agronomy

IMPACT FACTOR 3.4

CITESCORE 6.7

Article

Continental Patterns of Electrical Conductivity and Soil Aggregates in European Wheat Agroecosystems

Manuel Conde-Cid, Andrés Rodríguez-Seijo, Antía Gómez-Armesto, José Ángel Cid-Fernández, Paula Pérez-Rodríguez, Daniel Arenas-Lago, Manuel Arias-Estévez, Irene Ollio, Eva Lloret, Silvia Martínez-Martínez et al.

Special Issue

Soil Health and Properties in a Changing Environment—2nd Edition

Edited by

Dr. Eugenija Bakšienė, Prof. Dr. José De la Rosa and Dr. Vaida Steponavičienė

MDPI

https://doi.org/10.3390/agronomy16050561

agronomy

Article

Continental Patterns of Electrical Conductivity and Soil Aggregates in European Wheat Agroecosystems

Manuel Conde-Cid [1,2,3,*], Andrés Rodríguez-Seijo [1,2], Antía Gómez-Armesto [1,2,3], José Ángel Cid-Fernández [4], Paula Pérez-Rodríguez [1,2], Daniel Arenas-Lago [1,2], Manuel Arias-Estévez [1,2], Irene Ollio [5,6], Eva Lloret [5,6], Silvia Martínez-Martínez [5], Raúl Zornoza [5,6], Lieven Waeyenberge [7], Stefan Schrader [8], Kristian Koefoed Brandt [9], Merrit Shanskiy [10], Krista Peltoniemi [11] and David Fernández-Calviño [1,2]

[1] Section for Soil Science and Agricultural Chemistry, Department of Plant Biology and Soil Science, Faculty of Sciences, University of Vigo, As Lagoas s/n, 32004 Ourense, Spain; andresrodriguezseijo@uvigo.gal (A.R.-S.); angomez@uvigo.gal (A.G.-A.); paulaperezr@uvigo.gal (P.P.-R.); darenas@uvigo.gal (D.A.-L.); mastevez@uvigo.es (M.A.-E.); davidfc@uvigo.gal (D.F.-C.)
[2] Institute of Agroecology and Food (IAA), University of Vigo, Campus Auga, 32004 Ourense, Spain
[3] REQUIMTE/LAQV, Instituto Superior de Engenharia do Instituto Politécnico do Porto, Rua Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal
[4] Department of Marine Geo-Science and Territory Rationalization, Faculty of Sciences, University of Vigo, 32004 Ourense, Spain; jcid@uvigo.es
[5] Department of Agricultural Engineering, Polytechnic University of Cartagena, Paseo Alfonso XIII 48, 30203 Cartagena, Spain; irene.ollio@upct.es (I.O.); eva.lloret@upct.es (E.L.); silvia.martinez@upct.es (S.M.-M.); raul.zornonza@upct.es (R.Z.)
[6] Institute of Plant Biotechnology (IBV), Campus Muralla del Mar, Edificio I+D+I, Polytechnic University of Cartagena, 30202 Cartagena, Spain
[7] Plant Sciences Unit, ILVO (Flanders Research Institute for Agriculture, Fisheries and Food), 9820 Merelbeke-Melle, Belgium; lieven.waeyenberge@ilvo.vlaanderen.be
[8] Thünen Institute of Biodiversity, Bundesallee 65, D-38116 Braunschweig, Germany; stefan.schrader@thuenen.de
[9] Section for Microbial Ecology and Biotechnology, Department of Plant and Environmental Sciences, University of Copenhagen, Thorvaldsensvej 40, DK-1871 Frederiksberg, Denmark; kkb@plen.ku.dk
[10] Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, 5 Fr. R. Kreutzwaldi St., 51006 Tartu, Estonia; merrit.shanskiy@emu.ee
[11] Natural Resources Institute Finland (Luke), Natural Resources, Soil Ecosystems, Latokartanonkaari 9, FI-00790 Helsinki, Finland; krista.peltoniemi@luke.fi
* Correspondence: manconde@uvigo.es

Abstract

Soil electrical conductivity (EC) and aggregate-size distribution are critical indicators of soil salinity risk, structural integrity, and overall soil health. We assessed the status of these properties in 188 wheat plots across nine European pedoclimatic zones to quantify the influence of climate and agricultural management. Most soils (~88%) were non-saline, 9% slightly saline, and 3% moderately saline, with the highest salinity in Mediterranean regions. EC was generally lower under organic management, reflecting higher soil organic carbon, improved porosity, and enhanced cation retention. Soils were dominated by small macroaggregates (250–2000 μm) and large microaggregates (53–250 μm), together accounting for an average of 73% of total aggregates. Climate was the primary determinant of both EC and aggregate distribution, with drier and warmer conditions promoting salinization and smaller aggregate sizes, whereas wetter conditions favored macroaggregate formation. Agricultural management had a secondary but context-dependent effect, particularly on soil aggregation, with organic farming, integrated organomineral fertilization, crop residue incorporation, and legume rotations enhancing macroaggregate formation, especially in low-SOC soils. These results indicate that pedoclimatic conditions largely shape soil salinity and structure, but adopting targeted, site-specific management practices can sustain soil

Academic Editor: Tomasz Głąb

Received: 30 January 2026
Revised: 26 February 2026
Accepted: 28 February 2026
Published: 3 March 2026

 https://doi.org/10.3390/agronomy16050561

health and mitigate risks related to salinity and structure, particularly under projected climate change.

Keywords: soil salinity; soil structure; organic farming; conventional farming; agricultural management practices; climate change; pedoclimatic zones; fertilization; aggregate mean weight diameter (AMWD); wheat agroecosystems

1. Introduction

Agricultural soils are crucial for sustaining food production in the face of a growing global population. Maintaining soil health is therefore essential for long-term food security and the sustainability of agri-food systems [1]. Healthy soils must provide adequate nutrient availability, a stable structure, high biological activity, sufficient water-holding capacity, and resilience to environmental stresses. Together, these attributes not only support plant growth but also underpin vital ecosystem services, including biogeochemical cycling, biodiversity conservation, water regulation, and climate regulation through carbon sequestration [1,2].

Despite their importance, soils are increasingly threatened by the expansion and intensification of agriculture, which accelerates degradation and compromises long-term soil functionality [1,3,4]. Indeed, in the European Union, 60–70% of soils are currently considered unhealthy due to multiple, often interacting degradation processes [5], many of which are exacerbated by climate change, now recognized as a major driver of soil degradation [6]. Rising temperatures accelerate organic matter decomposition, leading to carbon losses and declining fertility, while thermal extremes disrupt soil structure and increase risks of compaction and erosion. At the same time, altered precipitation patterns intensify nutrient leaching, acidification, erosion, and salinization, particularly during droughts or heavy rainfall events [1,7–9]. Collectively, these pressures undermine soil health, ecosystem functioning, and agricultural productivity [10–12].

Among soil degradation processes, salinization is particularly concerning. Together with aridity, vegetation loss, soil erosion, and organic carbon depletion, salinization is a major global threat to agricultural land [13], affecting ~20% of cultivated soils and causing yield reductions of roughly 20% [14]. Although severe salinization affects a smaller proportion of European arable land compared to arid regions elsewhere, it is increasingly recognized as a latent and spatially heterogeneous risk, particularly in Mediterranean climates and in areas experiencing irrigation pressure or climate-driven aridification [1,14]. Its recent expansion has been driven both by climate change, which alters the hydrological cycle and exacerbates salt accumulation, and by intensive agricultural practices such as excessive fertilization, irrigation with poor-quality water, and soil structural degradation leading to poor drainage [15–20]. Importantly, salinity not only affects nutrient availability but can also compromise soil structure, as high salt concentrations destabilize aggregates and reduce soil aggregation [1,20]. To monitor this process, soil electrical conductivity (EC) is widely used as a reliable and rapid proxy, as it reflects soluble salt concentrations in the soil solution and thus allows an efficient assessment of salinity levels in agricultural soils [17,20,21].

In addition to salinity, soil structural degradation poses a major threat to agricultural functionality, compromising water retention, root growth, and overall soil performance. Aggregate-size distribution is a central component of soil structure, governing porosity, water infiltration, aeration, root penetration, and resistance to erosion. Aggregates also protect organic carbon, thereby linking soil structure to carbon sequestration and climate regulation [22,23]. Their hierarchical organization, from small microaggregates (<53 μm) and large microaggregates (53–250 μm) to small macroaggregates (250–2000 μm) and large macroaggregates (>2000 μm), reflects the balance between formation and breakdown processes occurring over multiple temporal scales. Large macroaggregates are transient and associated with recent organic inputs, such as crop residues and roots, acting as binding agents through microbial and fungal activity, whereas microaggregates are stabilized by more persistent organo-mineral associations and contribute to long-term carbon stabilization [24–27]. Macroaggregates improve porosity, facilitate water infiltration, aeration, and root growth, and buffer against erosion, while microaggregates ensure long-term stability and physically protect organic matter. The functional significance of aggregates depends not only on their size but also on their turnover and the mechanisms governing their formation, which are influenced by environmental factors such as moisture, temperature, and organic matter availability [23,28].

Given the substantial effects of salinization and structural degradation on soil health, the adoption of targeted agricultural management practices could help mitigate these threats and support soil functionality under changing climatic conditions. Organic farming systems, for example, enhance soil organic carbon, improve porosity, and increase effective cation exchange capacity (eCEC), collectively reducing EC and salinization risks [29–32]. Similarly, integrated organomineral fertilization, crop residue management, and legume-based rotations are thought to influence soil aggregation through their effects on organic matter inputs and microbial and fungal activity, key drivers of aggregate formation and stabilization, potentially enhancing the development and persistence of macroaggregates under favorable management and environmental conditions [33,34]. However, most evidence comes from field-scale studies, whereas continental-scale assessments remain extremely scarce, leaving critical gaps in understanding how climate, management practices, and soil properties interact across broad geographic gradients.

Wheat (*Triticum aestivum* L.) is a staple crop for ~35% of the global population, providing roughly one-fifth of worldwide food calories [35]. Beyond human nutrition, wheat is a key component of livestock feed, supplying energy and protein to ruminants, particularly dairy cattle, and supporting animal productivity [36]. In Europe, wheat is among the most important cereal crops by area and production volume. In 2024, the European Union harvested ~111.6 million tonnes, representing 43% of EU cereal production and ~15% of global wheat output [37,38]. Wheat cultivation spanned ~61.6 million hectares across Europe over the past decade (2014–2023), equivalent to 28.3% of the global wheat area [39], highlighting its strategic role in food security, agri-food systems, and rural economies.

Wheat agroecosystems are particularly suitable for evaluating soil-climate-management interactions, as they are cultivated across diverse European pedoclimatic zones, from Mediterranean to Boreal regions. This wide distribution, combined with the use of conventional and organic farming systems, provides an ideal setting to assess how climate and management shape soil salinity and aggregate-size distribution at continental scales [40,41].

Considering these aspects, the present study aimed to: (i) assess the current status of soil electrical conductivity and aggregate-size distribution in 188 wheat-growing agricultural soils across nine European pedoclimatic zones; (ii) examine the influence of climate and farming system (conventional versus organic) on these soil properties; and (iii) evaluate the effects of specific management practices, including crop rotation versus monoculture, crop residue incorporation, legume inclusion, tillage system, and fertilization strategy, on soil EC and aggregate-size distribution. We hypothesized that organic systems, together with practices that enhance carbon inputs and biological activity, would lead to lower EC and a higher proportion of macroaggregates, thereby mitigating soil degradation under both climatic and anthropogenic pressures.

2. Materials and Methods

2.1. Study Area, Soil Sampling, and Data Collection

As part of the European project SoildiverAgro (https://soildiveragro.eu/), a total of 188 agricultural fields cultivated with wheat were sampled across nine European pedoclimatic zones: Atlantic Central (AC, Belgium, n = 25), Atlantic North (AN, Denmark, n = 20), Boreal (BOR, Finland, n = 20), Continental (CON, Germany, n = 20), Lusitanian (LUS, northwestern Spain, n = 23), Mediterranean North (MN, eastern Spain, n = 20), Mediterranean South (MS, southeastern Spain, n = 20), Nemoral (NEM, Estonia, n = 20), and Pannonian (PAN, Serbia and Hungary, n = 20) (Figure S1, Table S1).

Within each pedoclimatic zone, fields were selected to represent the two dominant farming systems, conventional and organic. At least 10 fields under each system were included per zone, resulting in a total of 93 conventionally managed and 95 organically managed fields (Table S1). All selected fields had been managed under their respective system for a minimum of five consecutive years; fields under organic management for less than five years were included only when access to suitable long-term organic farmland was not possible.

To minimize confounding effects associated with climatic conditions and soil parent material, field selection within each zone followed a paired-site design whenever feasible. Specifically, conventionally and organically managed fields were selected as adjacent or closely located plots, maximizing environmental homogeneity and enabling robust comparisons between farming systems [42]. All organically managed fields complied with current European Union regulations for organic farming, which prohibit the use of synthetic fertilizers and pesticides [43].

Soil sampling was conducted immediately after wheat harvest and prior to any subsequent agricultural operations. Depending on the pedoclimatic zone, sampling occurred between July and October 2019. In each field, multiple soil subsamples were collected from the 0–25 cm soil layer using an Edelman auger (Eijkelkamp, Giesbeek, The Nederland), following a zigzag sampling pattern across approximately 1 ha. These subsamples were combined to form a composite sample of ~2–3 kg per field. During sampling, visible extraneous materials such as stones and coarse roots were manually removed.

Upon arrival at the laboratory, soil samples were homogenized and air-dried at room temperature. A subsample of each soil was sieved to <2 mm for electrical conductivity determination, while the remaining fraction was kept unsieved for aggregate-size distribution analyses. A detailed description of the field sampling protocol is provided in Fernández-Calviño et al. [42].

In parallel with soil sampling, field-specific metadata were collected in collaboration with land managers. For each field, a standardized soil information sheet was completed, compiling data on geographical location and management history. Management information reflected field-level practices implemented during the five years preceding soil sampling, including crop rotation schemes, tillage practices, and fertilization types, and was obtained through a structured survey administered to land managers [42].

All raw data corresponding to soil physicochemical properties, farming systems, and management practices are publicly available through Zenodo [44]. In addition, Tables S2–S4 provide a detailed overview of the main soil physicochemical properties across pedoclimatic zones and agricultural management systems. Overall, soil pH and total organic carbon (TOC) exhibited substantial variability among zones, with pH values ranging from 5.0 to 9.1 and TOC concentrations ranging from 4.6 to 103.3 g kg^{-1} (Table S2). Within this framework, soils from the LUS zone were the most acidic (mean pH of 5.4), whereas soils from the MN and MS zones were the most alkaline, with means of 8.6 and 8.7, respectively. In parallel, TOC content was highest in BOR and LUS soils, with mean values of 32.1 and

25.8 g kg^{-1}, respectively, while the lowest TOC contents were observed in MN and MS soils (mean values of 10.8 and 8.9 g kg^{-1}, respectively). Available phosphorus (P_{av}) also showed pronounced variability across sites, ranging from 4.4 to 262.9 mg kg^{-1}; in this case, LUS soils displayed the highest mean P_{av} content (127.27 mg kg^{-1}), whereas MS soils exhibited the lowest values (16.8 mg kg^{-1}) (Table S2). Regarding the soil exchange complex, cation exchange capacity (CEC) varied between 4.5 and 42 cmolc kg^{-1} across all soils, with the lowest mean values recorded in LUS soils (13.3 cmolc kg^{-1}) and the highest in soils from the PAN zone (mean of 22.7 cmolc kg^{-1}) (Table S3). Finally, regarding soil particle-size distribution, soils from the AN zone exhibited the highest sand contents (mean of 64%), whereas soils from the CON zone showed the lowest sand proportions (mean of 33%); by contrast, clay contents were relatively similar and displayed limited variability across all soils, ranging from 4% to 27%, with an overall mean of 15% (Table S4). Consistent with these patterns, soil textural classes were largely homogeneous across sites, with most soils classified as loam, silt loam, or sandy loam, and only a small number of soils corresponding to the sandy clay loam class (Figure S2), thereby supporting the comparability of sites across pedoclimatic zones.

2.2. Electrical Conductivity and Soil Aggregate Determination

2.2.1. Electrical Conductivity

Soil electrical conductivity (EC) was measured on a 1:5 soil-to-water suspension, following the procedure described by Fernández-Calviño et al. [42]. Briefly, 2 g of air-dried soil sieved to <2 mm were weighed into a 25 mL beaker, and 10 mL of distilled water were added. The suspension was stirred continuously for 1 h to ensure thorough mixing. Prior to measurement, the conductivity meter (XS COND 8 PRO, XS Instruments, Giorgio Bormac S.r.l., Carpi, Italy) was calibrated with a 0.01 M KCl solution (1413 µS cm^{-1}). EC was then measured by immersing the electrode directly into the suspension.

2.2.2. Soil Aggregate-Size Distribution

Soil aggregate-size distribution was determined using the wet-sieving method described by Fernández-Calviño et al. [42]. An 80 g subsample of air-dried soil was weighed and evenly placed on a 2000 µm sieve submerged in deionized water, with the water level maintained ~1 cm above the sieve mesh. The sample was pre-wetted for 5 min to allow gradual slaking and minimize aggregate disruption.

The sieve was then oscillated vertically for 2 min (50 oscillations, ~3 cm amplitude) with a slight inclination to facilitate particle passage. After a 30 s settling period, floating plant residues were removed by aspiration, and the sieve was rinsed to ensure complete particle recovery. Aggregates retained on the 2000 µm sieve (>2000 µm, large macroaggregates) were backwashed into pre-weighed drying pans and oven-dried at 60 °C overnight.

The suspension passing through the 2000 µm sieve was sequentially wet-sieved through 250 and 53 µm sieves under identical conditions. Aggregates retained between 250 and 2000 µm (small macroaggregates) were oven-dried at 60 °C overnight, while aggregates retained between 53 and 250 µm (large microaggregates) were oven-dried at 105 °C overnight. Particles <53 µm (small microaggregates) were collected in pre-weighed pans and oven-dried at 105 °C overnight.

After drying, all aggregate fractions were weighed, and their masses were used to calculate the aggregate-size distribution. In addition, the aggregate mean weight diameter (AMWD) was determined following Nimmo and Perkins [45] as:

$$AMWD = \sum_{i=1}^{n} W_i \, x \, \overline{X}_i$$

where $\overline{X}_i$ is the mean diameter of the aggregates retained on the *i*-th sieve (mm), W_i is the ratio of the weight of aggregates retained on the *i*-th sieve to the total sample weight, and n is the total number of sieves used.

AMWD provides a single quantitative measure of soil aggregate size distribution, reflecting the contribution of each aggregate fraction. Higher AMWD values indicate a greater proportion of macroaggregates and generally higher soil structural stability.

2.3. Statistical Analysis

Significant differences in electrical conductivity (EC), aggregate size fractions, and aggregate mean weight diameter (AMWD) were assessed using analysis of variance (ANOVA). Differences among pedoclimatic zones were first evaluated using one-way ANOVA, and pairwise comparisons were performed using Tukey's Honest Significant Difference (HSD) post hoc test. To evaluate whether the response of these soil properties to the farming system depended on the pedoclimatic context, a two-way ANOVA including pedoclimatic zone, farming system (conventional versus organic), and their interaction was performed. When a significant pedoclimatic zone x farming system interaction was detected, differences between farming systems within each pedoclimatic zone were explored using pairwise comparisons based on estimated marginal means (emmeans). In accordance with the presence of significant interactions, the main effects of the farming system were not interpreted. In all analyses, statistical significance was evaluated at $\alpha = 0.05$.

Spearman correlation analysis was performed to explore relationships among EC, aggregate fractions, and AMWD with climatic variables (mean annual precipitation [MAP30] and mean annual temperature [MAT30] over the 30 years preceding sampling), farming system, and specific management practices. These practices included legume incorporation into rotations, crop rotation versus monoculture, crop residue incorporation, tillage intensity (conventional vs. reduced), and fertilization type (none, mineral, organic, or organomineral). Additionally, the relationships between EC and climatic variables (MAT30 and MAP30) were further visualized by fitting simple regression models: a linear regression for EC-MAT30 and a nonlinear (exponential decay) regression for EC-MAP30.

To identify the main climatic and management drivers of soil EC and AMWD, Random Forest models were applied. Prior to model fitting, highly collinear predictors (Pearson's correlation coefficient $r > 0.7$) were excluded. The models were trained using the randomForest package in R, with default parameters and variable importance estimation enabled. Model performance was evaluated using the coefficient of determination (R^2), root mean square error (*RMSE*), and mean absolute error (*MAE*), calculated by comparing observed and predicted values. Variable importance was assessed based on the increase in mean squared error (%*IncMSE*) and normalized to allow comparison among predictors. This approach enabled ranking the relative contributions of climatic and management variables to EC and AMWD variability across the studied European wheat agroecosystems.

All statistical analyses, as well as the generation of figures, were performed in R version 4.5.2 [46].

3. Results

3.1. Electrical Conductivity

Figure 1 shows the electrical conductivity (EC) values of all soils studied here as a function of the nine European pedoclimatic zones and the farming system (conventional vs. organic). Table S5 summarizes the descriptive statistics—including minimum, maximum, mean, and standard deviation—by pedoclimatic zone and farming system, while Table S6 provides the descriptive statistics according to agricultural management practices (e.g., monoculture versus crop rotation, legume inclusion in the rotation, and reduced versus conventional tillage, among others).

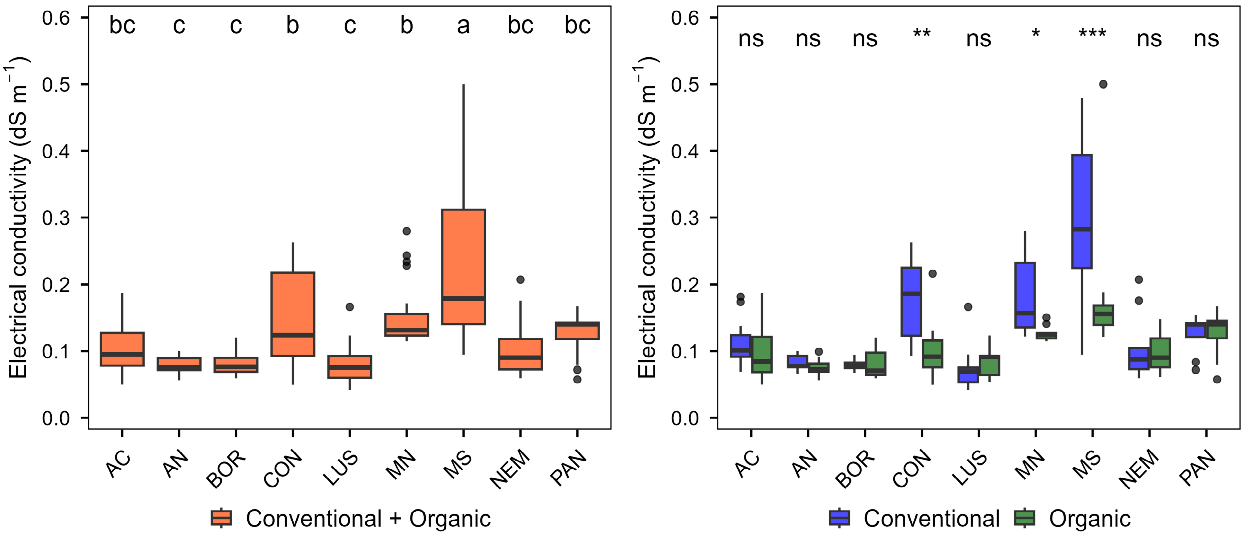

Figure 1. Electrical conductivity (EC) of soils across pedoclimatic zones and farming systems. The left panel shows EC distributions by pedoclimatic zone considering both farming systems together, while the right panel shows EC distributions by farming system (conventional vs. organic) within each pedoclimatic zone. *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *CON*, Continental; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian. Different letters indicate statistically significant differences among pedoclimatic zones based on Tukey's HSD post hoc test following the one-way ANOVA for zone ($p < 0.05$). Asterisks indicate significant differences between farming systems within each zone based on pairwise comparisons derived from the two-way ANOVA (zone × system): *ns*, not significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. Full statistical results, including ANOVA tables and post hoc comparisons, are provided in the Supplementary Material (Tables S7–S10).

Considering soils from all pedoclimatic zones collectively (n = 188), EC values ranged from 0.04 to 0.50 dS m^{-1}, with an average of 0.12 ± 0.08 dS m^{-1} (CV = 67%) (Table S5). EC exhibited high variability across pedoclimatic zones, with statistically significant differences among them ($p < 0.05$). In this sense, the following sequence was observed: MS > MN ≈ CON ≥ PAN ≈ AC ≈ NEM ≥ AN ≈ BOR ≈ LUS (Figure 1, Tables S7 and S8). As expected, the Mediterranean zones, which are characterized by warmer and drier climatic conditions, showed the highest EC levels, ranging from 0.09 to 0.50 dS m^{-1} (average of 0.24 ± 0.13 dS m^{-1}) in MS and from 0.11 to 0.28 dS m^{-1} (average of 0.15 ± 0.05 dS m^{-1}) in MN. In contrast, the BOR and LUS zones, characterized by cool or temperate and humid climates, exhibited the lowest EC values, ranging from 0.06 to 0.12 dS m^{-1} (average of 0.08 ± 0.02 dS m^{-1}) in BOR and from 0.04 to 0.17 dS m^{-1} (average of 0.08 ± 0.03 dS m^{-1}) in LUS (Table S5). In fact, EC was positively and significantly correlated with MAT30 (ρ = 0.443, $p < 0.01$; Figure 2) and negatively and significantly correlated with MAP30 (ρ = −0.512, $p < 0.001$; Figure 2). These relationships are further illustrated in Figure 3. As shown, the EC-MAP30 relationship follows a potential function, indicating that soils in low-precipitation areas exhibit markedly elevated EC values, which decline sharply as precipitation increases from approximately 250 mm to 500–800 mm. Beyond this precipitation range, EC values remain consistently low (Figure 3).

https://doi.org/10.3390/agronomy16050561

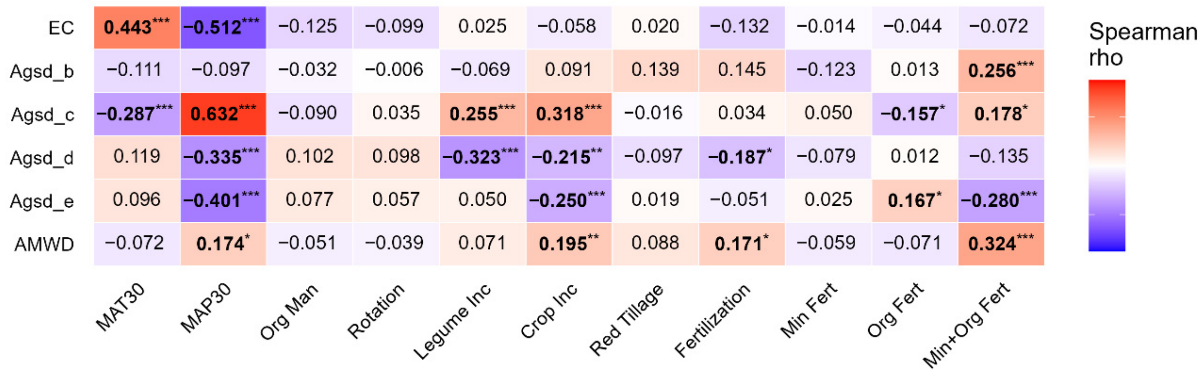

Figure 2. Spearman's rho coefficients depicting the relationships of electrical conductivity (EC, dS m^{-1}) and soil aggregate-size distribution with the climatic and management variables considered. *Agsd_b*, large macroaggregate content (>2000 µm, %); *Agsd_c*, small macroaggregate content (250–2000 µm, %); *Agsd_d*, large macroaggregate content (53–250 µm, %); *Agsd_e*, small macroaggregate content (<53 µm, %); *AMWD*, aggregate mean weight diameter (mm); *MAT30*, mean annual temperature over the 30 years preceding the sampling campaigns (°C); *MAP30*, mean annual precipitation over the 30 years preceding the sampling campaigns (mm); *Org Man*, organic farming system; *Legume Inc*, legume incorporation in the rotation; *Crop Inc*, crop residue incorporation; *Red Tillage*, reduced tillage; *Min Fert*, mineral fertilization; *Org Fert*, organic fertilization; *Min+Org Fert*, organomineral fertilization. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

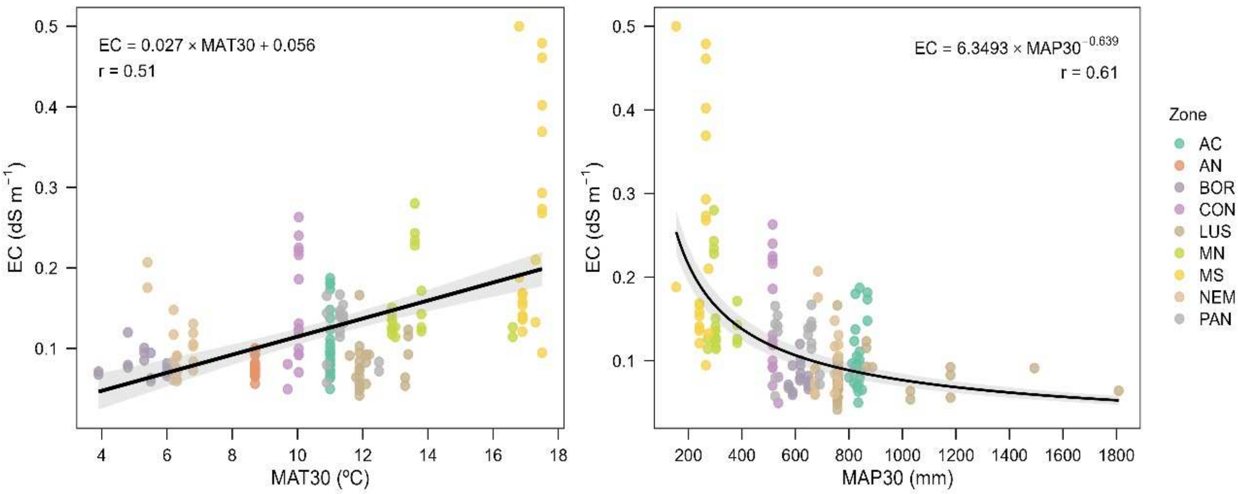

Figure 3. Graphical representation of the correlations between electrical conductivity (EC) and mean annual temperature over the 30 years preceding the sampling campaigns (MAT30, °C), as well as between EC and mean annual precipitation over the same period (MAP30, mm). *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *CON*, Continental; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian.

Regarding the impact of agricultural management systems, a significant interaction between farming system and pedoclimatic zone was detected for soil EC (F = 2.970, $p < 0.01$, Table S9), indicating that the effect of management varied across zones. Specifically, soils under conventional management exhibited significantly higher EC values than those under organic management in the CON ($p < 0.01$), MN ($p < 0.05$), and MS ($p < 0.001$) zones (Figure 1, Table S10). These results suggest that, although pedoclimatic conditions are the dominant driver of soil EC at the continental scale, agricultural management can exert regionally relevant effects within certain zones. Finally, no significant effects of specific management practices (e.g., crop rotation vs. monoculture, legume or crop residue incorporation, reduced vs. conventional tillage, or fertilization type) were detected on EC (Figure 2).

To further investigate the drivers of soil electrical conductivity (EC), a Random Forest (RF) model was applied. The RF model exhibited good predictive performance (R^2 = 0.767, *RMSE* = 0.04, *MAE* = 0.02) and confirmed that climatic factors (MAP30 and MAT30) are the main drivers of EC (Figure 4). In addition, the results also confirm that the farming system exerts a moderate influence, whereas other specific management practices have little effect at the continental scale, thereby supporting and refining the patterns previously observed in the correlation analyses.

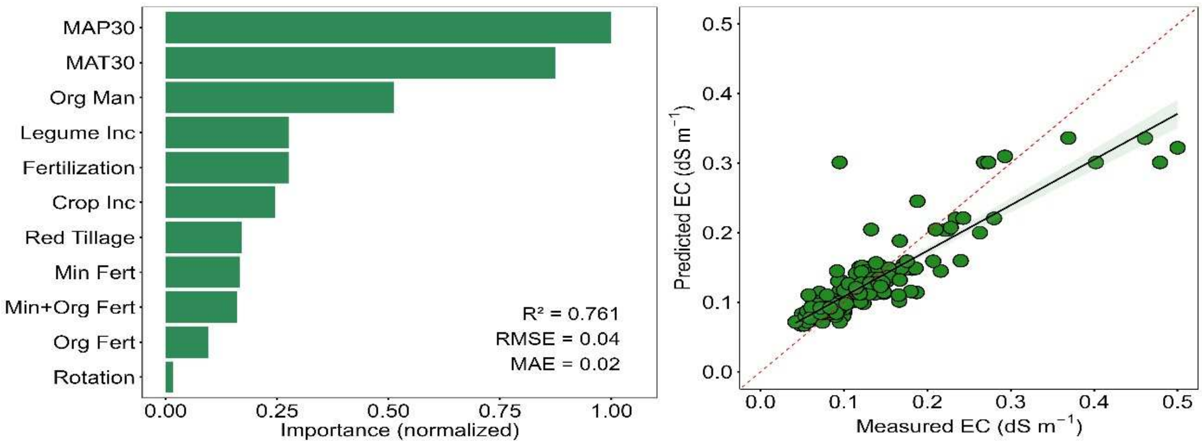

Figure 4. Relative (normalized) importance of predictor variables in the Random Forest model for explaining soil electrical conductivity (EC) (**Left**), and the relationship between observed and predicted values of soil EC (**Right**). The red dashed line represents the 1:1 reference line, while the black line shows the linear fit with its corresponding 95% confidence interval (CI).

3.2. Soil Aggregate Size Distribution

Figure 5 shows the relative contribution (%) of the four soil aggregate-size fractions in the studied soils, grouped by pedoclimatic zone and farming system (conventional vs. organic). Descriptive statistics for each zone and farming system are provided in Table S11.

Overall, soil aggregate-size fractions exhibited a high degree of variability across the dataset. When all soils were considered collectively (n = 188), the proportion of large macroaggregates (>2000 µm) ranged from 0.0 to 60.8% (average of 8.2 ± 11.5%, CV = 140%), small macroaggregates (250–2000 µm) from 4.3 to 76.3% (average of 32.0 ± 17.5%, CV = 55%), large microaggregates (53–250 µm) from 8.3 to 75.1% (average of 40.1 ± 13.8%, CV = 34%), and small microaggregates (<53 µm) from 2.0 to 65.2% (average of 19.7 ± 11.5%, CV = 58%) (Table S11).

Despite this overall variability, differences in large macroaggregate content among pedoclimatic zones were generally modest, with the notable exception of soils from the Mediterranean North (MN) and Boreal (BOR) zones, which exhibited significantly higher proportions of this fraction than all other zones. The observed pattern followed the sequence: MN > BOR ≥ AC ≈ AN ≈ CON ≈ LUS ≈ MS ≈ NEM ≥ PAN (Figure 5, Tables S7 and S8). Specifically, large macroaggregate content ranged from 2.4 to 60.8% in MN soils (average of 28.1 ± 20.0%) and from 1.7 to 39.2% in BOR soils (average of 12.4 ± 11.8%), whereas soils from the PAN zone showed the lowest values, ranging from 0.0 to 2.6% (average of 0.7 ± 0.8%) (Table S11). Nevertheless, no significant correlations were detected between large macroaggregate content and the climatic variables considered (Figure 2).

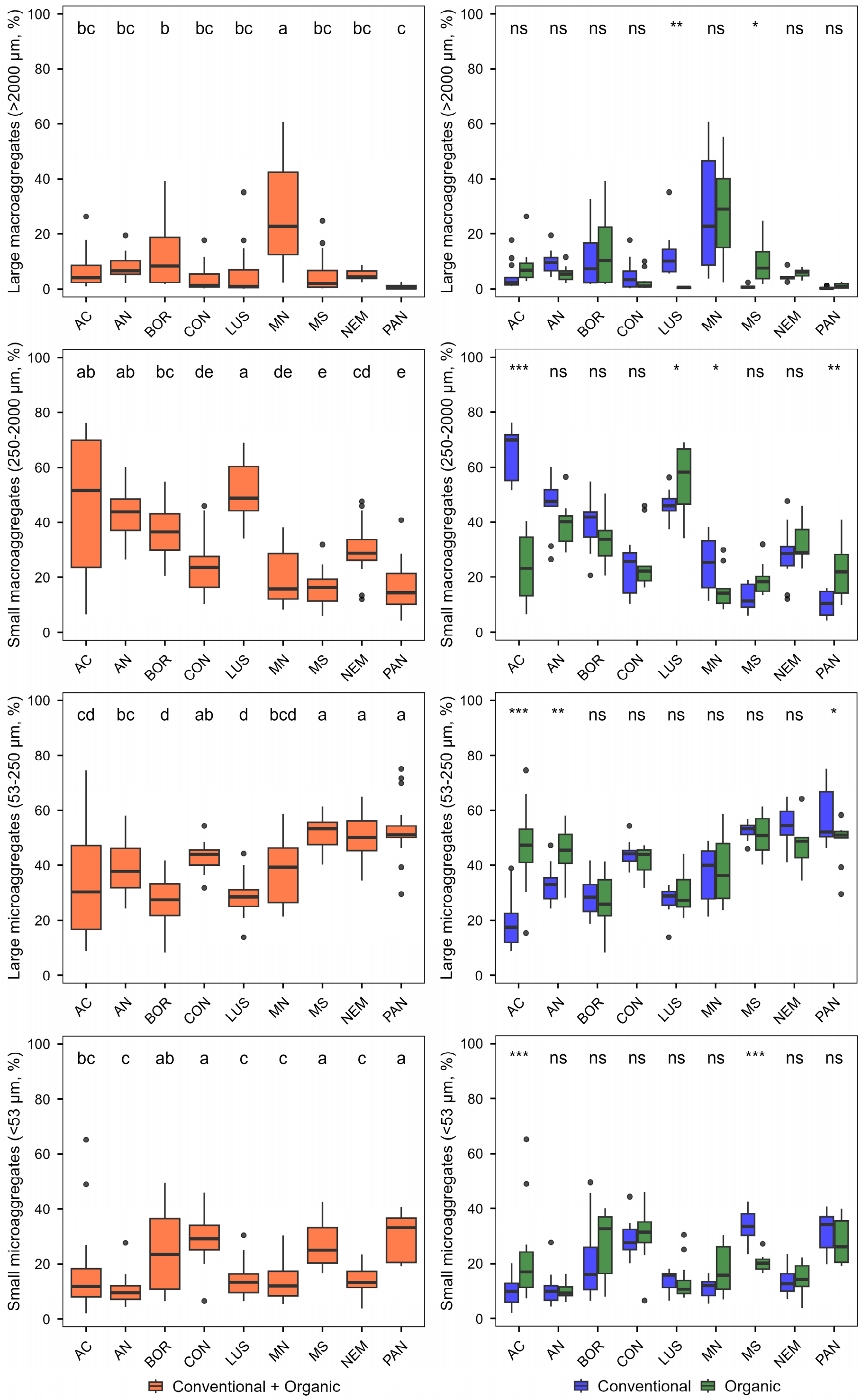

Figure 5. Content (%) of soil aggregate-size fractions across pedoclimatic zones and farming systems. The left panel shows the distribution of aggregate-size fractions by pedoclimatic zone considering both farming systems together, while the right panel shows aggregate-size fractions by farming system (conventional vs. organic) within each pedoclimatic zone. *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *CON*, Continental; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian. Different letters indicate statistically significant differences among pedoclimatic zones based on Tukey's HSD post hoc test following the one-way ANOVA for zone ($p < 0.05$). Asterisks indicate significant differences between farming systems within each zone based on pairwise comparisons derived from the two-way ANOVA (zone × system): *ns*, not significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. Full statistical results, including ANOVA tables and post hoc comparisons, are provided in the Supplementary Material (Tables S7–S10).

In contrast, small macroaggregate content (250–2000 μm) showed more pronounced differences among pedoclimatic zones, following the sequence: LUS ≥ AC ≈ AN ≥ BOR ≥ NEM ≥ CON ≈ MN ≥ MS ≈ PAN (Figure 5, Tables S7 and S8). Soils from the LUS zone exhibited the highest content, ranging from 34.2 to 69.0% (average of 51.6 ± 10.4%), whereas soils from the MS and PAN zones had the lowest contents, ranging from 6.0 to 32.0% (average of 16.0 ± 6.1%) for MS and from 4.3 to 40.9% (average of 16.4 ± 9.5%) for PAN (Table S11). Furthermore, small macroaggregate content correlated negatively and significantly with MAT30 ($\rho = -0.287$, $p < 0.01$) and positively and significantly with MAP30 ($\rho = 0.632$, $p < 0.01$) (Figure 2).

Large microaggregate content (53–250 μm) also varied substantially across pedoclimatic zones, following the sequence: PAN ≈ MS ≈ NEM ≥ CON ≥ AN ≥ MN ≥ AC ≥ BOR ≈ LUS (Figure 4, Tables S7 and S8). Soils from the PAN, MS, and NEM zones exhibited the highest large microaggregate contents, ranging from 29.6 to 75.1% (average of 53.1 ± 10.3%) for PAN, from 40.2 to 61.0% (average of 51.9 ± 5.5%) for MS, and from 34.5 to 64.8% (average of 50.7 ± 8.4%) for NEM. In contrast, BOR and LUS soils showed the lowest contents, ranging from 8.3 to 41.8% (average of 27.3 ± 9.3%) and from 13.9 to 44.2% (average of 28.9 ± 6.6%), respectively (Table S11). Despite these marked differences among pedoclimatic zones, no significant correlation with MAT30 was observed. However, a significant negative correlation was found between large microaggregate content and MAP30 ($\rho = -0.335$, $p < 0.01$) (Figure 2).

Finally, small microaggregate content (<53 μm) showed moderate variability among pedoclimatic zones, following the sequence: PAN ≈ CON ≈ MS ≥ BOR ≥ AC ≈ MN ≈ NEM ≈ AN ≈ LUS (Figure 5, Tables S7 and S8). Soils from the PAN and CON zones exhibited the highest contents, ranging from 19.1 to 40.8% (average of 29.8 ± 7.9%) and from 6.5 to 46.1% (average of 29.4 ± 8.7%), respectively, whereas soils from the AN and LUS zones had the lowest contents, ranging from 4.4 to 27.7% (average of 10.6 ± 5.2%) and from 6.5 to 30.4% (average of 13.8 ± 5.7%), respectively (Table S11). Similar to what was observed for large microaggregates, small microaggregate content correlated negatively with MAP30 ($\rho = -0.401$, $p < 0.01$), but no significant correlation was found with MAT30 (Figure 2).

When the effect of the farming system was evaluated, significant interactions between farming system and pedoclimatic zone were detected for all aggregate-size fractions, including large macroaggregates ($F = 2.314$, $p < 0.05$), small macroaggregates ($F = 19.53$, $p < 0.001$), large microaggregates ($F = 8.428$, $p < 0.001$), and small microaggregates ($F = 3.763$, $p < 0.001$) (Table S9), indicating that the effect of management varied across zones. In this sense, large macroaggregate content was significantly higher under conventional farming in the LUS zone ($p < 0.01$), whereas organic soils showed higher contents in the MS zone ($p < 0.05$). For small macroaggregates, conventional farming resulted in higher contents in the AC ($p < 0.001$) and MN ($p < 0.05$) zones, while organic farming was associated with higher contents in the LUS ($p < 0.05$) and PAN ($p < 0.01$) zones. Large microaggregate content was significantly higher under organic farming in the AC ($p < 0.001$) and AN ($p < 0.01$) zones, whereas conventional soils had higher contents in the PAN zone ($p < 0.05$). Finally, small microaggregates were more abundant under organic farming in the AC zone ($p < 0.001$) but under conventional farming in the MS zone ($p < 0.001$) (Figure 5, Table S10).

These results clearly demonstrate that the effect of agricultural management on soil aggregate-size distribution is strongly dependent on pedoclimatic conditions. In general, in cold-temperate and humid regions characterized by higher soil organic matter contents, conventional farming tended to be associated with higher proportions of large macroaggregates. In contrast, in warm and semiarid regions, organic farming favored the accumulation of these larger aggregate fractions. Conversely, for small microaggregates, conventional farming was associated with lower contents in cold-temperate and humid regions, whereas organic farming resulted in lower contents in warm and semiarid zones.

In addition to the effects of the pedoclimatic zone and farming system described above, several specific management practices also exerted a significant influence on aggregate-size distribution. Both large and small macroaggregate contents were positively correlated with organomineral fertilization ($\rho = 0.256$, $p < 0.001$ and $\rho = 0.178$, $p < 0.05$, respectively). In addition, small macroaggregate content was positively correlated with legume incorporation ($\rho = 0.255$, $p < 0.001$) and crop residue incorporation ($\rho = 0.318$, $p < 0.001$) and negatively correlated with organic fertilization ($\rho = -0.157$, $p < 0.05$) (Figure 2). In contrast, both large and small microaggregates correlated negatively with crop residue incorporation ($\rho = -0.215$, $p < 0.01$ and $\rho = -0.250$, $p < 0.001$, respectively). Moreover, large microaggregates were negatively correlated with legume incorporation ($\rho = -0.323$, $p < 0.001$) and fertilization ($\rho = -0.187$, $p < 0.05$), whereas small microaggregates correlated negatively with organomineral fertilization ($\rho = -0.280$, $p < 0.001$) and positively with organic fertilization ($\rho = 0.167$, $p < 0.05$) (Figure 2).

Figure 6 presents the aggregate mean weight diameter (AMWD) across pedoclimatic zones and farming systems, with descriptive statistics summarized in Table S11. In addition, descriptive statistics according to the different agricultural management practices (e.g., monoculture versus crop rotation, legume inclusion in the rotation, and reduced versus conventional tillage, among others) are presented in Table S6.

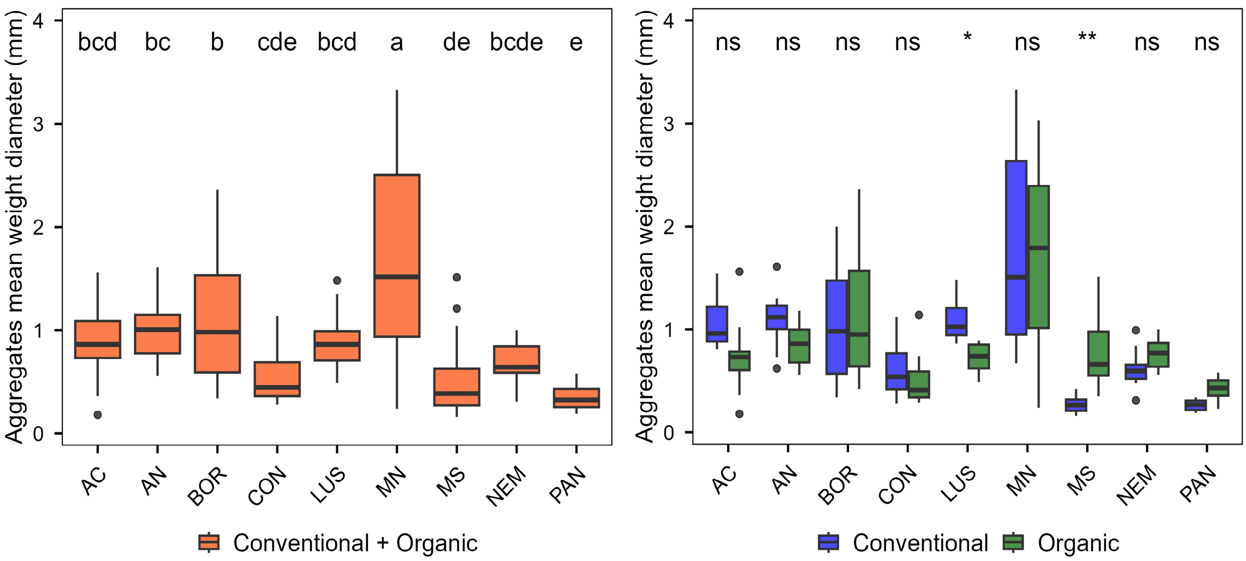

Figure 6. Aggregate mean weight diameter (AMWD) across pedoclimatic zones and farming systems. The left panel shows AMWD distributions by pedoclimatic zone considering both farming systems together, while the right panel shows AMWD distributions by farming system (conventional vs. organic) within each pedoclimatic zone. *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *CON*, Continental; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian. Different letters indicate statistically significant differences among pedoclimatic zones based on Tukey's HSD post hoc test following the one-way ANOVA for zone ($p < 0.05$). Asterisks indicate significant differences between farming systems within each zone based on pairwise comparisons derived from the two-way ANOVA (zone × system): ns, not significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. Full statistical results, including ANOVA tables and post hoc comparisons, are provided in the Supplementary Material (Tables S7–S10).

Considering all soils (n = 188), AMWD ranged from 0.16 to 3.33 mm (average of 0.86 ± 0.58 mm, CV = 67%) (Table S11). AMWD varied significantly among pedoclimatic zones, following the sequence: MN > BOR > AN > AC ≈ LUS ≥ NEM ≥ CON ≥ MS > PAN

(Figure 6, Tables S7 and S8). Soils from the MN zone exhibited the highest AMWD values, ranging from 0.24 to 3.33 mm (average of 1.75 ± 0.98 mm), whereas PAN soils showed the lowest AMWD values, ranging from 0.19 to 0.58 mm (average of 0.35 ± 0.12 mm) (Table S11). In addition, AMWD was positively correlated with MAP30 (ρ = 0.174, $p < 0.05$) (Figure 2).

Regarding the farming system, a significant interaction between the farming system and pedoclimatic zone was detected for AMWD (F = 2.186, $p < 0.05$; Table S9), indicating that the effect of management varied across zones. In this sense, soils under conventional management exhibited significantly higher AMWD values in the LUS zone ($p < 0.05$), whereas soils under organic management showed significantly higher values in the MS zone ($p < 0.01$) (Figure 6, Table S10).

Regarding specific management practices, AMWD was positively correlated with crop residue incorporation (ρ = 0.195, $p < 0.01$), overall fertilization (ρ = 0.171, $p < 0.05$), and particularly with organomineral fertilization (ρ = 0.324, $p < 0.001$) (Figure 2).

To further disentangle the combined effects of climate and agricultural management on soil aggregate distribution, a Random Forest approach was applied, in which AMWD was established as the response variable, while long-term climatic conditions (MAT30 and MAP30) together with agricultural management practices were considered as predictor variables. The model showed satisfactory predictive performance (R^2 = 0.757, RMSE = 0.28, MAE = 0.20; Figure 7), indicating that the selected predictors explained a substantial proportion of the variability in AMWD across European wheat agroecosystems. In contrast to electrical conductivity, both climatic and management-related variables contributed markedly to AMWD variability. Among the predictors, climatic variables (MAT30 and MAP30) and fertilization type, particularly organomineral fertilization, exhibited the highest importance for predicting AMWD (Figure 7).

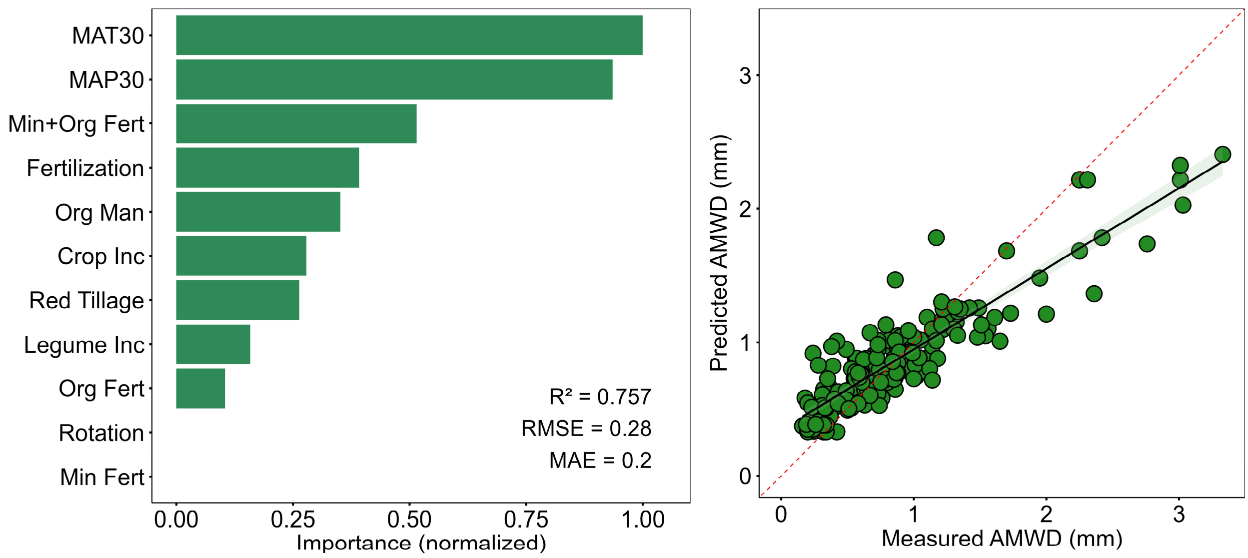

Figure 7. Relative (normalized) importance of predictor variables in the Random Forest model for explaining aggregate mean weight diameter (AMWD) (**Left**), and the relationship between observed and predicted AMWD values (**Right**). The red dashed line represents the 1:1 reference line, while the black line shows the linear fit with its corresponding 95% confidence interval (CI).

Overall, these results reinforce the patterns identified in the correlation analyses, confirming that while climate exerts an overarching control on soil aggregate-size distribution, agricultural management practices play a key role in modulating soil structural organization within European wheat systems.

4. Discussion

4.1. General Status of Soil Electrical Conductivity in Wheat Plots Across Europe

To assess the risk of salinity in European soils dedicated to wheat cultivation, the electrical conductivity (EC) values measured in this study (using a 1:5 soil-to-solution ratio) were interpreted according to soil texture, following Schillaci et al. [20] and the Australian Department of Primary Industries and Regional Development classification [47]. This approach defines different salinity classes (non-saline, slightly saline, moderately saline, highly saline, severely saline, and extremely saline) based on EC ranges specific to three broad soil texture categories: sandy, loamy, and clayey soils. According to the FAO-USDA textural classification, sandy soils are those with textures ranging from sand to loamy sand; loamy soils include sandy loam, loam, silty loam, silt, clay loam, sandy clay loam, and silty clay loam; and clayey soils comprise sandy clay, silty clay, and clay [20].

Based on this classification, all soils analyzed in this study (n = 188) fall within the loamy soils category, for which the EC-based salinity classes are defined as follows: non-saline (0–0.18 dS m^{-1}), slightly saline (0.19–0.36 dS m^{-1}), moderately saline (0.37–0.72 dS m^{-1}), highly saline (0.73–1.45 dS m^{-1}), severely saline (1.46–2.90 dS m^{-1}), and extremely saline (>2.90 dS m^{-1}) [47]. According to these thresholds, only five of the 188 wheat soils studied (<3%) were classified as moderately saline, and seventeen (~9%) as slightly saline, while the vast majority (~88%) were classified as non-saline.

It is noteworthy that the five soils with the highest salinity levels were all located in the Mediterranean South pedoclimatic zone, which is characterized by warm and arid conditions. This observation is consistent with previous studies [1,14,20,21]. In this context, both Fernández-Ugalde et al. [21] and Arias-Navarro et al. [1], who assessed soil salinity across Europe using the LUCAS Topsoil Survey based on EC values, concluded that most soils in the EU are non-saline, with Mediterranean countries being the most affected. Similarly, Schillaci et al. [20], who classified salinity in LUCAS 2018 soils based on EC, reported that 68% of soils were non-saline, 24% slightly saline, 6% moderately saline, and 1% severely saline, which closely matches the results obtained in the present study.

4.2. Climatic and Management Drivers of Soil Conductivity in Wheat Plots Across Europe

The results of this study indicate that climate is the primary driver of soil EC across European wheat agroecosystems. This finding aligns with previous research, which also identifies climate, together with factors such as parent material, soil porosity and compaction, and soil texture, as key determinants of salinity and EC in agricultural soils at the global scale [16,17,21,48].

Climate influences soil EC both directly and indirectly. Directly, soils in warmer regions (higher mean temperatures) and drier regions (lower mean precipitation) tend to exhibit higher EC values, indicating a greater risk of salinity. Precipitation influences EC mainly as it washes soluble salts from the topsoil, which lowers the concentration of mobile ions. Consequently, soils in regions with high rainfall generally show greater leaching of soluble salts and lower EC values, whereas soils in arid or semi-arid regions often display elevated levels of soluble salts and exchangeable sodium, leading to higher EC [20]. Temperature also directly affects salinity, particularly in arid and semi-arid zones, where high temperatures promote increased evaporation and/or evapotranspiration, concentrating salts in the topsoil and exacerbating salinization [17,49].

Indirectly, climate affects soil EC by influencing soil properties that modulate salinity. For example, soils in cooler and wetter regions generally have higher organic matter content than those in warmer and drier climates [21,50,51]. Higher organic matter promotes the formation and stability of soil aggregates, which improves soil structure, increases porosity, and enhances drainage, thereby facilitating the leaching of soluble salts from the topsoil.

Additionally, organic matter increases the soil's cation exchange capacity, allowing more cations to be retained on exchange sites rather than remaining in the soil solution, which directly influences EC. Together, these processes contribute to lower EC values in soils with higher organic matter content, whereas soils depleted in organic carbon are more prone to salt accumulation and elevated EC [21,50,52].

Agricultural farming systems (conventional vs. organic) also exert an influence on soil EC and, consequently, soil salinity. However, the effect of management, although significant, is more moderate than that of climate and tends to be localized, showing significant impacts only in specific pedoclimatic regions. These results are consistent with previous studies, which have recognized certain agricultural practices, such as the type and intensity of the farming system, inadequate irrigation, and suboptimal fertilization, as secondary drivers of soil EC [16,17,21,48].

While some studies have reported higher EC in organically managed soils, mainly due to salts derived from feed additives in manures [53], our results, showing higher EC values under conventional management, are in line with the general literature [29–32]. Higher EC values under conventional management reflect the accumulation of salts from the continuous application of chemical fertilizers and pesticides [29,32]. Conversely, organically managed soils typically have higher organic matter content due to the greater application of organic amendments. This translates into lower bulk density, higher porosity, improved infiltration rates, and increased water-holding capacity [31,53,54], which collectively reduce waterlogging and contribute to lower EC levels.

4.3. General Status of Soil Aggregate Size Distribution in Wheat Plots Across Europe

In this study, European wheat agroecosystems exhibited substantial variability in both soil aggregate-size fractions and aggregate mean weight diameter (AMWD) at the continental scale, highlighting the highly heterogeneous structural organization of soils across different pedoclimatic zones. Nevertheless, across all zones, small macroaggregates (250–2000 μm) and large microaggregates (53–250 μm) were the dominant fractions, together accounting for 61–86% of total aggregates depending on the pedoclimatic zone, with an overall mean contribution of 73%. In contrast, large macroaggregates (>2000 μm) were relatively scarce, averaging only 8.2% of total aggregates, which is typical in agricultural soils because they are transient and easily disrupted by physical and chemical disturbances, including tillage and other management practices that break down large structural units [24,25]. Similarly, small microaggregates (<53 μm) represented a minor fraction, averaging 11.5% of total aggregates, which can be attributed to the loss of fine particulate matter due to repeated soil cultivation, erosion, and redistribution of fine silt and clay particles, a common feature in intensively managed arable soils [22].

Although large-scale assessments of soil aggregate distribution are rare, this pattern is consistent with previous smaller-scale studies, which also reported a dominance of small macroaggregates and large microaggregates in arable soils subjected to periodic disturbances [55–57]. Similarly, Zhao et al. [58], who examined aggregate distribution in a Chinese agricultural soil under different management treatments over nine years, observed the same dominance of small macroaggregates and large microaggregates. Although conducted in a different region and under distinct soil and management conditions, these results suggest that this pattern is broadly consistent across diverse agroecosystems.

The observed dominance of small macroaggregates and large microaggregates is generally considered indicative of good soil structural quality and fertility. Together, these aggregate fractions form a hierarchical soil structure, in which each size class contributes distinct yet complementary functions. Small macroaggregates (250–2000 μm) are transient structural units composed of smaller microaggregates and organic binding agents (e.g.,

https://doi.org/10.3390/agronomy16050561

roots, fungal hyphae, microbial exudates). They provide overall structural integrity and form a matrix that physically protects the microaggregates and the soil organic matter (SOM) they contain. By stabilizing and occluding microaggregates, small macroaggregates reduce the accessibility of SOM to microbial decomposition, potentially enhancing carbon retention in the soil [24,25].

Meanwhile, large microaggregates (53–250 μm) and the microaggregates contained within macroaggregates are associated with more persistent SOM and with structural porosity at finer scales. Aggregation creates pore networks that influence water retention, aeration, and nutrient dynamics, thereby supporting microbial activity and root growth [22,24]. This hierarchical organization balances aggregate turnover with soil tilth, facilitating water infiltration, root development, and overall soil fertility. Macroaggregates contribute to macroporosity, enhancing drainage and aeration, while microaggregates and internal pore spaces contribute to microporosity, retaining water and nutrients essential for plant growth and microbial activity [22].

The AMWD values obtained in this study ranged from 0.16 to 3.33 mm, with an overall mean of 0.86 ± 0.58 mm (Table S3). These values are consistent with those reported by Panagea et al. [33] for agricultural soils across five European countries, as well as with the range of 0.33–2.80 mm observed by Nayana et al. [53] in Indian croplands. Moreover, the results are also comparable to those reported by Edlinger et al. [27], who assessed AMWD in 104 agricultural soils along a 3000 km European gradient and reported a mean value of 1.25 mm, which is close to the average obtained in the present study.

Such consistency suggests that the soils analyzed here maintain a typical aggregate-size distribution for arable soils, reflecting a balance between aggregate formation and breakdown processes that supports overall soil fertility and structural integrity. Overall, the prevalence of small macroaggregates and large microaggregates observed across European wheat agroecosystems suggests that, despite regular disturbances associated with arable management, these soils retain a structure favorable for nutrient cycling, water regulation, and sustainable crop production. The relatively lower proportion of large macroaggregates and small microaggregates does not necessarily indicate poor soil quality, as these fractions are more sensitive to management disturbances and are often less abundant in tilled systems [24,59]. Collectively, these findings underscore the importance of monitoring aggregate-size distribution as an indicator of soil health and functional quality in European croplands.

4.4. Climatic and Management Drivers of Soil Aggregate Size Distribution in Wheat Plots Across Europe

The combined results from correlation and Random Forest analyses demonstrate that both climate and agricultural management play crucial roles in shaping soil aggregate-size distribution across European wheat agroecosystems, although their relative importance differs from that observed for soil EC. Unlike EC, which is predominantly controlled by climatic variables, aggregate organization appears to result from a stronger interplay between climate and management. These findings are consistent with previous studies, which indicate that climate and management, along with other factors such as soil properties and lithology, strongly influence soil aggregate distribution and stability [22,27,60].

Among climatic drivers, the positive and significant correlation between MAP30 and AMWD highlights the fundamental role of water availability in promoting soil aggregation, consistent with the findings of Edlinger et al. [27], who reported a strong positive relationship between precipitation and AMWD and identified aridity as the most important climatic predictor of aggregate stability. In this context, adequate and consistent moisture supports plant growth, enhances organic matter inputs, stimulates microbial activity, and promotes the production of transient and persistent binding agents such as polysaccharides, fungal hyphae, and microbial necromass. Conversely, limited precipitation restricts these processes, favoring aggregate breakdown and leading to a predominance of microaggregates and fine particles [22,27,61].

The contrasting responses of different aggregate-size fractions to precipitation further support this interpretation. MAP30 was positively and significantly correlated with small macroaggregates, whereas both large and small microaggregate fractions showed significant negative correlations with this variable. This pattern reflects the hierarchical nature and dynamic turnover of soil aggregates, whereby microaggregates serve as relatively stable structural units that are progressively incorporated into macroaggregates under favorable conditions such as adequate moisture and supporting factors. Such hierarchical organization has been widely documented, with microaggregates acting as building blocks for macroaggregates under the influence of organic binding agents and environmental conditions [61,62].

Adequate water availability stimulates root and shoot growth and microbial activity, favoring the formation of transient binding agents that facilitate the assembly of microaggregates into macroaggregates. Conversely, under water-limited conditions, macroaggregates, due to their transient nature and strong biological mediation, are more prone to physical breakdown [22,27]. Moisture stress and intensified wet-dry cycles accelerate macroaggregate turnover, leading to fragmentation and the release of enclosed microaggregates. This process results in a relative increase in free microaggregate fractions and a concomitant decline in macroaggregate abundance under low-precipitation regimes [22,63].

Temperature also influences soil aggregate distribution at broad scales. A significant negative relationship was observed between MAT30 and the content of small macroaggregates, indicating a tendency toward smaller aggregate sizes under higher temperature conditions. This pattern can be explained by the strong control that temperature exerts over soil organic matter decomposition rates, as higher temperatures reduce soil organic carbon (SOC) accumulation [27]. Because SOC is a key binding agent in soil aggregate formation, lower SOC contents under warmer conditions likely result in reduced aggregation, whereas increased SOC is generally associated with enhanced aggregate stability [22,53,58].

Regarding agricultural farming systems, although most previous studies report that organic farming increases both aggregate size and stability compared to conventional farming—mainly due to higher inputs of SOC [27,53,58,64–66]—our results indicate that the effect of management is zone-specific, varying according to the pedoclimatic context. This discrepancy may be attributed to the larger geographical scale of our study, encompassing soils under diverse climatic conditions, whereas previous studies focused on one or a few soils within a single climate.

These findings indicate that climate is the primary driver of aggregate size distribution at large spatial scales, in agreement with Edlinger et al. [27], whereas management effects are more pronounced at smaller, localized scales, i.e., among soils under similar climatic conditions. In this context, the impact of management was dependent on regional climate and SOC content: in cold, humid regions with high SOC, conventionally managed soils generally exhibited higher macroaggregate content and lower microaggregate content, whereas in warm, arid regions with low SOC, organically managed soils showed the opposite pattern, with greater macroaggregate formation. This pattern can be explained by the interaction between initial SOC levels and the relative contribution of organic inputs from management. In high-SOC soils, typical of cold and humid climates [50], SOC content may already suffice to promote aggregate stability, so additional inputs from organic farming have limited impact, and conventional management may even enhance macroaggregate formation through the incorporation of inorganic fertilizers [21,34]. Conversely, in low-SOC soils, typical of warm and arid climates [21,51], organic management provides essential carbon inputs via manures, compost, or other organic amendments, which act as binding agents, promoting macroaggregate formation and improving soil structural stability [22,34]. Therefore, the observed regional differences emphasize that the effect of farming system on aggregate size is strongly mediated by initial SOC content and the potential for management to augment carbon availability, largely determined by climate.

In addition to climate and farming system, both the Random Forest model and correlation analyses indicated that specific agricultural management practices significantly influence soil aggregate size distribution. Fertilization, particularly integrated organomineral fertilization, promoted macroaggregate formation and was positively correlated with AMWD. In contrast, the exclusive application of either organic or mineral fertilizers alone did not significantly enhance aggregation. These results suggest that the combined application of organic and mineral fertilizers enhances soil aggregation more effectively than either fertilizer type alone, consistent with previous studies [33,34]. The synergistic effect of organomineral fertilization is likely due to increased SOC content and enhanced soil biotic activity [34]. Organic amendments additionally enhance soil hydrophobicity, further promoting aggregation [34]. Moreover, mineral fertilizers increase plant productivity, thereby increasing both above- and below-ground plant residues, labile carbon, microbial activity, and microbial biomass carbon, all of which contribute to aggregate stability [67]. Phosphate fertilizers specifically enhance soil aggregation through chemical mechanisms: phosphoric acid lowers soil pH, mobilizes Al^{+3}, and facilitates the precipitation of aluminum phosphate, which acts as a cementing agent promoting the formation of stable aggregates [22]. Supporting this, Chen et al. [68] demonstrated that long-term phosphorus fertilizer application significantly increased macroaggregate stability, primarily through the formation of organic–calcium complexes that act as cementing agents within soil aggregates.

Finally, other agricultural practices that enhanced soil aggregation included the incorporation of legumes into crop rotations and the addition of crop residues. Crop residue incorporation has been shown to increase the proportion of macroaggregates by facilitating the coalescence of smaller particles into larger aggregates through microbial decomposition of organic substrates and the production of transient binding agents [69]. Legume-based rotations increase rhizosphere inputs and stimulate microbial and fungal activity, generating organic binding agents (e.g., polysaccharides, hyphal networks) that contribute to aggregate formation and stability [70,71].

4.5. Implications of Climate Change and Potential Mitigation Strategies

The results of this study highlight climate as a primary driver of both soil electrical conductivity (EC) and aggregate-size distribution in European wheat agroecosystems. Across the range of pedoclimatic zones sampled, drier and warmer conditions were associated with higher EC values and a lower proportion of macroaggregates, indicating that both salinity and soil structural organization are strongly influenced by precipitation and temperature gradients.

In this context, projected increases in temperature and alterations in precipitation regimes under climate change are likely to exacerbate these patterns. Specifically, Mediterranean regions, which already experience high evapotranspiration and limited rainfall, are expected to be particularly vulnerable, with further increases in soil salinization and a shift toward a higher relative contribution of smaller microaggregates. Such changes could compromise soil structural organization, reduce water retention, limit nutrient cycling, and ultimately affect crop productivity [17,21,22,61].

Our findings also indicate that agricultural management can help mitigate some of these climate-driven risks. Soils under organic management generally exhibited lower EC, likely reflecting higher soil organic carbon, improved porosity, and increased effective cation exchange capacity (eCEC), all of which enhance cation retention and facilitate the leaching of soluble salts [29,31,53,54].

In terms of soil aggregate distribution, practices such as integrated organomineral fertilization, crop residue incorporation, and legume-based rotations were associated with an increased proportion of macroaggregates. These practices likely enhance SOC inputs and stimulate microbial and fungal activity, promoting the assembly of smaller aggregates into larger structural units [22,61,62]. By favoring macroaggregate formation, such management strategies could help maintain soil structural organization and resilience under conditions of reduced precipitation and higher temperatures [21,27].

Taken together, these results emphasize the importance of climate-smart, site-specific soil management for sustaining soil structure and mitigating salinity risks under future climate scenarios. Implementing practices that increase organic matter inputs and promote macroaggregate formation, adapted to local pedoclimatic conditions, can enhance the adaptive capacity of European wheat agroecosystems in the face of climate change [22,61,72,73].

Overall, our findings underscore that maintaining soil health in European croplands under changing climate conditions requires an integrated approach, combining monitoring of EC and aggregate-size distribution with management strategies that enhance organic matter, improve soil structure, and mitigate salinization. Such an approach can support sustainable crop production, ensure nutrient cycling, and maintain water regulation even under increasingly challenging environmental conditions.

5. Conclusions

The results obtained in the present study demonstrate that climate is the dominant factor determining soil electrical conductivity and aggregate-size distribution across European wheat agroecosystems, with warmer and drier conditions favoring increased salinity and a higher proportion of smaller aggregates, whereas cooler and wetter conditions promote macroaggregate formation and lower electrical conductivity. Nevertheless, agricultural management plays a key modulating role, as organic farming systems, integrated organomineral fertilization, crop residue incorporation, and legume-based rotations can substantially reduce salinity levels and enhance macroaggregate formation, particularly in soils with low organic carbon content, thereby mitigating some of the adverse effects imposed by climate change. These findings underscore that while climatic conditions largely establish the baseline soil environment, targeted, site-specific management practices are essential for sustaining soil health, maintaining favorable aggregate distributions, and controlling salinity risks. Integrating knowledge of local climatic drivers with adaptive agricultural strategies can improve the functional capacity, resilience, and long-term quality of soils, ensuring that European wheat agroecosystems remain productive, structurally sound, and capable of delivering vital ecosystem services under future climate change scenarios. Collectively, this study highlights the critical need for management approaches that are both climate-aware and soil-specific to preserve soil functionality and support sustainable agricultural production across diverse European landscapes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy16050561/s1. Figure S1: Geographic distribution of the 188 wheat fields included in this study, according to pedoclimatic zone and farming system (organic vs. conventional). Figure S2: USDA soil textural triangle showing the distribution of all soil samples according to their sand and clay contents. Table S1: Number of wheat fields included in the study, by farming system, pedoclimatic zone, and country. Table S2: Descriptive statistics (minimum [Min], maximum [Max], mean, and standard deviation [SD]) of soil pH, total organic carbon (TOC), total nitrogen (TN), and available phosphorus (P_{av}) for each pedoclimatic zone and farming system. Table S3: Descriptive statistics (minimum [Min], maximum [Max], mean, and standard deviation [SD]) of cation exchange capacity (CEC) and exchangeable calcium (Ca_{ex}), magnesium (Mg_{ex}), potassium (K_{ex}), and sodium (Na_{ex}) for each pedoclimatic zone and farming system. Table S4: Descriptive statistics (minimum [Min], maximum [Max], mean, and standard deviation [SD]) of sand, silt, and clay contents for each pedoclimatic zone and farming system. Table S5: Descriptive statistics (minimum—Min, maximum—Max, mean, and standard deviation—SD) of soil electrical conductivity (EC) across pedoclimatic zones and farming systems. Table S6: Descriptive statistics (minimum—Min, maximum—Max, mean, and standard deviation—SD) of soil electrical conductivity (EC) and mean aggregate weight diameter (AMWD) according to the different agricultural management practices tested in this study. Table S7: Results of one-way ANOVA assessing the effect of pedoclimatic zone on electrical conductivity (EC) and aggregate-size distribution across European wheat agroecosystems. Table S8: Results of Tukey's HSD post hoc test showing pairwise differences among pedoclimatic zones for electrical conductivity (EC) and aggregate-size distribution across European wheat agroecosystems. Table S9: Results of two-way ANOVA assessing the effects of pedoclimatic zone (Zone) and management system (Organic vs. Conventional, System) on electrical conductivity (EC) and aggregate-size distribution across European wheat agroecosystems. Table S10. Pairwise comparisons of soil electrical conductivity (EC), aggregate-size fractions, and mean weight diameter (AMWD) between conventional and organic management within each pedoclimatic zone. Significant differences ($p < 0.05$) are indicated in bold. Table S11: Descriptive statistics (minimum—Min, maximum—Max, mean, and standard deviation—SD) of large macroaggregates, small macroaggregates, large microaggregates, small microaggregates, and aggregate mean weight diameter (AMWD), by pedoclimatic zone and farming system.

Author Contributions: Conceptualization, M.C.-C., A.G.-A., M.A.-E., R.Z. and D.F.-C.; methodology, A.R.-S., A.G.-A., J.Á.C.-F., P.P.-R. and D.A.-L.; validation, M.C.-C., P.P.-R. and M.A.-E.; formal analysis, M.C.-C., A.R.-S., J.Á.C.-F. and P.P.-R.; investigation, M.C.-C., I.O., E.L. and S.M.-M.; resources, D.F.-C.; data curation, M.C.-C., A.R.-S., A.G.-A., J.Á.C.-F., P.P.-R. and D.A.-L.; writing—original draft preparation, M.C.-C., A.G.-A. and P.P.-R.; writing—review and editing, M.A.-E., I.O., E.L., S.M.-M., R.Z., L.W., S.S., K.K.B., M.S. and K.P.; supervision, R.Z., L.W., S.S., K.K.B., M.S., K.P. and D.F.-C.; project administration, D.F.-C.; funding acquisition, D.F.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the European Union's Horizon 2020 research and innovation program under grant agreement 817819 through the SoildiverAgro project: *Soil biodiversity enhancement in European agroecosystems to promote their stability and resilience by reducing external inputs and increasing crop performance*. Additional financial support was provided by the Consellería de Cultura, Educación e Universidade (Xunta de Galicia) through contract ED431C 2025/43-GRC, granted to the research group BV1 at the University of Vigo. P.P.R. and A.R.S. acknowledge their postdoctoral contracts Juan de la Cierva Incorporación (IJC 2020-044426-I and IJC 2020-044197-I, respectively), funded by MICINN/AEI/10.13039/501100011033 and the European Union EU/PRTR. V.S.M. and M.C.C. hold postdoctoral fellowships (ED481D-2025/012 and ED481B-2025/055) financed by Xunta de Galicia. A.G.A. holds a postdoctoral contract within Campus Auga (1625/160733), funded by the Xunta de Galicia-Universidade de Vigo agreement. Funding for open access publication was provided by Universidade de Vigo/CISUG.

Data Availability Statement: The authors confirm that all data supporting the findings of this study are fully available within the article and its Supplementary Materials. Additionally, the complete dataset is provided as a reusable data file and can be accessed at Zenodo: https://zenodo.org/record/7682445 (accessed on 5 December 2025).

Acknowledgments: The authors thank Ari Eskola, Ari Rajala, Juha-Matti Pitkänen, Thibault Devolder, Rubén Rodríguez Gómez, Miguel Fernández-Calviño, Servando Álvarez Pousa, Sabine El Sayed, and Marion Krause for their assistance with soil sampling. The contribution of INORDE in facilitating field access is also gratefully acknowledged. We further thank CACTI Ourense (University of Vigo) for conducting the soil analyses.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EC	Electrical Conductivity
eCEC	Effective Cation Exchange Capacity
SOC	Soil Organic Carbon
AMWD	Aggregate Mean Weight Diameter
MAT30	Mean Annual Temperature
MAP30	Mean Annual Precipitation
AC	Atlantic Central
AN	Atlantic North
BOR	Boreal
CON	Continental
LUS	Lusitanian
MN	Mediterranean North
MS	Mediterranean South
NEM	Nemoral
PAN	Pannonian

References

1. Arias-Navarro, C.; Baritz, R.; Jones, A. *The State of Soils in Europe: Fully Evidenced, Spatially Organised Assessment of the Pressures Driving Soil Degradation*; Publications Office of the European Union: Luxembourg, 2024. [CrossRef]
2. Lehmann, J.; Bossio, D.A.; Kögel-Knabner, I.; Rillig, M.C. The concept and future prospects of soil health. *Nat. Rev. Earth Environ.* **2020**, *1*, 544–553. [CrossRef] [PubMed]
3. Kopittke, P.M.; Menzies, N.W.; Wang, P.; McKenna, B.A.; Lombi, E. Soil and the intensification of agriculture for global food security. *Environ. Int.* **2019**, *132*, 105078. [CrossRef] [PubMed]
4. Pozza, L.E.; Field, D.J. The science of Soil Security and Food Security. *Soil Secur.* **2020**, *1*, 100002. [CrossRef]
5. European Commission. *Caring for Soil is Caring for Life—Ensure 75% of Soils are Healthy by 2030 for Food, People, Nature and Climate*; Report of the Mission Board for Soil Health and Food; Publications Office of the European Union: Luxembourg, 2020.
6. IPCC. *Climate Change and Land. An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2019; Available online: https://www.ipcc.ch/srccl (accessed on 5 December 2025).
7. Hermans, K.; McLeman, R. Climate change, drought, land degradation and migration: Exploring the linkages. *Curr. Opin. Environ. Sustain.* **2021**, *50*, 236–244. [CrossRef]
8. Panagos, P.; Ballabio, C.; Himics, M.; Scarpa, S.; Matthews, F.; Bogonos, M.; Poesen, J.; Borrelli, P. Projections of soil loss by water erosion in Europe by 2050. *Environ. Sci. Policy* **2021**, *124*, 380–392. [CrossRef]
9. Wang, C.; Morrissey, E.M.; Mau, R.L.; Hayer, M.; Piñeiro, J.; Mack, M.C.; Marks, J.C.; Bell, S.L.; Miller, S.N.; Schwartz, E.; et al. The temperature sensitivity of soil: Microbial biodiversity, growth, and carbon mineralization. *ISME J.* **2021**, *15*, 2738–2747. [CrossRef]
10. Panagos, P.; Borrelli, P.; Poesen, J.; Ballabio, C.; Lugato, E.; Meusburger, K.; Montanarella, L.; Alewell, C. The new assessment of soil loss by water erosion in Europe. *Environ. Sci. Policy* **2015**, *54*, 438–447. [CrossRef]
11. Bibi, F.; Rahman, A. An Overview of Climate Change Impacts on Agriculture and Their Mitigation Strategies. *Agriculture* **2023**, *13*, 1508. [CrossRef]
12. Simelane, M.P.Z.; Soundy, P.; Maboko, M.M. Effects of Rainfall Intensity and Slope on Infiltration Rate, Soil Losses, Runoff and Nitrogen Leaching from Different Nitrogen Sources with a Rainfall Simulator. *Sustainability* **2024**, *16*, 4477. [CrossRef]
13. Prăvălie, R.; Patriche, C.; Borrelli, P.; Panagos, P.; Roșca, B.; Dumitraşcu, M.; Nita, I.-A.; Săvulescu, I.; Virsan, M.-V.; Bandoc, G. Arable lands under the pressure of multiple land degradation processes. A global perspective. *Environ. Res.* **2021**, *194*, 110697. [CrossRef]
14. Ivushkin, K.; Bartholomeus, H.; Bregt, A.K.; Pulatov, A.; Kempen, B.; de Sousa, L. Global mapping of soil salinity change. *Remote Sens. Environ.* **2019**, *231*, 111260. [CrossRef]
15. Obi, J.C.; Ogban, P.I.; Ituen, I.J.; Udoh, B.T. Development of pedotransfer functions for coastal plain soils using terrain attributes. *Catena* **2014**, *123*, 252–262. [CrossRef]
16. Daliakopoulos, I.N.; Tsanis, I.K.; Koutroulis, A.; Kourgialas, N.N.; Varouchakis, A.E.; Karatzas, G.P.; Ritsema, C.J. The threat of soil salinity: A European scale review. *Sci. Total Environ.* **2016**, *573*, 727–739. [CrossRef] [PubMed]
17. Corwin, D.L. Climate change impacts on soil salinity in agricultural areas. *Eur. J. Soil Sci.* **2021**, *72*, 842–862. [CrossRef]

18. Mohanavelu, A.; Naganna, S.R.; Al-Ansari, N. Irrigation Induced Salinity and Sodicity Hazards on Soil and Groundwater: An Overview of its Causes, Impacts and Mitigation Strategies. *Agriculture* **2021**, *11*, 983. [CrossRef]
19. Mukhopadhyay, R.; Sarkar, B.; Jat, H.S.; Sharma, P.C.; Bolan, N.S. Soil salinity under climate change: Challenges for sustainable agriculture and food security. *J. Environ. Manag.* **2021**, *280*, 111736. [CrossRef]
20. Schillaci, C.; Scarpa, S.; Yunta, F.; Lipani, A.; Visconti, F.; Szatmári, G.; Balog, K.; Koganti, T.; Greve, M.; Bondi, G.; et al. Empirical estimation of saturated soil-paste electrical conductivity in the EU using pedotransfer functions and Quantile Regression Forests: A mapping approach based on LUCAS topsoil data. *Geoderma* **2025**, *454*, 117199. [CrossRef]
21. Fernández-Ugalde, O.; Scarpa, S.; Orgiazzi, A.; Panagos, P.; Van Liedekerke, M.; Marechal, A.; Jones, A. *LUCAS 2018 Soil Module. Presentation of Dataset and Results*; Publications Office of the European Union: Luxembourg, 2022. [CrossRef]
22. Bronick, C.J.; Lal, R. Soil structure and management: A review. *Geoderma* **2005**, *124*, 3–22. [CrossRef]
23. Lavallee, J.M.; Soong, J.L.; Cotrufo, M.F. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Glob. Change Biol.* **2020**, *26*, 261–273. [CrossRef]
24. Tisdall, J.M.; Oades, J.M. Organic matter and water-stable aggregates in soils. *J. Soil Sci.* **1982**, *33*, 141–163. [CrossRef]
25. Six, J.; Elliott, E.T.; Paustian, K. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biol. Biochem.* **2000**, *32*, 2099–2103. [CrossRef]
26. Cotrufo, M.F.; Wallenstein, M.D.; Boot, C.M.; Denef, K.; Paul, E. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soilorganic matter stabilization: Do labile plant inputs formstable soil organic matter? *Glob. Change Biol.* **2013**, *19*, 988–995. [CrossRef] [PubMed]
27. Edlinger, A.; Garland, G.; Banerjee, S.; Degrune, F.; García-Palacios, P.; Herzog, C.; Pescador, D.S.; Romdhane, S.; Ryo, M.; Saghaï, A.; et al. The impact of agricultural management on soil aggregation and carbon storage is regulated by climatic thresholds across a 3000 km European gradient. *Glob. Change Biol.* **2022**, *29*, 3177–3192. [CrossRef] [PubMed]
28. Oades, J.M. Soil organic matter and structural stability: Mechanisms and implications for management. *Plant Soil* **1984**, *76*, 319–337. [CrossRef]
29. Velmourougane, K. Impact of Organic and Conventional Systems of Coffee Farming on Soil Properties and Culturable Microbial Diversity. *Scientifica* **2016**, *1*, 3604026. [CrossRef]
30. Sihi, D.; Dari, B.; Sharma, D.K.; Pathak, H.; Nain, L.; Parkash, O. Evaluation of soil health in organic vs. conventional farming of basmati rice in North India. *J. Plant Nutr. Soil Sci.* **2017**, *180*, 389–406. [CrossRef]
31. Sahu, H.; Kumar, U.; Mariappan, S.; Mishra, A.P.; Kumar, S. Impact of organic and inorganic farming on soil quality and crop productivity for agricultural fields: A comparative assessment. *Environ. Chall.* **2024**, *15*, 100903. [CrossRef]
32. Angadi, V.M.A.; Murthy, R.K.; Govinda, K.; Bahvya, N.; Kumar, S.N.U.; Manjunatha, M.H.; Raghu, H.B.; Veeranagappa, P.; Sathish, B.N.; Hareesh, T.S. Soil quality and microbial diversity across organic and conventional coffee in central Western Ghats India. *Sci. Rep.* **2025**, *15*, 34184. [CrossRef]
33. Panagea, I.S.; Apostolakis, A.; Berti, A.; Bussell, J.; Čermak, P.; Diels, J.; Elsen, A.; Kusá, H.; Piccoli, I.; Poesen, J.; et al. Impact of agricultural management on soil aggregates and associated organic carbon fractions: Analysis of long-term experiments in Europe. *Soil* **2022**, *8*, 621–644. [CrossRef]
34. Ponyane, P.; Ebouel, F.J.D.; Eze, P.N. Formation pathways, ecosystem functions, and the impacts of land use and environmental stressors on soil aggregates. *Front. Environ. Sci.* **2025**, *13*, 1628746. [CrossRef]
35. Alomari, D.Z.; Schierenbeck, M.; Alqudah, A.M.; Alqahtani, M.D.; Wagner, S.; Rolletschek, H.; Borisjuk, L.; Röder, M.S. Wheat Grains as a Sustainable Source of Protein for Health. *Nutrients* **2023**, *15*, 4398. [CrossRef] [PubMed]
36. Horadagoda, A.; Fulkerson, W.J.; Barchia, I.; Dobos, R.C.; Nandra, K.S. The effect of grain species, processing and time of feeding on the efficiency of feed utilization and microbial protein synthesis in sheep. *Livest. Sci.* **2008**, *114*, 117–126. [CrossRef]
37. Eurostat. Agricultural Production—Crops. European Commission. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_crops (accessed on 17 January 2025).
38. USDA FAS. Production—Wheat. USDA Foreign Agricultural Service, U.S. Department of Agriculture. Available online: https://www.fas.usda.gov/data/production/commodity/0410000 (accessed on 17 January 2025).
39. Vučkovski, B.G.; Grubor, A.; Ćurčić, N. Trade dependence and food security: A comparative analysis of the wheat sector in Europe. *Econ. Agric.* **2025**, *72*, 1021–1038. [CrossRef]
40. Heinemann, H.; Durand-Maniclas, F.; Seidel, F.; Ciulla, F.; Bárcena, T.G.; Camenzind, M.; Corrado, S.; Csűrös, Z.; Czakó, Z.; Eylenbosch, D.; et al. Optimising Root and Grain Yield Through Variety Selection in Winter Wheat Across a European Climate Gradient. *Eur. J. Soil Sci.* **2025**, *76*, e70077. [CrossRef]
41. Veršulienė, A.; Hirte, J.; Ciulla, F.; Camenzind, M.; Don, A.; Durand-Maniclas, F.; Heinemann, H.; Herrera, J.M.; Hund, A.; Seidel, F.; et al. Wheat varieties show consistent differences in root colonization by mycorrhiza across a European pedoclimatic gradient. *Eur. J. Soil Sci.* **2024**, *75*, e13543. [CrossRef]

42. Fernández-Calviño, D.; Soto-Gómez, D.; Koefoed Brandt, K.; Waeyenberge, L. *Protocols for Sampling General, General Soil Characterization and Soil Biodiversity Analysis*; Universidade de Vigo: Pontevedra, Spain; Zenodo: Geneva, Switzerland, 2020. [CrossRef]
43. European Council. Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007. *Off. J. Eur. Union* **2018**, *150*, 1–92. Available online: http://data.europa.eu/eli/reg/2018/848/oj (accessed on 5 December 2025).
44. Fernández-Calviño, D.; Pérez-Rodríguez, P.; Arias-Estévez, M.; Gómez-Armesto, A.; Soto-Gómez, D.; Álvarez-Pousa, S.; Zornoza, R.; Lloret, E.; Ollio, I.; Sánchez-Navarro, V.; et al. *General Soil Properties of Wheat Fields Along 9 Pedoclimatic Regions in Europe (Version v1) [Data set]*; Zenodo: Geneva, Switzerland, 2023. [CrossRef]
45. Nimmo, J.R.; Perkins, K.S. Aggregate stability and size distribution. In *Methods of Soil Analysis. Part 4. Physical Methods*; Warren, A.D., Ed.; Soil Science Society of America: Madison, WI, USA, 2002; pp. 317–328.
46. *R Core Team: A Language and Environment for Statistical Computing*, version 4.5.3; R Foundation for Statistical Computing: Vienna, Austria, 2021. Available online: https://www.R-project.org/ (accessed on 5 December 2025).
47. DPIRD. Department of Primary Industries and Regional Development, Western Australia. *Measuring Soil Salinity*; Factsheet DPIRD-181; Department of Primary Industries and Regional Development: Perth, Australia, 2024; Volume 181. Available online: https://library.dpird.wa.gov.au/nrm_factsheets/26 (accessed on 5 December 2025).
48. Omuto, C.T.; Vargas, R.R.; El Mobarak, A.M.; Mohamed, N.; Viatkin, K.; Yigini, Y. *Mapping of Salt-Affected Soils: Technical Manual*; FAO: Rome, Italy, 2020. [CrossRef]
49. Batlle-Sales, J. Salt-affected soils: A sustainability challenge in a changing world. *Ital. J. Agron.* **2023**, *18*, 2188. [CrossRef]
50. Rial, M.; Martínez Cortizas, A.; Rodríguez-Lado, L. Understanding the spatial distribution of factors controlling topsoil organic carbon content in European soils. *Sci. Total Environ.* **2017**, *609*, 1411–1422. [CrossRef]
51. Yanni, S.F.; Diochon, A.; Helgason, B.L.; Ellert, B.H.; Gregorich, E.G. Temperature response of plant residue and soil organic matter decomposition in soil from different depths. *Eur. J. Soil Sci.* **2018**, *69*, 325–335. [CrossRef]
52. Lakhdar, A.; Rabhi, M.; Ghnaya, T.; Montemurro, F.; Jedidi, N.; Abdelly, C. Effectiveness of compost use in salt-affected soil. *J. Hazard. Mater.* **2009**, *171*, 29–37. [CrossRef]
53. Nayana, M.V.; Gladis, R.; Joseph, B.; Nath, O.M.S. Comparative Study of Soil Properties and Organic Matter Fractions in Organic and Conventional Farms of Kerala, India. *Int. J. Environ. Clim. Change* **2023**, *13*, 4305–4318. [CrossRef]
54. Sheoran, H.S.; Kakar, R.; Kumar, N.; Seema. Impact of organic and conventional farming practices on soil quality: A global review. *Appl. Ecol. Environ. Res.* **2019**, *17*, 951–968. [CrossRef]
55. Wick, A.F.; Ingram, L.J.; Stahl, P.D. Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes. *Soil Biol. Biochem.* **2009**, *41*, 201–209. [CrossRef]
56. Medinski, T.V.; Freese, D.; Böhm, C.; Slazak, A. Soil carbon fractions in short rotation poplar and black locust coppices, Germany. *Agrofor. Syst.* **2014**, *88*, 505–515. [CrossRef]
57. Parajuli, B.; Luo, M.; Ye, R.; Ducey, T.F.; Park, D.; Smith, M.; Sigua, G. Aggregate Distribution and the Associated Carbon in Norfolk Soils under Long-term Conservation Tillage and Short-term Cover Cropping. *Commun. Soil Sci. Plant Anal.* **2021**, *52*, 859–870. [CrossRef]
58. Zhao, Z.; Mao, Y.; Gao, S.; Lu, C.; Pan, C.; Li, X. Organic carbon accumulation and aggregate formation in soils under organic and inorganic fertilizer management practices in a rice-wheat cropping system. *Sci. Rep.* **2023**, *13*, 3665. [CrossRef]
59. Six, J.; Paustian, K.; Elliot, E.T.; Combrink, C. Soil Structure and Organic Matter: I. Distribution of Aggregate-Size Classes and Aggregate-Associated Carbon. *Soil Sci. Soc. Am. J.* **2000**, *64*, 681–689. [CrossRef]
60. Wei, C.; Gao, M.; Shao, J.; Xie, D.; Pan, G. Soil aggregate and its response to land management practices. *China Particuology* **2006**, *4*, 211–219. [CrossRef]
61. Six, J.; Bossuyt, H.; Degryze, S.; Denef, K. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* **2004**, *79*, 7–31. [CrossRef]
62. Oades, J.M.; Waters, A.G. Aggregate Hierarchy in Soils. *Aust. J. Soil Res.* **1991**, *29*, 815–828. [CrossRef]
63. Liu, S.; Huang, X.J.; Gan, L.; Zhang, Z.B.; Dong, Y.; Peng, X.H. Drying-wetting cycles affect soil structure by impacting soil aggregate transformations and soil organic carbon fractions. *Catena* **2024**, *243*, 108188. [CrossRef]
64. Siegrist, S.; Schaub, D.; Pfiffner, L.; Mäder, P. Does organic agriculture reduce soil erodibility? The results of a long-term field study on loess in Switzerland. *Agric. Ecosyst. Environ.* **1998**, *69*, 253–264. [CrossRef]
65. Pulleman, M.; Jongmans, A.; Marinissen, J.; Bouma, J. Effects of organic versus conventional arable farming on soil structure and organic matter dynamics in a marine loam in the Netherlands. *Soil Use Manag.* **2003**, *19*, 157–165. [CrossRef]
66. Chung, J.-B. Comparison of Soil Physical Properties in Conventional and Organic Farming Apple Orchards. *Korean J. Environ. Agric.* **2007**, *26*, 279–285. [CrossRef]
67. Neff, J.C.; Townsend, A.L.; Gleixner, G.; Lehman, S.J.; Turnbull, J.; Bowman, W. Variable effects of nitrogen additions on the stability and turnover of soil carbon. *Nature* **2002**, *419*, 915–917. [CrossRef]

68. Chen, M.; Liu, L.; Song, X.; Zhang, S.; Cheng, B.; Ding, X. How does phophorous fertilizer improve the stability of soil aggregates? Evidence from a decade fertilization experiment. *Plant Soil* **2024**, *504*, 643–657. [CrossRef]
69. Xie, N.; Sun, L.; Lu, T.; Zhang, X.; Duan, N.; Wang, W.; Liang, X.; Fan, Y.; Liu, H. Effects of Adding Different Corn Residue Components on Soil and Aggregate Organic Carbon. *Agriculture* **2025**, *15*, 1050. [CrossRef]
70. Ding, T.; Guo, Z.; Hua, K.; Yu, Z.; Li, J.; Chen, Y.; Guo, Z.; Wang, D.; Liu, J.; Peng, X. Effects of legume-cover crop rotations on soil pore characteristics and particulate organic matter distributions in Vertisol based on X-ray computed tomography. *Geoderma* **2025**, *461*, 117464. [CrossRef]
71. Gentsch, N.; Riechers, F.L.; Boy, J.; Schweneker, D.; Feuerstein, U.; Heuermann, D.; Guggenberger, G. Cover crops improve soil structure and change organic carbon distribution in macroaggregate fractions. *Soil* **2024**, *10*, 139–150. [CrossRef]
72. Ding, Z.; Kheir, A.M.S.; Ali, M.G.A.; Abdelaal, A.I.N.; Lin, X.; Zhou, Z.; Wang, B.; Liu, B.; He, Z. The integrated effect of salinity, organic amendments, phosphorus fertilizers, and deficit irrigation on soil properties, phosphorus fractionation and wheat productivity. *Sci. Rep.* **2020**, *10*, 2736. [CrossRef]
73. Mao, X.; Yang, Y.; Guan, P.; Geng, L.; Ma, L.; Di, H.; Liu, W.; Li, B. Remediation of organic amendments on soil salinization: Focusing on the relationship between soil salts and microbial communities. *Ecotoxicol. Environ. Saf.* **2022**, *239*, 113616. [CrossRef]