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RESEARCH ARTICLE

Climate and farming system dominate wheat yield responses across European pedoclimatic zones, despite widespread soil nutrient surpluses

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Abstract
Background and aims European wheat production faces the challenge of maintaining yields while reducing environmental impacts from agrochemicals. Organic farming is often considered a sustainable alternative to promote soil health and reduce chemical inputs. This study assessed nutrient status in wheat soils across nine European pedoclimatic zones, comparing conventional and organic systems and evaluating management practices such as crop rotation, tillage and fertilization type.

Methods A total of 188 soils were analyzed for macro- and micronutrients, and wheat yield data were evaluated in relation to soil nutrients, climate, wheat type (winter- vs. spring-sown), and management using correlation, random forest, and regression analyses.

Results Soils showed excess P, K, Mg, Cu, Fe, Mn, and Zn, but S and B deficiencies. Organic systems increased total N, while conventional farming enhanced nitrate, sulfate, and boron.

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Wheat yield was primarily driven by temperature, precipitation, wheat type (winter- vs. spring-sown), and farming system, with additional contributions from fertilization and nutrients (particularly exchangeable Ca, Fe, Mn, and Zn). On average, organic yields were 37% significantly lower than conventional, but these differences were smaller in Mediterranean zones due to reduced pest pressure and improved water retention and infiltration. Practices such as crop rotation, residue incorporation, and reduced tillage positively influenced yield.

Conclusion Organic farming supports soil health and sustainable use of resources, but may reduce wheat yield in northern and central European pedoclimatic zones. Tailored nutrient management combined with agronomic practices can enhance productivity while minimizing environmental impacts, especially in climate-stressed regions.

Keywords Wheat yield · Soil nutrients · Fertilization · Sustainable agriculture · Crop production · Random forest analysis

Abbreviations list

NH_4^+	Ammonium
AC	Atlantic Central
AN	Atlantic North

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P*av*	Available phosphorous
SO_4^{-2}	Available sulphate
B_{av}	Available boron
Cu_{av}	Available copper
Fe_{av}	Available iron
Mn_{av}	Available manganese
Zn_{av}	Available zinc
BOR	Boreal
CON	Continental
Ca_{ex}	Exchangeable calcium
Mg_{ex}	Exchangeable magnesium
K_{ex}	Exchangeable potassium
Na_{ex}	Exchangeable sodium
LUS	Lusitanian
MN	Mediterranean North
MS	Mediterranean South
Mineral-N	Mineral nitrogen
NEM	Nemoral
NO_3^-	Nitrates
NO_2^-	Nitrites
PAN	Pannonian
TN	Total nitrogen
TMN	Total mineral nitrogen
WY	Wheat yield

Introduction

It is estimated that global agricultural production will need to increase by 30–62% to meet the growing demand for food by 2050 (Hu et al. 2025). In this context, wheat (*Triticum* spp.) is one of the most important crops worldwide, serving as the primary food source for more than one-third of the global population and playing a crucial role in Europe's food security (Rawal et al. 2022). Wheat yields have increased sharply over the past decades, rising by 232% between 1960 and 2023, while the area harvested for wheat rose by less than 10% (FAOSTAT 2025). However, much of this increase in productivity is attributable to a rise in pesticide use (Hossard et al. 2014), which has been critical in preventing annual agricultural losses exceeding 45% due to pest infestations (Abhilash and Singh 2009). Supporting this, a recent study across 188 wheat fields in Europe revealed a clear relationship between pesticide residues and wheat yield, indicating that pesticide application directly contributes to higher production (Rodríguez-Seijo et al. 2025).

Although wheat can be cultivated on a wide range of soils, optimal growth requires adequate nutrient levels. High yields can be obtained after additions of up to 150 kg ha^{-1} of nitrogen (N), 35–45 kg ha^{-1} of phosphorus (P), and 25–50 kg ha^{-1} of potassium (K) (FAO 2019). However, the extensive use of chemical fertilizers and pesticides poses serious risks to human health and the environment (UNEP 2022). Pesticides, designed to be toxic to agricultural pests (such as insects, weeds, fungi, nematodes, and others), can cause biodiversity loss, ecotoxicity in non-target organisms, pest resistance, and ultimately, threats to food security (Rodríguez-Seijo et al. 2025; Zhou et al. 2025). Moreover, pesticide residues may enter the food chain, creating potential human health risks, including chronic diseases and cancer (Kaur et al. 2024). Chemical fertilizers, when overused or inefficiently applied, lead to nutrient losses and environmental degradation, including soil salinization or soil acidification, nutrient depletion, heavy metal accumulation, water eutrophication, and emissions of nitrogenous and sulfurous gases that contribute to greenhouse effects and air pollution (UNEP 2022). Collectively, the overuse of pesticides and fertilizers degrades soil, harms surrounding ecosystems, reduces essential ecosystem services, and undermines long-term agricultural sustainability (Devi et al. 2022).

In response to these challenges, the European Commission's Farm to Fork strategy aims to reduce the use and risks of chemical pesticides by 50% by 2030, alongside a reduction of nutrient losses by at least 50%, which is expected to reduce fertilizer use by at least 20% (European Commission 2020). In this context, organic agriculture, designed to produce food while minimizing harm to ecosystems, animals, and humans, has been proposed as a sustainable alternative (Seufert et al. 2012; de Cárcer et al. 2019). Organic farming systems cannot apply synthetic fertilizers and pesticides, relying instead on practices such as organic amendments (e.g. manure), crop rotations, legume integration or incorporation of crop residues, among others (Herencia et al. 2007; Rodríguez-Seijo et al. 2025). These practices offer multiple environmental benefits, including enhanced soil health through increased organic matter, carbon sequestration and biodiversity, reduced pollution and soil erosion, and improved water retention. Moreover, organic farming enhances agroecosystem resilience to pests and climate change by supporting systems that withstand temperature fluctuations and drought while biologically controlling pests (De la Cruz et al. 2023; Gamage et al. 2023).

Despite these benefits, critics argue that organic farming often produces lower yields, potentially requiring additional land to match conventional production and thereby leading to increased deforestation and biodiversity loss (Seufert et al. 2012). Yet, there are studies suggesting that organic systems with specifically adapted management practices can improve soil fertility and, consequently, increase crop yields (Ahmed et al. 2015; Gajda et al. 2019; Rani et al. 2023). However, meta-analyses and original research have shown that wheat yields can decline under organic management, particularly during the initial years of transition (Seufert et al. 2012; Knapp and van der Heijden 2018; Hinson et al. 2022). Importantly, these studies are often conducted at local or regional scales and do not always account for varying climatic conditions or differences in wheat species and sowing season (winter- vs. spring-sown wheat), all of which can substantially influence soil fertility and the yield gap between organic and conventional systems (Entz and Fowler 1991; Benincasa et al. 2016; De la Cruz et al. 2023). Consequently, continental-scale studies examining the effects of conventional versus organic farming on soil nutrient status and wheat yield, while also considering climatic conditions, wheat type, and specific management practices, are still lacking.

Therefore, considering the aspects outlined above, the main objectives of this study are: i) to analyze the current nutrient status of soils used for wheat cultivation across nine European pedoclimatic zones; ii) to investigate the effects of farming management system (organic vs. conventional), agricultural practices (crop rotation, monoculture, tillage type, crop residue incorporation, and fertilization type), and climate on soil nutrient status; and iii) to assess how soil nutrients, climate variables, wheat type (winter- vs. spring-sown), farming system, and specific management practices collectively influence wheat yield.

Materials and Methods

Experimental design and soil sampling

Soil samples were collected across nine European pedoclimatic zones and nine countries: Boreal (BOR, Finland), Continental (CON, Germany), Atlantic Central (AC, Belgium), Lusitanian (LUS, northwestern Spain), Nemoral (NEM, Estonia), Atlantic North (AN, Denmark), Mediterranean North and Mediterranean South (MN and MS, eastern and southern Spain), and Pannonian (PAN, Hungary and Serbia) (Fig. S1, Supplementary material). Collectively, these countries represent 86% of the EU-27. For field selection, at least 20 farms were selected per zone, including at least ten conventional and ten organic farms that had applied the specified agricultural management regime for at least five years. Farms under organic management for less than five years were included only when access to suitable long-term organic farmland was not possible. Whenever feasible, pairs of fields, one organic and one conventional, located in close proximity (e.g. neighboring farms) were selected to ensure comparable pedoclimatic conditions and similar soil characteristics (Fernández-Calviño et al. 2020). This selection resulted in a total of 93 conventional and 95 organic fields (Table S1, Supplementary material). Selected fields were mostly planted with common wheat (*T. aestivum*) (> 96% of the fields), with a limited number of fields cultivated with other species, such as triticale or *Triticum spelta,* among others. Information on whether wheat was sown as winter (51% of samples) or spring (46%) wheat is shown in Table S1.

Soil sampling was conducted shortly after wheat harvest, within two weeks, and before any subsequent management operations. In each plot, a single composite soil sample (minimum 2 kg) was collected from the 0–25 cm soil layer using an auger. Sixty soil cores were randomly collected across an area of approximately 1 ha following a zigzag sampling pattern. Composite samples were homogenized and divided into two subsamples: one was wet-sieved through a 2 mm mesh and used for the determination of soil ammonium, nitrite, and nitrate; the other subsample was air-dried at room temperature, sieved (< 2 mm), and used for the determination of the remaining soil properties. Detailed descriptions of the soil sampling strategy can be found in Waeyenberge (2020) and Rodríguez-Seijo et al. (2025).

In each experimental area, a soil information sheet was completed in collaboration with the land manager. This information sheet compiled data on the field's geographical location and management history. The management information was obtained through a standardized survey completed with the land managers and reflects field-level practices applied during the five years preceding soil sampling, including crop rotation, tillage practices, and fertilization types (Fernández-Calviño et al. 2020). Regarding fertilization, it was not possible to obtain complete information on fertilizer application rates, especially under conventional management, or on application dates. All raw data for the measured parameters, farming systems, and management practices are available in Fernández-Calviño et al. (2023).

Soil nutrients analysis

Total nitrogen (TN) was determined in ground samples using an elemental analyzer. Inorganic nitrogen forms (NH_4^+, NO_3^-, and NO_2^-) were extracted with 2 M KCl following the procedures of Sempere et al. (1993), Kandeler and Gerber (1988), and Keeney and Nelson (1982), respectively, and quantified by ion chromatography (nitrate and nitrite) and spectrophotometry (ammonium). Mineral nitrogen (Mineral-N) was estimated as the sum of NH_4^+, NO_3^-, and NO_2^-. Available phosphorus (P_{av}) was analyzed using the Olsen method (Olsen and Sommers 1982). Available sulfur (as sulphate, SO_4^{2-}) was extracted with water at a 1:5 soil-to-solution ratio and measured by HPLC with conductivity detection (Hern et al. 1983; Schmalz et al. 2001).

Exchangeable base cations (Ca_{ex}, K_{ex}, Mg_{ex}, and Na_{ex}) were determined following ISO 11260 (ISO 2018) and measured by inductively coupled plasma optical emission spectroscopy (ICP-OES). Available micronutrients, including Fe_{av}, Mn_{av}, Zn_{av}, and Cu_{av}, were extracted using DTPA (Lindsay and Norvell 1978) and quantified by inductively coupled plasma mass spectrometry (ICP-MS). Finally, available boron (B_{av}) was obtained through hot-water extraction (50 °C, 1:5 soil-to-solution ratio) and measured using microwave plasma atomic emission spectroscopy (MP-AES) (Bingham 1982). Detailed descriptions of all methods are provided in Fernández-Calviño et al. (2020).

Wheat yield

Wheat yield was measured by completely harvesting each experimental plot with a commercial harvester and reported by the farmers during the sampling campaign (2019 season) as kg ha^{-1}, reflecting field gate grain moisture (i.e. as harvested, not adjusted to dry matter) (Sóto-Gomez et al. 2020).

Statistical analysis

Significant differences in soil nutrient levels among pedoclimatic zones were assessed using one-way ANOVA, followed by Tukey's Honest Significant Difference (HSD) test for post hoc pairwise comparisons. Pairwise t-tests were also conducted to compare farming systems (conventional vs. organic) within each zone. Spearman correlation analysis was performed to examine relationships among soil nutrients, wheat yield, wheat type (winter- vs. spring-sown), farming system, specific management practices (including legume and crop residue incorporation, monoculture versus crop rotation, conventional versus reduced tillage, and fertilization type), and climatic variables (average of annual precipitation [P_{12m}] and temperature [T_{12m}] of twelve months preceding wheat harvest). Information about management practices can be found at Fernández-Calviño et al. (2023).

Multiple linear regression analysis was used to predict wheat yield based on soil nutrients, climatic variables, wheat type (winter- vs. spring-sown), farming system, and agricultural practices. In parallel, a Random Forest model was developed to predict wheat yield using the same set of predictors. For the Random Forest analysis, 80% of the samples were used for model training and the remaining 20% for model evaluation. Prior to model fitting, observations with missing values were excluded, and highly collinear predictors (Pearson's correlation coefficient $r > 0.7$) were excluded. The Random Forest model was trained using the R package randomForest (version 4.7–1.2; Breiman et al. 2024), and model performance was evaluated using R^2, root mean square error (RMSE) and mean absolute error (MAE). Variable importance was assessed and visualized to identify the main predictors contributing to wheat yield. All statistical analyses were performed in IBM SPSS v25 and R version 4.4.1 (R Core Team 2021).

Results

Primary macronutrients

Tables 1 and S2-S6 show the descriptive statistics (minimum, maximum, mean, and standard deviation) of soil nutrient contents across nine European pedoclimatic zones, along with corresponding wheat yield data. Additionally, Table 2 presents Spearman's rho correlation coefficients for soil nutrient content, wheat yield, wheat type (winter- vs. spring-sown), climatic variables, farming systems, and agricultural management practices.

Total soil nitrogen and mineral nitrogen

Total nitrogen (TN) across all soils ($n = 188$) ranged from 0.5 to 7.1 g kg^{-1}, with a mean of 1.8 ± 0.8 g kg^{-1}, showing significant differences among pedoclimatic zones (Table 1). The BOR and LUS zones, characterized by humid-cold or temperate conditions, exhibited the highest TN levels, whereas the Mediterranean zones (MS and MN), with arid-warm conditions, showed the lowest values (Tables 1 and S2). TN was negatively correlated with T_{12m} ($r = -0.48$, $p < 0.01$) and positively correlated with P_{12m} ($r = 0.53$, $p < 0.01$) (Table 2).

Ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-) concentrations, and hence, total mineral nitrogen ($TMN = NH_4^+ + NO_3^- + NO_2^-$), varied widely

Table 1 Descriptive statistics (minimum – Min, maximum – Max, mean, and standard deviation – SD) of the analyzed soil nutrients and wheat yield across pedoclimatic zones

Parameter	Units	n	Min	Max	Mean	SD	Pedoclimatic zone variation
Total Nitrogen (Total N)	g kg^{-1}	188	0.5	7.1	1.8	0.8	BOR^{a} ≥ LUS^{ab} ≈ NEM^{ab} ≈ PAN^{ab} ≥ AN^{b} ≈ CON^{b} ≈ AC^{b} > MS^{c} ≈ MN^{c}
Ammonium (NH_4^+)	mg kg^{-1}	188	1.1	9.7	3.2	1.4	PAN^{a} ≥ LUS^{ab} ≈ BOR^{ab} ≈ MS^{ab} ≈ MN^{ab} ≈ NEM^{ab} ≈ AN^{ab} ≥ AC^{b} ≈ CON^{b}
Nitrate (NO_3^-)	mg kg^{-1}	188	17.4	188.2	72.9	30	AN^{a}≈BOR^{a}≈NEM^{a}≈AC^{a} ≥ MN^{ab}≈LUS^{ab}≥MS^{b}≈ CON^{b} ≈ PAN^{b}
Nitrite (NO_2^-)	mg kg^{-1}	143	1.4	11.7	6.6	3.1	BOR^{a} ≥ ≈ AN^{ab} ≈ MN^{ab} ≈ AC^{ab} ≥ NEM^{b} ≈ MS^{b} ≈ CON^{b} ≈ PAN^{b} > LUS^{c}
Mineral N ($NH_4^+ + NO_3^- + NO_2^-$)	mg kg^{-1}	188	22.7	204.1	81.2	32	AN^{a}≈ BOR^{a}≥ AC^{ab} ≈ NEM^{ab} ≈ MN^{ab} ≥ LUS^{b} > MS^{c} ≥ CON^{cd} ≥ PAN^{d}
Available P (P_{av})	mg kg^{-1}	188	4.4	262.9	48.9	48.9	LUS^{a} > AC^{b} ≥ PAN^{bc} ≥ BOR^{c} ≈ CON^{c} ≈ AN^{c} ≥ NEM^{cd} ≈ MN^{cd} ≥ MS^{d}
Exchangeable K (K_{ex})	mg kg^{-1}	188	53	1105	231	141	CON^{a} ≈ MS^{a} ≈ AC^{a} ≥ PAN^{ab} ≈ LUS^{ab} ≈ BOR^{ab} ≈ AN^{ab} ≥ MNb ≈ NEM^{b}
Available sulphate (SO_4^{-2})	mg kg^{-1}	186	2	512	29	67	MS^{a} > MN^{b} ≈ CON^{b} ≈ AN^{b} ≈ LUS^{b} ≈ NEM^{b} ≈ AC^{b} ≈ BOR^{b} ≈ PAN^{b}
Exchangeable Ca (Ca_{ex})	mg kg^{-1}	188	231	6098	2128	1186	PAN^{a} > MN^{b} ≈ CON^{b} ≈ MS^{b} ≥ BOR^{bc} ≈ AC^{bc} ≈ NEM^{bc} ≥ AN^{c} > LUS^{d}
Exchangeable Mg (Mg_{ex})	mg kg^{-1}	188	23	752	192	141	MS^{a} ≈ BOR^{a} ≈ PAN^{a} > MN^{b} ≈ AC^{b} ≈ NEM^{b} ≈ CON^{b} > AN^{c} ≈ LUS^{c}
Exchangeable Na (Na_{ex})	mg kg^{-1}	188	8	807	70	91	MS^{a} > CON^{b} ≈ AN^{b} ≈ BOR^{b} ≈ AC^{b} ≈ LUS^{b} ≈ MN^{b} ≈ PAN^{b} ≈ NEM^{b}
Available B (B_{av})	mg kg^{-1}	186	0.04	2.73	0.40	0.43	MS^{a} > CON^{b} > PAN^{c} ≥ MN^{cd} ≈ AC^{cd} ≥ NEM^{de} ≈ AN^{de} ≈ BOR^{de} ≥ LUS^{e}
Available Cu (Cu_{av})	mg kg^{-1}	188	0.12	50.23	1.67	3.74	PAN^{a} ≈ AC^{a} ≥ BOR^{ab} ≈ LUS^{ab} ≥ CON^{b} ≥ AN^{bc} ≥ MS^{c} ≈ MN^{c} ≈ NEM^{c}
Available Fe (Fe_{av})	mg kg^{-1}	188	1.30	345.90	55.50	60.60	BOR^{a} > AC^{b} ≥ LUS^{bc} ≥ NEM^{c} > AN^{d} ≥ CON^{de} ≥ PAN^{e} > MN^{f} ≈ MS^{f}
Available Mn (Mn_{av})	mg kg^{-1}	188	2.20	82.70	13.10	10.60	AN^{a} ≈ PAN^{a} ≈ CON^{a} ≈ LUS^{ab} ≥ NEM^{ab} ≈ AC^{b} ≈ BOR^{b} ≈ MN^{b} ≈ MS^{b}
Available Zn (Zn_{av})	mg kg^{-1}	188	0.10	64.90	4.40	8.20	CON^{a} > AC^{b} ≥ LUS^{bc} ≥ PAN^{c} ≈ AN^{c} ≈ NEM^{c} ≈ BOR^{c} ≈ MN^{c} ≈ MS^{c}
Wheat Yield (WY)	kg ha^{-1}	174	250	12,300	3970	2606	AC^{a} ≥ AN^{ab} ≥ CON^{b} ≈ PAN^{bc} ≥ NEM^{c} ≥ BOR^{cd} ≥ MN^{de} ≈ MS^{de} ≥ LUS^{e}

n, number of valid samples. Different letters at each pedoclimatic zone mean statistically significant differences in the measured parameter ($p < 0.05$)

Table 2 Spearman's correlation analysis between measured soil nutrients, climatic variables, specific agricultural practices and wheat type (winter- vs. spring-sown)

	WY	TN	NH_4^+	NO_3^-	NO_2^-	Mineral N	P_{av}	K_{ex}	Ca_{ex}	Mg_{ex}	Na_{ex}	SO_4^{2-}	B_{av}	Cu_{av}	Fe_{av}	Mn_{av}	Zn_{av}
T_{12m}	**−0.42****	**−0.48****	**0.16***	**−0.26****	**−0.26****	**−0.25****	**−0.19****	**0.20****	**0.17***	0.14	**0.16***	**0.29****	**0.49****	−0.11	**−0.63****	**−0.18***	**−0.22****
P_{12m}	0.13	**0.53****	0.08	**0.23****	**0.24****	**0.19****	**0.40****	**−0.27****	**−0.47****	**−0.46****	**−0.28****	**−0.31****	**−0.60****	0.01	**0.53****	**0.21****	**0.20****
Manag Org	**−0.36****	0.13	**0.15***	**−0.18***	−0.14	**−0.18***	**−0.17***	−0.05	0.00	**0.14***	0.06	**−0.33****	−0.12	−0.07	0.01	0.01	−0.05
Monoculture	**−0.25****	**−0.19****	0.07	−0.06	−0.07	−0.06	0.00	0.03	−0.10	−0.09	−0.06	**0.15***	−0.05	−0.06	−0.13	−0.14	−0.10
Legume Inc	−0.01	**0.27****	0.10	−0.01	0.14	0.00	**−0.18***	−0.08	0.12	**0.26****	−0.01	**−0.22****	−0.03	0.02	**0.17***	−0.08	−0.10
Crop Inc	**0.23****	**0.25****	−0.03	**0.18***	0.12	**0.18***	0.14	−0.07	−0.04	0.08	0.04	−0.10	−0.14	**0.23****	**0.36****	0.00	0.14
Tillage Red	**0.27****	**0.17***	−0.01	0.00	**−0.20***	−0.02	**0.19***	0.01	−0.10	−0.13	−0.01	0.05	−0.13	**0.22****	**0.18***	−0.03	**0.26****
Fertilization	**0.36****	0.11	−0.09	**0.20****	**0.28****	**0.20****	**0.21****	0.02	0.02	−0.10	0.06	−0.01	**−0.17***	**0.15***	**0.15***	0.09	0.05
Fert Org	**−0.18***	**0.15***	0.07	−0.02	0.04	−0.03	0.07	0.08	0.04	0.12	**0.15***	−0.08	−0.11	0.09	0.04	0.04	0.03
Fert Min	0.13	0.06	0.00	0.08	0.16	0.08	0.05	−0.08	0.01	**−0.16***	**−0.24****	0.08	**−0.15***	−0.09	0.04	−0.02	−0.14
Fert Org + Min	**0.47****	−0.13	**−0.17***	**0.16***	0.09	**0.17***	0.08	0.00	−0.04	−0.09	0.12	0.01	0.11	0.13	0.07	0.06	**0.17***
Winter wheat	**0.15**$*$	**−0.48**$**$	**−0.27**$**$	−0.01	−0.01	−0.01	**−0.22**$**$	**0.18**$**$	**0.14**$*$	0.01	**0.38**$**$	**0.33**$**$	**0.39**$**$	−0.11	**−0.49**$**$	0.01	0.03
WY		−0.03	**−0.23****	**0.20**$**$	0.03	**0.20**$**$	−0.07	0.04	**0.23****	−0.09	−0.07	**−0.17***	−0.00	0.07	0.01	**0.15***	**0.28****

**Significant at $p < 0.01$; * significant at $p < 0.05$. T_{12m}, mean annual temperature during the 12 months preceding the sampling campaigns (ºC); P_{12m}, mean annual precipitation during the 12 months preceding the sampling campaigns (mm); *Manag Org*, organic farming system (n = 95); *Monoculture* (n = 17); *Legume Inc*, legume in the rotation (n = 59); *Crop Inc*, incorporation of crop residues into the soil (n = 38); *Tillage Red*, no tillage, minimum tillage, or reduced tillage (n = 44); *Fertilization* (n = 147); *Fert Org*, organic fertilization (n = 74); *Fert Min*, mineral fertilization (n = 37); *Fert Org + Min*, organomineral fertilization (n = 36); *WY*, wheat yield; *TN*, total N; K_{ex}, Ca_{ex}, Mg_{ex}, and Na_{ex}, exchangeable K, Ca, Mg, and Na, respectively; P_{av}, B_{av}, Cu_{av}, Fe_{av}, Mn_{av}, and Zn_{av}, available P, B, Cu, Fe, Mn, and Zn across soils. NH_4^+ ranged from 1.1 to 9.7 mg kg^{-1} (mean 3.2 ± 1.4 mg kg^{-1}), NO_3^- from 17.4 to 188.2 mg kg^{-1} (mean 72.9 ± 30 mg kg^{-1}), NO_2^- from 1.4 to 11.7 mg kg^{-1} (mean 6.6 ± 3.1 mg kg^{-1}), and total mineral nitrogen from 22.8 to 204.1 mg kg^{-1} (mean 81.2 ± 32 mg kg^{-1}) (Table 1). The highest total mineral nitrogen levels were observed in the AN and BOR zones, while the lowest ones were found in the CON and PAN zones (Tables 1 and S2). Similar to TN, total mineral nitrogen was negatively correlated with T_{12m} ($r = -0.25$, $p < 0.01$) and positively correlated with P_{12m} ($r = 0.19$, $p < 0.01$) (Table 2).

Figure 1 shows the average values of TN (Fig. 1a) and TMN (Figs. 1b-e) at each pedoclimatic zone and farming system. No consistent pattern emerged when comparing farming systems within individual zones, and higher or lower N levels under organic or conventional management depended on the specific pedoclimatic zone. However, when all samples were analyzed collectively ($n = 188$), TN, NO_3^-, and TMN differed significantly between systems. Accordingly, TN was higher under organic farming, whereas NO_3^- and TMN were higher under conventional farming. Consistently, NO_3^- and TMN were negatively correlated with organic management ($r = -0.18$, $p < 0.05$), while NH_4^+ showed a positive correlation ($r = 0.15$, $p < 0.05$) (Table 2). NH_4^+ and NO_2^- did not differ significantly between systems.

Regarding specific management practices, TN was positively correlated with legume incorporated ($r = 0.27$, $p < 0.01$), crop residue incorporation ($r = 0.25$, $p < 0.01$), reduced tillage ($r = 0.17$, $p < 0.05$), and organic fertilization ($r = 0.15$, $p < 0.05$), and negatively correlated with monoculture ($r = -0.19$, $p < 0.01$) (Table 2). NO_3^- and TMN were positively correlated with crop residue incorporation ($r = 0.18$, $p < 0.05$), fertilization ($r = 0.20$, $p < 0.01$), and organo-mineral fertilization ($r = 0.16$ and $p < 0.05$ for NO_3^-; $r = 0.17$ and $p < 0.05$ for TMN).

Finally, wheat type (winter- vs. spring-sown) also had a significant effect on soil nitrogen levels. In this sense, winter wheat was significantly and negatively correlated with TN ($r = -0.48$, $p < 0.01$) and NH_4^+ ($r = -0.27$, $p < 0.01$) (Table 2).

Available P and exchangeable K

Available phosphorus (P_{av}) varied widely across soils ($n = 188$), ranging from 4.4 to 262.9 mg kg^{-1} (mean 48.9 ± 48.9 mg kg^{-1}) (Table 1), with significant differences among pedoclimatic zones. The highest P_{av} values occurred in LUS and AC, and the lowest in MN and MS (Tables 1 and S3). In fact, P_{av} was negatively correlated with T_{12m} ($r = -0.19$, $p < 0.01$) and positively with P_{12m} ($r = 0.40$, $p < 0.01$) (Table 2).

Exchangeable potassium (K_{ex}) also showed high variability (53–1105 mg kg^{-1}; mean 231 ± 141 mg kg^{-1}) and differed significantly among zones. Accordingly, the highest K_{ex} levels were found in CON, MS, and AC, and the lowest in MN and NEM (Tables 1 and S3). Unlike P_{av}, K_{ex} was positively correlated with T_{12m} ($r = 0.20$, $p < 0.01$) and negatively with P_{12m} ($r = -0.27$, $p < 0.01$) (Table 2).

The P_{av} levels were higher under conventional farming in LUS, MN, MS, and NEM (Fig. 2a), consistent with a negative correlation with organic management ($r = -0.17$, $p < 0.05$), although no overall difference was observed when all soils were considered collectively. On the other hand, K_{ex} was higher under organic farming in AN but higher under conventional management in NEM (Fig. 2b), showing no consistent trend across systems.

For more specific management practices, P_{av} was negatively correlated with legume incorporated in the rotation ($r = -0.18$, $p < 0.05$) and positively correlated with reduced tillage ($r = 0.19$, $p < 0.05$) and fertilization ($r = 0.21$, $p < 0.01$) (Table 2). In contrast, K_{ex} did not show significant associations with any of the agricultural practices considered.

Finally, regarding wheat type, P_{av} showed a significant negative correlation with winter wheat ($r = -0.22$, $p < 0.01$), while K_{ex} was significantly and positively correlated ($r = 0.18$, $p < 0.01$) (Table 2).

Secondary macronutrients and exchangeable sodium

Available sulphate

Available sulphate (as SO_4^{2-}) content ranged from 2 to 512 mg kg^{-1}, with a mean of 29 ± 67 mg kg^{-1} across all soils studied, showing little variation among pedoclimatic zones (Tables 1 and S4). Soils from the MS zone exhibited significantly higher SO_4^{2-} concentrations than those from other zones, while no significant differences were observed among the remaining zones (Table 1). Despite the low variability across zones, SO_4^{2-} was positively correlated

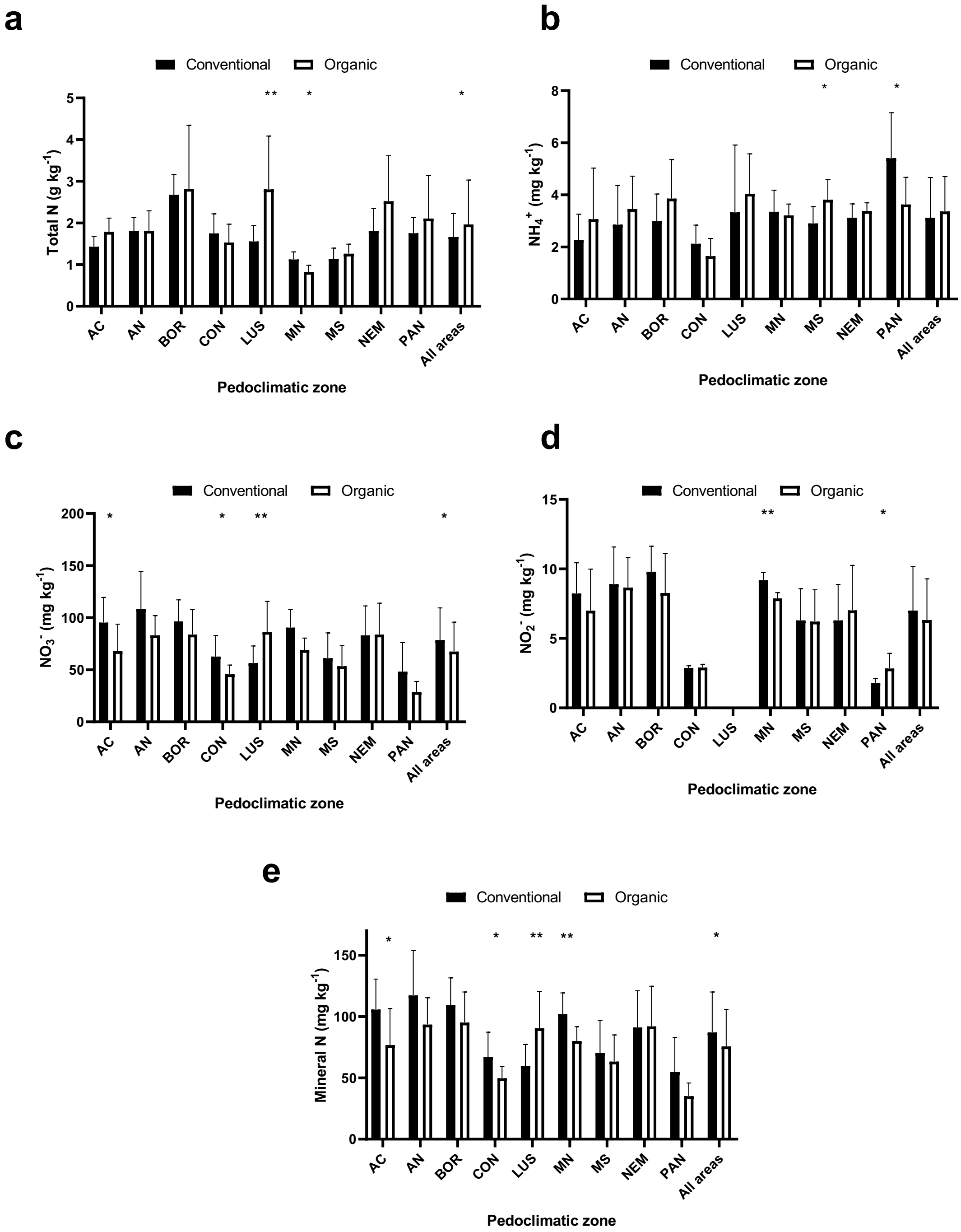

Fig. 1 Average values (±SD) of total soil nitrogen (Total N) (**a**), ammonium (NH_4^+) (**b**), nitrate (NO_3^-) (**c**), nitrite (NO_2^-) (**d**), and TMN ($NH_4^+ + NO_3^- + NO_2^-$) (**e**) measured in wheat soils at each of the studied pedoclimatic zones under conventional and organic farming systems. *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian. Asterisks above bars indicate significant differences between farming systems within each pedoclimatic zone and across all zones combined ("All areas") (* $p < 0.05$ and ** $p < 0.01$)

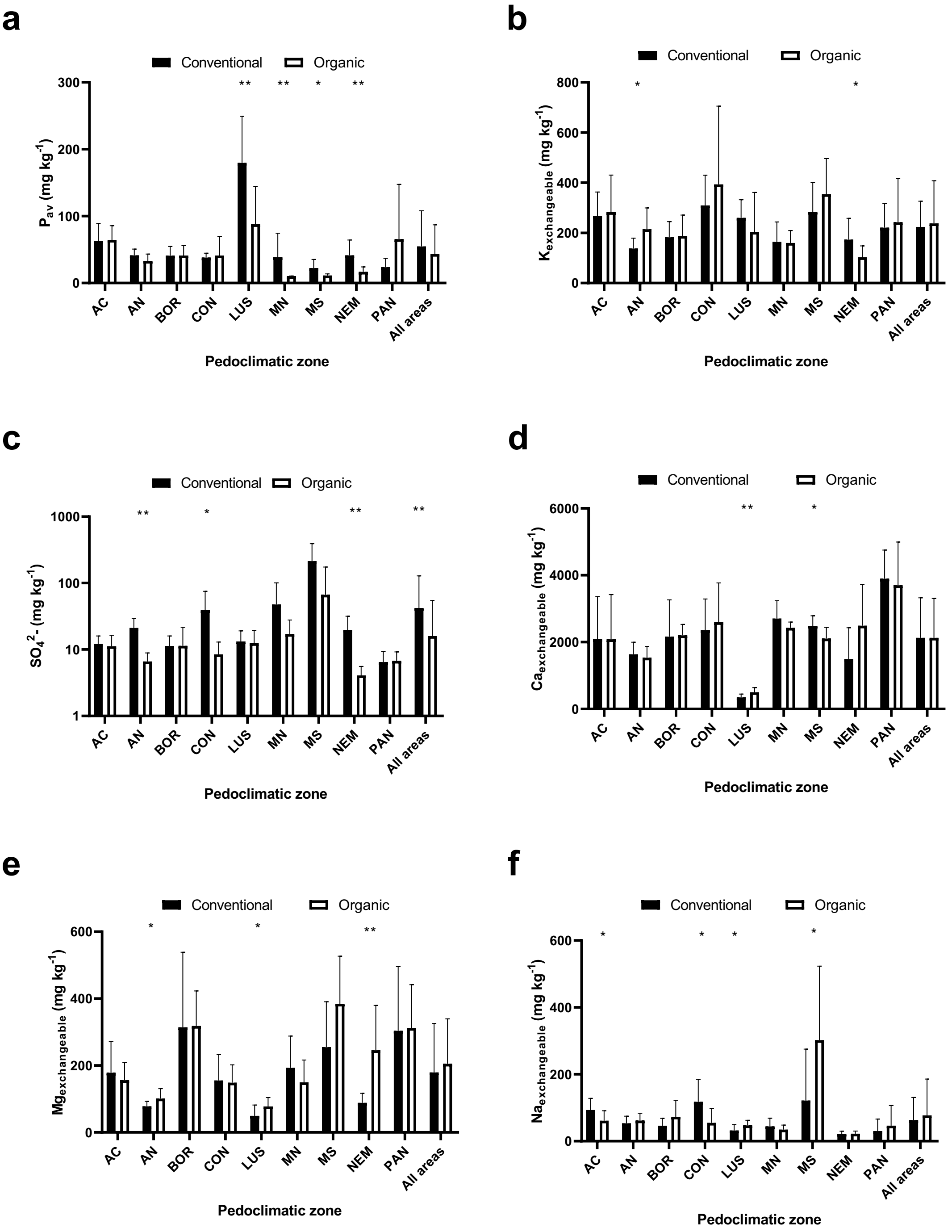

Fig. 2 Average values (±SD) of soil available P (P_{av}) (**a**), exchangeable K (**b**), sulphate (SO_4^{-2}) (**c**), exchangeable Ca (Ca_{ex}) (**d**), exchangeable Mg (Mg_{ex}) (**e**), and exchangeable Na (Na_{ex}) (**f**) measured in wheat-grown soils from the studied pedoclimatic zones under conventional and organic farming systems.. *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian. Asterisks above bars indicate significant differences between farming systems within each pedoclimatic zone and across all zones combined ("All areas") (* $p < 0.05$ and ** $p < 0.01$). For visualization, the sulphate contents are plotted on a logarithmic scale

with T_{12m} ($r = 0.29$, $p < 0.01$) and negatively correlated with P_{12m} ($r = -0.31$, $p < 0.01$) (Table 2).

Soils under conventional farming showed significantly higher SO_4^{2-} concentrations than those under organic farming in the LUS, MN, MS, and NEM zones (Fig. 2c). When all samples were analyzed collectively, SO_4^{2-} levels were also higher under conventional management (Fig. 2c), consistent with a significant negative correlation between SO_4^{2-} content and organic management ($r = -0.33$, $p < 0.01$) (Table 2).

Regarding specific agricultural practices, SO_4^{2-} content was positively correlated with monoculture ($r = 0.15$, $p < 0.05$) and negatively correlated with legume incorporation ($r = -0.22$, $p < 0.01$) (Table 2). Additionally, with respect to the influence of wheat type (winter- vs. spring-sown), SO_4^{2-} levels were negatively correlated with winter wheat ($r = -0.33$, $p < 0.01$) (Table 2).*Exchangeable calcium, magnesium, and sodium.*

Exchangeable calcium (Ca_{ex}), magnesium (Mg_{ex}), and sodium (Na_{ex}) ranged from 231 to 6098 mg kg^{-1} (mean 2128 ± 1186 mg kg^{-1}), 23 to 752 mg kg^{-1} (mean 192 ± 141 mg kg^{-1}), and 8 to 807 mg kg^{-1} (mean 70 ± 91 mg kg^{-1}), respectively (Table 1). Ca_{ex} and Mg_{ex} varied significantly across zones, with PAN and MS showing the highest Ca_{ex} and Mg_{ex} levels, respectively, and LUS exhibiting the lowest concentrations of both (Tables 1 and S4). In relation to this, Ca_{ex} and Mg_{ex} were negatively correlated with P_{12m} ($r = -0.47$ and $p < 0.01$ for Ca_{ex}; $r = -0.46$, $p < 0.01$ for Mg_{ex}), but Ca_{ex} was also positively correlated with T_{12m} ($r = 0.17$, $p < 0.05$) (Table 2).

Na_{ex} levels were relatively consistent across zones, with significantly higher values only in the MS zone (Tables 1 and S4). Despite this, Na_{ex} was negatively correlated with P_{12m} ($r = -0.28$, $p < 0.01$) and positively correlated with T_{12m} ($r = 0.16$, $p < 0.05$) (Table 2).

No consistent effect of farming system on Ca_{ex} was observed (Fig. 2d). Despite zone-specific differences, such as higher Ca_{ex} under organic management in LUS and higher Ca_{ex} under conventional management in MS, they did not reflect a broader trend. Similarly, Mg_{ex} showed no overall difference between systems, but in AN, LUS, and NEM zones, soils under organic management had significantly higher Mg_{ex} than in conventional systems (Fig. 2e), consistent with a positive correlation with organic farming ($r = 0.14$, $p < 0.05$) (Table 2). For Na_{ex}, AC and CON soils showed higher values under conventional farming, whereas LUS and MS soils had higher Na_{ex} under organic farming (Fig. 2f), leading to a non-consistent overall trend. No significant differences were observed when all samples were analyzed collectively.

Regarding specific agricultural practices, Ca_{ex} was not significantly affected by any of the practices considered (Table 2). In contrast, Mg_{ex} was positively correlated with legume incorporation in the rotation ($r = 0.26$, $p < 0.01$) and negatively correlated with mineral fertilization ($r = -0.16$, $p < 0.05$), whereas Na_{ex} was positively correlated with organic fertilization ($r = 0.15$, $p < 0.05$) and negatively correlated with mineral fertilization ($r = -0.24$, $p < 0.01$) (Table 2).

Finally, regarding wheat type, both Ca_{ex} and Na_{ex} were positively correlated with winter wheat ($r = 0.14$, $p < 0.05$ for Ca_{ex}; $r = 0.38$, $p < 0.01$ for Na_{ex}).

Micronutrients (Fe, Mn, B, Zn and Cu)

The available contents of the studied micronutrients ranged across all soils (regardless of pedoclimatic zone or farming system) from 0.04 to 2.73 mg kg^{-1} for B, 0.12 to 50.23 mg kg^{-1} for Cu, 1.3 to 345.9 mg kg^{-1} for Fe, 2.2 to 82.7 mg kg^{-1} for Mn, and 0.1 to 64.9 mg kg^{-1} for Zn (Table 1). Concentrations of all micronutrients varied significantly among pedoclimatic zones. Available boron (B_{av}) was highest in soils from the MS zone and lowest in the LUS zone (Tables 1 and S5). Available copper (Cu_{av}) was highest in PAN and AC zones, and lowest in the Mediterranean zones (MS and MN) and the NEM zone (Tables 1 and S5). Available iron (Fe_{av}), manganese (Mn_{av}), and zinc (Zn_{av}) were highest in BOR, AN, and CON zones, respectively, whereas the Mediterranean zones (MN and MS) consistently showed the lowest values (Tables 1 and S5). This spatial variability was further supported by correlation analyses with climatic variables: B_{av} was positively correlated with T_{12m} ($r = 0.49$, $p < 0.01$) and negatively with P_{12m} ($r = -0.60$, $p < 0.01$), whereas Fe_{av}, Mn_{av}, and Zn_{av} were negatively correlated with T_{12m} ($r = -0.63$, $p < 0.01$ for Fe_{av}; $r = -0.18$, $p < 0.05$ for Mn_{av}; and $r = -0.22$, $p < 0.01$ for Zn_{av}) and positively correlated with P_{12m} ($r = 0.53$, $p < 0.01$ for Fe_{av}; $r = 0.21$, $p < 0.01$ for Mn_{av}; and $r = 0.20$, $p < 0.01$ for Zn_{av}) (Table 2).

Considering the effect of farming system across all soils, significant differences were observed only for B_{av}, which was higher under conventional farming (Fig. 3a). Zone-specific analysis revealed more complex patterns: conventional farming resulted in higher values of B_{av} in AC, CON, MS, and PAN, whereas organic farming led to higher contents of B_{av} in AN, LUS, and NEM (Fig. 3a). For Fe_{av}, soils under organic management had higher concentrations in NEM and PAN, whereas the opposite trend was observed in MN (Fig. 3c). Zn_{av} showed significant differences only in CON, with conventional farming producing the highest values (Fig. 3e). Finally, no significant farming system effects were observed for Cu_{av} or Mn_{av} in any of the investigated zones (Figs. 3b and 3 d).

Regarding specific agricultural practices, B_{av} was negatively correlated with overall fertilization ($r = -0.17$, $p < 0.05$) and mineral fertilization ($r = -0.15$, $p < 0.05$). Cu_{av} and Fe_{av} were positively correlated with crop residue incorporation ($r = 0.23$, $p < 0.01$ for Cu_{av}; $r = 0.36$, $p < 0.01$ for Fe_{av}), reduced tillage ($r = 0.22$, $p < 0.01$ for Cu_{av}; $r = 0.18$, $p < 0.05$ for Fe_{av}), and overall fertilization ($r = 0.15$, $p < 0.05$ for both). Zn_{av} was positively correlated with reduced tillage ($r = 0.26$, $p < 0.01$) and organo-mineral fertilization ($r = 0.17$, $p < 0.05$) (Table 2).

Finally, certain micronutrients also showed some association with wheat type. In this regard, B_{av} was positively correlated with winter wheat ($r = 0.39$, $p < 0.01$), whereas Fe_{av} was negatively correlated ($r = -0.49$, $p < 0.01$) (Table 2).

Wheat Yield

Wheat yield (WY) varied considerably across the studied soils, ranging from 250 to 12,300 kg ha^{-1}, with a mean of 3970 ± 2606 kg ha^{-1} (Table 1). Pedoclimatic zone had a significant effect on WY, with soils from the AC and AN zones showing the highest yields, while soils from MN, MS, and LUS zones recorded the lowest values (Tables 1 and S6). Furthermore, WY was negatively correlated with T_{12m} ($r = -0.42$, $p < 0.01$) (Table 2).

In addition to the pedoclimatic factor, significant differences were observed between farming systems within most zones. Soils under conventional farming exhibited significantly higher wheat yields than those under organic farming, except in the Mediterranean areas (MN and MS), where no significant differences were detected (Fig. 4). Nevertheless, in these Mediterranean zones, a tendency toward higher yields in conventional fields was still observed, despite the lack of statistical significance. Considering all soils collectively, WY was significantly higher under conventional farming (4930 ± 3014 kg ha^{-1}) than under organic farming (3079 ± 1756 kg ha^{-1}) (Fig. 4; Table S6). This finding is further supported by a significant negative correlation between WY and organic management($r = -0.36$, $p < 0.01$) (Table 2).

Regarding specific agricultural practices, WY was negatively correlated with monoculture ($r = -0.25$, $p < 0.01$) and organic fertilization ($r = -0.18$, $p < 0.05$), and positively correlated with crop residue incorporation ($r = 0.23$, $p < 0.01$), reduced tillage ($r = 0.27$, $p < 0.01$), fertilization in general ($r = 0.36$, $p < 0.01$), and organo-mineral fertilization ($r = 0.47$, $p < 0.01$) (Table 2). With respect to soil nutrients, WY showed significant positive correlations with NO_3^- ($r = 0.20$, $p < 0.01$), Ca_{ex} ($r = 0.23$, $p < 0.01$), Mn_{av} ($r = 0.15$, $p < 0.05$), and Zn_{av} ($r = 0.28$, $p < 0.01$), whereas it was negatively correlated with NH_4^+ ($r = -0.23$, $p < 0.01$) and SO_4^{2-} ($r = -0.17$, $p < 0.05$) (Table 2). Finally, wheat type also had a significant influence on WY, with a positive correlation observed between WY and winter wheat ($r = 0.15$, $p < 0.01$) (Table 2).

To further evaluate the combined effects of climate, soil nutrients, farming system, specific agricultural management practices, and wheat type on wheat yield, both Random Forest analysis and stepwise multiple regression were performed. The Random Forest model (Fig. 5a and b) identified climatic variables (T_{12m} and P_{12m}), farming system (Manag Org), fertilization type (Fert Org + Min), wheat type (winter wheat), and soil contents of Ca_{ex}, Fe_{av}, and P_{av} as the most important predictors of WY, collectively explaining 77% of its variance. The multiple linear regression model (Eq. 1) explained 62.9% of the variance, further highlighting that fertilization type, temperature, agricultural management practices, wheat type, and specific soil nutrient levels are key determinants for wheat productivity.

$$\text{Wheat Yield} = (5249 \pm 830) + (2468 \pm 406)FertOrgMin + (1437 \pm 307)WhinterWheat - (1231 \pm 334)ManagOrg + (1290 \pm 330)CropInc + (915 \pm 331)TillRed - (868 \pm 450)Monoculture + (454 \pm 427)FertMin - (291 \pm 55)T12m + (21 \pm 12)Mn_{av} + (19 \pm 17)Zn_{av} - (4.9 \pm 2.6)Fe_{av} + (1.5 \pm 1.0)K_{ex} + (0.4 \pm 0.1)Ca_{ex} \tag{1}$$

$F = 23.610; p - \text{value} < 0.000; \text{adjusted } R^2 = 0.629$

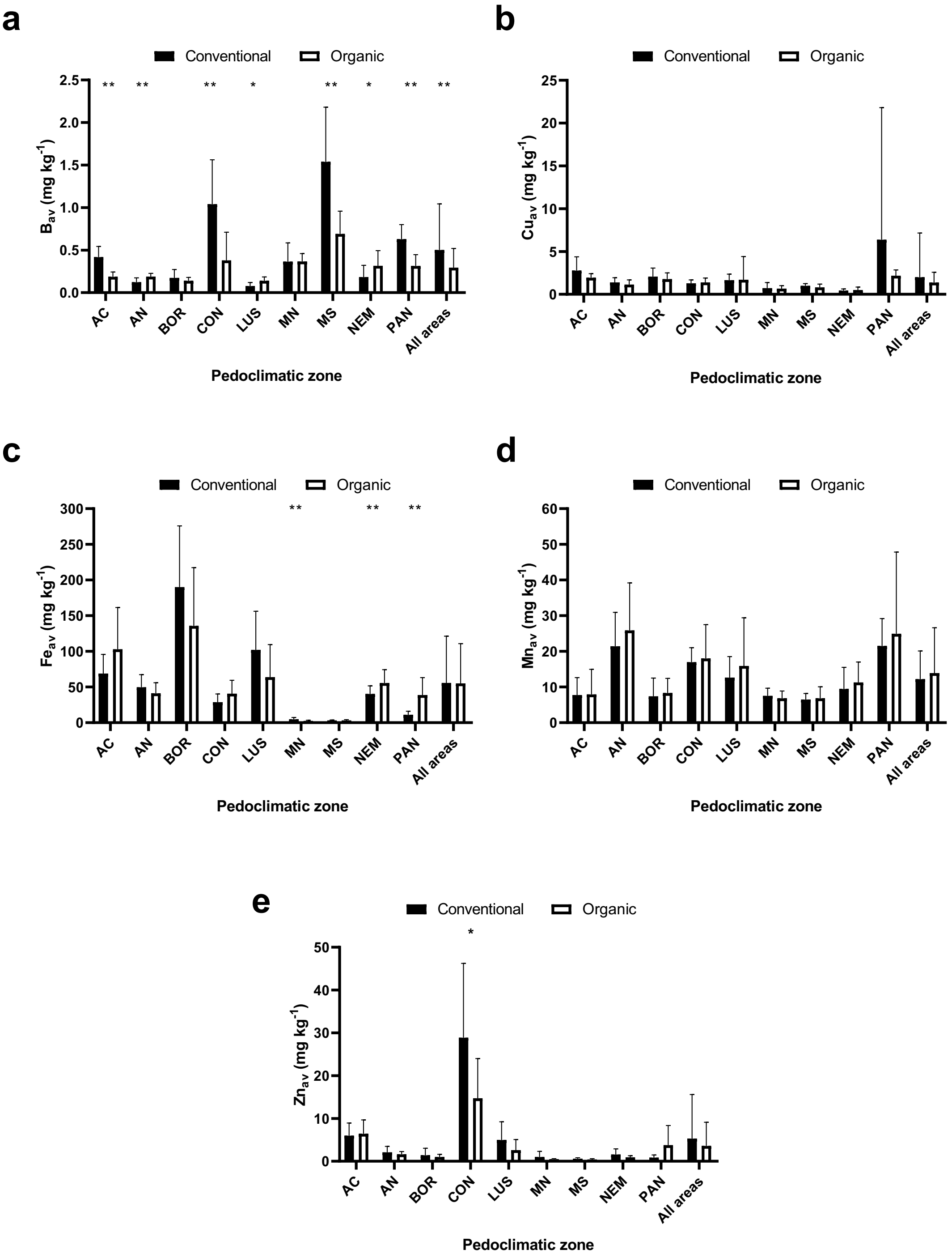

Fig. 3 Average values (± SD) of soil available B (B_{av}) (**a**), available Cu (Cu_{av}) (**b**), available Fe (Fe_{av}) (**c**), available Mn (Mn_{av}) (**d**), and available Zn (Zn_{av}) (**e**) measured in wheat-grown soils from the studied pedoclimatic zones under conventional and organic farming systems. *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian. Asterisks above bars indicate significant differences between farming systems within each pedoclimatic zone and across all zones combined ("All areas") (* $p < 0.05$ and ** $p < 0.01$)

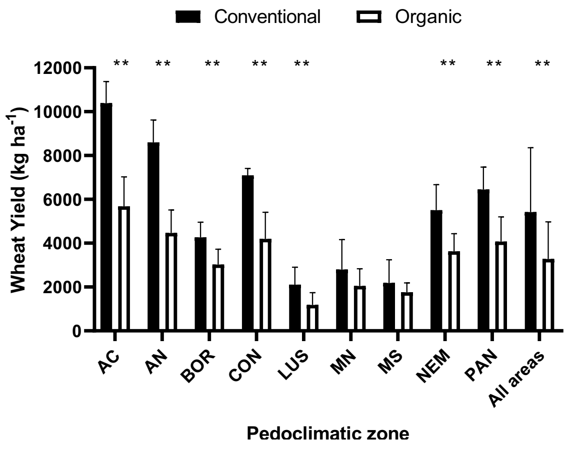

Fig. 4 Average values (±SD) of wheat yield (kg ha^{-1}) measured in wheat-grown soils from the studied pedoclimatic zones under conventional and organic farming systems. *AC*, Atlantic Central; *AN*, Atlantic North; *BOR*, Boreal; *LUS*, Lusitanian; *MN*, Mediterranean North; *MS*, Mediterranean South; *NEM*, Nemoral; *PAN*, Pannonian. Asterisks above bars indicate significant differences between farming systems within each pedoclimatic zone and across all zones combined ("All areas") (* $p < 0.05$ and ** $p < 0.01$)

Discussion

Primary macronutrients

Total nitrogen and nitrogen forms

The total N levels observed across European wheat fields in this study, averaging 1.81 ± 0.87 g kg^{-1}, are very similar to those reported by Fernández-Ugalde et al. (2022) in the LUCAS Soil Survey 2018, which documented 1.8 ± 1.3 g kg^{-1} across more than 7,000 croplands. Total N varied substantially among pedoclimatic zones, highlighting climate as the main driver of soil N dynamics (Ballabio et al. 2019). It should be noted, however, that soil samples were collected shortly after harvest, and therefore the measured N contents reflect post-harvest conditions rather than in-season nitrogen availability. Specifically, colder and wetter regions exhibited higher concentrations, likely because these conditions enhance biomass production while simultaneously slowing organic residue decomposition at low temperatures, thereby favoring organic matter accumulation (Rial et al. 2017; Fernández-Ugalde et al. 2022). Thus, the observed differences should be interpreted as relative

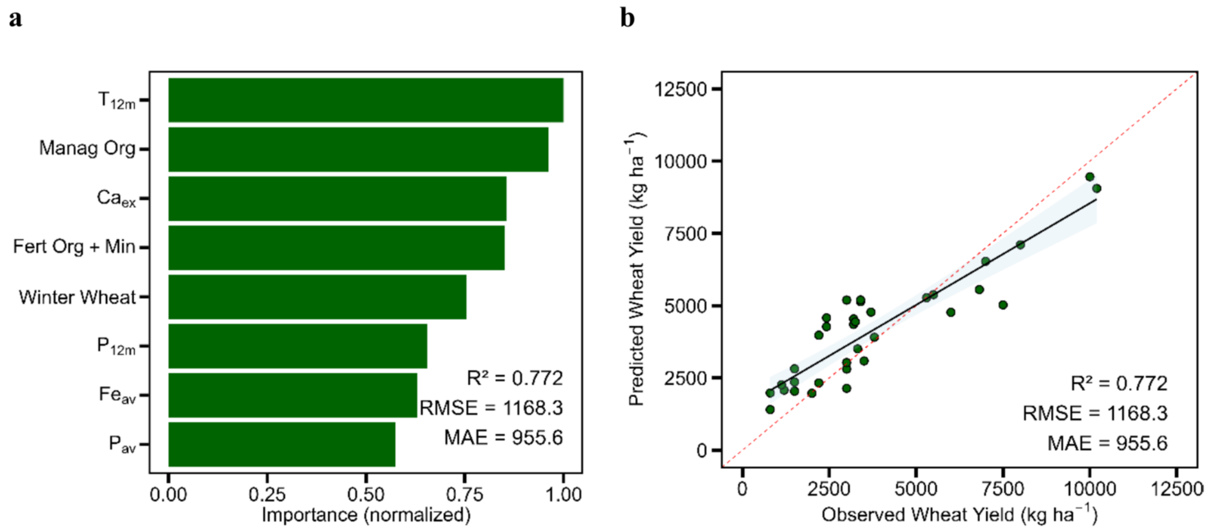

Fig. 5 Relative (normalized) importance of predictor variables in the Random Forest model for explaining wheat yield (WY) (**a**), and the relationship between observed and predicted values for wheat yield (**b**). The red dashed line represents the 1:1 reference line, while the black line shows the linear fit with its corresponding 95% confidence interval (CI)

patterns among pedoclimatic zones rather than absolute indicators of nitrogen availability during the wheat growing period.

The farming system also exerted a strong influence on soil N content. Soils under organic management generally contained higher total N, primarily in organic form, consistent with earlier studies (Reganold 1988; Chung and Lee 2008; Lorenz et al. 2024). This enrichment is attributable to practices such as the use of organic fertilizers, crop residue incorporation, and the application of organic amendments (Herencia et al. 2007; Chung and Lee 2008). The combination with other management practices reinforced these patterns. For instance, legume rotations enhanced N inputs through biological fixation (Barbieri et al. 2023), while reduced tillage promoted N retention by minimizing soil disturbance, thereby slowing mineralization and preserving organic matter in surface horizons (Tian et al. 2024).

The observed pattern in which organic farming increases NH_4^+ but lowers NO_3^- is consistent with previous findings (Kwiatkowski and Harasim 2020). Organic amendments typically result in slow release of NH_4^+, which is adsorbed to soil colloids, allowing for subsequent plant uptake as NH_4^+ or, after microbial nitrification, as NO_3^-. Hence, this slow-release mechanism aligns N availability with crop uptake, thereby reducing losses through N leaching and volatilization (Herencia et al. 2007; Sheoran et al. 2019; Kwiatkowski and Harasim 2020). By contrast, synthetic fertilizers commonly applied in conventional systems deliver N primarily as NO_3^-, which allows rapid plant uptake but increases the risk of leaching when timing or uptake efficiency is suboptimal (Wang et al. 2018; Kwiatkowski and Harasim 2020).

The negative association of winter wheat with soil TN and NH_4^+ may be attributable to its longer growth cycle and more extensive nitrogen uptake compared with spring wheat, consistent with findings that winter wheat can exploit deeper soil nitrogen pools and thus remove more N from soil than spring wheat (Thorup-Kristensen et al. 2009). Considering that optimal NO_3^- concentrations for wheat cultivation range from 24.5 to 65.5 mg kg^{-1} (Yang et al. 2024), approximately 59% of the soils analyzed exceeded this range, while only six soils (≈3%) were deficient. Overall, these findings suggest that fertilization strategies based on organic amendments and lower mineral N inputs can sustain adequate NO_3^- levels for wheat production, while simultaneously reducing the risk of nitrate leaching. Such management practices are characteristic of organic systems, but may also occur in mixed or conventional farms integrating livestock and organic residues.

Available P

Available phosphorus (P_{av}) levels varied markedly across pedoclimatic zones, with colder and wetter regions exhibiting the highest concentrations, a pattern consistent with earlier reports (Ballabio et al. 2019; Fernández-Ugalde et al. 2022) and largely attributable to the higher fertilization rates typically applied in humid climates (Ballabio et al. 2019; Muntwyler et al. 2024).

The optimal P_{av} range for wheat is 8.3–46 mg kg^{-1}, while concentrations above 80 mg kg^{-1} are considered excessive (Jordan-Meille et al. 2012; Nawara et al. 2017; Steinfurth et al. 2022; Van Eynde et al. 2025). In this study, more than one-third of soils exceeded the 46 mg kg^{-1} values, and over 14% surpassed 80 mg kg^{-1}. In contrast, only one sample from the Pannonian zone was deficient (< 8.3 mg kg^{-1}). These results indicate that, despite the substantial reductions in P application across the EU since the 1990 s, along with increased crop uptake due to higher yields (Panagos et al. 2022), excess phosphorus remains widespread in European croplands, as previously documented (Panagos et al. 2022; Batool et al. 2025; Van Eynde et al. 2025). This surplus poses major environmental risks, through leaching and runoff, by increasing water pollution, eutrophication, and algal blooms that compromise water quality, biodiversity, and human health (Panagos et al. 2022; Muntwyler et al. 2024; Batool et al. 2025). In this study, this problem was particularly acute in the Lusitanian zone, where P_{av} reached up to 262.9 mg kg^{-1} (average 127.7 mg kg^{-1}), and more than 60% of soils exceeded 80 mg kg^{-1}. Importantly, Van Eynde et al. (2025) estimated that P applications in the EU could be reduced by 21% without yield losses, underscoring the need to adjust inputs in regions with substantial surpluses.

Although some studies report higher P_{av} in organic systems, attributed to organic acids being released during amendment decomposition that decrease P sorption and increase availability (Herencia et al. 2007; Chung and Lee 2008), this increased trend was not observed here. In fact, the opposite pattern appeared in several zones, including LUS, MN, MS, and NEM, aligning with previous studies reporting lower P_{av} in organic compared to conventional systems (Gosling and Shepherd 2005; Kwiatkowski and Harasim 2020). The absence of a consistent trend in our study likely reflects variability in fertilizer inputs, and is supported by the observed positive association between P_{av} and fertilization (Table 2). Accordingly, higher P_{av} levels in conventional systems likely reflect greater contributions from mineral fertilizers compared to manure (Muntwyler et al. 2024).

Specific agricultural practices also influenced P_{av}. The decline in P_{av} associated with legumes in the rotations likely reflects the high P demand of forage legumes, which extract more P from the soil than other crops (Giacometti et al. 2021). By contrast, reduced tillage was associated with higher P_{av} than conventional tillage. Two factors could explain this outcome: first, conventional tillage incorporates phosphorus into the plow layer, diluting its concentration, whereas reduced tillage leaves it concentrated at the surface (Messiga et al. 2010; Kushwa et al. 2016). Second, reduced tillage tends to enhance soil organic matter, moisture, and biological activity, conditions that favor phosphorus mineralization under water-limited conditions and thereby increase surface P_{av} (Kushwa et al. 2016; Daryanto et al. 2017).

Similarly to what was observed for nitrogen, winter wheat was negatively associated with P_{av}. This pattern likely reflects the longer growth cycle of winter wheat compared with spring wheat, which allows for greater cumulative nutrient uptake over the season. The extended vegetative and early reproductive growth phases, combined with deeper and more extensive root systems, enable winter wheat to extract more nutrients from the soil, including phosphorus, resulting in lower soil P_{av} levels after harvest (Thorup-Kristensen et al. 2009).

In summary, European wheat-growing soils show clear phosphorus surpluses. Beyond routine soil testing to better align fertilizer inputs with crop requirements, targeted practices, such as incorporating legumes in the rotations, offer practical strategies to mitigate excess phosphorus and reduce its environmental impacts.

Exchangeable K

Soil exchangeable potassium (K_{ex}) levels, although comparable to those previously reported for European croplands (Fernández-Ugalde et al. 2022), generally exceeded the recommended range for wheat cultivation (80–160 mg kg^{-1}; Loke et al. 2014). In this sense, more than 65% of soils showed concentrations above 160 mg kg^{-1}. Excessive K_{ex} is a common feature of agricultural systems, typically resulting from the repeated application of synthetic cation-rich fertilizers (e.g. K^+, NH_4^+, Ca^{2+}) (Guo et al. 2016; Chaudhry et al. 2021) or organic manures (Bader et al. 2021; Martín-Lammerding et al. 2021). Such inputs can disrupt the balance among exchangeable cations and affect micronutrient bioavailability (Vázquez-Blanco et al. 2023).

K_{ex} levels also varied substantially across pedoclimatic zones, in line with Ballabio et al. (2019), who concluded that soil K distribution is strongly controlled by parent material and climate. In wetter and cooler areas, K_{ex} values were generally lower, reflecting both the coarser texture of soils in these regions and greater precipitation, which enhances cation leaching, including K_{ex}. Conversely, finer-textured soils with higher clay content, typical of drier regions with lower rainfall, retain more cations and reduce leaching losses of basic elements (Ballabio et al. 2019; Belay et al. 2023; Ma et al. 2023).

Regarding farming systems, K_{ex} levels were slightly higher in organically managed soils, likely due to cation release from organic amendments and the greater number of exchange sites provided by higher organic matter inputs (Chung and Lee 2008). However, these differences were not statistically significant.

Overall, these findings highlight the importance of routine soil testing to prevent nutrient surpluses and optimize fertilization. Such monitoring not only improves economic efficiency for farmers but also helps mitigate environmental risks associated with nutrient imbalances.

Secondary macronutrients and exchangeable sodium

Available sulphate

Sulfur (S) is essential for wheat production, and its deficiency reduces nitrogen-use efficiency while limiting both grain size and quality (Yesmin et al. 2021; Sharma et al. 2024). Hue et al. (1984) estimated that a minimum soil *sulphate* (SO_4^{2-}) concentration of 18 mg kg^{-1} is required to achieve maximum growth, while Yesmin et al. (2021) classified SO_4^{2-} levels in wheat soils as low (< 45 mg kg^{-1}), medium (45–75 mg kg^{-1}), or high (> 75 mg kg^{-1}). Based on these thresholds, approximately 68% of the soils analyzed in this study were deficient (< 18 mg kg^{-1}), whereas fewer than 10% contained high levels (> 75 mg kg^{-1}). These findings are consistent with those of Yu et al. (2021), who reported a widespread decline in available sulfate in recent decades, largely due to reduced atmospheric sulfur deposition and modern agricultural practices that decrease sulfur inputs while increasing sulfur outputs through intensive cropping systems with high yields.

Although SO_4^{2-} levels varied considerably among soils, differences across pedoclimatic zones were modest, except in the MS zone, which exhibited significantly higher concentrations than the rest (Table 1). Nonetheless, sulfate availability was linked to climate (Table 2), and thus, in cooler and wetter regions, higher rainfall promotes leaching of SO_4^{2-}, whereas warmer temperatures in Mediterranean regions (MS and MN) accelerate organic matter mineralization and enhance sulfate release (Table S4; Fig. 2c). Farming system also influenced sulfate availability. Overall, conventional systems contained higher SO_4^{2-} concentrations, in agreement with Paulsen (2005), who noted that organic amendments typically supply little sulfur. In colder regions, particularly AN, CON, and NEM, where significant differences between the two systems were observed, low temperatures likely slowed organic matter decomposition and, consequently, organic sulfur mineralization, leading to reduced SO_4^{2-} availability under organic management. By contrast, conventional systems regularly receive sulfate-based fertilizers, which directly replenish soil sulfate and prevent depletion. In Mediterranean regions, however, higher temperatures promote rapid mineralization of organic matter and subsequent sulfate release, explaining both generally higher SO_4^{2-} levels and the absence of significant differences between farming systems (Itanna 2005; Chen et al. 2022).

Finally, regarding specific practices, crop rotation was associated with lower SO_4^{2-} availability compared with wheat monoculture. This pattern likely reflects the higher sulfur demand of other crops commonly included in rotations, such as oilseeds, crucifers, and legumes, relative to wheat (Sharma et al. 2024).

Exchangeable calcium, magnesium, and sodium

Calcium (Ca) and magnesium (Mg) are essential for wheat growth and development, fulfilling multiple physiological roles. Their deficiency reduces grain weight and negatively affects grain quality (Dolatabadian et al. 2013; Wang et al. 2020). According to Urbano-Terrón (1995), soils with Ca_{ex} contents below 700 mg kg^{-1} are considered very poor, 700–2000 mg kg^{-1} poor, 2000–4000 mg kg^{-1} medium, and above 4000 mg kg^{-1} rich. Similarly, soils with Mg_{ex} below 80 mg kg^{-1} are classified as very poor, 80–300 mg kg^{-1} poor, 300–600 mg kg^{-1} medium, 600–900 mg kg^{-1} rich, and above 900 mg kg^{-1} very rich. Based on these thresholds, more than 47% of the soils analyzed were poor or very poor in Ca_{ex}, and over 84% were poor or very poor in Mg_{ex}.

Exchangeable Ca, Mg, and Na exhibited substantial geographic variability, with the wettest areas showing the lowest concentrations. This pattern is consistent with the well-established influence of rainfall: higher precipitation enhances the leaching of basic cations, whereas arid and semi-arid regions experience minimal leaching, leading to cation accumulation in surface horizons (Belay et al. 2023).

No consistent trend in Ca_{ex} was observed across farming systems, in line with previous findings (Reganold 1988). By contrast, both Mg_{ex} and Na_{ex} were lower in soils that received only mineral fertilization, suggesting that organic amendments enhance the levels of these cations, consistent with earlier studies (Chung and Lee 2008; Kwiatkowski and Harasim 2020). The higher Mg_{ex} and Na_{ex} concentrations observed under organic management are likely due to the cation-rich composition of organic amendments, particularly animal manures (Hao and Chang 2001; Lishan and Alemu 2024), as well as the greater number of exchange sites provided by higher organic matter inputs (Chung and Lee 2008; Zhang et al. 2015; Lishan and Alemu 2024).

Given the widespread deficiencies in Ca and Mg identified in these soils, the use of organic amendments within organic farming systems is highly recommended to increase basic cation availability. However, this practice may also elevate Na levels, posing risks of salinity and sodicity. Therefore, routine soil testing prior to fertilization is strongly advised to ensure appropriate nutrient management.

Micronutrients

Although required only in trace amounts, micronutrients are essential for plant growth and crop productivity. Critical thresholds for optimal wheat production have been proposed by several authors (Lindsay and Norwell 1978; Agrawal 1992; Voss 1998; Chung and Lee 2008; Brdar-Jokanović 2020): 0.5–2 mg kg^{-1} for B, 0.4–0.8 mg kg^{-1} for Cu, 2.5–5 mg kg^{-1} for Fe, 1–5 mg kg^{-1} for Mn, and 0.6–0.8 mg kg^{-1} for Zn. Values outside these ranges may indicate potential deficiency or toxicity.

Available boron (B_{av}) was deficient in the majority of the investigated soils, with over 75% of samples below 0.5 mg kg^{-1}. Exceptions occurred in certain pedoclimatic zones, such as the MS, where some soils exhibited very high B_{av} concentrations. Previous studies (Goldberg 1997) have also found that B deficiency is more common in coarse-textured soils under humid conditions, whereas excesses typically occur in arid and semi-arid regions. These patterns result from the interplay of climate and soil properties: in humid regions, abundant rainfall combined with acidic, sandy soils enhances B mobility and leaching, often leading to deficiency, while higher organic matter content can further immobilize B through complexation. Conversely, in arid and warmer regions, alkaline, clay-rich soils with low precipitation restrict B mobility, favoring accumulation in surface horizons (Goldberg 1997; Dhassi et al. 2019; Thakur and Kumar 2020).

Management practices also affected B_{av}. Levels were negatively associated with mineral fertilization, likely due to antagonistic interactions with other nutrients supplied in chemical fertilizers, such as Mg, SO_4^{2-}, P, and Zn (Kaya et al. 2009; Mühlbachová et al. 2018, 2020). Overall, conventional farming systems exhibited higher B_{av} than organic systems, although this difference diminished in zones with high organic matter content, such as AN, BOR, LUS, and NEM regions, where B is expected to be strongly bound in organic complexes.

In contrast to B, most other micronutrients were present in excess relative to crop requirements. More than 70% of soils had Cu concentrations above 0.8 mg kg^{-1}, 81% exceeded 5 mg kg^{-1} for Fe, 83% surpassed 5 mg kg^{-1} for Mn, and 67% had Zn levels above 0.8 mg kg^{-1}. Despite this general abundance, Fe availability in MN and MS soils approached or fell below critical thresholds, likely due to low Fe solubility under alkaline conditions (pH 7.4–8.5) typical of these Mediterranean regions (Prasad and Power 1997; Fernández-Calviño et al. 2023). Although Mn, Cu, and Zn were often in excess, levels remained below toxicity thresholds (140–200 mg kg^{-1} for Mn, 17–25 mg kg^{-1} for Cu, 15–20 mg kg^{-1} for Zn) (Sillanpää 1982; Fan et al. 2012), except in CON soils, where Zn reached up to 64 mg kg^{-1} (Fig. 3e).

Geographic variability was pronounced for Fe, Mn, and Zn, contents being lowest in warm, arid areas and the highest in cooler and humid zones. These differences are largely explained by soil pH and organic matter content, which regulate micronutrient bioavailability beyond total metal content (Moreno-Jiménez et al. 2021). High organic matter and low pH in humid and cold regions enhance Fe, Zn, and Mn availability (Ballabio et al. 2019; Zhou et al. 2024), whereas the combination of low organic matter and high pH in warm, arid soils reduces solubility and promotes the formation of insoluble mineral species, limiting bioavailability. Organic matter further increases availability by forming soluble chelates, enhancing reducing conditions, raising cation exchange capacity, and supplying additional nutrients that increase decomposition of plant residues and microbial biomass (Dhaliwal et al. 2019). Together, these processes explain why soils rich in organic matter tend to exhibit higher bioavailable micronutrient levels, even under contrasting climates.

Finally, specific agricultural practices also influenced micronutrient dynamics. In this sense, the incorporation of crop residues was associated with higher Cu and Fe availability, while reduced tillage enhanced Cu, Fe, and Zn levels. These effects can be explained by several mechanisms. Crop residues recycle a substantial proportion of micronutrients absorbed by plants, up to 50–80% for Zn, Cu, and Mn, while also enriching soil organic matter, promoting the formation of organo-metallic complexes, and stimulating microbial activity, all of which increase micronutrient availability (Dhaliwal et al. 2019; Fu et al. 2021; Mirzaei et al. 2021). In parallel, reduced tillage helps to preserve organic matter and soil structure, thereby minimizing leaching and erosion. It also maintains more stable microenvironments that favor gradual mineralization and nutrient release, ultimately enhancing micronutrient supply to crops (Angon et al. 2023; Calistru et al. 2024).

Wheat yield

Wheat yield across European soils varied substantially among pedoclimatic zones, reflecting a complex interplay of climatic conditions, soil nutrient availability, farming systems, specific management practices, and wheat type. Random Forest analysis indicated that climatic variables, particularly temperature, wheat type (winter- vs. spring-sown), and farming system (conventional vs. organic) were the primary determinants of yield, consistent with previous studies (Lobell et al. 2002; Seufert et al. 2012; Ray et al. 2014; de Cárcer et al. 2019). For example, Ray et al. (2014) estimated that up to 66% of global wheat yield variability can be attributed to climate, whereas Lobell et al. (2002) found that management accounted for over 80% of yield variability in a field study in northwestern Mexico. Similarly, Farhadi et al. (2024) reported that 63% of wheat yield variation was explained by climate (temperature and precipitation) and 37% by management practices in northeastern Iran.

Temperature emerged as the dominant climatic factor directly affecting wheat yield, while precipitation had a comparatively smaller influence (Lobell and Field 2007; Pirttioja et al. 2015; Demirhan and Bayraktar 2025). Wheat generally performs best under mild conditions, with an optimal mean growing-season temperature of 17–23 °C. In addition, exceeding maximum thresholds at critical phenological stages (32.7 °C from sowing to emergence, 31 °C at anthesis, and 35.4 °C during grain filling) accelerates development, shortens the grain-filling period, reduces dry matter accumulation, and ultimately lowers yields (Pirttioja et al. 2015; Porter and Gawith 1999). Although precipitation plays a smaller role than temperature, water availability remains critical, and drought during reproductive and grain-filling stages significantly reduces yields (Zhao et al. 2020; Wan et al. 2022; Xu et al. 2023).

These climatic patterns explain the observed yield differences: the warmest and driest zones, such as MN and MS, exhibited the lowest wheat yields, whereas cooler regions with moderate precipitation, such as AC and AN, recorded the highest yields. These results also suggest that climate change may negatively affect wheat production in southern Europe, with Hristov et al. (2020) projecting a yield reduction up to 49% by 2050, primarily due to heat stress and drought.

Climate also indirectly influences wheat yield by affecting nutrient availability. Accordingly, cooler, wetter regions, which exhibited the highest yields, also showed higher levels of nitrogen (total and mineral), available phosphorus, and micronutrients such as Fe, Mn, and Zn.

Regarding farming systems, wheat yields were on average 37% lower under organic compared to conventional systems, with the largest yield gap in the AC zone (45%) and the smallest in Mediterranean zones (19–27%). This aligns with previous reports of 15–46% yield reductions under organic farming (Jones et al. 2010; Murphy et al. 2007; Bilsborrow et al. 2013; Annicchiarico et al. 2010; Campiglia et al. 2015; Verdi et al. 2022). Cereals, including wheat, typically show the largest yield gaps between organic and conventional systems because high-yielding varieties have been optimized for high-input conventional agriculture (Ponisio et al. 2014). In addition, lower yields in organic systems are mainly linked to reduced nutrient inputs, particularly N and P, a pattern confirmed in the present study, where organic fertilization negatively affected wheat yield, while mineral and organo-mineral fertilization enhanced it. Nevertheless, as most soils exceeded crop nutrient requirements, lower nutrient availability alone does not fully explain the yield gap. Previous studies on organic wheat indicate that yield reductions may also be related to a limited synchrony between nitrogen supply and crop demand, as nitrogen from organic sources is released gradually through mineralization processes and may not coincide with periods of peak N uptake by the crop, whereas mineral fertilizers provide immediately available nitrogen that can be more easily timed to match crop requirements (Cox et al. 2019).

The wheat type (winter- vs. spring-sown) also emerged as a key determinant of wheat yield, in agreement with previous studies (Entz and Fowler 1991; Thorup-Kristensen et al. 2009). For example, based on multiple field trials conducted in Canada, Entz and Fowler (1991) reported that winter wheat outyielded spring wheat by an average of 36%. This yield advantage has been primarily attributed to the longer growing period of winter wheat, which allows for extended biomass accumulation and resource acquisition over time (Entz and Fowler 1991). Consistent with this interpretation, in the present study, fields cultivated with winter wheat showed lower soil total nitrogen (TN), ammonium (NH_4^+), and available phosphorus (P_{av}) levels compared with those under spring wheat. This pattern likely reflects the greater cumulative nutrient uptake associated with the longer growing cycle of winter wheat (approximately eight months versus four months for spring wheat). Although root growth rates are generally comparable between winter and spring wheat, the extended duration of winter wheat growth allows roots to explore a larger soil volume and greater depth, resulting in lower residual soil N and P levels after harvest (Thorup-Kristensen et al. 2009).

The absence of synthetic pesticides is another critical factor in determining wheat productivity. Hossard et al. (2014) estimated that reducing pesticide application by half can reduce yields by 5–13%, while complete exclusion can lead to 24–33% losses. The regional patterns observed in the present study indicate that yield differences between farming systems were smaller in Mediterranean regions, where high temperatures and frequent water stress reduce pest survival, and larger in Atlantic regions, where mild, humid climates favor pest proliferation (Bregaglio et al. 2013; Fones et al. 2017; Lima et al. 2021; Matengu et al. 2023). Moreover, in southern Europe, organic management can enhance soil water-holding capacity and infiltration, sometimes achieving yields comparable to those of conventional systems under drought-resilient conditions (Seufert et al. 2012).

Specific agricultural practices, such as crop residue incorporation, crop rotation, and reduced tillage, also positively affected wheat yield, in agreement with previous studies (Bakht et al. 2009; Woźniak 2019; Jalli et al. 2021; Woźniak et al. 2021; Gupta et al. 2024). Lower yields under monoculture result from weed proliferation and higher pathogen incidence, which limit spike density and grain weight. Crop rotation mitigates these pressures, promotes soil biodiversity, and improves soil health. Residue incorporation and reduced tillage complement each other by enhancing soil organic matter, nutrient cycling, aggregate stability, porosity, and water retention, ultimately supporting higher yields and long-term productivity (Bakht et al. 2009; Fu et al. 2021; Gupta et al. 2024; Swella et al. 2025).

In conclusion, although organic systems generally exhibit lower yields than conventional systems, targeted practices such as crop rotation, residue incorporation, and reduced tillage can significantly enhance wheat productivity, narrow the yield gap, and improve system resilience and sustainability, particularly in Mediterranean regions vulnerable to climate stress (Sommer et al. 2012; Schrama et al. 2018; Topa et al. 2025).

Conclusions and environmental implications

This study provides an integrated assessment of soil fertility and wheat yield across European wheat croplands, highlighting both nutrient surpluses and critical deficiencies. Potassium, phosphorus, copper, manganese, and zinc frequently exceeded crop requirements, reflecting long-term accumulation from repeated fertilizer applications. In contrast, boron was deficient across 75% of soils, while magnesium and sulfur shortages were also widespread, particularly in wetter regions due to leaching. These patterns emphasize the need for regular soil monitoring and nutrient management to maintain productivity while minimizing environmental risks associated with nutrient losses and eutrophication.

Wheat yield varied markedly across pedoclimatic zones, with the highest values in cooler, moderately wet regions and the lowest in Mediterranean zones. Climatic drivers, especially temperature, emerged as the primary drivers of yield, followed by farming system, wheat type, fertilization type, and key soil nutrients. Cooler and wetter climates supported higher nutrient availability and greater productivity, while heat and drought in southern Europe shortened grain filling and reduced yields.

The farming system also affected wheat productivity. On average, yields under organic management were 37% lower, mainly due to reduced nutrients and pesticide inputs. However, in Mediterranean zones the yield gap was smaller, likely because organically managed soils enhance water retention and infiltration, mitigating heat and drought stress, and because warmer, drier conditions naturally limit pest pressure, reducing the impact of pesticide exclusion. This indicates that practices applied in organic farming can be more competitive under climate-stressed conditions, even if yield gaps persist in northern Europe.

Agricultural practices also played a critical role. Crop rotation, residue incorporation, and reduced tillage enhanced yields by improving nutrient cycling, soil structure, and water retention, while reducing pest and weed pressures. Monoculture and unbalanced fertilization, by contrast, limited productivity and increased environmental risks.

Another important factor with a strong influence on wheat yield was wheat type (winter- vs. spring-sown), with winter wheat consistently achieving higher yields, primarily due to its longer growing cycle compared with spring wheat. Finally, European wheat production faces a dual challenge: widespread nutrient surpluses (P, K, Cu, Mn, Zn) and deficiencies (B, Mg, SO_4^{2-}), coupled with the strong influence of climate on yield. Achieving sustainable intensification requires targeted fertilization informed by soil testing, selective use of organic amendments, and agricultural practices that enhance soil health and water use efficiency. Such strategies can reduce nutrient excesses, address deficiencies, narrow yield gaps, and increase resilience to climate change, particularly in Mediterranean regions where warming and drought are projected to intensify in the near future.

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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, which can be found at Zenodo (https://zenodo.org/record/7682445; Fernández-Calviño et al. (2023).

Declarations

Competing interests The authors declare no relevant financial or non-financial interests. The founders had no role in the design of the study, the collection, analysis, or interpretation of data, the writing of the manuscript, or the decision to publish the results.

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