007**, 4/5: **0.035**
9	Luochuan	0–20 cm	**1.09** (0.17)	**0.86** (0.08)	**0.92** (0.21)	**0.36** (0.04)	**0.001**	1/4: **0.002**, 2/4: **0.001**, 3/4: **0.010**
		20–60 cm	0.58 (0.07)	0.55 (0.10)	0.56 (0.12)	0.75 (0.07)	0.080	—
10	Nagyhörcsök[b]	0–30 cm	1.91 (0.10)	1.91 (0.10)	1.91 (0.10)	—	—	—
11	Hollabrunn	0–15 cm	**1.76** (0.06)	**1.62** (0.05)	**1.27** (0.05)	—	**0.000**	1/2: **0.002**, 1/3: **0.000**, 2/3: **0.003**
		16–30 cm	**1.29** (0.06)	**1.33** (0.03)	**1.40** (0.04)	—	**0.006**	1/3: **0.009**, 2/3: **0.021**
		31–50 cm	**0.47** (0.05)	**0.37** (0.03)	**0.33** (0.02)	—	**0.000**	1/2: **0.006**, 1/3: **0.001**, 2/3: **0.032**
12	Řisuty	0–12 cm	1.80 (0.39)	1.41 (0.19)	1.43 (0.37)	—	0.233	—
		13–25 cm	1.10 (0.17)	1.15 (0.21)	1.38 (0.37)	—	0.329	—
13	Yangling	0–20 cm	1.66 (0.05)	1.78 (0.11)	—	—	0.266	—
		20–40 cm	0.98 (0.04)	1.02 (0.64)	—	—	0.440	—
14	Villafranca Piemonte	0–15 cm	0.91 (0.06)	0.99 (0.18)	0.80 (0.15)	—	0.189	—
		16–30 cm	0.97 (0.15)	0.91 (0.18)	0.92 (0.26)	—	0.889	—
		31–45 cm	0.71 (0.02)	0.55 (0.13)	0.54 (0.12)	—	0.085	—

(Continues)

TABLE 3 | (Continued)

ID	Location	Sampling depth	Soil organic carbon by management				ANOVA	*t*-test
15	Yongshou[c]	0–20 cm	0.99 (0.12)	0.87 (0.23)	0.87 (0.23)	0.91 (0.02)	0.395	—
		20–60 cm	0.68 (0.11)	0.69 (0.09)	0.69 (0.15)	0.70 (0.08)	0.371	—
16	Troyan	0–20 cm	0.58 (0.13)	0.87 (0.20)	0.87 (0.14)	0.58 (0.15)	0.221	—
17	Tsalapitsa	0–20 cm	0.90 (0.17)	1.16 (0.22)	—	—	0.421	—
18	Tetto Frati	0–15 cm	**3.81** (0.61)	**1.43** (0.09)	**2.23** (0.21)	—	**0.000**	1/2: **0.000**, 1/3: **0.000**, 2/3: **0.003**
		16–30 cm	**1.54** (0.17)	**1.19** (0.04)	**1.51** (0.06)	—	**0.002**	1/2: **0.008**, 2/3: **0.000**
19	Colt Park	0–10 cm	4.89 (0.85)	5.28 (0.67)	4.89 (0.85)	—	0.727	—
20	Plovdiv	0–20 cm	0.93 (0.11)	0.98 (0.14)	—	—	0.505	—

Note: Averages of OC and standard deviation (in brackets) in % ($n = 4$). Differences were tested using a one-way analysis of variance (ANOVA) and subsequently with a post hoc paired *t*-tests with Bonferroni adjustment (*p*-values given). Managements with significant differences are marked in bold. Management treatment numbers are reported in Table 2.
[a]8 Baishui additionally with 5 OC in 0–20 cm: **1.07**% (0.26%) and OC in 20–60 cm: **1.19**% (0.24%).
[b]10 Nagyhörcsök experiment started only the year before measurement.
[c]15 Yongshou additionally with 5 a control variant (no cover crop): OC in 0–20 cm: 0.73% (0.04%) and OC in 20–40 cm: 0.55% (0.02%).

only a few cm thick with increased compaction and smeared pores. The detection of plough pans using penetrometers is one of the most important applications. The preliminary laboratory experiments with artificially produced compacted layers showed that thin (3 cm) compacted layers can be detected, although the peak of the SPR may not represent but underestimate the actual extent. This potential underestimation of resistance of thin compacted layers is due to the measurement procedure where individual hammer blows and penetrations start and end also outside the thin layers. In addition, the soil can more easily deflect vertically into less compacted areas. In the case of very thin plough pan compaction, the peak of the SPR profile may therefore be lower and the profile curve more widely dispersed than is actually the case. Accordingly, the maximum values of the measured SPRs in the plough pan (15–18 cm soil depth) were only about half as high as in the deeper layer (30–55 cm soil depth) although the bulk density here was even greater than in the deeper layer (1.9 vs. 1.75 g cm^{-3}) (Figure 3). It should also be noted that the bevelled part of the 30° tip itself is almost 3 cm long, which limits its use in thin layers. However, with on-site evaluation, identified problem zones can be further assessed by reducing hammer fall height around the depth of interest.

In the field a minimum repetition of three measurements was mostly sufficient to make statements about differences between management systems (e.g., 1, 8, 13). With at least 5 replicates the differentiability further improved (e.g., 11, 12). However, in some cases the spatial heterogeneity or single stones broadened the confidence intervals and similar numbers of replicates did not ensure significance of the measured SPR profiles and allow identification of existing differences. This includes the inherent within-field spatial variability of soil properties (Peeters et al. 2024; Taylor et al. 2003) and different soil depths at different slope positions in hilly regions (Toth et al. 2024).

4.2 | Evaluation of the Effects of Management on Soil Compaction

Except for the two sites 3 and 7 tillage management had a long-term effect on soil compaction—some had higher SPR values than the compared management system, while others had lower ones. In a few cases (e.g., sites 2, 8, 9, 12, 18) the SPR in tilled fields was at least partially lower than in not- or less-intensively tilled fields down to the ploughing depth, although measurements were not taken immediately after tillage. Even at site 3, where the long-term effects of tillage were unclear, the long-term experiment involving two identical systems with an annual alternating management system shifted by 1 year shows the short-term effects of tillage. Of the two identical systems, the one with the less recent tillage at the time of measurement (approx. 18 months ago) had a different SPR profile compared to the other two treatments. Despite differing in tillage and cover crop management, these two systems had similar SPR profiles, with a lower SPR compared to management 1. Both systems had their last tillage approximately 6 months prior to measurement. This apparent long- and short term relationship between soil loosening and higher porosity is often observed (Badalíková 2009; Farahani et al. 2022). Pöhlitz et al. (2019) found that ploughing has a positive effect of on soil structure and pore connectivity, provided that macroporosity is maintained. This is the case when compaction and soil disturbance occur under dry soil conditions which is easier to ensure in the predominantly dry regions we studied (Table 1) than in more humid areas. However, frequent and intensive tillage is also known to be detrimental to soil structure, as it destroys soil aggregates, thus weakening soil structure (Wiermann et al. 2000). As a result, soils become more susceptible to compaction (Blanco-Canqui et al. 2022) and loosened soils may collapse into a denser matrix than undisturbed soils (e.g., sites 1 and 10). However, most tillage practices in the study fields were found to be appropriate and sufficient for maintaining loose soil structure and SPR values below 2.5 MPa.

TABLE 4 | Soil physical parameters for each management for selected long-term experiment sites.

ID	Location	Parameter	Management			ANOVA	*t*-test
			1	**2**	**3**		
1	Donnerskirchen	BD 0–20 cm	1.52 (0.06)	1.60 (0.04)	1.62 (0.04)	0.094	—
		BD 20–40 cm	1.56 (0.05)	1.59 (0.03)	1.53 (0.02)	0.155	—
		IC	**19.6** (6.3)	**37.9** (8.4)	**83.8** (21.0)	**0.000**	1/3: **0.000**, 2/3: **0.003**
2	Balatoncsicsó	BD 0–10 cm	1.49 (0.07)	**1.42** (0.04)	**1.58** (0.06)	**0.012**	**0.011**
		BD 10–20 cm	**1.58** (0.08)	**1.39** (0.07)	**1.61** (0.03)	**0.001**	1/2: **0.050**, 2/3: **0.002**
		IC	9.7 (6.7)	5.6 (1.8)	37.6 (42.2)	0.192	—
3	Rocchetta Ligure	BD 0–12 cm	**1.38** (0.06)	1.14 (0.07)	1.18 (0.15)	**0.018**	**0.024**
		BD 12–25 cm	1.39 (0.08)	1.36 (0.03)	1.40 (0.04)	0.628	—
		IC	16.5 (6.1)	9.3 (5.1)	12.1 (15.7)	0.621	—
4	La Partera	BD 0–20 cm	1.27 (0.12)	1.14 (0.06)	—	0.095	—
		BD 20–40 cm	1.29 (0.04)	1.41 (0.09)	—	0.054	—
		IC	**87.0** (24.4)	**222.2** (67.4)	—	**0.009**	**0.009**
5	Chesley, Kent	BD 0–15 cm	1.26 (0.06)	1.31 (0.13)	—	0.568	—
		BD 15–30 cm	1.26 (0.11)	1.26 (0.15)	—	0.995	—
		IC	119.3 (56.4)	134.6 (64.8)	—	0.733	—
6	Baishui	BD 0–20 cm	1.63 (0.02)	1.61 (0.02)	—	0.488	—
		BD 20–30 cm	1.49 (0.11)	1.57 (0.04)	—	0.320	—
		IC	800.9 (241.0)	636.9 (169.0)	—	0.389	—
11	Hollabrunn	BD 0–20 cm	**1.43** (0.21)	1.32 (0.16)	**1.27** (0.15)	**0.028**	**0.029**
		BD 20–50 cm	1.42 (0.13)	1.42 (0.12)	1.42 (0.12)	0.997	—
		IC	**65.0** (12.9)	**104.2** (19.3)	96.8 (20.2)	**0.028**	**0.037**
12	Řisuty	BD 0–12 cm	1.31 (0.13)	1.46 (0.08)	1.31 (0.17)	0.213	—
		BD 12–25 cm	1.54 (0.10)	1.40 (0.13)	1.37 (0.05)	0.071	—
13	Yangling	BD 0–10 cm	**1.46** (0.02)	**1.29** (0.05)	—	**0.048**	**0.048**
		BD 10–20 cm	1.50 (0.04)	1.31 (0.06)	—	0.066	—
		BD 20–40 cm	1.62 (0.00)	1.68 (0.10)	—	0.466	—
14	Villafranca Piemonte	BD 0–15 cm	1.35 (0.09)	1.38 (0.08)	1.35 (0.10)	0.914	—
		BD 15–30 cm	1.42 (0.08)	1.43 (0.11)	1.46 (0.06)	0.795	—
		BD 30–45 cm	1.42 (0.06)	1.48 (0.03)	1.47 (0.10)	0.442	—
		IC	99.1 (69.9)	177.9 (162.7)	187.5 (108.9)	0.543	—
15	Yongshou[a]	BD 0–10 cm	1.32 (0.14)	1.30 (0.06)	1.27 (0.08)	0.903	—
		BD 10–20 cm	1.62 (0.02)	1.59 (0.06)	1.63 (0.02)	0.920	—
		BD 20–40 cm	1.63 (0.03)	1.66 (0.11)	1.68 (0.06)	0.695	—
		IC	636.9 (169.0)	704.1 (361.0)	528.0 (173.3)	0.313	—
18	Tetto Frati	BD 0–15 cm	**1.07** (0.07)	**1.33** (0.08)	**1.31** (0.06)	**0.001**	1/2: **0.001**, 1/3: **0.003**
		BD 15–30 cm	1.43 (0.05)	1.47 (0.04)	1.40 (0.03)	0.079	—
		IC	**95.0** (58.1)	**18.1** (10.5)	71.5 (18.3)	**0.037**	**0.042**

Note: Averages and standard deviations in brackets. Infiltration capacity (IC) in cm h^{-1} ($n = 4$) and Bulk Density (BD) in g cm^{-3} ($n1 = 3$, $n_{2\text{-}5} = 4$, $n_6 = 3$, $n_{11\text{-}15} = 4$, $n_{18} = 4$). Differences were tested using a one-way analysis of variance (ANOVA) and subsequently with a post hoc paired *t*-tests with Bonferroni adjustment (*p*-values given). Managements with significant differences are marked in bold.

[a]15 Yongshou additionally with IC: (4) Gaodan grass cover 975.8 cm h^{-1} (265.1 cm h^{-1}) and (5) a control variant (no cover crop): IC: 800.9 cm h^{-1} (241.0 cm h^{-1}) and BD (4) Gaodan grass cover BD 0–10 cm is 1.28 g cm^{-3} (0.06 g cm^{-3}), BD 10–20 cm is 1.60 g cm^{-3} (0.06 g cm^{-3}) and BD 20–40 cm is 1.51 g cm^{-3} (0.33 g cm^{-3}); and (5) a control variant (no cover crop): BD 0–10 cm is 1.26 g cm^{-3} (0.08 g cm^{-3}), BD 10–20 cm is 1.63 g cm^{-3} (0.10 g cm^{-3}) and BD 20–40 cm is 1.66 g cm^{-3} (0.07 g cm^{-3}).

In a few cases (e.g., 10, 11), SPR was at lowered in certain soil depths by reducing tillage intensity. An increased biological activity in less or undisturbed soils can lead to the formation of secondary pores, resulting in lower SPR and similar or even higher hydraulic conductivity and water holding capacity due to greater porosity in the large pore range compared to mechanically loosened soils (Hayashi et al. 2006; Liebhard, Guzman, et al. 2024; Liebhard, Winter, et al. 2024). If the cover crop does not develop sufficiently (e.g., 4), no positive effect on soil compaction is apparent, though. Increases in the soil organic carbon content due to conservation management were only measurable at a few sites, though. Even at these few sites, where the soil organic carbon content was significantly lower than in more soil-conserving management systems, regular tillage better maintained low penetration resistance in the cultivation horizon (e.g., sites 6, 8, 9, 11 and 18). Only very intensive tillage (e.g., three ploughs per year at site 9, Luochuan) resulted in evident structural degradation and (plough pan) compaction that is associated with severe soil organic carbon loss (Figure 4, Table 3), even in orchards, where the nature of orchard management suggests lower compressive loads than on arable land.

An increase in bulk density due to management does not necessarily impair soil functions. This was observed in some of the analysed sites, with significant differences in only some cases, with measured SPRs falling below the critical range. Furthermore, lower porosity may imply a greater water retention capacity (Badalíková 2009; Hayashi et al. 2006). In addition to the water retention capacity, the effects of different degrees of compaction depend on the soil's actual infiltration capacity. However, the measured infiltration capacities at individual locations did not reflect the different degrees of compaction across the profile, but rather the compaction close to the surface (Table 4, Figures 4 and 5). If there were large differences directly below the soil surface, as in Balatoncsicsó (2), La Partera (4) and Hollabrunn (11), the infiltration decreased with higher compaction. In Donnerskirchen (1), no-till vineyards had the lowest bulk densities and SPRs, but still had lower infiltration rates than vineyards with reduced tillage management. One reason for this could be a shift in the pore size distribution under no-till towards medium and fine pores, which reduce the flow capacity. A more likely reason could be the silting up of the surface, which could have occurred despite protection from cover crops. The soils at the sites studied (Table 1) are prone to silting up at heavy rainfall events. This would prevent a higher hydraulic conductivity of a more porous soil from having any effect on the infiltration capacity. In Rocchetta Ligure (3) and Tetto Frati (18), tillage had less effect on infiltration capacity than cover crop management did. At these two sites in particular, the frequent use of tractors for vineyard management is considered to be responsible for decreasing infiltration rates and increasing runoff in tilled soils compared to grass-covered soils (Capello et al. 2019). Comparing infiltration rates showed that, at most sites, infiltration rates were generally higher in bare soils than in soils that were either permanently or temporarily covered with cover crops (sites 1, 2, 4 and 11). At three other sites, the trend was similar, but less pronounced (3, 14, 18). No site with cover crops had higher infiltration rates than sites without cover crops. This result is surprising in its clarity. Firstly, cover crops preserve the surface roughness, preventing erosion processes and pore sealing and promoting the formation of well-connected stable biopores (Basche and DeLonge 2019; Bodner et al. 2023; Hudek et al. 2014; Klik and Rosner 2020). Secondly, the effect of cover crops on soil compaction and also on soil organic carbon was unclear and insignificant at many sites. Thus, the reported positive effect of cover crops on the infiltration capacity, which is connected to decreased bulk density and increased abundance of biopores (Auler et al. 2014; Blanco-Canqui et al. 2011; Haruna et al. 2018; Koudahe et al. 2022), was not confirmed by our results. However, our results might reflect the higher density of soil aggregates compared to the aggregated bulk soil (Horn et al. 1994). The pore system of these naturally formed soil aggregates has finer, more tortuous pores and correspondingly slower water fluxes (Horn et al. 1994). Consequently, the loosening and infiltration-enhancing effect of biopores from decomposed roots and increased soil life was less than the increase in firming and tortuosity caused by the root system. Accordingly, the reduction in infiltration capacity was more pronounced than the increase in bulk density for cover crop variants (Table 4). Furthermore, the water-repellent properties of root exudates may have contributed to the lower infiltration capacity in variants with cover crops (Zeppenfeld et al. 2017).

The effect of cover crops on bulk density and the soil structure varies greatly depending on the intensity and implementation of the cover crops. When adapted species are used intensively, the roots of cover crops induce biopores and stabilize the soil structure through fine root enmeshment and the binding effects of root exudates, thereby reducing soil compaction (Bodner et al. 2021; Williams and Weil 2004; Xiong et al. 2022). However, insufficient intensity or duration of cover crops means it is not possible to achieve a comparable effect to that of permanent vegetation systems or mechanical soil loosening (Schlüter et al. 2018; Wardak et al. 2022). This was observed at the two arable management sites (10 and 14), where different cover crop management in autumn, alongside the same tillage practices, did not result in differences in compaction parameters. Also the temporal cover crop at site 4 with low biomass development could not contribute to soil loosening similarly as mechanical soil loosening. The same has also been found for other Spanish vineyards that have similarly challenging conditions for temporary cover crops (Liebhard, Guzman, et al. 2024; Liebhard, Winter, et al. 2024). Paradoxically, the example at site 1 in Donnerskirchen shows that also well-developed cover crops in a mechanically tilled vineyard increased the SPR in the root zone compared to a vineyard without catch crops. A dense and branched root system fills in voids and mechanically stabilizes the soil structure, which can increase the local SPR. However, as we did not consider the effect of cover crops separately at most of the other sites, we measured the overall effect of the management system including tillage, which was mostly dominant. The greatest impact on the soil structure stability by roots can be achieved by permanently vegetated systems without mechanical disturbance. There, greater aggregate stability is achieved with greater total root length and root surface area (Hudek et al. 2022). Accordingly, permanently vegetated sites (16–20) except in Tetto Frati (18) had SPR values within a range that is not considered to be affected by harmful compaction. In the case of no-till sites with long-term vegetation cover throughout the year (1–3, 5, 7–11), several sites already experienced higher and problematic compaction than tilled soils (5, 8, 9). In addition to the continuity of undisturbed vegetation cover, permanently vegetated systems are less impacted by traffic and soil management. At the sites with grass cutting management and grazing livestock (e.g., site 16) the additional load contributes to surface compaction, but it is assumed that it hardly affects the lower soil layers due to the low total weight (Söhne 1958), in contrast to the impact of tillage and harvesting farm machinery. Thus, grassland showed more compaction near the topsoil but similar compaction below 15 cm to fallow land (16). The difference between different (cover) crops and the same tillage was negligible at several sites (6, 14, 16, 19, 20), sometimes detectable but not decisive (3, 7, 10, 18) and significant in two cases only (5, 8). Although the roots of various cover crop species and mixtures have specific functional properties that contribute to soil remediation and various aspects of soil health (Blanco-Canqui and Ruis 2020; Bodner et al. 2021; Hudek et al. 2022), the effect of the different cover crops used on soil compaction was negligible. Therefore, differences can only be expected if attention is paid to the loosening effect of the cover crop mixtures that include both deep-rooted tap roots and ramifying fibrous roots.

4.3 | Implications for Agricultural Practice

Our comparison of different tillage and cover crop management systems in various regions confirms previous findings that the effects of specific management systems vary depending on the inherent characteristics and conditions of the soil, including its texture and type, as well as the climate (da Silva et al. 1997). Similar SPR profiles for a specific management system were only measured under similar local conditions (e.g., 15 and 16). The mechanistic processes involved in the formation or disruption of soil structure are known (Bronick and Lal 2005; Lucas et al. 2019). Some of these effects are confirmed by the measurements shown here. For example, the lower hydraulic conductivity in denser, more structured topsoil in undisturbed, vegetated soils (e.g., 1, 2, 4 and 11) (Bronick and Lal 2005; Horn et al. 1994), and the formation of a plough pan below tillage depth in tilled fields (e.g., 9) (Birkás et al. 2004). Nevertheless, several long-term test sites show insignificant differences, contrary results, or unexpected SPR profiles. For example, there is an increase in SPR values to a multiple due to cover crops compared to bare soils (4), and different effects of spontaneous compared to manually seeded cover crop vegetation (e.g., 5 and 6). In addition, soils can have different sensitivities to management, with different management practices not resulting in any observed differences in SPR at some sites (e.g., 6 and 7). Accordingly, the importance of simple penetrometer measurements on site becomes apparent. However, customary static penetrometers are not standard equipment for farmers and measurements taken with handheld devices can be influenced by the operator (Herrick and Jones 2002). In contrast, simple dynamic penetrometers can even be home-built by farmers and used to identify to soil compaction that may have gone unnoticed. While farmers are often well informed about soil organic carbon, nutrients, pH and cation exchange capacity through soil sampling and analysis and adjust their management including fertilization, accordingly, soil compaction can develop unnoticed and reach problematic levels. This was also shown at our long-term sites, where problematic compaction horizons were measured at various soil depths and phenomena such as plough pans were revealed.

Since soil water content is the most important factor influencing SPR profile measurements, farmers must primarily pay attention to the soil moisture conditions when taking measurements. To detect compacted layers in the profile, uniform water distribution across the profile should be checked by use of a pit. Measuring at conditions close to field capacity is usually easiest to achieve in spring. As the comparison of confidence intervals showed, representative profiles can be determined even with few measurement repetitions. In the case of high spatial heterogeneity of the soil, the added value of increasing the number of measurement repetitions and the informative value of the profiles is limited.

The results of the field campaign show that harmful soil compaction can occur in different management systems. Some degree of soil compaction can be reversed by natural processes such as swelling and shrinking due to freezing/thawing, wetting/drying, and absorption/dehydration processes, roots disturbance, and soil loosening by soil fauna (Kozlowski 1999). However, these natural restoration processes are long-lasting and limited to low levels of compaction. Penetrometer measurements may indicate the need for a change in management system or minor interventions, whereas bulk density measurements showed no differences (Table 4). Nevertheless, the informative value of penetrometer measurements is also limited, as they do not allow conclusions to be drawn immediately about infiltration capacity (Figures 4 and 5, Table 4), a relevant impact of compaction on soil functions. Even though conservation agriculture can improve the soil structure and the pore size distribution (Bodner et al. 2023), no-tillage management still resulted in unfavourable compaction in some cases. For example, penetrometer measurements could quantify the soil loosening effect of extraordinary tillage in no-tillage systems (Peixoto et al. 2020). Furthermore, in the case of varying spatial conditions and degrees of compaction, they could identify the areas where adapted soil loosening measures would be necessary (Arruda et al. 2021). It should be considered that the remediation of plough-induced pans can take several years (Capowiez et al. 2009) and therefore requires repeated measurements.

The choice of management system and individual management measures affects the organic carbon levels, nutrient availability, susceptibility to and control of pests and in particular the soil structure and the degree of compaction. In our study, the management system had a significant and long-term effect on compaction across the soil profile in over half (2, 4, 5, 8, 9, 10, 11, 12, 16, 17) of the sites analysed, which we did not select systematically. Higher soil density does not necessarily negatively impact plant growth and yield, provided the three-phase system is in balance and soil functions such as water storage capacity and provision of habitat for soil organisms are maintained. However, once a level of compaction is reached that limits soil functions, as at several of the investigated sites, measures should be taken to counteract harmful levels of compaction. These harmful levels of compaction were reached in both extensively managed (no-till) fields (2, 5, 8, 9 and 18) and intensively managed and tilled fields (4, 11 and 14). In cases of harmful compaction in undisturbed soil, the shallowest possible mechanical loosening down to the compaction layer can be attempted. Conversely, in cases of intensive tillage and compaction, it should be recognized that conversion towards a soil-conserving system is not feasible in the short term.

5 | Conclusion

We evaluated 20 sites, each with a different and mostly long-term management system, including various tillage and cover cropping strategies, using a home-built dynamic penetrometer. Prior to the field study, we tested various settings of the dynamic penetrometer in the laboratory to ensure the comparability of the results. These tests showed that the different settings—30° or 60° cones and hammer falling heights of 30 or 40 cm—produced no different soil penetration resistance profiles. Even a shallow plough pan of 3 cm could be detected, although the degree of compaction was not measured in terms of actual intensity. Laboratory tests with two different soils demonstrated the importance of considering the high dependence on soil water content and texture, even with preset conditions close to field capacity. The field study showed that tillage management had a greater effect on soil compaction than cover crop management. The majority of fields that were tilled more intensively had at least partially lower penetration resistance compared to fields that were tilled less intensively or not at all, down to the ploughing depth. However, there were also sites where reduced or no-tillage systems led to less compaction. The effects of cover crops were less clear; however, at several sites they did result in soil consolidation in the tillage horizon. In contrast, the reduced infiltration capacity due to cover crops, which was measured at some sites, was clear. Despite these findings, the effects of management practices on the degree of compaction varied and resulted in different soil penetration resistance profiles. These soil penetration resistance profiles were more sensitive to changes in compaction than bulk density measurements. We therefore recommend that farmers incorporate the simple soil penetration resistance measurements into their routine to monitor the compaction of soil and develop mitigation strategies before critical compaction levels are observed.

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Ethics Statement

The authors declare that the research complies with the ethical standards of Soil Use and Management and relevant national/international guidelines. The work is original, has not been published elsewhere, and all sources are cited appropriately.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article or are openly available in Zenodo at https://zenodo.org/records/17277734, reference number 17277734.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supporting Information: S1.** SPR_protocol_anonym. **Supporting Information: S2.** Table SM1: Means of the volumetric soil water contents (and standard deviations in brackets) at the soil penetration resistance measurement sites. The number of the management variant (1–5) corresponds to the management variant in Table 2 of the manuscript. **Supporting Information: S3.** Man_Rocchetta_Ligure. **Supporting Information: S4.** UK Plant composition.