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Visual assessment of the impact of agricultural management practices on soil quality

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Abbreviations: AMP, agricultural management practices; SOC, soil organic carbon; SOM, soil organic material; SSA, study site area.

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Abstract

The intensification of agricultural practices to increase food and feed outputs is a pressing challenge causing deterioration of soil quality and soil functions. Such a challenge demands provision of empirical evidence to provide context-sensitive guidance on agricultural management practices (AMPs) that may enhance soil quality. The objectives of this study are to identify the most promising AMPs (and their combinations) applied by farmers with the most positive effects on soil quality and to evaluate the sensitivity of the soil quality indicators to the applied AMPs. The effect of selected AMPs on soil quality was assessed using a visual soil assessment tool in a total of 138 pairs of plots spread across 14 study site areas in Europe and China covering representative pedo-climatic zones. The inventory and scoring of soil quality were conducted together with landowners. Results show that 104 pairs show a positive effect of AMPs on soil quality. Higher effects of the AMPs were observed in lower fertile soils (i.e., Podzols and Calcisols) as opposed to higher fertile soils (i.e., Luvisols and Fluvisols). For the single use applications, the AMPs with positive effects were crop rotation; manuring, composting, and no-tillage; followed by organic agriculture and residue maintenance. Cluster analysis showed that the most promising combinations of AMPs with the most positive effects on soil quality are composed of crop rotation, mulching, and min-till. The agreement between scientific skills and empirical knowledge in the field identified by the farmers confirm our findings and ensures their applicability.

1 | INTRODUCTION

Agricultural soils are under a wide variety of pressures, including increasing global demand for food associated with population growth, land degradation, and productivity reductions, potentially exacerbated by climate change effects (Rogger et al., 2017). Restoration of soil ecological functions, productivity, and regulation services, as well as prevention of further degradation, can be achieved with appropriate management practices. Because such practices are highly adaptable to the specific conditions where they are applied, they may reduce the potential negative effects of extensive areas of monocultures and the intensive use of heavy machinery (e.g., Sarker et al., 2018). Over the last decade, there has been growing interest on the effect of agricultural management practices (AMPs) on soil organic carbon (SOC), nutrient cycling, and storage worldwide (Dalal, Allen, Wang, Reeves, & Gibson, 2011; Hoyle & Murphy, 2011; Hoyle, Antuono, Overheu, & Murphy, 2013; Kopittke, Dalal, & Menzies, 2016). The nutrient contents of soil may be maintained or enhanced with appropriate AMPs, such as incorporation of organic matter into the system (Sarker et al., 2018). Management practices such as (a) long-term no-till or reduced-tillage with stubble retention (i.e., crop residues) and/or organic manure incorporation combined with synthetic fertilizer application, and (b) mixed crop–pasture and perennial pastures are usually associated with increasing or maintenance of soil organic matter (SOM) and associated nutrients (Dalal et al., 2011; Hoyle et al., 2013; Sarker et al., 2018). Maintenance and/or addition of crop residue are also vital to maintain and increase soil carbon (C) stocks through the formation of humus and soil macro-aggregates (Alidad, Mehdi, Sadegh, Hassan, & Sanaz, 2012; Liu, Lu, Cui, Li, & Fang, 2014), and hence help mitigate climate change effects (Chatterjee, 2013; Dikgwatlhe, Chen, Lal, Zhang, & Chen, 2014).

Conservation tillage, including many practices such as non-inversion tillage with tined tools at depths down to 15–20 cm, redistributes C content within the soil profile (Cookson, Murphy, & Roper, 2008; Cooper et al., 2016; Powlson, Stirling, Thierfelder, White, & Jat, 2016), with positive effects on soil chemical properties in the upper soil layer and contributes to the increase of wheat biomass (Peigné, Vian, Payet, & Saby 2018). Direct seeding without prior cultivation intends to protect the soil surface from crusting and erosion by leaving crop residues and organic matter at the surface. All these practices enhance the quantity, activity, and diversity of soil microorganisms in the upper soil layers (Cookson et al., 2008), as well as earthworm biomass and diversity (Pelosi

Core Ideas

- The effects of agricultural management practices on soil quality was assessed.
- Selected AMPs have high positive effects on soil quality in low fertile soils.
- Selection of visual soil indicators was confirmed by the farmers' knowledge.

et al., 2014). These benefits are accompanied by reduced labor requirements, energy consumption, and machinery costs (Soane et al., 2012).

To manage agricultural soils appropriately, decision makers need science-based, easily applicable, and cost-effective tools to assess soil quality and functions. Since the assessment of soil quality comprises measuring key soil properties and their variations in space and time, providing such tools remains a research challenge. Assessment of soil quality is required for evaluation of the overall sustainability of agricultural systems, identification of areas with production problems, estimation of biomass production, and monitoring environmental changes driven by AMPs (Doran & Parkin, 1996). In recent years, several methods of visual field examination have been developed to provide a direct description of soil structure, which is considered as the property most frequently evaluated when determining soil quality under different land uses and tillage practices (Ball & Munkholm, 2015).

The main aim of this study is to evaluate the effect of different AMPs in use by farmers in 138 pairs of plots spread across 14 different pedo-climatic zones of Europe and China, based on a visual soil assessment (VSA) method. Areas within both continents are evaluated separately to highlight soil quality differences from developed and developing areas, where agricultural intensification based on conventional approaches is expected to result in severe soil degradation. The specific objectives of the present study are to (a) identify the most promising AMPs (and/or their combinations) with high positive effects on soil quality, and (b) evaluate the sensitivity of the soil quality indicators used for the assessment of AMPs.

2 | MATERIALS AND METHODS

2.1 | Plots and AMPs evaluated

In 2016, the effect of selected AMPs on soil quality was assessed in a total of 138 pairs of plots spread across 14 study site areas (SSA), including 10 located in Europe and four in China (Figure 1). These plots were used as case studies under the European iSQAPER project – Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience. The criteria used to select the pairs of plots and full descriptions of the SSAs, including the pedo-climatic regions, farming systems, and AMPs tested, is provided in Barão, Basch, Alaoui, and Schwilch (2019). In 2018, a second assessment of soil quality was carried out to check the first outcomes. A total of 58 pairs of plots were considered (40 in Europe, and 18 in China).

To ensure reliable comparison between results of all case study sites, standardized methods with related guidelines on how to assess the indicators have been compiled into a manual established for this purpose. This allows for a harmonization of the methods across Europe and China (See Supplemental Material for manual). The case study site leaders were asked to follow the procedure described in the manual for the assessment of soil quality.

While not always possible, sampling soils in their original, native, nondisturbed conditions and comparing with a plot serving as reference soil is important to determine whether an area was subject to deterioration, such as soil compaction or loss of organic matter, as result of applied AMPs (Ball et al.,

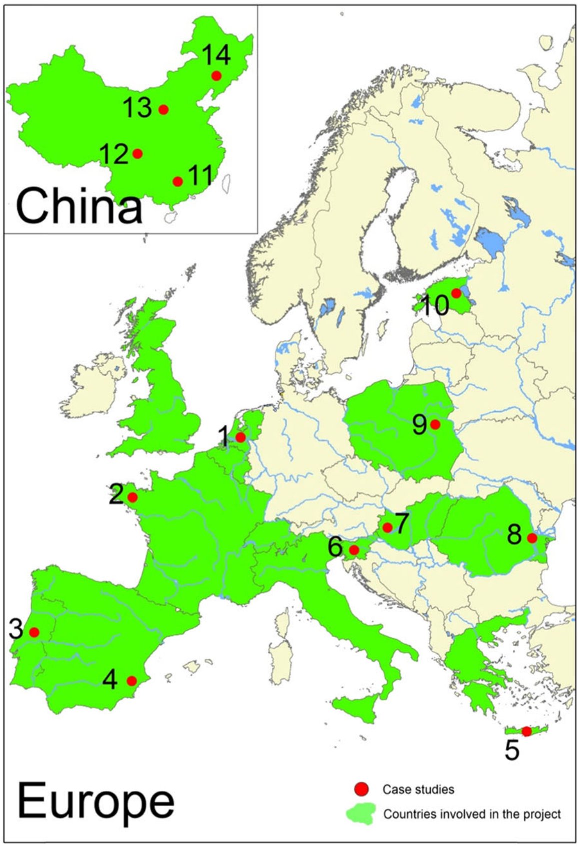

FIGURE 1 Fourteen case study sites covering the major types of farming systems and pedo-climatic zones across Europe and China used in the current study

2017). In all case study sites, soil quality was assessed at the topsoil between 0 and 30 cm.

Each pair includes a plot where the AMP has been used for at least the last five years (plot-AMP) and a plot where the corresponding conventional practice was implemented for a similar period (plot-control). As an example, if the farmer uses crop rotation in the plot-AMP, a monoculture was practiced in the plot-control over the last five years. In order to be comparable, pairs of plots have the same soil type and land use history and are located within a few meters of distance.

The previously selected 138 pair of plots include a myriad of AMPs and their combinations (Barão et al., 2019) in use by European and Chinese farmers and, thus, represent the promising management choices undertaken locally. This study includes the soil quality assessment of (a) 98 pairs of plots where 17 different AMPs were used in isolation (e.g., no-till, residue maintenance, irrigation management), (b) 23 pairs of plots where 19 different combinations of two AMPs were used (e.g., min-till and irrigation management), and (c) 17 pairs of plots where 16 different combinations of 3–7 AMPs were used (Table 1). The majority of the evaluated pairs of plots (92) are practiced in arable lands, 17 pairs address management practices in pasture, and 29 pairs represent permanent farming systems.

2.2 | Visual soil assessment

The effect of using AMPs by farmers on soil quality was evaluated with 11 visual soil indicators in the plot-AMP and related plot-control.

Based on extensive literature review (e.g., Ball et al., 2017; Mueller et al., 2009, 2013; Shepherd 2000), the indicators selected in this study are divided into three categories: (a) baseline indicators: surface ponding and susceptibility to wind and water erosion; (b) VSA indicators: presence of a cultivation pan, soil color, soil porosity, soil structure and consistency, and soil slaking test for soil stability; and (c) quantitative indicators: earthworm count indicating biodiversity, infiltration experiment and/or penetration resistance, pH, and labile organic carbon. Labile organic carbon method was adapted from Weil, Islam, Stine, Gruver, and Samson-Liebig (2003), pH was measured using water (pH H_2O), and the infiltration experiment method was adapted from the falling head method and validated in the laboratory using different soil texture (see Supplemental Material). The above indicators were selected and used to classify the soil conditions in each of the 138 pairs of plots. The inclusion of four quantitative indicators was necessary to cover important biological, chemical, and physical alterations which are expected when different management practices are implemented in the agricultural fields.

For each indicator, we provided the following information: (a) importance: information on the significance of the indicators for soil quality; (b) assessment: guidelines for the assessment of the variables in situ or in the lab; (c) scoring: evaluation of soil property under consideration based on scores; and (d) literature: additional details and illustrations (see Supplemental Material).

A qualitative score was established for the 11 variables according to three conditions: good (Score 2), moderate (Score 1), and bad (Score 0), illustrated with standardized photos serving as references or classes of established limits and corresponding to associated scores. The full manual describing the VSA and the scorings is available as supporting information. The inventory and scoring of soil quality were conducted together with land users, between July and December 2016, for all paired plots. The paired plots methodology was used to compare the sensitivity of the 11 selected soil indicators and their response across different pedo-climatic regions.

The scores of the 11 indicators assessed in plot-AMP and plot-control were compared. If the scores are similar in both plots, no improvement (0) is considered. If there is an improvement in plot-AMP, then a moderate or strong positive effect is considered (+1 or +2, respectively), according with score values difference between paired plots. Conversely, if the plot-AMP induces degradation of soil conditions, then a moderate or strongly negative effect is considered (−1 or −2, respectively). Finally, the VSA index was calculated by summing all positive and negative effects of each soil variable:

$$\mathrm{VSA}_{\mathrm{index}} = \sum_{\text{soil variable 1}}^{\text{soil variable 11}} \mathrm{score}_{\text{soil variable}}$$

Where, $\mathrm{score}_{\text{soil variable}}$ corresponds to the value obtained by the difference between the soil conditions from plot-AMP and plot-control for a given soil variable under analysis, and soil variable refers to each one of the eleven variables analyzed.

Farmers dealing with the implementation of the AMPs were also requested to express their opinion with regard to the meaning of the 11 soil quality variables used for the VSA. As so, for each pair of plots (AMP-control) considered in this study, farmers were requested to select the most important indicators to assess soil quality in their field according to their perception. Selected indicators by farmers were then compared with the ones showing positive effects to AMPs implementation. All the analyses were performed separately for the European and Chinese study sites due to distinct sociocultural aspects, which may affect the AMPs adopted by farmers and their perception about the soil quality indicators.

2.3 | Data analyses

Cluster analysis was performed to detect groups of AMPs with similar effects through the calculation of Euclidian distance.

TABLE 1 Agricultural management practices (AMPs) used by European and Chinese farmers in different farming systems and investigated under the current study, either single-use or in combination

	Farming System			
AMP tested	**Arable**	**Pasture**	**Permanent**	**Total plots farms^{-1}**
Single AMP tested				
No-till	4		6	10
Min-till	8		2	10
Permanent soil cover/Removing less vegetation cover		3		3
Cover crops	3		1	4
Residue maintenance/Mulching	7		1	8
Cross-slope measure	1		2	3
Measures against compaction	2			2
Leguminous crop	5			5
Green manure/Integrated soil fertility management	2			2
Manuring and composting	12			12
Crop rotation/Control or change of species composition	12		1	13
Integrated pest and disease management including organic agriculture	3		4	7
Water diversion and drainage			1	1
Irrigation management	4			4
Major change in timing of activities	1			1
Area closure/rotational grazing		3		3
Change of land use practices/intensity level	2	8		10
Total number of plots	**66**	**14**	**18**	**98**
Combination of 2 AMP tested				
Crop rotation/Control or change of species composition; Integrated pest and disease management including organic agriculture	1			1
Integrated pest and disease management including organic agriculture; major change in timing of activities	1			1
Leguminous crop; residue maintenance/Mulching			1	1
Manuring and composting; crop rotation/Control or change of species composition	1			1
Manuring and composting; integrated pest and disease management including organic agriculture			1	1
Manuring and composting; change of land use practices/intensity level		1		1
Manuring and composting; crop rotation/Control or change of species composition	1			1
Manuring and composting; cross-slope measure			1	1
Manuring and composting; integrated pest and disease management including organic agriculture	1			1
Min-till; Crop rotation/control or change of species composition	1			1
Min-till; Crop rotation/Control or change of species composition	1			1
Min-till; Irrigation management			1	1
Min-till; Manuring and composting	1		2	3
Min-till; Residue maintenance/Mulching	1			1
No-till; Crop rotation/Control or change of species composition	1			1
No-till; Residue maintenance/Mulching	1			1
Permanent soil cover/Removing less vegetation cover; Leguminous crop			1	1
Permanent soil cover/Removing less vegetation cover; Manuring and composting	1	2		3
Residue maintenance/Mulching; Irrigation management	1			1

(Continues)

TABLE 1 (Continued)

	Farming System			**Total plots farms^{-1}**
AMP tested	**Arable**	**Pasture**	**Permanent**	
Total number of plots	**13**	**3**	**7**	**23**
Combination of 3 AMP tested				
Green manure/Integrated soil fertility management; integrated pest and disease management including organic agriculture; irrigation Management	1			1
Manuring and composting; crop rotation/Control or change of species composition; Irrigation management	1			1
Min-till; cover crops; green manure/Integrated soil fertility management			1	1
Min-till; manuring and composting; crop rotation/Control or change of species composition	1			1
Min-till; permanent soil cover/removing less vegetation cover; Manuring and composting			1	1
Permanent soil cover/removing less vegetation cover; manuring and composting; Residue maintenance/Mulching			1	1
Total number of plots	**3**	**0**	**3**	**6**
Combination of 4 AMP tested				
Manuring and composting; residue maintenance/Mulching; crop rotation/Control or change of species composition; measures against compaction	1			1
Min-till; Cover crops; green manure/Integrated soil fertility management; Integrated pest and disease management including organic agriculture			1	1
Min-till; residue maintenance/Mulching; Crop rotation/Control or change of species composition; measures against compaction	1			1
Total number of plots	**3**	**0**	**1**	**3**
Combination of 5 AMP tested				
Cover crops; green manure/Integrated soil fertility management; residue maintenance/Mulching; crop rotation/Control or change of species composition; measures against compaction	1			1
Min-till; leguminous crops; residue maintenance/Mulching; crop rotation/Control or change of species composition; measures against compaction	1			1
Min-till; manuring and composting; residue maintenance/Mulching; crop rotation/Control or change of species composition; measures against compaction	1			
Total number of plots	**3**	**0**	**0**	**3**
Combination of 6 AMP tested				
Min-till; manuring and composting; residue maintenance/Mulching; crop rotation/Control or change of species composition; cross-slope measure; measures against compaction	1			1
Min-till; manuring and composting; residue maintenance/Mulching; crop rotation/Control or change of species composition; measures against compaction; measures against compaction	1			1
Total number of plots	**2**	**0**	**0**	**2**
Combination of 7 AMP tested				
Min-till; leguminous crops; manuring and composting; residue maintenance/Mulching; crop rotation/Control or change of species composition; measures against compaction; water diversion and drainage	1			1
Min-till; permanent soil cover/Removing less vegetation cover; leguminous crops; manuring and composting; residue maintenance/Mulching; crop rotation/Control or change of species composition; measures against compaction	2			2
Total number of plots	**3**	**0**	**0**	**3**

The obtained results were depicted using dendrograms based on Sneath´s dissimilarity criteria, a single binding agglomeration requiring one to obtain the matrix of dissimilarity, from which the most similar pair of individuals is identified. These individuals form the initial cluster. Beginning from there, the possibility of inclusion of other individuals is evaluated, adopting the criteria that the average intracluster distance should be lower than the average intercluster distance (Sneath & Sokal, 1973). The clustering analysis was used to highlight the AMPs that cluster together, indicating significant similarities in showing effects on soil quality between them. The analysis was performed using Statistica software version 13.1.

3 | RESULTS AND DISCUSSION

3.1 | Soil quality indicators

Results show that the most sensitive soil quality indicators (displaying higher VSA index) in Europe and China are those describing soil structure, such as soil structure and consistency, porosity, aggregate stability inferred by the slaking test, and soil color, followed by soil compaction indicated by the presence of a cultivation pan (Figure 2a & c). In China, however, labile organic carbon and infiltration are also sensitive indicators. Although labile organic carbon is much more sensitive to changes in soil management practices that total organic carbon (Haynes, 2005), in our case, labile organic carbon was unexpectedly one of the VSA indicators least affected by the implementation of the AMPs in Europe, probably due to the spatial variability of labile organic carbon and/or variation in the fertilizers application. Surface ponding and susceptibility to erosion in a high number of plots showed neutral effects probably because they are not directly linked to the AMP implementation in the majority of the cases. Surface ponding depends on soil compaction which is spatially variable. Naveed et al. (2016) reported that in their topsoils, stress propagation was heterogeneous and occurred through specific pathways as long as macropores were not deformed (cited in Guimarães, Lamandé, Munkholm, Ball, & Keller, 2017). In our case, biodiversity (indicated by earthworm number) and infiltration rate are relatively sensitive to the changes in the management practices, indicating existing intact macropores that can partially explain the neutral effect of surface ponding (Figure 2). The fact that the presence of cultivation pan is a less sensitive indicator than those describing soil structure can be explained by different factors. The persistence of subsoil compaction over decades (Alaoui, Rogger, Peth, & Blöschl, 2018; Kellner & Hubbart, 2016) indicated a long memory effect probably older than the effect of the AMP under consideration. In addition to land use effect, potential factors controlling this memory are land use, soil type, topography, and

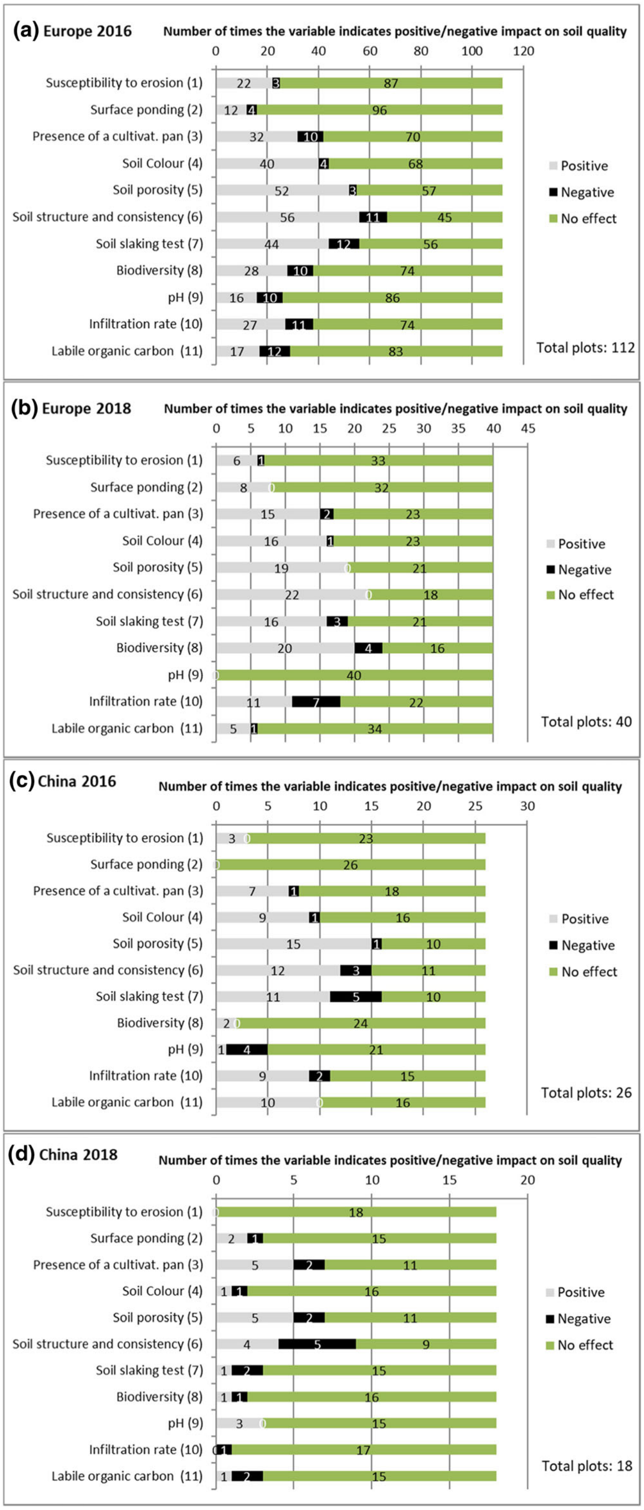

FIGURE 2 Results of Visual Soil Assessment index for each of the 11 soil quality indicators used to assess the effect of agricultural management practices (AMPs) on soil quality in Europe in 2016 (a) and 2018 (b) and in China in 2016 (c) and 2018 (d). Numbers represent the percentage of plots where the indicators return positive (white), negative (black), or no effect (green) between AMPs and control

climate (Cambi, Certini, Neri, & Marchi, 2015; Rogger et al., 2017). The focus on soil structure examination without considering textural or stone effects on agronomic potential did not allow distinguishing compacted layers of anthropic origin from changes in in texture between different horizons (Ball et al., 2015).

In Europe, soil porosity and infiltration capacity behave very similarly, and are closely linked with labile organic carbon (Figure 2a). However in Chinese study sites, surface ponding and susceptibility to erosion were the closest parameters, grouping with presence of the cultivation pan, biodiversity, pH, and infiltration rate (Figure 2c). The remaining indicators showed more independent responses to applied management practices, as resulted from the cluster analysis.

Earthworm indicator, however, should be interpreted carefully since it may be affected by other parameters, such as the timing of field assessment, and thus its inclusion in VSA methodologies should be better considered for future studies. Previous studies showed that the type of tillage significantly affects earthworm populations. Baldivieso-Freitas et al. (2018) reported that plots that had been moldboard ploughed (soil inversion) in the year prior to their sampling presented more juveniles than adults.

Variables describing biodiversity (earthworm counts) and the infiltration rate provide similar results within European plots and are in agreement with each other (Figure 2a). This can be explained by the fact that soil biopores, representing only 0.2–2.0% of the total soil volume, may account for about 74–100% of the total water flux (Alaoui & Helbling, 2006). These observations were not noticed in Chinese case studies, possibly because of the restricted number of investigated sites (26 in China against 112 in Europe) and the wider range of pedo-climatic zones than monitored in Europe.

It is worth noting that some AMPs were implemented only over 3 years, which may be too short to provide positive effects on soil quality. Overall, the sensitivity of the indicators related to soil structure is confirmed in Europe by the outcomes of 2018 (Figure b), while in China, only porosity and soil structure and consistency were sensitive to the changes in AMPs, probably due to the low number of Chinese sites considered (Figure 2d).

There was some overlap between the indicators selected by farmers as the most convenient to evaluate soil quality and the most sensitive indicators to soil quality, namely soil structure (Figure 3). These indicators include soil porosity (reported by 61 farmers in Europe and 25 in China), soil structure and consistency (reported by 63 farmers in Europe and 23 in China), and soil slaking test (reported by 47 farmers in Europe and 23 in China). These results show that generally, both in Europe and China, farmers are aware of the visual soil indicators that are sensitive to the rapid changes in their fields. This fact highlights the link between the scientific knowledge with farmers' background and empirical knowledge of their fields and attests to the applicability of our findings.

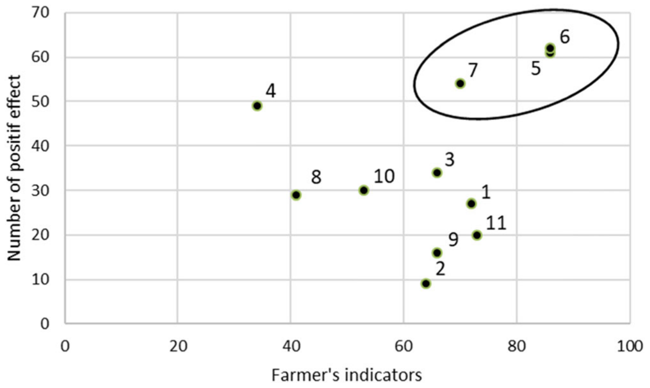

FIGURE 3 Correlation between the number of positive effects observed for a single indicator and the number of farmer's selecting this indicator as significant for soil quality evaluation (numbers represent the indicators given in the y-axis of Figure 2)

3.2 | Effects of selected AMPs in Europe and China

Globally, the results show that between the 138 sets of paired plots, 104 pairs (75.4%) showed a positive effect of the AMPs on soil quality, 20 pairs (14.5%) did not show any difference in soil quality between soils under selected practices and soils in the control, and the remaining 14 plots (10.1%) showed an inverse effect. These effects are similarly distributed between both continents, with positive effects of selected AMPs recorded in 73.2% of the European and 84.6% of the Chinese paired plots, and negative effects representing a minority of the plots (9.8 and 11.5%, respectively). The neutral effects of AMPs represent 17% of the plots in Europe and 3.8% in China.

When investigating single AMPs implemented by farmers representing the largest number of the analyzed paired plots (98 out of 138), results show that no-till (10 pairs), residue maintenance (8 pairs), manuring and composting (9 pairs), crop rotation (10 pairs), and integrated pest and diseases (6 pairs) provide the highest positive effects on soil quality. However, when looking at Europe and China separately the majority of positive effects from no-till, crop rotation, and integrated pest and diseases occurred in European plots. In China, however, the highest positive effects were associated with residue maintenance, manuring and composting, and to some extent, green manure and/or integrated soil fertility management, and irrigation management show positive effects on soil quality (Figure 4a and c). Within these highlighted AMPs, both no-till and residue maintenance show no neutral or negative effects, whereas manuring and composting, crop

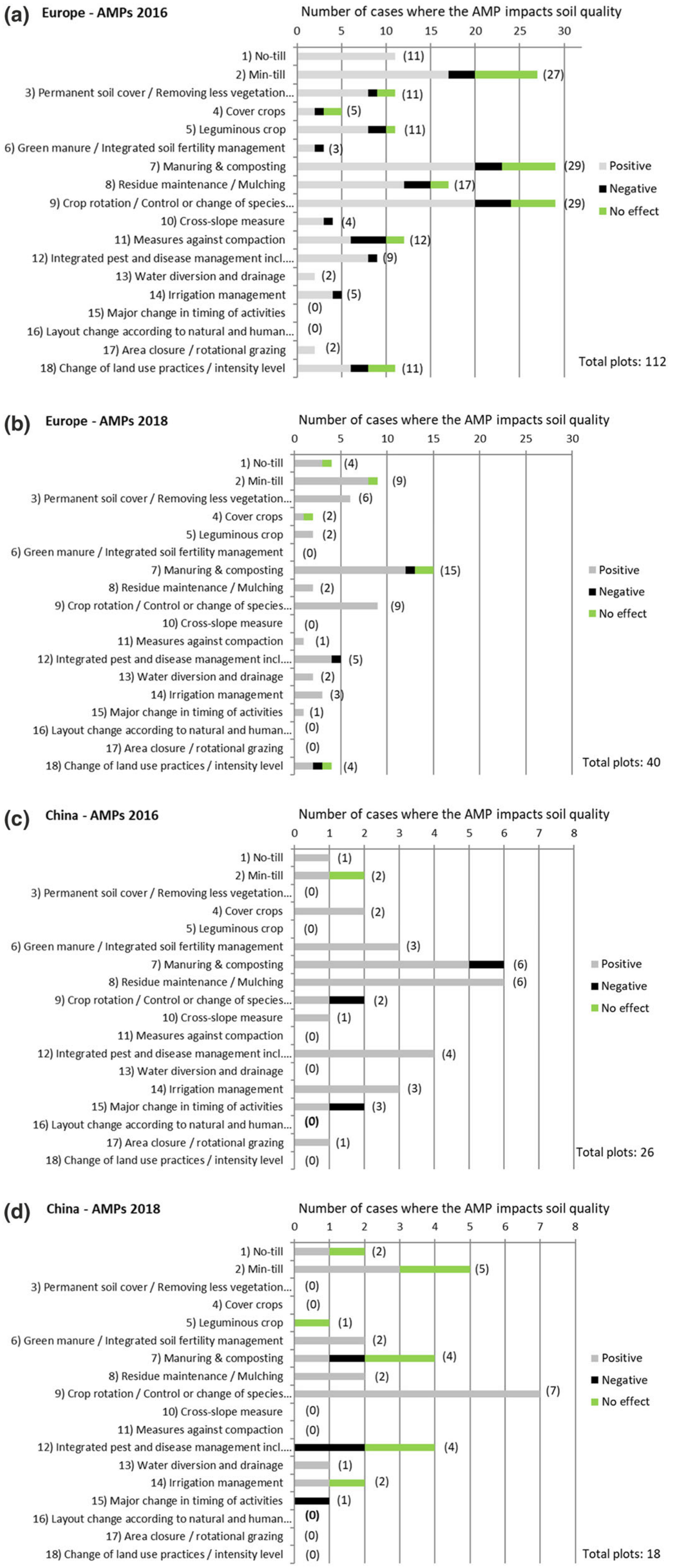

FIGURE 4 Number of study site areas where the single-used agricultural management practices (AMPs) affect soil quality positively (gray), negatively (black), and neutrally (green) in Europe in 2016 (a) and 2018 (b) and in China in 2016 (c) and 2018 (d)

rotation, and integrated pest and diseases also show some cases of neutral and/or negative effects. Negative effects on soil quality are also recorded in practices such as measures against compaction, leguminous crops, irrigation management, changes in timing of activities, and change of land use practices. The assessment carried out in Europe in 2018 confirmed similar trends in terms of proportionality (Figure 4b). In China, crop rotation, min-till, green manure, integrated soil

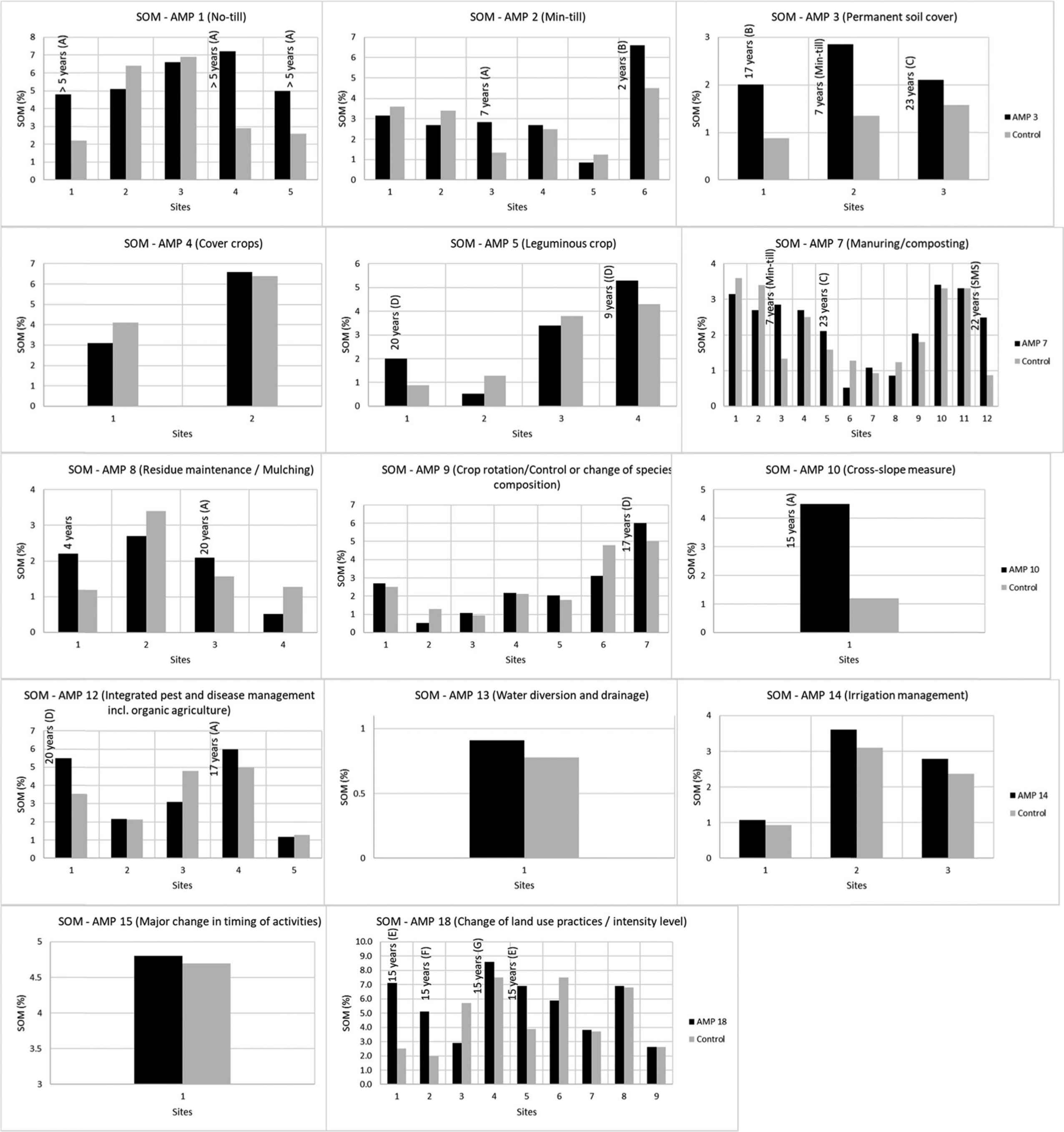

FIGURE 5 Correlation between changes in soil organic matter (SOM) and agricultural management practices (AMPs). Text vertically aligned within the graphs indicates the number of years of implementation; (A): permanent crop cover; (B): organic fertilizer; (C): Manuring, residue maintenance; (D): organic farming; (E): pasture, intensive grazing; (F): permanently irrigated land; (G): pasture, intensive grazing; SMS: manuring with spent Mushroom substrate. These practices are used in combination with the main AMPs indicated in the subtitles of each graphic

fertility management, and to some extent no-till show positive effects on soil quality (Figure 4d).

When correlating the AMPs with positive effects on soil quality with changes in SOM, it appears that AMP 1 (no-till) in combination with permanent crops, and AMP 3 (permanent soil cover) in combination with no-till and organic farming positively affect SOM (Figure 5). The year of implementation tends to increase SOM, but a clear generalization cannot be made. This last observation is also valid for the inverse phenomena: Short periods of implementation cannot explain decreases in SOM (Table 2). Our findings highlight the positive effect of permanent soil cover, which supplements and strengthens the effects of other AMPs such as min-till or no-till. These tillage practices have been shown to preserve the

TABLE 2 Agricultural management practices (AMPs) for which a decrease in soil organic material was observed. Refer to Figure 3 for the identification of the AMPs and corresponding sites

AMP and corresponding site	Used as single AMP/combination	Year of implementation
AMP 1 – Site 2	Single AMP	5
AMP 7 – Site 1	Combined with Min-till	4
AMP 7 – Site 2	Combined with Min-till	20
AMP 7 – Site 6	Cereal mixed with leguminous, organic manure applied	2
AMP 8 – Site 2	Combined with Min-till	20
AMP 9 – Site 6	Combined with integrated management including organic farming (AMP 12)	9
AMP 12 – Site 3	Combined with residue maintenance, mulching (AMP8)	9
AMP 18 – Site 3	Single AMP	>5
AMP 18 – Site 6	Single AMP	>5

organic matter in surface soil layers favoring earthworm diversity, rather than throughout the soil profile (Baldivieso-Freitas et al. 2018). Previous studies have shown that the inclusion of cover crops may provide a range of vital ecosystem services and benefits. Permanent soil cover may reduce nutrient losses during winter (Gómez, Guzmán, Giráldez, & Fereres, 2009; Munkholm & Hansen, 2012), improve soil quality and C sequestration (Luo, Wang, & Sun, 2010; Mutegi, Petersen, & Munkholm, 2013; Weil & Kremen, 2007), and alleviate problems with soil compaction, thereby reducing the need for intensive tillage (Abdollahi & Munkholm, 2014; Chen & Weil, 2010). The above considerations show the potential benefit of using combinations of different AMPs such as cover crop treatments and no-till or min-till to enhance their positive effects. In comparison, the potential contribution of the single no-till treatment to the sustainable intensification of agriculture is more limited than often assumed (Pittelkow et al., 2014).

When considering the Sneath criterion 66%, the results of cluster analysis showed that some of the AMPs clustered together in Europe and China, indicating significant similarities in the effects on soil quality between them and thus, either AMP of this group can be used to improve soil quality (Figure 6). Considering the more restrictive Sneath criterion (33%), only two groups of AMPs were observed, and the rest of the other AMPs are distinguished as separate clusters, for both locations in Europe and China. In Europe, the investigated AMPs are displayed in two separate clusters: the first cluster comprises crop rotation, mulching and min-till, with rather positive or neutral effects on soil quality, and a second cluster including measures against compaction, irrigation management, change of land use practices, and manuring and composting, with negative effects. However in Chinese SSAs, although two separate clusters were observed for tested AMPs, there were no trends in the direction of soil quality effects among the two groups of practices.

When comparing the effects of one single AMP with the effects of their combinations, the results show that in Europe, the positive effects are higher when two or three AMPs are practiced together (83 and 80%, respectively), followed by the single application (73%). In fact, the percentage of positive effects increases from the single use to two combinations, while the combinations of three AMPs resulted in fewer positive effects but also fewer negative effects in detriment of more neutral effects. In China, combinations of two and three

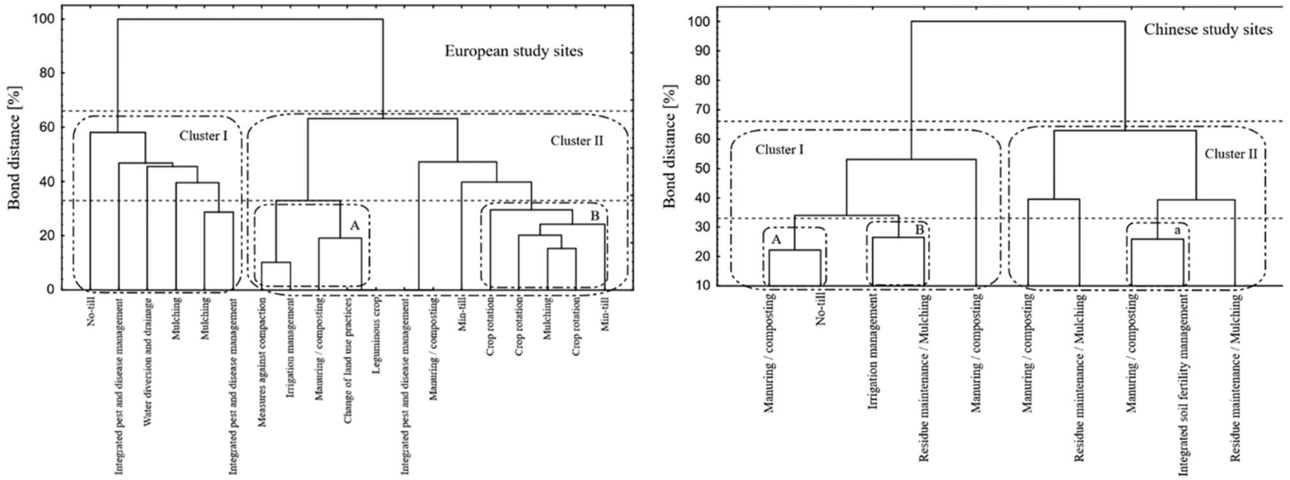

FIGURE 6 Cluster analysis of the agricultural management practices AMPs showing similarities in the effect on soil quality in Europe and China

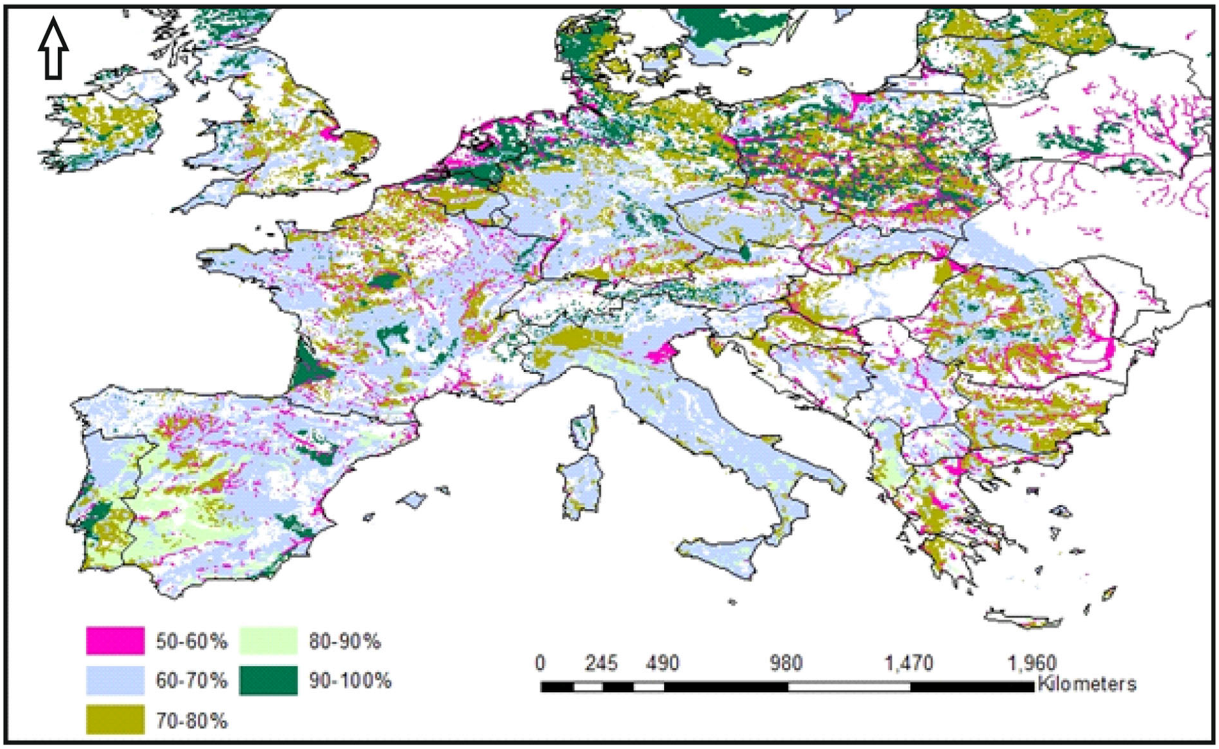

FIGURE 7 Distribution of soil types where the agricultural management practices have potential to improve soil quality in Europe and China, based on visual soil analysis methodology. The values in the legend correspond to the percentage of the cases where a positive effect was seen in the study sites with similar soil type

AMPs also resulted in more positive effects than the single application, although the number of paired plots analyzed is substantially lower (data not presented here).

The combination of two or three AMPs with higher positive effects on soil quality often included crop rotation, minimum tillage, and manuring and composting. This suggests that these AMPs have a complementary function and that their overall benefits are increased by their mutual application. Crop rotation affects the nutrient balance (Bullock, 1992, Martin-Rueda et al., 2017) by covering soil with organic matter which increases soil fertility (Altieri & Nicholls, 2003, Wiesmeier et al. 2017), whereas nondisturbance avoids soil breakdown and CO_2 emissions (Wander & Bidart, 2000). By acting on different management aspects, such as soil and nutrient management strategies, the combination of these AMPs can provide synergetic effects on soil quality (Barão et al., 2019). Therefore, we hypothesize that a good combination should include AMPs from different management classes such as soil, water, nutrient, and pest and crop management, each one acting on a different level and without overlapping, as suggested by Barão et al. (2019), who investigated the same SSA. The better effect of AMP combinations was also previously reported, particularly in conservation agriculture where crop rotation is practiced together with no-till or minimum tillage and residue maintenance (Giller et al., 2015).

The relatively low number of plots using three or more AMPs (12% of all study sites) does not allow a clear understanding of the effect on soil quality, given the small difference between SSA with positive, neutral, and negative effects. Nevertheless, the combination of four or more AMPs doesn't seem to result in increasing soil quality when assessing it with the VSA method used in this study.

These findings open new avenues in land management strategies for helping practitioners, advisers, and policymakers to improve soil quality and the sustainability of farming systems.

3.3 | Effect of AMPs in different soil types

Considering the AMPs that had a positive effect on soil quality in more than 10 instances across all study sites, we observe that these AMPs are mostly implemented on Podzols (positive effects observed in 100% of cases), Calcisols (91%), Regosols (84.6%), Antrosols (71.4%), Luvisols (70.6%), Cambisols (62.5%), and Fluvisols (58%). However, Cambisols, Fluvisols, and Luvisols are also linked to negative effects (37.5, 42, and 29.4% respectively; Figure 7).

The effect of AMPs could have been affected by pedoclimatic variations. The use of selected AMP in plots located in Podzols and Calcisols revealed a positive VSA_{index} for all

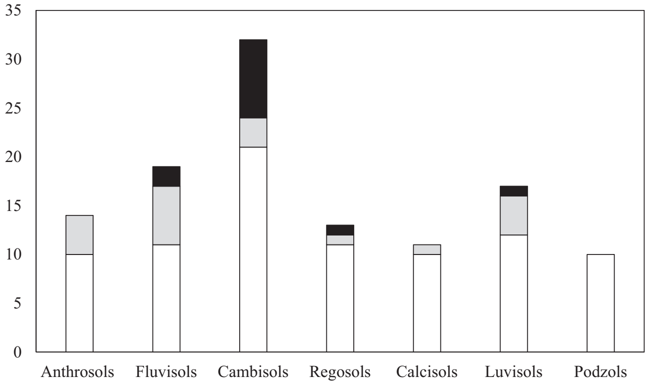

FIGURE 8 Positive, negative, and neutral effects of different agricultural management practices, taking into account the soil type; white color indicates positive effect, gray color indicates no effect, and black color indicates negative effect on soil quality.

cases, whereas the use of the same AMP in Fluvisols was advantageous in 50–60% of the cases (Figure 8). However, this can be associated with the inherent soil properties of distinct soils and their intrinsic soil quality. For instance, Podzols are normally acidic soils with low levels of organic matter and where agricultural activities are difficult (Jordanova et al., 2017), so the adoption of AMPs will always represent an improvement for soil quality. In Calcisols, which are common in semi-arid regions and associated with calcareous parent material and stoniness, crop productivity is limited without proper soil management practices. On the contrary, Fluvisols and Luvisols are very fertile soils, typically with high levels of clay and organic matter. On these types of soils, improvements on soil quality assessed with VSA method are limited, unless the soil is already intensively explored and has become degraded. Similar AMPs also revealed some contrasting effects on soil quality based on long-term experiments (≥5 yr; Bai et al., 2018).

Agricultural areas with naturally lower soil quality (i.e., Podzols and Calcisols) greatly benefit from AMPs (Figure 8). These AMPs might be quite different, ranging from strategies to avoid disturbance, such as no-till operations, to fertility strategies such as the integration of manure and the inclusion of leguminous crops, to crop rotations, or even irrigation management strategies, since all of them have positive effects on such soils.

On high fertile soils however, the strategy to manage agriculture soils should be different, since the same AMPs resulted in different outcomes when applied in plots located in Luvisols or Fluvisols. For example, leguminous crops, crop rotation, or no-till resulted in high $\text{VSA}_{\text{index}}$ in Portuguese and Romanian SSAs, whereas the effect in Slovenian plots was negative (data not shown). In some plots, the application of selected AMPs resulted in neutral effects that might indicate that some management practices would require a longer time of implementation to have a positive effect. Management strategies designed for these areas

TABLE 3 Agricultural management practices (AMPs) that improve soil quality in different soil types; the table exclude plot results with no and negative effects on soil quality

	Soil type					
Promising AMPs	**Podzols**	**Cambisols**	**Fluvisols**	**Calcisols**	**Luvisols**	**Regosols**
Min-till; cover crops; green manure/Integrated soil fertility management	x					
Min-till	x					
Min-till; irrigation management	x					
Manuring and composting	x	x				
Leguminous crops	x		x			
Crop rotation/Control or change of species composition	x	x	x	x		
No-till		x		x	x	x
Cross-slope measure		X		x		
Change of land use practices/intensity level				x	x	
Cover crops				x		
Area closure/rotational grazing			x	x		
Residue maintenance/Mulching		x	x	x		
Integrated pest and disease management including organic agriculture		x	x		x	
Permanent soil cover/Removing less vegetation cover		x			x	
Water diversion and drainage		x				
Measures against compaction			x			
Irrigation management			x			

should focus on site-specific threats and climatic variability to ensure that new solutions effectively contribute to improving soil quality or that more time is required for noticing the positive effects.

When considering only the AMPs that positively affect soil quality (excluding neutral and no effect) of a given soil type, extrapolating results of Table 3 using spatial distribution of soil types (Tóth et al.,2013) show two distinct areas where different agricultural approaches should be applied (Figure 8). Low fertile soils such as Podzols and Calcisols are mainly located southeast of the Iberian Peninsula, northern area of Germany, and in the Netherlands, Denmark, and other Scandinavian countries where any implementation of AMPs should be encouraged to improve the overall low soil quality of the agricultural fields. However, in Central Europe where more fertile soils are present, such as the United Kingdom and the Balkans, the agricultural management strategies should be site-specific. These results do not include the effect of cropping systems (i.e., crop rotation) which may be additional key pieces to improve the quality and fertility of soils. Further investigations are needed to refine our findings by investigating additional regions to include all pedoclimatic zones and by considering land use in the upscaling exercise.

4 | CONCLUSIONS

From the 11 indicators selected to evaluate soil quality, the ones describing soil structure (porosity, structure and consistency, aggregate stability) were revealed to be the most responsive to improved management practices both in Europe and China. The indicators selected by farmers for the assessment of soil quality are also related to soil structure and confirm the consistency of researchers' choice either in Europe or China. Between the European plots, soil porosity, infiltration rate, and labile organic carbon presented similar behavior in response to AMPs investigated. In China, however, the most sensitive cluster of parameters included infiltration rate, pH, biodiversity, presence of the cultivation pan, surface ponding, and susceptibility to erosion.

The VSA was applied in 138 paired plots where different AMPs (single or in combination) in use by local farmers are compared with control agriculture practices. Among the 138 sets of paired plots, 75.4% show a positive effect of AMPs on soil quality, 14.5% do not show any difference in soil quality between soils under the practices and soils in the control plots, and the remaining 10.1% show negative effects on soil quality. The AMPs providing higher $\mathrm{VSA}_{\mathrm{index}}$ were no-till, manuring and composting, crop rotation, and residue maintenance and mulching. Cluster analyses showed similarities in the effect on soil quality between crop rotation, residue maintenance and mulching, and min-till, and therefore, either AMP from this group can be used to improve soil quality. Nevertheless, plots using combinations of two or three AMPs showed greater positive effects on soil quality than single applications of AMPs. More specifically, AMP–SOM relationships show the potential benefit of using combinations of cover crop treatments and no-till or min-till to preserve or even enhance the organic matter in surface soil layers.

The effects of APMs were more noticed when plots were implemented in naturally less fertile soils, such as Podzols and Calcisols. In these soils, AMPs presented higher percentage of positive effects (90–100%), whereas in other soils with intrinsic high fertility, such as Luvisols and Fluvisols, the positive effects of AMPs were lower (50–60%). This shows that site-specific decisions should be considered for efficient implementation of the management strategies. The outcomes of our study should be considered to establish such strategies.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflict of interest.

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SUPPORTING INFORMATION

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