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Physicochemical properties of surface soils in European wheat fields under conventional and organic farming: Current status and climate change influence

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A R T I C L E I N F O

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A B S T R A C T

Recognizing the critical role of healthy soils in global food security, this large-scale study evaluated the physicochemical properties of 188 wheat soils across nine European pedoclimatic zones and assessed the influence of climate and farming system. Soils exhibited substantial variability in bulk density (0.7–1.7 g cm^{-3}), pH$_{H2O}$ (5.0–9.1), effective cation exchange capacity (4.5–42.0 cmol$_c$ kg^{-1}), base saturation (14%-100%), organic matter (1.6%-19.1%), and total inorganic carbon (0.7–106.3 g kg^{-1}). Redundancy Analysis (RDA) showed that climatic and geographic factors were more strongly associated with soil properties than farming system, whose effects were significant but smaller and context-dependent. Mean annual temperature and precipitation were associated

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with soil pH, base saturation, organic matter, and inorganic carbon, and indirectly influenced bulk density and eCEC. Soil properties were primarily structured by climatic gradients, reinforcing climate as a dominant soil-forming factor. Farming system effects were detectable but variable across pedoclimatic zones, indicating that management can locally modulate specific soil properties, although with lower explanatory power than climate. Based on these spatial associations and literature projections, warming trends may contribute to increased organic matter decomposition, higher bulk density, and reduced nutrient retention. Mediterranean regions appear particularly vulnerable due to declining precipitation, potentially linked to alkalinization and salinization. Although organic farming can locally enhance organic matter, reduce bulk density, and maintain inorganic carbon stocks, its effects are secondary to climate at the continental scale. These findings, based on spatial rather than temporal relationships, support region-specific soil management strategies integrating climate adaptation to sustain soil quality, productivity, and ecosystem services.

1. Introduction

Food security constitutes the cornerstone of human health and economic stability. Accordingly, ensuring access to safe, nutritious, and affordable food is essential for the sustainable development of the global population (Goel et al., 2024). Within this framework, maintaining healthy soils to guarantee food supplies is becoming increasingly critical (Pozza and Field, 2020).

Soils suitable for agricultural production must exhibit adequate nutrient availability, balanced structure, optimal pH, low erosion rates, high microbial and faunal diversity, good water retention, and resilience to environmental stresses, including pathogens and pests (Lehmann et al., 2020; Toor et al., 2021; Davis et al., 2023). Beyond providing support, nutrients, and water for plants, soils deliver key ecosystem services, such as carbon storage and pollutant filtration, which are essential for sustainable development (Pozza and Field, 2020; Rodríguez-Lado and Martínez-Cortizas, 2015; Arias-Navarro et al., 2024).

The expansion and intensification of agricultural production are exerting increasing pressure on soils worldwide, leading to degradation and a reduced long-term capacity to provide essential ecosystem services (Kopittke et al., 2019; Pozza and Field, 2020). In the European Union, 60–70% of soils are currently considered unhealthy due to multiple severe degradation processes (European Commission, 2020), many of which are exacerbated by climate change, now recognized as a major driver of soil degradation (IPCC, 2019). Rising temperatures are associated with faster organic matter decomposition, with potential implications for carbon losses and reduced soil fertility, while extreme temperatures can alter soil structure and increase the risks of compaction and erosion (Panagos et al., 2021; Wang et al., 2021; Arias-Navarro et al., 2024). Concurrently, changes in precipitation patterns affect soil quality by enhancing erosion through surface runoff, promoting nutrient leaching and acidification under excessive rainfall, or increasing erosion and salinization during prolonged droughts (Hermans and McLeman, 2021). Overall, these processes are associated with declines in soil health and agricultural productivity (Panagos et al., 2015; Simelane et al., 2024).

Wheat (*Triticum* spp.) is a major cereal crop and serves as a staple food for a significant portion of the global population (Morugán-Coronado et al., 2025; Sharma et al., 2024a). In 2019, Europe ranked as the world's second-largest wheat producer after Asia, with wheat being the most extensively cultivated cereal across the continent. That year, more than 266 million tons were harvested from over 62 million hectares of agricultural land (FAOSTAT, 2021). Therefore, the management of wheat fields is critically important to prevent soil degradation and declines in soil quality, as wheat is typically grown in large areas with high soil fertility (Galieni et al., 2016; Zaicou-Kunesch, 2021).

Given the high importance of soils dedicated to wheat cultivation, as well as their fragility and vulnerability to climate variability and other anthropogenic pressures, it is essential to develop and implement more regenerative practices and adaptation measures to ensure the long-term sustainability of these agricultural systems. As a first step, it is crucial to assess the current state of agricultural soils at a large scale and to understand how climate and soils interact, as well as how climatic variability is associated with soil properties and functions across different European pedoclimatic regions (Joseph et al., 2018; Ballabio et al., 2019). In addition, it is also necessary to evaluate, on a broad scale, the effectiveness of organic farming systems as sustainable strategies to prevent soil degradation, improve soil health and fertility, and enhance associated ecosystem services, while also serving as an adaptation measure to climate change. In this context, numerous studies have shown that sustainable management practices implemented in organic farming systems for wheat production can improve physicochemical soil properties, including increased soil organic matter, enhanced fertility, and greater soil water availability, among other benefits (Gajda et al., 2019; Lemanowicz et al., 2020; Martínez-Mena et al., 2020). However, none of these studies have been conducted at a continental scale.

Therefore, considering all the aspects discussed above, the main objectives of this study are: a) to assess the current state of selected physicochemical properties (bulk density, texture, pH, effective cation exchange capacity, base saturation, organic matter, and total inorganic carbon) of surface soils dedicated to wheat cultivation across nine pedoclimatic regions of Europe; b) to examine the influence of climate and agricultural management system (conventional vs organic) on these soil properties; and c) to explore how climatic gradients are associated with variations in these soil properties and to discuss their potential implications in the context of ongoing climate change.

We hypothesize that climate is the primary driver of variability in the physicochemical properties of wheat soils across Europe, whereas the agricultural management system (conventional vs organic) exerts a secondary but measurable effect. We further hypothesize that observed differences associated with management practices are not uniform across regions and may vary depending on local pedoclimatic conditions.

To the best of our knowledge, this is the first study to link, at a continental scale, the physicochemical properties of wheat soils with climatic and management variables.

2. Material and methods

2.1. Soil sampling

Wheat fields managed under either conventional or organic farming systems were selected across nine distinct European pedoclimatic zones (Figure S1, Table 1), arranged from north to south: Boreal (BOR), Nemoral (NEM), Atlantic North (AN), Continental (CON), Atlantic Central (AC), Pannonian (PAN), Lusitanian (LUS), Mediterranean North (MN), and Mediterranean South (MS). For each pedoclimatic zone, based on Europe's environmental stratification, a minimum of ten field sites under conventional management and ten under organic management were selected. Within each zone, pairs of conventional and organic fields located in close proximity were preferentially selected to ensure comparable soil properties and pedoclimatic conditions, thereby allowing a clearer assessment of the effects of the management system. Field selection was also influenced by practical considerations, including field availability and farmer consent. Certification for organic

Table 1
Pedoclimatic zones, corresponding countries, types of agricultural farming systems, and number of sampled fields.

Pedoclimatic zone	Country	Fields per type
AN	Denmark	10 (Org), 10 (Conv)
AC	Belgium	12 (Org), 13 (Conv)
BOR	Finland	10 (Org), 10 (Conv)
CON	Germany	10 (Org), 10 (Conv)
LUS	Spain	13 (Org), 10 (Conv)
MN	Spain	10 (Org), 10 (Conv)
MS	Spain	10 (Org), 10 (Conv)
NEM	Estonia	10 (Org), 10 (Conv)
PAN	Serbia and Hungary	10 (Org), 10 (Conv)

AN, Atlantic North; *AC*, Atlantic Central; *BOR*, Boreal; *CON*, Continental; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian. *Org*, organic farming system; *Conv*, Conventional farming system.

wheat production was a required criterion for selecting organic fields. In total, soil samples were collected from 188 agricultural fields, 95 organically managed and 93 conventionally managed (Table 1).

According to European Commission regulations, organic crop rotations must consist of legumes comprising more than 30% of the plants, and cereals may not be cultivated for more than three consecutive years. The use of synthetic fertilizers and pesticides is strictly prohibited in organic farming (European Commission, 2018). Soil sampling was conducted once, 15–30 days after wheat harvest, within a restricted post-harvest seasonal window (July-October) according to the pedoclimatic zone. This timing ensured that soils were sampled under comparable post-harvest conditions within each region, when crop influence is minimal and major field management activities have ceased, thereby limiting short-term seasonal variability in key soil properties.

Detailed information for each field—including climatic, geographical, and topographic characteristics, as well as the type of agricultural farming system [organic (Org) or conventional (Conv)] and the number of years under the specified system (ranging from 1 to 60 years)—is provided in the raw dataset (Fernández-Calviño et al., 2023). Exact sampling dates for each field are also available in this dataset. The sampling procedure was outlined by Soto-Gómez et al. (2020). Briefly, a composite soil sample (minimum 2 kg) from the 0–25 cm depth layer was obtained by combining 60 individual soil cores collected with a soil auger (13–50 mm diameter) from 60 randomly distributed points across each field. These composite samples were homogenized and air-dried at room temperature. In addition, three soil cores per field were collected to determine bulk density (BD) at two depths: 0–10 cm and 10–25 cm (Campbell and Hensall, 1991).

2.2. Soil analysis

For each physicochemical property, measurements for all 188 soils were performed in a single laboratory using a standardized protocol. This ensured that each property was determined consistently and comparably across the nine pedoclimatic regions and between soils under conventional and organic management. The methods are described in detail in Soto-Gómez et al. (2020) and Fernández-Calviño et al. (2020).

Briefly, bulk density was determined using the cylinder method described by Campbell and Henshall (1991), while the content of rock fragments and gravels (Rfg) (particles larger than 2 mm) was determined by sieving with a 2-mm mesh. Subsequently, the fraction with particle sizes smaller than 2 mm was used to determine the remaining physicochemical properties. Firstly, regarding soil texture, sand (2–0.05 mm) was determined by wet sieving, whereas silt (0.05–0.002 mm) and clay (<0.002 mm) were measured using the international Robinson pipette method. Secondly, soil pH was measured in water (pH_{H2O}), 0.1 M KCl (pH_{KCl}), and 0.01 M $CaCl_2$ (pH_{CaCl2}), using a soil-to-solution ratio of 1:5 and a pH meter (Crison, Barcelona, Spain). Thirdly, the effective cation exchange capacity (eCEC) and base saturation (Bs) were determined using barium chloride as the exchangeable salt, following the ISO, (2018) protocol. Fourthly, organic matter (OM) content was estimated using the loss-on-ignition (LOI) method, whereby the soil sample was combusted in a muffle furnace at 450 °C for 4 h, and the OM content was subsequently calculated based on the weight loss before and after combustion. Finally, the carbon content in the combusted sample was determined by elemental analysis using a Thermo-Finnigan 1112 Series NC analyzer (ThermoFinnigan, The Netherlands), thereby obtaining the total inorganic carbon (TIC).

2.3. Statistical analysis

Redundancy analysis (RDA) was performed to explore the relationships between soil physicochemical properties (response variables) and environmental factors (explanatory variables). The response variables included sand, silt, clay, Rfg, pH_{H2O}, pH_{KCl}, pH_{CaCl2}, eCEC, Bs, OM, and TIC. The explanatory variables were mean annual precipitation (MAP30) and temperature (MAT30) of the last 30 years before sampling campaigns, longitude, latitude, altitude, and agricultural management system (conventional vs organic). MAP30 and MAT30 represent long-term spatial averages for each site and were not treated as time series, ensuring that the analysis focuses on spatial rather than temporal variation. Prior to analysis, all variables were standardized (z-transformed) to ensure comparability. The significance of the global model and individual explanatory variables was assessed through permutation tests (999 permutations). Bulk density values were excluded from the RDA analysis due to incomplete data coverage, which limited their inclusion in the multivariate analysis.

A Spearman correlation analysis was conducted to assess the relationships among soil physicochemical properties, climatic variables, geographic factors, and the agricultural management system.

Significant differences in soil physicochemical properties among zones were assessed using one-way ANOVA after checking assumptions. Data normality was tested using the Kolmogorov-Smirnov test for $n \geq 30$ and the Shapiro-Wilk test for $n < 30$, and homogeneity of variance was assessed using Levene's test. For normally distributed data with equal variances, one-way ANOVA was applied followed by Bonferroni post hoc tests. For normally distributed data with unequal variances, Games-Howell post hoc tests were applied, which are robust to heteroscedasticity. When data were not normally distributed, log or square root transformations were applied; if normality was still not achieved, the Kruskal-Wallis test was used. Based on statistical recommendations (McDonald, 2014), one-way ANOVA followed by Games-Howell post hoc tests was applied when data were not normally distributed and variances were unequal. In addition, pairwise *t*-tests were conducted to compare agricultural management types within each zone.

Finally, to predict and explain the variability of soil organic matter content, a Random Forest analysis was conducted. Predictor variables included soil physicochemical properties (pH_{CaCl2}, eCEC, Rfg, silt, and clay), climatic and geographical variables (MAP30, MAT30, and altitude), and agricultural management systems (organic management system). Variables with missing data were excluded, and highly correlated predictors (correlation > 0.7) were removed to minimize multicollinearity. The model was trained using the selected variables, and variable importance was assessed. Model performance was evaluated using RMSE, MAE, and R^2.

These complementary statistical approaches addressed different aspects of the research questions, including multivariate structure (RDA), pairwise relationships (Spearman correlations), group comparisons (ANOVA), and predictive importance (Random Forest), thereby providing a complementary and integrated interpretation of soil variability.

All statistical analyses and figures were performed using R version 4.4.1, with the following packages: *vegan* for RDA; *Hmisc* and *reshape2* for Spearman correlations; *randomForest* and *caret* for Random Forest modeling; and *ggpubr*, *dplyr*, and *ggplot2* for ANOVA, Bonferroni or Games-Howell post hoc tests, Kruskal–Wallis tests, pairwise *t*-tests, data handling, and figure preparation.

3. Results and discussion

Fig. 1 shows the biplot from the Redundancy Analysis (RDA), illustrating the associations between climatic variables (MAP30 and MAT30), geographical factors (longitude, latitude, and altitude), and agricultural management systems (conventional or organic) with the physicochemical properties of the 188 wheat soils sampled. Results from the permutation test indicated that the overall RDA model was highly significant (F = 19.24, $p < 0.001$), with the first four canonical axes (RDA1, RDA2, RDA3, and RDA4) also being statistically significant (F = 86.33, $p < 0.001$ for RDA1; F = 17.68, $p < 0.001$ for RDA2; F = 5.29, $p < 0.01$ for RDA3; and F = 3.64, $p < 0.05$ for RDA4). The first two canonical axes (RDA1 and RDA2) together accounted for 35.1% of the total variance in the dataset (29.1% and 6.0%, respectively; see Fig. 1).

Term-wise analysis revealed that all explanatory variables—climatic, geographic, and management-related—included in the model contributed significantly to explaining the variance in soil properties, with longitude being the most influential factor (F = 12.46, $p < 0.001$), followed by MAT30 (F = 10.12, $p < 0.001$), MAP30 (F = 9.44, $p < 0.001$), altitude (F = 6.07, $p < 0.001$), latitude (F = 5.55, $p < 0.001$), and the farming system (F = 2.60, $p < 0.05$), the latter having the weakest influence among the variables assessed.

The RDA biplot (Fig. 1) shows a clear differentiation between pedoclimatic regions, with soil samples tending to cluster according to their region of origin. This highlights the association between soil properties and pedoclimatic zones and geographical factors. These findings support the widely accepted understanding that general soil characteristics are primarily shaped by intrinsic factors such as soil type, altitude, and geological or climatic conditions, rather than by agricultural management practices associated with organic or conventional systems (Kassai and Sisák, 2018; Wesołowska et al., 2022).

In contrast, the farming system (conventional vs organic) exerted the least influence on the soil properties studied. Nonetheless, its effect was statistically significant ($p < 0.05$), suggesting that certain soil parameters can be locally modulated by the agricultural practices implemented at each site. In this regard, several studies have reported that soil pH, eCEC, BD, and soil OM content and their stability can be enhanced through fertilization regimes, crop rotation, and overall management strategies (Sheoran et al., 2019; Kwiatkowski et al., 2020; Tiefenbacher et al., 2020; Rachwał et al., 2021; Jia et al., 2022).

Finally, based on the results of the RDA analysis, it can also be observed that the climatic variables (MAT30 and MAP30) were strongly associated with soil chemical properties such as OM, TIC, pH, and Bs. In contrast, they exhibited a weak influence on soil physical properties related to particle size distribution, including Rfg and the proportions of sand, silt, and clay (Fig. 1). These results are consistent with those reported by Gebauer et al. (2022), who indicated that soil-forming factors such as parent material and relief exert a much greater influence on soil texture than climatic variables.

A detailed discussion of the response of each soil parameter in relation to pedoclimatic zone and farming system (conventional vs organic) is provided in the following sections. In addition, a statistical summary of the physicochemical properties analyzed in the 188 soil samples included in this study is presented in Table 2 and Tables S1-S5 (Supplementary Material), while the results of the Spearman correlation analysis are shown in Fig. 2.

3.1. Soil bulk density

Soil bulk density (BD), one of the most commonly used indicators for characterizing soil compaction, is a key physical property that influences both soil health and essential ecosystem services. In this context, soil BD is inversely related to soil porosity and, consequently, governs the movement of water and air through the soil (McNabb et al., 2001). Moreover, soil compaction is widely recognized as a major threat

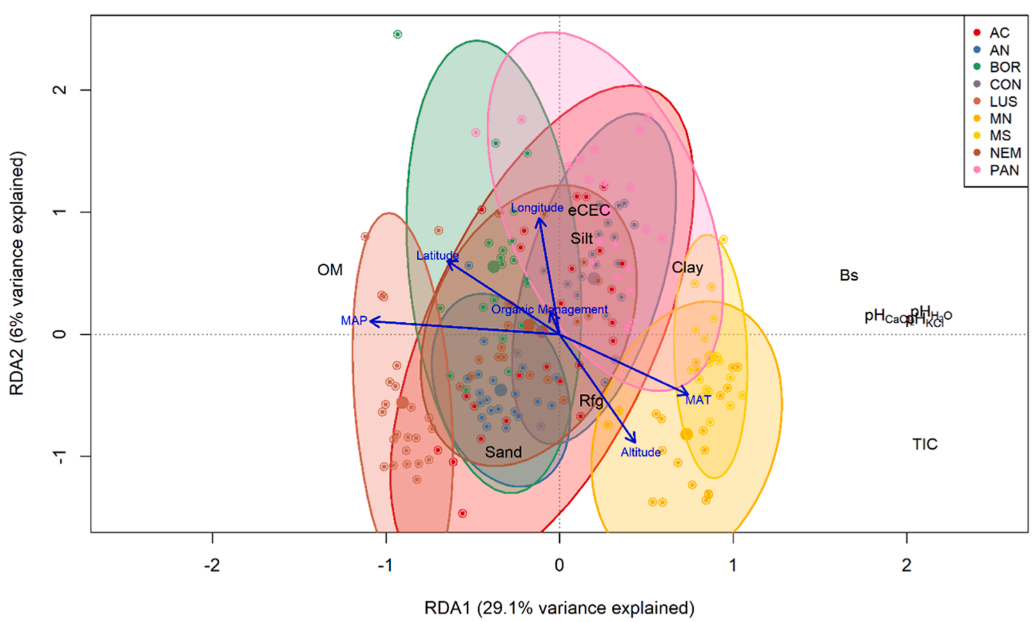

Fig. 1. Biplot of the Redundancy Analysis (RDA) performed on 188 soil samples from wheat fields across nine pedoclimatic regions in Europe. Ellipses represent 95% confidence intervals for each pedoclimatic region. Blue arrows indicate the direction and magnitude of the gradients associated with the explanatory variables, including climatic, geographical, and management-related factors. *Rfg*, rock fragments and gravels (%); *pH_{H2O}*, pH in H_2O; *pH_{KCl}*, pH in 1 M KCl; *pH_{CaCl2}*, pH in 0.01 M $CaCl_2$; *eCEC*, effective cation exchange capacity ($cmol_c\ kg^{-1}$); *Bs*, base saturation (%); *OM*, organic matter content (%); *TIC*, total inorganic carbon ($g\ kg^{-1}$); *MAP30*, mean annual precipitation of the last 30 years before sampling campaigns (mm); *MAT30*, mean annual temperature of the last 30 years before sampling campaigns (ºC); *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *CON*, Continental; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Panonian.

Table 2
Descriptive statistics (minimum – Min, maximum – Max, mean, and standard deviation – SD) of the physicochemical properties analysed in the 188 soil samples included in this study.

Variable	Units	Min	Max	Mean	SD
Bulk density (BD) (0–10 cm)[a]	g cm^{-3}	0.7	1.5	1.2	0.2
Bulk density (BD) (10–25 cm)[a]	g cm^{-3}	0.8	1.7	1.3	0.2
Rock fragments and gravels (Rfg)	%	0.1	64.5	15.1	14.7
Sand	%	8.7	75.8	50.2	16.0
Silt	%	10.3	70.2	34.5	15.0
Clay	%	4.0	26.5	15.3	3.7
pH_{H2O}		5.0	9.1	7.3	1.1
pH_{KCl}		3.8	8.2	6.3	1.3
pH_{CaCl2}		3.8	8.1	6.4	1.2
Effective cation exchange capacity (eCEC)	cmol$_c$ kg^{-1}	4.46	41.97	16.77	6.18
Base saturation (Bs)	%	14	100	78	28
Organic matter content (OM)	%	1.57	19.09	4.25	2.19
Total inorganic carbon (TIC)	g kg^{-1}	0.70	106.25	16.09	27.27

[a] Data from the Panonian zone was not available for BD (0–10 cm). Data from the Mediterranean North and Mediterranean South zones were not available for BD (10–25 cm). *pH_{H2O}*, pH in water; *pH_{KCl}*, pH in 1 M KCl; *pH_{CaCl2}*, pH in 0.01 M $CaCl_2$. More detailed information on each parameter according to pedoclimatic zone and agricultural management system can be found in Tables S1–S5 (Supplementary Material)

to soil quality, particularly in intensive agricultural systems. Specifically, compaction reduces water infiltration and restricts root growth, while also increasing nutrient loss through runoff and elevating the risk of erosion. Ultimately, these effects lead to decreased agricultural productivity and crop yields (Panagos et al., 2024).

Table 2 provides a statistical summary of the BD data obtained from the 188 soil samples analyzed in this study, both from the topsoil layer (0–10 cm) and the subsoil layer (10–25 cm), while Table S1 presents the variation in BD across different farming systems within each pedoclimatic zone.

On the one hand, in the topsoil layer (0–10 cm) and considering all soil samples, BD values ranged from 0.7 to 1.5 g cm^{-3}, with an average of 1.2 ± 0.2 g cm^{-3} (Table 2). These results indicate that all soils from the studied pedoclimatic zones exhibited acceptable BD values for wheat cultivation, as all measurements remained below the critical threshold of 1.60 g cm^{-3} reported by Sabir et al. (2021). In addition, BD at this depth varied significantly ($p < 0.05$) among pedoclimatic zones, allowing the sequence: $AC^a \geq MN^{ab} \geq MS^b \approx CON^b \approx LUS^b \approx NEM^b \approx BOR^b \approx AN^b$ (Fig. 3, Table S1). On the other hand, in the subsoil layer (10–25 cm), BD values ranged from 0.8 to 1.7 g cm^{-3}, with an average of 1.3 ± 0.2 g cm^{-3} (Table 2). Consistent with the observations in the topsoil layer, the pedoclimatic zone also showed significant associations ($p < 0.05$) with BD in the subsoil layer (Fig. 3, Table S1).

Although BD varied significantly across pedoclimatic zones in both the topsoil and subsoil layers, no significant relationship was found between BD and MAP30 (Fig. 2). However, a positive and statistically significant correlation was observed between BD and MAT30 (ρ = 0.21, $p < 0.01$ for topsoil BD; ρ = 0.30, $p < 0.001$ for subsoil BD; Fig. 2). This temperature-related effect on soil BD is consistent with the findings of Ma et al. (2024), who reported that long-term warming significantly increased soil BD. The increase in soil BD with rising temperature could be attributed to the fact that soil BD is closely linked to OM content, and higher temperatures tend to reduce OM content (see Section 3.5). This, in turn, leads to increased BD, in agreement with previous observations by other authors (Franzluebbers et al., 2001; Ma et al., 2024). In fact, in the present study, a strong negative correlation was found between soil BD and soil OM content at both depths: 0–10 cm (ρ = −0.50, $p < 0.001$) and 10–25 cm (ρ = −0.59, $p < 0.001$) (Figs. 2 and 4). Therefore, the observed association between temperature, organic matter, and bulk density suggests that projected warming trends reported in the literature may be associated with increases in soil bulk density in European agricultural soils, primarily through enhanced organic matter decomposition (Kumar et al., 2022; Ma et al., 2024). This increase in bulk density is, in turn, potentially associated with a higher risk of soil compaction and degradation, ultimately reducing agricultural productivity and

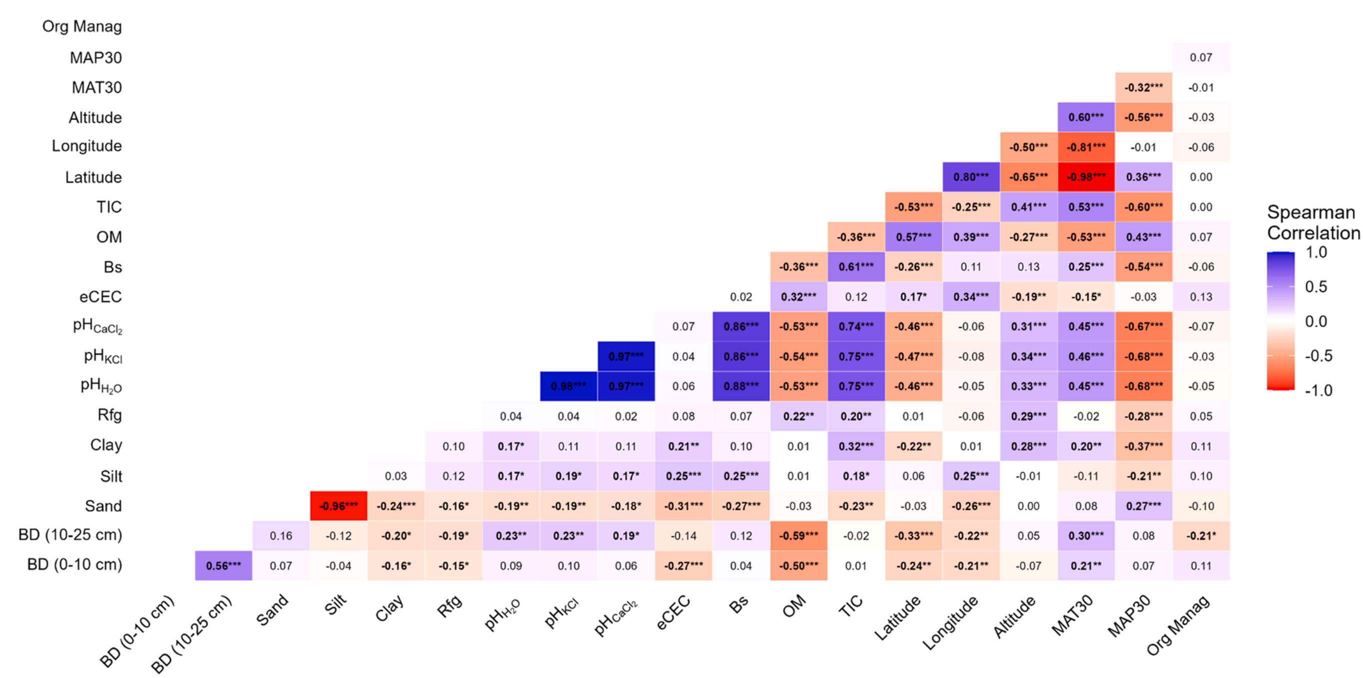

Fig. 2. Heatmap showing Spearman's ρ coefficients from the correlation analysis between soil physicochemical properties, geographical and climatic variables, and agricultural management systems. *BD*, bulk density (g cm^{-3}); *Rfg*, rock fragments and gravels (%); *pH_{H2O}*, pH in H_2O; *pH_{KCl}*, pH in 1 M KCl; *pH_{CaCl2}*, pH in 0.01 M $CaCl_2$; *eCEC*, effective cation exchange capacity (cmol$_c$ kg^{-1}); *Bs*, base saturation (%); *OM*, organic matter content (%); *TIC*, total inorganic carbon (g kg^{-1}); *MAP30*, average precipitation of the last 30 years before sampling campaings (mm); *MAT30*, average temperature of the last 30 years before sampling campaigns (°C); *Org Manag*, organic management.

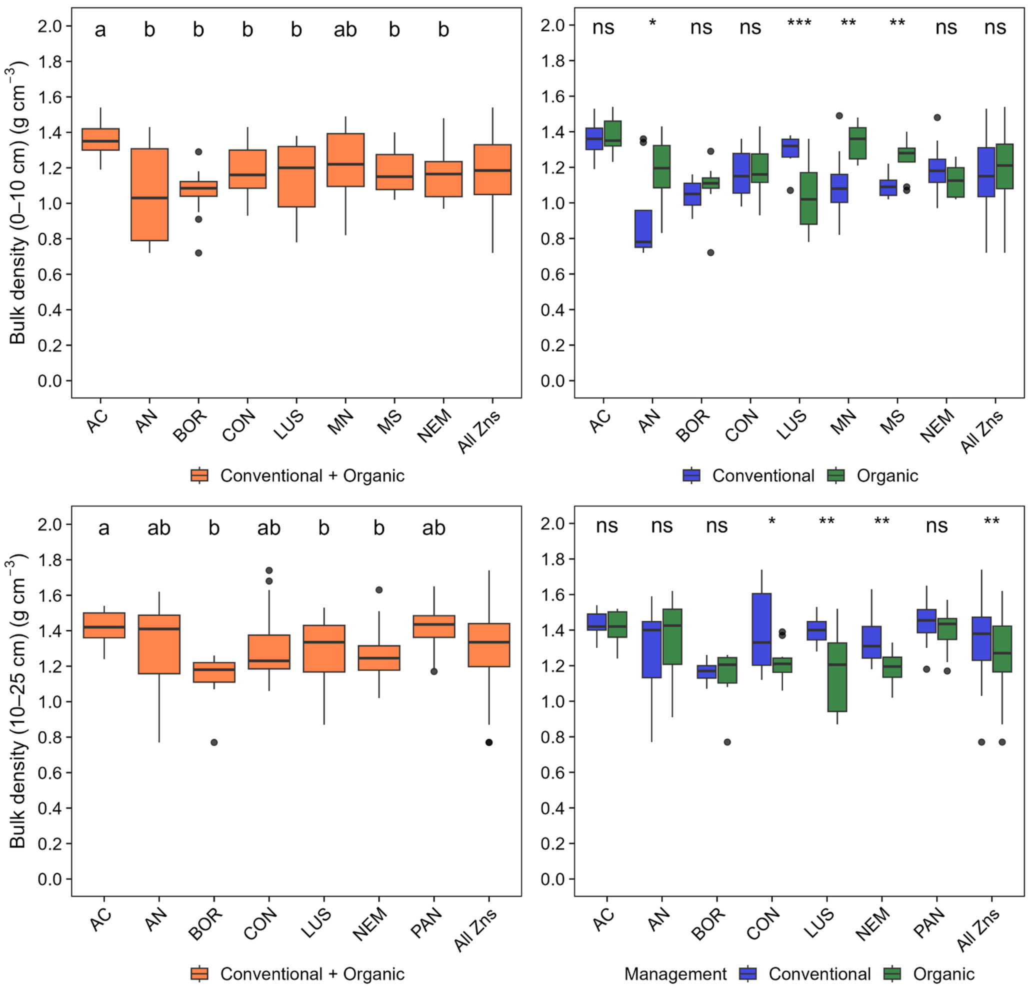

Fig. 3. Soil bulk density (g cm^{-3}) for the 0–10 cm and 10–25 cm layers across different pedoclimatic zones, as well as under conventional and organic farming systems. Data from the Pannonian zone were not available for BD (0–10 cm), and data from the Mediterranean North and Mediterranean South zones were not available for BD (10–25 cm). Different letters indicate statistically significant differences ($p < 0.05$) among pedoclimatic zones, while asterisks indicate significant differences between farming systems (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ****, $p < 0.0001$).

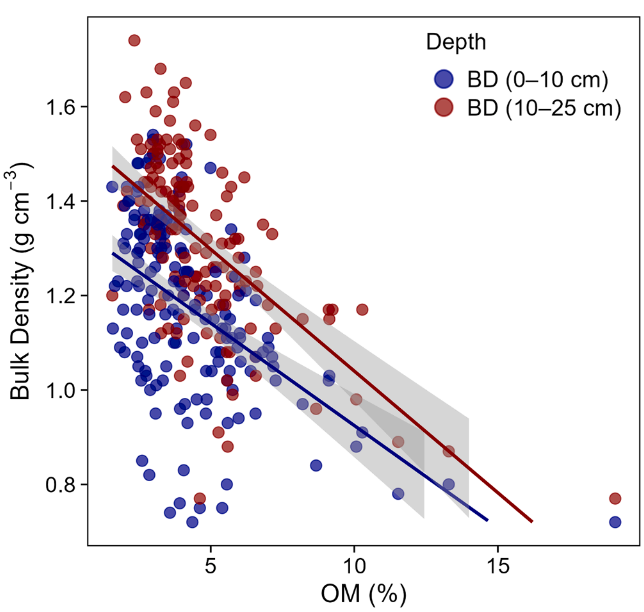

Fig. 4. Relationship between bulk density (0–10 cm and 10–25 cm depths) and soil organic matter (OM) content.

contributing to the deterioration or loss of other vital ecosystem services (Kumar et al., 2022; Panagos et al., 2024).

On the other hand, when considering the farming system as a factor of variation, BD values in the topsoil layer (0–10 cm) did not differ significantly between conventional and organic systems when all samples were analyzed collectively (Fig. 3). However, within specific pedoclimatic zones, significant differences were observed, although no consistent trend emerged (Fig. 3). These findings are consistent with previous research, which has shown that the effects of agricultural practices on topsoil BD can be variable or even negligible, as was also the case in the present study for the 0–10 cm layer (Reganold, 1988; Chung, 2007; Williams et al., 2017; Sheoran et al., 2019; Rachwał et al., 2021).

In contrast, in the subsoil layer (10–25 cm), the results showed a more consistent trend, with BD being significantly higher ($p < 0.01$) under conventional farming compared to organic farming when all data were analyzed together (Fig. 3). Moreover, when analyzed by zone, conventional farming was also associated with significantly higher BD values than organic farming in the CON ($p < 0.05$), LUS ($p < 0.01$), and NEM ($p < 0.01$) zones, while no significant differences were detected in the remaining four zones (Fig. 3). Furthermore, in the present study, a significant negative correlation was observed between BD in the 10–25 cm layer and organic management ($\rho = -0.21$, $p < 0.05$; Fig. 2), confirming that soils under organic management tended to have lower BD values than those under conventional management. This finding aligns with previous studies, which also reported higher BD values under conventional farming systems (Del Moral et al., 2012; Gao et al., 2019; Topa et al., 2021). In this sense, Williams et al. (2017) and Panagos et al. (2024) suggested that organic farming practices, such as the application of crop residues or manures, may reduce soil susceptibility to compaction by increasing OM content, thereby potentially lowering BD.

3.2. Rock fragments and gravels (Rfg) and particle size distribution

Rock fragments and gravels (Rfg), along with particle size distribution, including sand (2–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm) contents, are key determinants of soil structure and composition (Mukhopadhyay and Maiti, 2018). These are among the most important physical soil properties, as they influence soil hydrological behavior, susceptibility to erosion, fertility, crop productivity, and carbon sequestration, among other ecosystem services and processes (Gebauer et al., 2022).

In the present study, considering all soil samples, the content of Rfg ranged from 0.1% to 64.5% (average of 15.1 ± 14.7%), while the sand, silt, and clay fractions ranged from 8.7% to 75.8% (average of 50.2 ± 16.0%), 10.3–70.2% (average of 34.5 ± 15.0%), and 4.0–26.5% (average of 15.3 ± 3.7%), respectively (Table 2).

The zone factor led to significant differences ($p < 0.05$) in Rfg content, following the sequence: $CON^{a} \approx MN^{a} \geq BOR^{ab} \geq LUS^{b} > AC^{c} \approx AN^{c} \approx MS^{c} \approx NEM^{c} \approx PAN^{c}$ (Fig. 5, **Table S2**). However, despite this, no significant differences were observed among five of the nine pedoclimatic zones (AC, AN, MS, NEM, and PAN), indicating that Rfg content shows limited association with climatic variables, consistent with the patterns observed in the initial RDA analysis (Fig. 1). Nonetheless, a significant negative correlation was observed between Rfg content and MAP30 ($\rho = -0.28$, $p < 0.001$; Fig. 2), suggesting a tendency for higher Rfg content in areas with lower precipitation. This pattern may be attributed to slower rates of chemical weathering in drier environments, which favor the preservation of rock fragments and gravel in greater proportions (Grantham and Velbel, 1988).

With regard to the farming system, Rfg content did not differ significantly between systems when considering all soil samples collectively (Fig. 4). However, within the MS zone, values were significantly higher ($p < 0.01$) under organic compared to conventional farming when analyzed by pedoclimatic zone (Fig. 4).

On the other hand, sand, silt and clay contents differed significantly between pedoclimatic zones ($p < 0.05$; Fig. 6), indicating that both geographical location and climate could contribute to variations in the particle size distribution of European agricultural soils. Specifically, soil clay and silt contents showed significant negative correlations with MAP30 ($\rho = -0.37$ and $p < 0.001$ for clay; $\rho = -0.21$ and $p < 0.05$ for silt; Fig. 2), while sand content was positively and significantly correlated with MAP30 ($\rho = 0.27$, $p < 0.001$, Fig. 2). These associations are consistent with the notion that higher precipitation tends to be linked with enhanced leaching of finer particles (clay and silt) into deeper soil horizons, resulting in sandier topsoil layers (Ma et al., 2023). Moreover, soil clay content also exhibited a significant positive correlation with MAT30 ($\rho = 0.20$, $p < 0.01$, Fig. 2), suggesting that elevated temperatures may be associated with enhanced chemical weathering processes that contribute to the formation and accumulation of clay minerals in the soil. In addition, rising temperatures may also increase microbial activity in the soil, which in turn may contribute to aggregate formation and stability, thereby protecting fine particles from erosion and leaching (DowdeswellDowney et al., 2023; Xiao et al., 2025).

Regarding farming system, no significant differences in particle size distribution were observed when all pedoclimatic zones were considered collectively (Fig. 6). These results are consistent with previous findings reported by several authors (Diepeningen et al., 2006; Williams and Petticrew, 2009; Alfahham et al., 2021), who also found no differences in particle size distribution between farming systems. This supports the notion that soil texture is primarily governed by long-term weathering of the parent material and is not significantly altered over short and medium timescales (Fan et al., 2021).

3.3. Soil pH

Soil pH is a key factor regulating nutrient availability and release, microbial activity, contaminant behavior in soils, carbon and nitrogen dynamics, greenhouse gas emissions, and crop growth and development. Therefore, understanding its variability across different pedoclimatic zones in Europe, as well as its response to climatic variables, is of critical importance, especially in the context of climate change (Cheng-Jun et al., 2014; Zhang et al., 2019; Belay et al., 2023).

Descriptive statistics for soil pH measured in water (pH_{H2O}), indicative of current acidity, and in saline solutions (pH_{KCl} and pH_{CaCl2}), indicative of potential acidity, are presented in Table 2, whereas Table S3 displays the variation in these parameters according to farming systems within each pedoclimatic zone. When all soil samples were considered, pH_{H2O} ranged from 5.0 to 9.1 (average of 7.3 ± 1.1), whereas pH_{KCl} and pH_{CaCl2} ranged from 3.8 to 8.2 (average of 6.3 ± 1.3) and from 3.8 to 8.1 (average of 6.4 ± 1.2), respectively (Table 2).

As illustrated in Fig. 7, soil pH values varied significantly across the

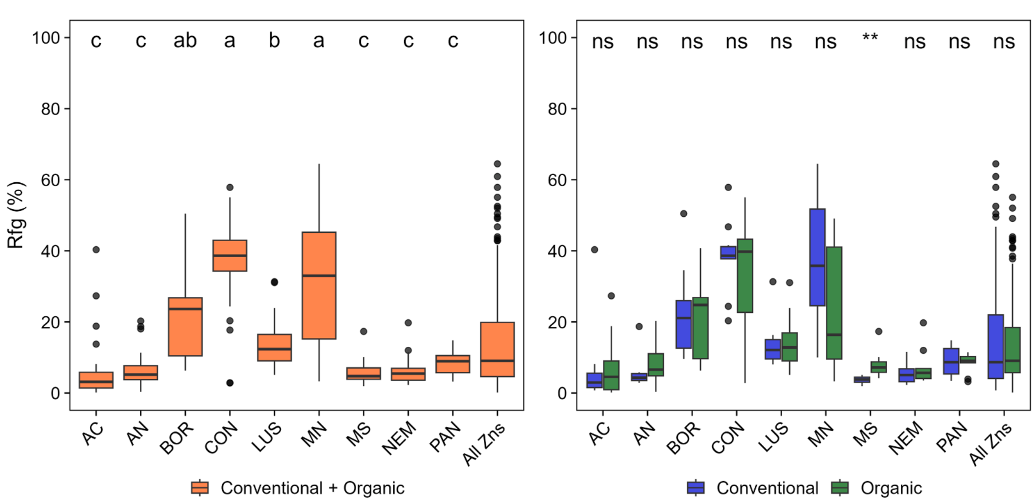

Fig. 5. Rock fragments and gravels (Rfg) content across different pedoclimatic zones, as well as under conventional and organic farming systems. Different letters indicate statistically significant differences ($p < 0.05$) among pedoclimatic zones, while asterisks indicate significant differences between farming systems (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ****, $p < 0.0001$).

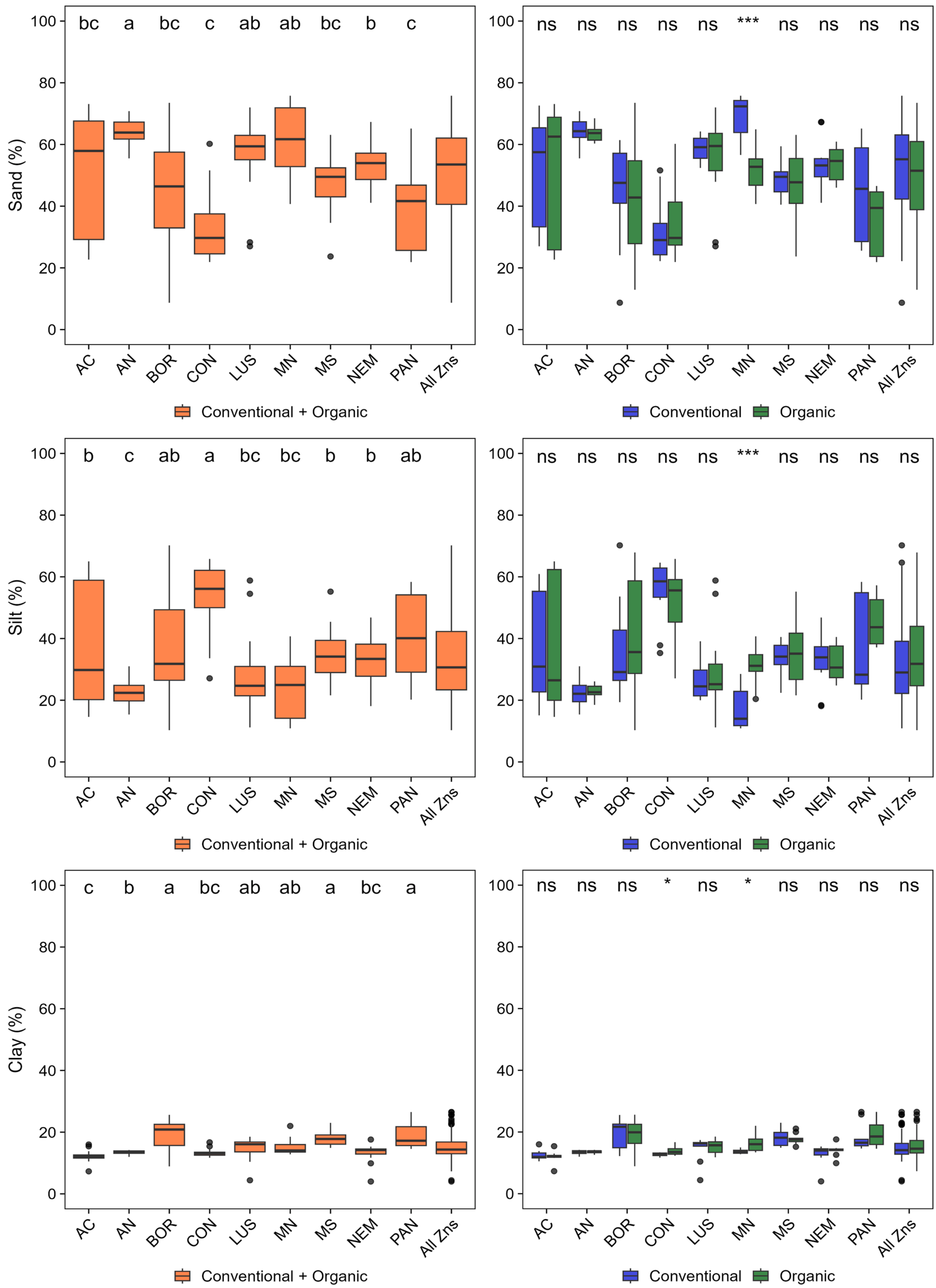

Fig. 6. Sand, silt and clay contents across different pedoclimatic zones, as well as under conventional and organic farming systems. Different letters indicate statistically significant differences ($p < 0.05$) among pedoclimatic zones, while asterisks indicate significant differences between farming systems (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ****, $p < 0.0001$).

different pedoclimatic zones. In this sense, for pH_{H2O}, the following sequence was observed: $MS^a \approx MN^a > PAN^b \approx CON^b > AC^c \approx NEM^c \geq AN^{cd} \geq BOR^d > LUS^e$. In addition, very similar sequences were observed for pH_{KCl} and pH_{CaCl2} (Fig. 7; Table S3). These findings highlight the strong associations of climatic variables with soil pH, consistent with previous studies, which identified temperature and precipitation as key factors controlling soil pH (Cheng-Jun et al., 2014; Zhang et al., 2019; Zhao et al., 2021). In fact, in this study it was observed that soil pH was negatively and significantly correlated with MAP30 ($\rho = -0.68$, $p < 0.001$ for pH_{H2O} and pH_{KCl}; $\rho = -0.67$, $p < 0.001$ for pH_{CaCl2}; Figs. 2 and 8), while showing a positive and significant correlation with MAT30 ($\rho = 0.45$, $p < 0.001$ for pH_{H2O} and pH_{CaCl2}; $\rho = 0.46$, $p < 0.001$ for pH_{KCl}; Fig. 2). These findings confirm that soils in arid and semi-arid climates tend to be more alkaline, exhibiting higher pH values, whereas soils in cold and humid climates are generally more acidic (Cheng-Jun et al., 2014; Zhang et al., 2019; Brady and Weil, 2002).

This pattern of association between precipitation, temperature, and soil pH can be explained by several mechanisms. Firstly, increased precipitation, along with lower temperatures and consequently reduced evapotranspiration, enhances the leaching of non-acidic cations retained on the exchange sites of humus–clay colloids, such as Ca^{2+}, Mg^{2+}, K^+, and Na^+, which are replaced by acidic cations like H^+ and Al^{3+}, thereby contributing to increased soil acidity (Zhang et al., 2019; Belay et al., 2023). Secondly, as previously mentioned, higher precipitation tends to result in more sandy surface soils due to the eluviation of finer particles (silt and clay) into deeper subsoil horizons. Consequently, sandy soils have a limited reservoir of basic elements. Furthermore, due to the high infiltration and percolation rates in sandy soils, basic cations are more readily leached, favoring further acidification of surface soils (Takala, 2019; Belay et al., 2023). In fact, in the present study, significant negative correlations were found between sand content and pH ($\rho = -0.19$, $p < 0.01$ for both pH_{H2O} and pH_{KCl}; $\rho = -0.18$, $p < 0.05$ for pH_{CaCl2}; Fig. 2), while significant positive correlations were observed between pH and both silt content ($\rho = 0.17$, $p < 0.05$ for pH_{H2O} and pH_{CaCl2}; $\rho = 0.19$, $p < 0.05$ for pH_{KCl}; Fig. 2) and clay content ($\rho = 0.17$, $p < 0.05$ for pH_{H2O}; Fig. 2). A third mechanism contributing to soil acidification under high precipitation regimes is the increased input of H^+ ions derived from carbonic acid (H_2CO_3). This weak acid forms in situ from carbon dioxide (CO_2) produced by root respiration and microbial decomposition of soil organic carbon. In humid environments, CO_2 accumulation within soil pores is enhanced by limited gas diffusion to the atmosphere. This favors its dissolution in soil water and subsequent formation of H_2CO_3, which partially dissociates, releasing H^+ ions at the solid–liquid interface and thereby lowering the soil pH (Cheng-Jun et al., 2014; Zhang et al., 2019; Belay et al., 2023).

Therefore, the observed associations between climatic variables and soil pH suggest that future shifts in temperature and precipitation patterns reported for Europe could potentially influence soil pH dynamics in agricultural soils. These shifts may, in turn, affect soil health and the ecosystem services that soils provide. This issue is particularly relevant for Mediterranean regions, where soils already tend to exhibit relatively high pH values (Table S3). In these areas, reduced precipitation combined with rising temperatures could favor conditions associated with alkalinization, salinization, and sodification processes, which are well-established soil degradation pathways that reduce the biodiversity of soil organisms, such as earthworms and beneficial microbes, that play key roles in maintaining soil health and driving nutrient cycling. Additionally, increased alkalinity can decrease the availability of essential nutrients for plants. As a result, climate-related shifts in soil pH in Mediterranean regions may negatively affect soil fertility and resilience, potentially compromising ecosystem services (Fernández-Ugalde et al., 2022; Arias-Navarro et al., 2024).

In contrast, in temperate-humid and boreal zones, where precipitation is expected to increase (Wood, 2023; Dittus et al., 2023), soils could become more prone to acidification. This trend could have detrimental effects on plant growth and soil microbial communities, as toxic elements such as aluminum, cadmium, and other heavy metals become more bioavailable under acidic conditions. Furthermore, soil acidification can negatively affect soil fertility and agricultural productivity by reducing the availability of key nutrients such as calcium (Ca), phosphorus (P), magnesium (Mg), and potassium (K). Therefore, to counteract this acidification trend and its associated impacts, an increased demand for liming—a common agricultural practice used to neutralize soil acidity—is expected (Wang et al., 2021b; Arias-Navarro et al., 2024).

On the other hand, regarding the effect of the farming system (conventional vs organic) on soil pH, when statistical analyses were performed for each individual zone, significant differences were observed in some regions (Fig. 7). However, the results were inconsistent, thereby precluding the identification of a clear trend in the influence of the farming system on soil pH (Fig. 7). These contrasting findings concerning the effect of the management system (conventional vs organic) on soil pH are also reflected in the existing literature. Several studies have reported a tendency for soil pH to decrease under conventional management in comparison to organic farming, primarily due to the use of ammonium-based fertilizers in conventional systems. In this sense, the nitrification of NH_4^+ results in the release of H^+ ions, thereby leading to soil acidification (Barak et al., 1997; Suja et al., 2017; Kiboi et al., 2020; Rachwał et al., 2021). However, other studies have reported the opposite trend, indicating that organic management may also contribute to soil acidification. This has been attributed to the mineralization of organic matter inputs, which may lead to the formation of NH_4^+. Its subsequent oxidation can likewise result in H^+ production (Condron et al., 2014; Maucieri et al., 2022). These contrasting findings may be explained by the heterogeneity of practices encompassed within organic farming systems, which can vary considerably across regions and farms. Variations in the type, quantity, and frequency of organic amendments, as well as differences in nutrient management strategies, can substantially influence soil pH dynamics and may therefore account for the inconsistencies observed among studies.

Finally, when statistical analyses were conducted considering all soils across all pedoclimatic zones collectively, no significant differences were found in pH_{H2O}, pH_{KCl}, or pH_{CaCl2} between the two farming systems (Fig. 7). This corroborates the initial findings from the RDA analysis (Fig. 1), which indicated a limited overall contribution of farming system to soil pH variability compared with climatic and geographic drivers, and suggests that other site-specific factors, such as climatic conditions and soil type, exert a considerably greater influence on soil pH than the management system (conventional vs organic). These findings agree with those of Diepeningen et al. (2006), who examined the effects of organic and conventional management on chemical and biological parameters in agricultural soils from 27 fields and found no significant differences in soil pH between the two systems.

3.4. Cation exchange capacity (eCEC) and Base Saturation (BS)

The effective cation exchange capacity (eCEC), which quantifies a soil's ability to retain and exchange cations, is considered a key indicator of soil quality. In this regard, eCEC is among the most important soil attributes, as it influences essential properties such as acidity, water and nutrient retention, and the immobilization of contaminants (Taghizadeh-Mehrjardi, 2016; Khaledian et al., 2017; Ballabio et al., 2019).

As shown in Table 2, considering all soils included in this study (n = 188), eCEC values ranged from 4.46 to 41.97 $cmol_c\ kg^{-1}$ (average of 16.77 ± 6.18 $cmol_c\ kg^{-1}$). In addition, statistically significant differences ($p < 0.05$) were observed among the pedoclimatic zones (Fig. 9, Table S4). However, despite these differences, variability in eCEC across pedoclimatic zones was not particularly pronounced. In fact, five pedoclimatic zones (AN, CON, LUS, MN, and MS) exhibited statistically indistinguishable mean eCEC values, making it difficult to establish a clear relationship between eCEC and climatic variables (Fig. 9). These

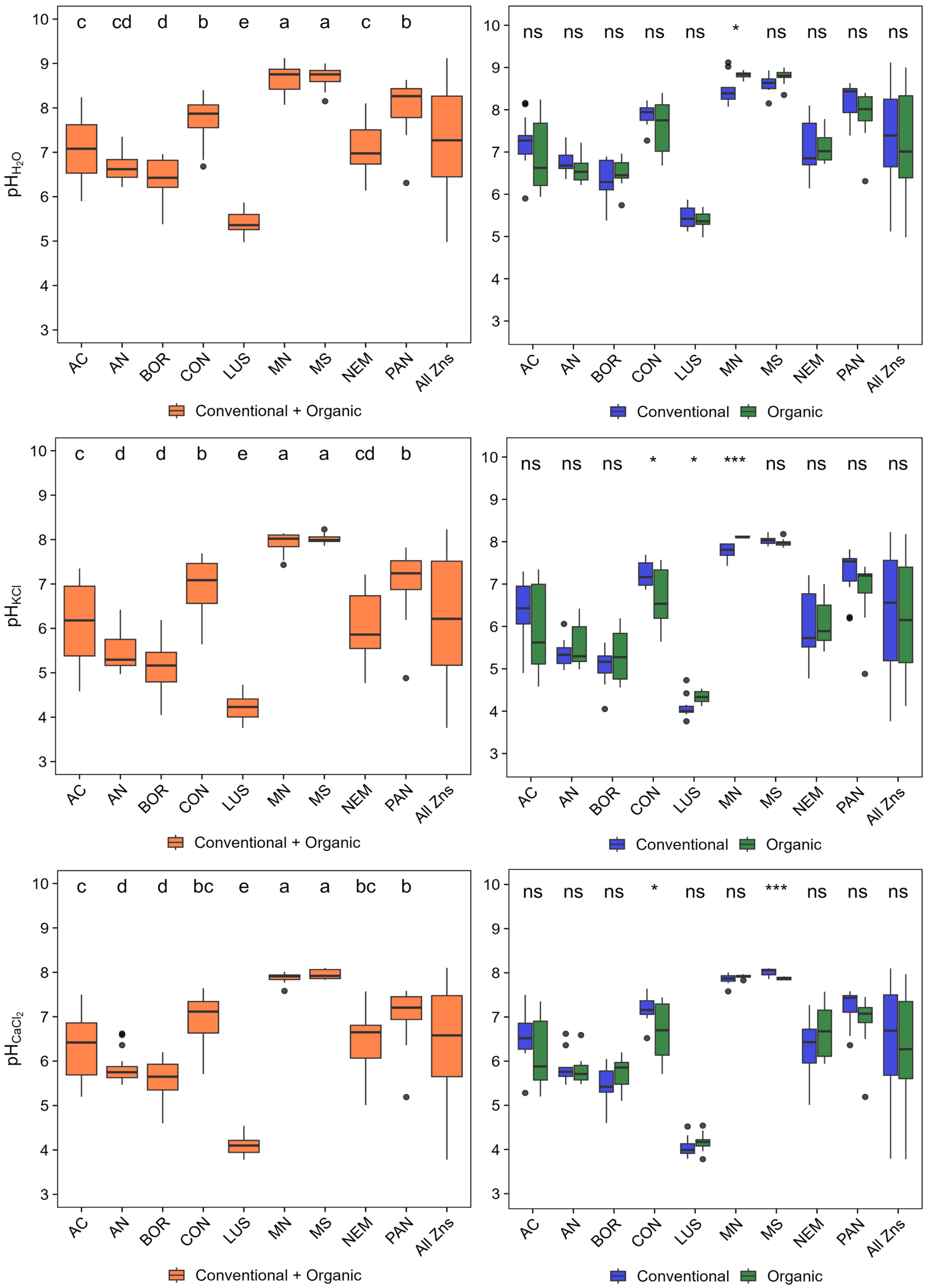

Fig. 7. Soil pH data across different pedoclimatic zones, as well as under conventional and organic farming systems. *pH*$_{H2O}$, pH in water; *pH*$_{KCl}$, pH in 1 M KCl; *pH*$_{CaCl2}$, pH in 0.01 M $CaCl_2$. Different letters indicate statistically significant differences ($p < 0.05$) among pedoclimatic zones, while asterisks indicate significant differences between farming systems (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ****, $p < 0.0001$).

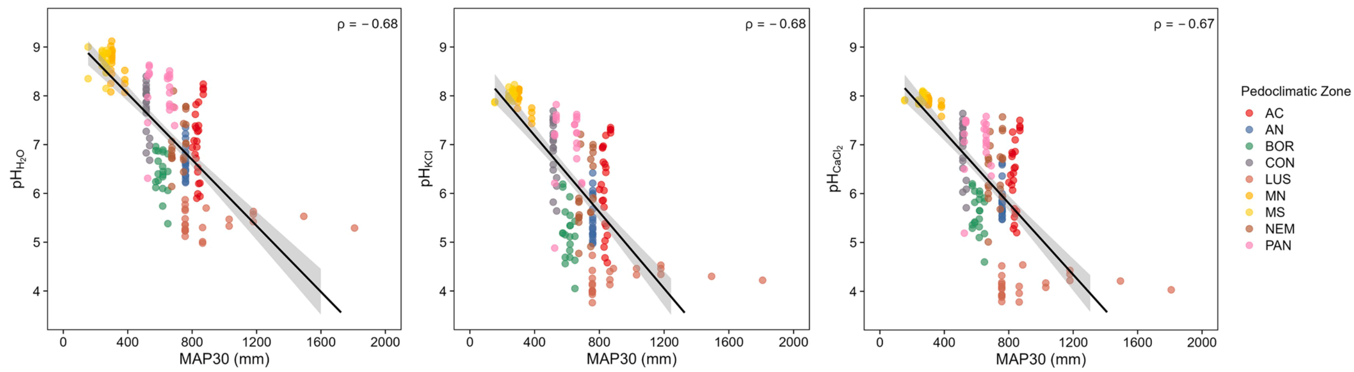

Fig. 8. Spearman correlations between soil pH measured in water (pH_{H2O}), 1 M KCl (pH_{KCl}), and 0.01 M $CaCl_2$ (pH_{CaCl2}), and the mean annual precipitation over the 30 years preceding the sampling campaigns (MAP30).

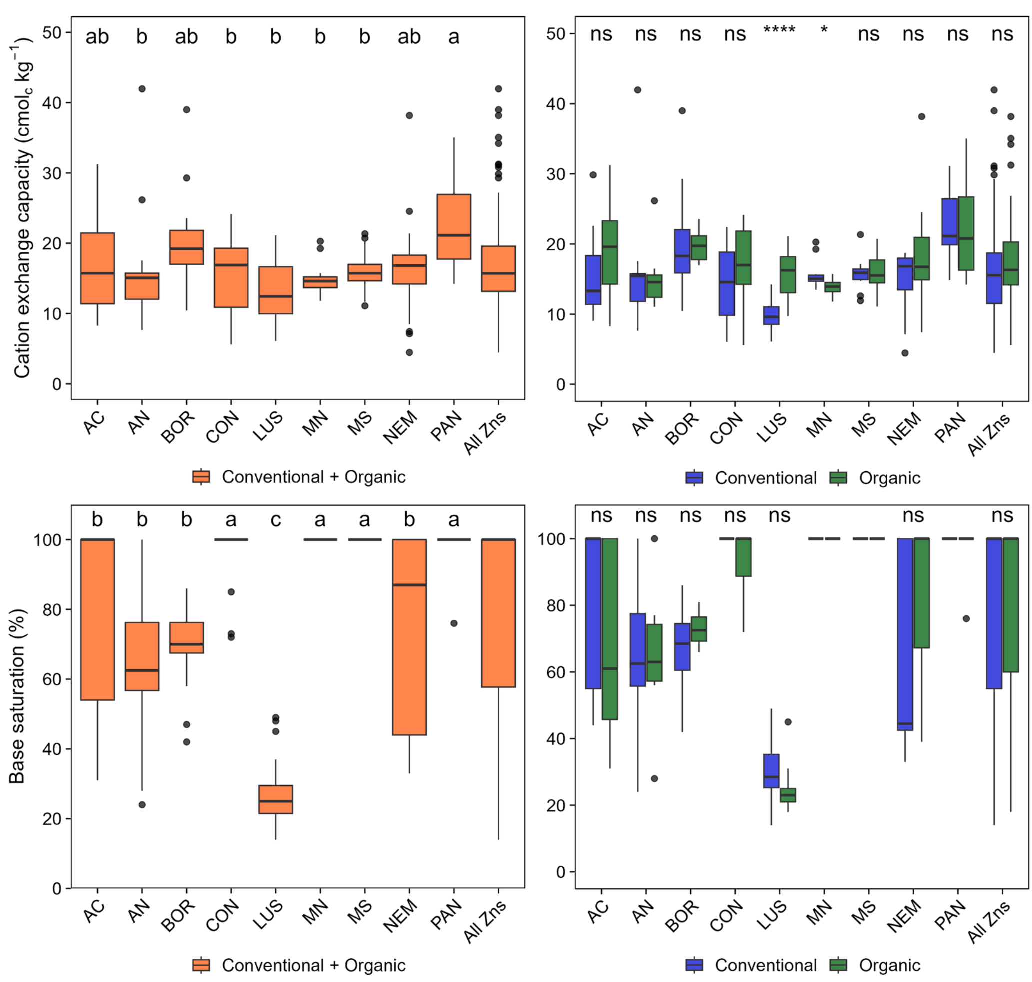

Fig. 9. Cation exchange capacity (cmolc kg-1) and base saturation (%)across different pedoclimatic zones, as well as under conventional and organic farming systems. Different letters indicate statistically significant differences ($p < 0.05$) among pedoclimatic zones, while asterisks indicate significant differences between farming systems (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ****, $p < 0.0001$).

findings are consistent with those obtained from the RDA analysis, which revealed little to no association between eCEC and climate variables such as MAP30 and MAT30 (Fig. 1). Furthermore, Spearman correlation analysis confirmed these observations, showing only weak relationships between eCEC and MAP30 or MAT30 (Fig. 2). In line with this, Ballabio et al. (2019), who analyzed and mapped the eCEC of approximately 20,000 topsoil samples from 24 EU Member States in 2009, along with over 2000 samples from Bulgaria and Romania in 2012 (as part of the Land Use and Cover Area Frame Survey—LUCAS), reported that eCEC is primarily influenced by soil texture, topography, and the geochemistry of the parent material. In this sense, in the present study, eCEC showed significant positive correlations with OM content ($\rho = 0.32$, $p < 0.001$), clay ($\rho = 0.21$, $p < 0.01$), and silt ($\rho = 0.26$, $p < 0.001$), and a significant negative correlation with sand content ($\rho = -0.31$, $p < 0.001$) (Fig. 2). These results are consistent with findings from previous studies (Seybold et al., 2005; Ghorbani et al., 2015; Khaledian et al., 2016; Taghizadeh-Mehrjardi, 2016; Ulusoy et al., 2016). It is well established that eCEC generally increases with higher content of the soil's active colloidal fraction, mainly clay and OM contents, due to their large surface area and abundance of negatively charged sites, which facilitate cation retention (Ulusoy et al., 2016; Solly et al., 2020). Therefore, based on the results obtained, changes in precipitation patterns and increases in temperature associated with climate variability and long-term climate change are not expected to directly control eCEC variability at the continental scale in European agricultural soils. However, climate may indirectly influence eCEC through its effects on soil organic matter dynamics, particularly via temperature-driven changes in decomposition rates. In this context, warming trends may accelerate soil organic matter turnover, thereby potentially reducing eCEC and, consequently, affecting soil fertility and productivity, as well as soil capacity to retain nutrients and buffer contaminants (Wang et al., 2021a; Arias-Navarro et al., 2024).

With respect to agricultural management systems, in the LUS pedoclimatic zone, soils under organic management exhibited significantly higher eCEC values ($p < 0.0001$), ranging from 9.74 to 21.13 $cmol_c\ kg^{-1}$ (average of 15.96 ± 3.47 $cmol_c\ kg^{-1}$), compared to those under conventional management, which ranged from 6.09 to 14.25 $cmol_c\ kg^{-1}$ (average of 9.83 ± 2.23 $cmol_c\ kg^{-1}$). Conversely, in the MN zone, the opposite trend was observed (Fig. 9, Table S4). This can be attributed to the fact that the organic management system in the LUS zone significantly increased soil OM content ($p < 0.0001$), whereas in the MN zone, organic management led to a significant decrease ($p < 0.05$) in OM content (Fig. 10, Table S5). These results reinforce the previously established relationship between eCEC and soil OM and align with findings from other studies that reported higher eCEC values in organically managed soils, primarily due to increased organic matter content (Reganold, 1988; Del Moral et al., 2012). In this sense, OM is rich in functional groups, such as carboxylic acids, capable of binding positively charged multivalent ions (Khadim et al., 2024).

Regarding base saturation, considering all soils analyzed (n = 188), values ranged from 14% to 100%, with an average of 78 ± 28% (Table 2). Statistically significant differences were also observed among the different pedoclimatic zones, with the sequence: $MN^a \approx MS^a \approx PAN^a \approx CON^a > AC^b \approx NEM^b \approx BOR^b \approx AN^b > LUS^c$, indicating a clear gradient associated with climatic conditions, particularly precipitation. In this sense, the Mediterranean zones, which are arid or semi-arid, exhibited the highest base saturation values, while the LUS zone, characterized by a humid climate, showed the lowest (Fig. 9). In fact, a strong negative correlation was found between base saturation and precipitation ($\rho = -0.54$, $p < 0.001$; Fig. 2), confirming this trend. As previously discussed, higher precipitation increases the leaching of basic cations from the soil profile, thereby reducing base saturation. In contrast, arid and semi-arid regions experience minimal leaching, leading to the accumulation of basic cations in the upper soil horizons (Zhang et al., 2019; Belay et al., 2023).

Finally, with regard to agricultural management systems, no significant differences were observed between soils under organic and conventional management, indicating that farming practices had no measurable effect on this particular soil property.

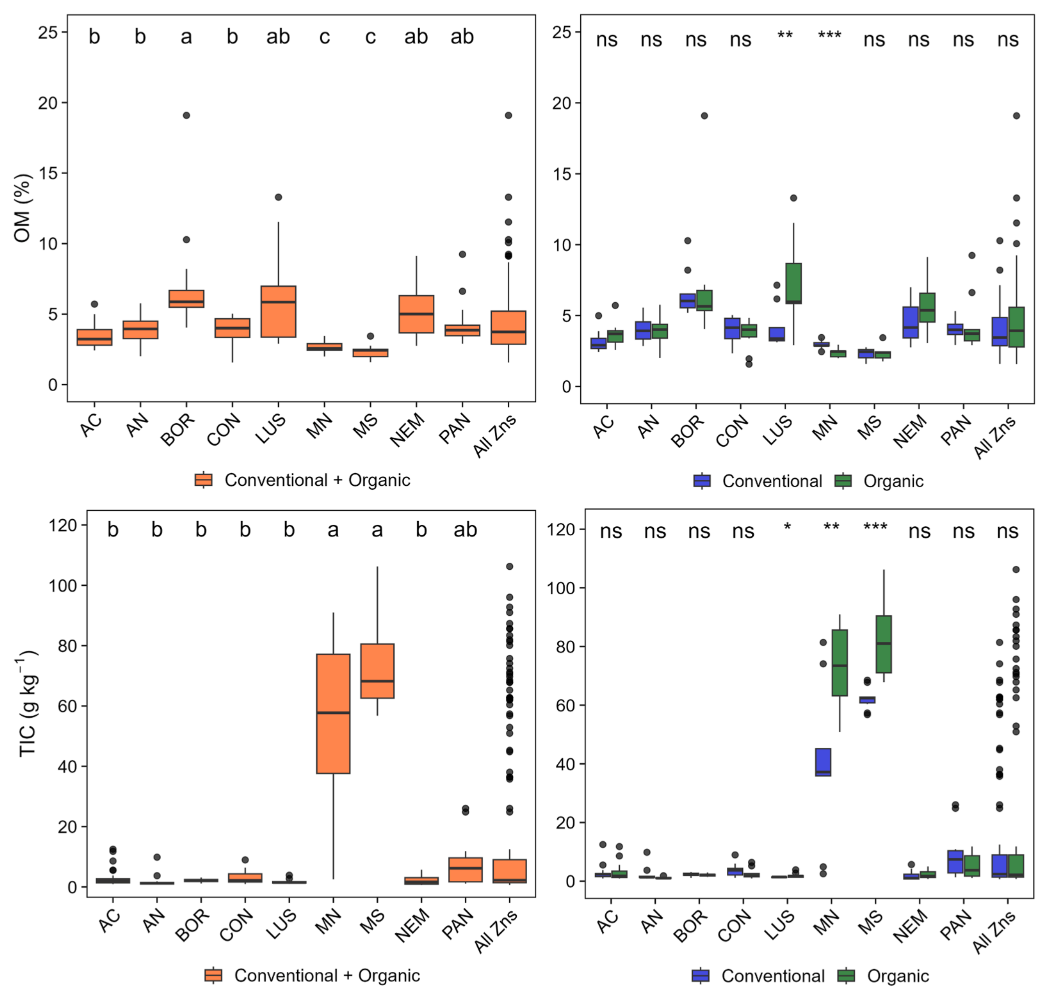

Fig. 10. Soil organic matter (OM, %) and total inorganic carbon (TIC, g kg-1) contents aross different pedoclimatic zones, as well as under conventional and organic farming systems. Different letters indicate statistically significant differences ($p < 0.05$) among pedoclimatic zones, while asterisks indicate significant differences between farming systems (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ****, $p < 0.0001$).

3.5. Organic matter (OM) content and total inorganic carbon (TIC)

Soil organic matter (OM) is essential for soil functionality and for ensuring food production (Ling et al., 2025) and is widely regarded as one of the most important indicators of soil health (Feeney et al., 2024). In this context, soil OM influences the physical, chemical, and biological properties, qualities, and processes of soil, thereby enhancing water retention capacity, nutrient retention and exchange, and ultimately soil fertility and crop growth. It also plays a key role in the retention of pollutants while reducing the risk of compaction and erosion (Panagos et al., 2013; Feeney et al., 2024; Sharma et al., 2024b). Moreover, soil OM strongly influences soil microbial biodiversity and biomass, which are critical regulators of ecosystem functions (Bastida et al., 2021). Importantly, soil OM also acts as a major reservoir of carbon, constituting the largest terrestrial pool of organic carbon. As such, it serves as a crucial sink for carbon released into the atmosphere by human activities (Rodríguez-Lado and Martínez-Cortizas, 2015) and can contribute to the reduction of atmospheric CO_2 levels (Yigini and Panagos, 2016). However, this organic carbon in soil is considered highly vulnerable to climate change, with estimates suggesting that one-third of global soils are rapidly losing organic carbon, and CO_2 fluxes from soils to the atmosphere have increased in recent years. Therefore, it is of vital importance to quantify and map the distribution of soil OM and assess its vulnerability to climate change, as well as to identify adaptive management practices in agriculture that can help mitigate the impacts of climate change (Lugato et al., 2021; Feeney et al., 2024).

In the present study, soil organic matter (OM) content across all analyzed soils (n = 188) ranged from 1.6% to 19.1% (average of 4.3 ± 2.2%) (Table 2), and significant differences ($p < 0.05$) were observed depending on the pedoclimatic zone, following the sequence BOR[a] ≥ LUS[ab] ≈ NEM[ab] ≈ PAN[ab] ≥ AN[b] ≈ CON[b] ≈ AC[b] > MN[c] ≈ MS[c] (Fig. 10, Table S5).

These results indicate that soil OM content in soils is strongly associated with the climatic conditions, consistent with the initial findings of the RDA analysis (Fig. 1). Specifically, OM content was positively and significantly correlated with MAP30 ($\rho = 0.43$, $p < 0.001$) and negatively and significantly correlated with MAT30 ($\rho = -0.53$, $p < 0.001$) (Figs. 2 and 11). Accordingly, cooler and more humid zones exhibited higher OM contents, primarily due to increased biomass production under these conditions (Rial et al., 2017), as well as reduced decomposition rates of organic residues resulting from lower temperatures (Fernández-Ugalde et al., 2022). In contrast, drier and warmer zones showed the lowest OM contents, mainly due to the accelerated decomposition of organic matter driven by elevated temperatures (Yanni et al., 2018; Fernández Calviño et al., 2020).

Fig. 12 presents the results obtained from a Random Forest model conducted to explain soil organic matter (OM) content based on climatic, geographic, edaphic, and soil management variables. As shown, MAP30, MAT30, pH, Rfg, elevation, clay and silt contents, and management emerged as the most important predictors of OM content, collectively explaining 87.2% of its variance. These findings are consistent with previous studies indicating that climate, elevation, soil texture and lithology, and anthropogenic factors such as land use and management are key determinants of topsoil organic matter content (Rodríguez-Lado and Martínez-Cortizas, 2015; Yigini and Panagos, 2016; Rial et al., 2017; Feeney et al., 2024). However, one important and somewhat unexpected observation from our results is the very limited influence of management agricultural system (conventional vs organic) on OM content (Figs. 10 and 12), in agreement with the initial findings from the RDA analysis (Fig. 1). This limited effect may be attributed to the fact that, under conventional agricultural systems, in addition to synthetic fertilizers and pesticides, similar organic amendments and management practices are often employed as in organic systems, for example, the application of manures and slurries, and the incorporation of crop residues.

As shown in Fig. 12, the climatic variables MAP30 and MAT30 exhibited the highest importance in predicting soil organic matter (OM) content, in agreement with previous studies which indicated that climatic conditions are the primary drivers of OM accumulation in European agricultural topsoils (Rodríguez-Lado and Martínez-Cortizas, 2015; Yigini and Panagos, 2016; Rial et al., 2017). Taken together, these results indicate that soil organic matter (OM) is strongly associated with climatic conditions across European wheat-growing regions. In this sense, even small variations in temperature or precipitation patterns may lead to significant changes in the rates of soil OM accumulation, regardless of the underlying lithology or management system (conventional vs organic). In this context, projected warming trends reported in the literature could potentially contribute to declines in soil OM content in European agricultural soils, primarily due to the accelerated decomposition of organic matter (Wiesmeier et al., 2016), thus reinforcing the downward trend observed in recent years. In this sense, Arias-Navarro et al. (2024) reported that agricultural soils across the European Union and the United Kingdom experienced an overall 0.75% decrease in soil organic carbon between 2009 and 2018. Moreover, this loss of soil OM is expected to be more pronounced in Mediterranean regions, where rising temperatures are projected to coincide with decreasing precipitation levels (Lozano-García et al., 2017; Arias-Navarro et al., 2024). These observations highlight the potential importance of adaptive soil management practices aimed at preserving soil organic matter under changing climatic conditions, such as no-tillage practices (Filimonenko et al., 2025; Zhang et al., 2025b), minimal tillage (Zhang et al., 2025a), straw return (Filimonenko et al., 2025; Zhang et al., 2025a, 2025b),

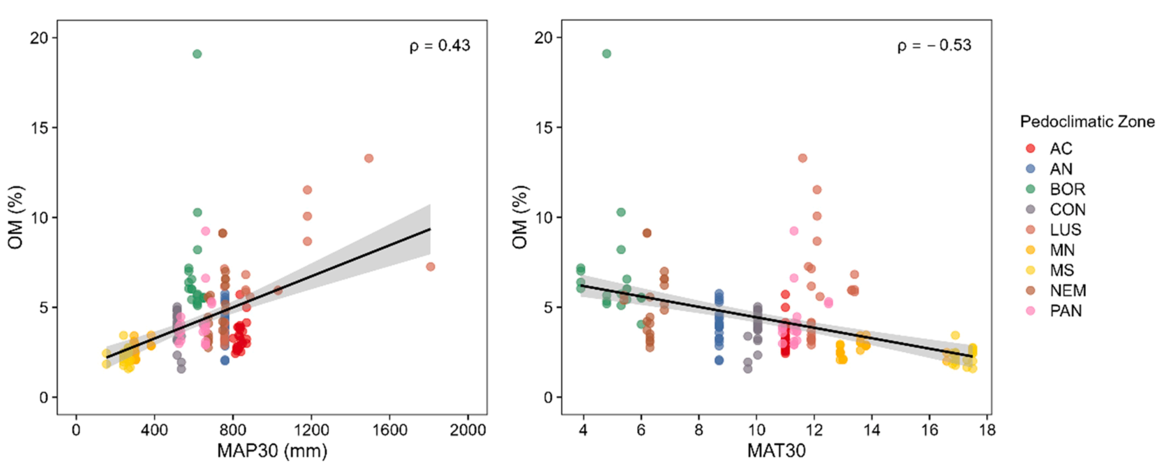

Fig. 11. Spearman correlations between soil organic matter content (OM, %) and the mean annual precipitation (MAP30, mm) and temperature (MAT30, °C) over the 30 years preceding the sampling campaigns.

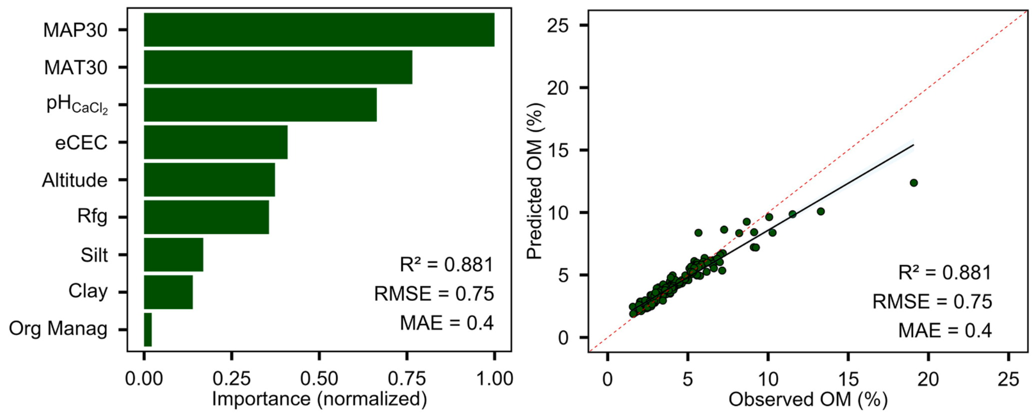

Fig. 12. Relative (normalized) importance of predictor variables in the Random Forest model for explaining soil organic matter (OM) content (Left), and the relationship between observed and predicted values of soil organic matter (Right). The red dashed line represents the 1:1 reference line, while the black line shows the linear fit with its corresponding 95% confidence interval (CI).

subsoiling (Filimonenko et al., 2025), the use of cover crops (Sail et al., 2025), crop rotation (Kumar et al., 2025), application of compost or organic amendments (Acar et al., 2025), and application of biochar (Liu et al., 2025), among others. This is particularly relevant considering that the adoption of organic farming systems did not consistently result in higher soil organic matter contents across all pedoclimatic zones evaluated in this study.

On the other hand, regarding soil inorganic carbon, it is well established that it primarily occurs in the form of carbonate minerals, such as calcium carbonate ($CaCO_3$) and dolomite ($MgCO_3$) (Mi et al., 2008). The loss of soil inorganic carbon can have far-reaching consequences, including declines in soil fertility and productivity, land degradation, biodiversity loss, and reduced carbon sequestration capacity. Thus, soil inorganic carbon is not only a relevant pool for carbon sequestration, but also a key component for maintaining soil health, ecosystem services, and essential soil functions (Ferdush and Paul, 2021; Arias-Navarro et al., 2024; Huang et al., 2024). Despite its importance, relatively few large-scale studies have investigated the spatial distribution of soil inorganic carbon or its response to climatic variables (Ferdush and Paul, 2021; Ebouel et al., 2024), largely because it has traditionally been considered a stable carbon pool with a turnover time spanning millennia (Huang et al., 2024). However, over the past few decades, the dynamics of soil inorganic carbon in agricultural soils have accelerated, primarily due to soil acidification driven by high nitrogen fertilizer inputs and climate change (Song et al., 2022). Therefore, it is crucial to assess soil inorganic carbon content at large spatial scales in agricultural soils (Huang et al., 2024).

Total inorganic carbon (TIC) contents across the full set of soils analyzed (n = 188) ranged from 0.7 to 106.3 g kg^{-1} (average of 16.1 ± 27.3 g kg^{-1}) (Table 2). The highest TIC values were observed in the Mediterranean zones (MN and MS), which are characterized by arid or semi-arid climates. Specifically, TIC values ranged from 56.8 to 106.3 g kg^{-1} (average of 72.2 ± 13.7 g kg^{-1}) in MS, and from 2.5 to 91.0 g kg^{-1} (average of 56.4 ± 26.1 g kg^{-1}) in MN. In contrast, the other pedoclimatic zones (AC, AN, BOR, CON, LUS, NEM, and PAN) exhibited substantially lower TIC values, ranging from 0.7 to 26.0 g kg^{-1} (Table S5), with no significant differences observed among them (Fig. 10). These findings are consistent with previous studies, which also reported that in arid and semi-arid regions, TIC is often the dominant form of soil carbon, with such regions accounting for approximately 80% of global inorganic carbon stocks (Mi et al., 2008; Ebouel et al., 2024). In fact, in the present study, TIC was found to be significantly and negatively correlated with MAP30 ($\rho = -0.60$, $p < 0.001$), and significantly and positively correlated with MAT30 ($\rho = 0.53$, $p < 0.001$) (Fig. 2), indicating that these variables strongly influence the distribution of TIC in agricultural soils. This finding is consistent with the observations of Arias-Navarro et al. (2024), who reported that the most relevant factors contributing to soil inorganic carbon concentration are soil parent material and climate. In this sense, low water availability in these dry regions due to reduced precipitation and high evapotranspiration limits the dissolution and leaching of carbonates (Huang et al., 2024). Conversely, higher precipitation enhances the leaching of base cations, including Ca^{2+} and Mg^{2+}, and leads to soil acidification by lowering pH, thereby facilitating the dissolution of carbonates. In fact, a strong positive correlation between TIC and soil pH was observed in this study ($\rho = 0.74$, $p < 0.001$ for pH_{H2O}; $\rho = 0.75$, $p < 0.001$ for pH_{KCl} and pH_{CaCl2}; Fig. 2), as well as between TIC and base saturation ($\rho = 0.61$, $p < 0.001$), indicating that more alkaline soils with higher base saturation tend to accumulate more TIC, which aligns with findings reported in previous studies (Mi et al., 2008; Ferdush and Paul, 2021; Huang et al., 2024). Regarding the positive effect of temperature on TIC accumulation, this is not only due to enhanced evapotranspiration, but also because higher temperatures reduce the constant solubility of $CaCO_3$, thereby promoting its precipitation (Mi et al., 2008).

Based on these results, in Mediterranean regions, the increase in temperatures associated with global warming, combined with reduced precipitation, could favor the accumulation of total inorganic carbon (TIC) in agricultural soils. However, in other European regions that are more humid and temperate-to-cold, the future trends of soil inorganic carbon under climate change remain less clear. On the one hand, the general rise in temperature may favor TIC accumulation; on the other hand, increased and more intense seasonal precipitation, particularly in boreal regions, could promote TIC losses. Nevertheless, no comprehensive information is currently available regarding trends in soil inorganic carbon concentration or storage in European soils, making future projections highly uncertain (Arias-Navarro et al., 2024).

Regarding the effect of agricultural system (conventional vs organic) on soil TIC content, no significant differences were observed when all soils (n = 188) were analyzed collectively. However, when soils were examined by pedoclimatic zone, significantly higher TIC contents were found under organic management in the LUS, MN, and MS zones (Fig. 10). This may be attributed to increases in soil pH and base cation saturation, primarily due to the application of manures rich in base cations such as Ca^{2+} and Mg^{2+} (Suja et al., 2017). In fact, in this study, significantly higher pH values were observed in organically managed soils compared to conventionally managed soils in the MN and LUS zones (Fig. 7), further supporting this hypothesis. Another possible explanation is that organic management systems typically contribute more organic matter to the soil, leading to increased microbial activity and, consequently, higher CO_2 production through microbial respiration. This CO_2, in the presence of sufficient base cations and appropriate pH levels, may enhance carbonate precipitation (Mdlambuzi et al., 2021).

4. Conclusions

This study provides a large-scale assessment of the physicochemical properties of European wheat soils across nine pedoclimatic zones, integrating climatic, geographic, and management factors. Soil variability was primarily linked to climate-related variables, with mean annual temperature and precipitation showing consistent relationships with bulk density, pH, base saturation, organic matter, and total inorganic carbon.

Quantitative relationships indicated that higher temperatures were associated with lower organic matter content ($\rho = -0.53$) and higher bulk density ($\rho = 0.30$), while precipitation strongly influenced soil pH ($\rho = -0.68$), base saturation ($\rho = -0.54$), and organic matter accumulation ($\rho = 0.43$). These spatial patterns highlight the sensitivity of soil properties to climatic variability across European agricultural systems.

Farming system effects were statistically significant but generally limited and spatially variable, indicating that the overall management system (conventional vs organic) can locally modulate specific soil properties, although with lower explanatory power than climate at the continental scale. Nevertheless, differences observed in organic matter and inorganic carbon suggest that management practices contribute to soil property regulation under certain pedoclimatic conditions.

Overall, these findings provide empirical evidence of climate–soil associations relevant to understanding the behaviour of agricultural soils under ongoing climate change. Rather than predicting specific future outcomes, the results suggest that shifts in temperature and precipitation regimes may influence key soil functions, particularly in climatically sensitive regions. This reinforces the need for region-specific soil management strategies that enhance resilience, maintain productivity, and sustain ecosystem services under changing climatic conditions.

Finally, it is important to acknowledge the limitations of this study. Soil sampling was conducted once, after harvest, which may not fully capture seasonal variability in soil physicochemical properties. The analysis is based on spatial relationships across pedoclimatic gradients; therefore, interpretations regarding climate change impacts should be made with caution, as no direct temporal or causal inference can be drawn. In addition, farming systems were broadly classified as conventional and organic, without detailed information on specific management practices (e.g., fertilization, tillage, crop rotation), which may have introduced variability within categories. Limited long-term management histories may also have influenced the observed soil properties. Furthermore, key factors such as soil type/parent material and detailed land-use history were not consistently available across all sites and therefore could not be explicitly included in the analysis, which may also contribute to unexplained variability in soil properties.

CRediT authorship contribution statement

Andrés Rodríguez-Seijo: Investigation, Formal analysis, Data curation. **Antía Gómez-Armesto:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Paula Pérez-Rodríguez:** Writing – review & editing, Visualization, Validation, Supervision. **Manuel Conde-Cid:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Vanesa Santás-Miguel:** Writing – review & editing, Supervision, Data curation. **Flora Alonso-Vega:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Juan Carlos Nóvoa-Muñoz:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Diego Soto-Gómez:** Software, Methodology, Investigation. **María J.I. Briones:** Writing – review & editing, Supervision. **Irene Ollio:** Methodology, Investigation, Data curation. **Eva Lloret:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Silvia Martínez-Martínez:** Writing – review & editing, Visualization, Software, Investigation. **Raúl Zornoza:** Writing – review & editing, Supervision, Conceptualization. **Jasper Vanbesien:** Writing – review & editing, Visualization, Investigation. **Noémie Hisette:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Maarten De Boever:** Supervision, Software, Investigation, Formal analysis. **Lieven Waeyenberge:** Writing – review & editing, Visualization, Validation. **Stefan Schrader:** Writing – review & editing, Visualization, Validation, Supervision. **Jozsef Dezso:** Writing – review & editing, Visualization, Validation, Supervision. **Nikola Grujić:** Writing – review & editing, Validation, Supervision, Conceptualization. **Barbara Simon:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Igor Dekemati:** Writing – review & editing, Software, Methodology, Investigation. **Simon Bo Lassen:** Supervision, Formal analysis, Conceptualization. **Kristian Koefoed Brandt:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Merit Sutri:** Methodology, Investigation, Formal analysis. **Marian Põldmets:** Writing – review & editing, Visualization, Validation, Supervision. **Merrit Shanskiy:** Supervision, Investigation, Conceptualization. **Juha-Matti Pitkänen:** Validation, Supervision, Investigation, Conceptualization. **Krista Peltoniemi:** Visualization, Validation, Conceptualization. **David Fernández-Calviño:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Ethical Approval, Consent to Participate and consent to publish

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2026.128317.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article and supporting information as a reusable data file that can be found at Zenodo https://zenodo.org/record/7682445 (Fernández-Calviño et al., 2023).

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