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Enhancing crop yield and quality on marginal soils through fertilization strategies with selenium and silicon applications

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ABSTRACT

A three-year field trial aimed to evaluate the influence of various fertilization strategies - i.e., mineral, organic, and combined applications - on yield, nutrient use efficiency, and quality of three cereal crops (spring barley, spring oats, and winter rye) grown on Lithuanian marginal sandy soils. The effectiveness of foliar selenium (Se) and silicon (Si) applications in enhancing crop nutritional quality and productivity was also assessed. Mineral fertilization significantly increased grain yield and nutrient uptake compared to organic and unfertilized treatments, with N being the primary limiting nutrient. However, integrated fertilization (mineral + compost) produced similar grain yields and offered promise for long-term soil improvement. Winter rye exhibited the highest N use efficiency (~70 %), while oats had the lowest (~33 %). P and K use efficiencies were considerably lower across all crops. Selenium application enhanced Se accumulation in grains and leaves, indicating successful biofortification without negatively impacting macro-nutrient uptake. In contrast, Si did not affect grain yield and nutrient use efficiency. Overall, the results highlighted the importance of balanced and crop-specific fertilization strategies in improving productivity and nutrient efficiency on low-fertility soils, while also exploring the potential of micronutrient biofortification to improve grain quality.

1. Introduction

By 2050, the global population is projected to reach approximately 9.5 billion [1], necessitating a substantial increase in food production to meet the needs of mankind. Given the limited availability of arable land in Europe, effectively utilizing previously underutilized and marginal lands - excluding those designated for biodiversity conservation - becomes a crucial strategy to maintain and potentially enhance agricultural outputs [2]. Despite a growing population, the European Green Deal (EGD) aims to achieve climate neutrality in Europe by 2050, emphasizing the transition to a more sustainable agricultural and food system [3]. The EDG seeks to mitigate climate change and protect biodiversity by reducing the use of synthetic chemicals and fertilizers, while promoting sustainable practices to ensure food security for the growing global population. Additionally, by 2030, the 27-member European Union aim to reduce chemical pesticide use by 50 %, decrease fertilizer application by 20 %, and cut nutrient and soil fertility losses by at least half [4]. These goals underline the challenge of feeding a growing population while reducing agriculture's environmental impact and aiming for climate neutrality.

Crop rotations and fertilization, particularly nitrogen (N) management, are critical agricultural practices in cropping systems with adequate water availability [5]. These management practices have long-term impacts on soil properties and crop yields, which vary according to specific climatic conditions, soil types, and the duration of land management practices [6]. Nitrogen typically represents the most

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limiting nutrient for crop production. However, excessive N fertilizer application that surpasses crop requirements can lead to environmentally harmful losses through nitrate leaching, runoff, and denitrification. For cash crops, N use efficiency (NUE) strongly depends on agroclimatic conditions, water availability, and N supply (timing and amount) during the growing season. The average NUE in the USA and European countries roughly ranges between 66 and 69 % [7], whereas in China and India, NUE reaches only 21–35 % [8,9]. Phosphorus (P) ranks second as macronutrient after N, yet its use efficiency in cereals remains low. On average, only about 16 % of applied P is taken up by cereal crops [10], while most of the fertilizer being either accumulates in the soil or rendered unavailable due to P reaction with soil compounds (e.g. iron oxyhydroxides, carbonates, silicates, etc.). Field trials typically show P recovery rates of just 15–25 % in the first crop. Similarly, potassium (K) is required by cereals in amounts comparable to N, but its use efficiency is also limited. The global K use efficiency (KUE) in cereals is estimated at around 19 %, indicating that only about one-fifth of the applied K is recovered by the harvested crop [11]. In addition to nutrient management, diverse crop rotations significantly enhance nutrient cycling, pest and disease control, soil structure, and the overall sustainability of cereal-based systems.

Barley (*Hordeumvulgare*) is often considered a “buffer” crop due to its modest input needs and adaptable growing season [12]. It efficiently scavenges soil nitrates and other nutrients, improving nutrient cycling. Oats (*Avena sativa*) enhance soil health and help break pest cycles more effectively than many other cereals [13]. Oats is especially valuable for suppressing soil-borne diseases, such as take-all in wheat. Winter rye (*Secale cereale*) is one of the most versatile cover and rotation crops. Renowned for its hardiness and deep root system, rye is often termed a “soil improver” or “scavenger crop” (Anapalli and Reddy, 2022). When planted in autumn, it germinates in cold conditions and survives harsh winters, thriving when most cash crops cannot.

Nutrient management involves fertilizer strategies aiming to enhance NUE by aligning fertilizer application with crop nutrient demand and soil nutrient availability [14]. This includes selecting the appropriate fertilizer type, applying the optimal rate and application timing to match critical crop growth stages [15]. A suitable example of an effective fertilizer type is the combined application of inorganic and organic fertilizers [16]. The use of inorganic and organic fertilizers each has distinct advantages and disadvantages in terms of their effects on plant growth and development, nutrient availability, and therefore, overall productivity. For instance, organic fertilizers enhance the soil’s physical properties and biological activity but generally have lower nutrient content. Consequently, larger amounts are typically required for effective fertilization [17]. Furthermore, the chemical composition of organic fertilizers heavily depends on the raw materials used, resulting in variability. Therefore, chemical composition analysis is essential each time organic fertilizers are applied to accurately develop fertilization plans. In contrast, inorganic fertilizers usually result in higher crop productivity but can also contribute to increased environmental pressure due to nutrient leaching and soil degradation risks [18]. Combining organic and inorganic fertilizers allows leveraging the strengths of both types, while minimizing their respective drawbacks. Although, the short-term and long-term effects of combining organic and mineral fertilizers have been extensively studied [19], there remains a lack of research focusing specifically on marginal soils and crop rotation systems.

Marginal soils can be defined by their biological, physical, economic, and environmental limitations that hinder sustainable agricultural productivity. They typically refer to lands unsuitable for stable food production or standard agricultural use [20]. According to the Muencheberg Soil Quality Rating (SQR) system, approximately 46 % of European land falls into this category [21]. At the EU scale, data from the EUSO Soil Health Dashboard indicate that 60–70 % of soils are affected by one or more degradation processes and can be classified as unhealthy [22]. Globally, marginal soils are estimated to cover over 1.2 billion hectares, supporting the livehoods of more than 400 million people, many of whom live in food-insecure regions [23].

High amounts of quality biomass can be produced even on marginal soils by enhancing their physico-chemical properties through amendments derived from agricultural by-products and biofortification of food and fodder crops. Additionally, soil additives such as selenium (Se) fertilization can enrich the nutritional value of grains. Se is generally recognized as one of the most critical micronutrients for human and animal nutrition [24]. The Se application has been recommended as either a base fertilizer or via foliar spraying to enhance plant productivity and quality, alleviate damage caused by environmental stresses, and increases the Se concentration in various crop parts [25]. Northern European countries are known to belong to Se-deficient regions due to limited Se bioavailability in the soil for plant uptake [26]. Additionally, at low concentrations, Se enhances plant stress tolerance by modulating reactive oxygen species (ROS) metabolism. Under abiotic stress conditions, plants typically experience elevated ROS production, resulting in oxidative damage. Selenium mitigates these effects by stimulating the activity of antioxidant enzymes, including glutathione peroxidase and superoxide dismutase, which neutralize harmful ROS [27,28]. The beneficial role of Se in enhancing abiotic stress tolerance has been documented across diverse plant species, leading to improved growth, resilience, and adaptability to challenging environmental conditions. However, the translocation of Se within plants is influenced not only by the specific chemical form of Se but also significantly varies among plant species.

Other soil additives, such as silicon (Si) f, can enhance crop resistance to biotic and abiotic stresses, improve plant resilience in marginal soils, increase water-use efficiency, strengthen resistance to diseases and pests, promote biodiversity, and thereby, can reduce agrochemical use in crop production [2]. Roots primarily absorb silicon (Si) from the soil solution as monosilicic acid, plants subsequently depositing it as hydrated silica within tissues, thereby enhancing structural integrity and stress resistance [29]. Although, Si is not an essential plant nutrient, it is widely recognized as beneficial, enhancing plant resilience by supporting metabolic, physiological, and structural processes that improve tolerance to abiotic and biotic stresses [30]. When absorbed by roots and transported to shoots, Si elicits biochemical, physiological, and molecular responses similar to those triggered by biotic and abiotic stresses, indicating its involvement in signaling pathways that regulate plant defenses. Silicon also deposits in cell walls as siliceous cells, strengthening resistance to stress and disease ([31]), reducing heavy metal toxicity, and supporting healthy growth [32].

Moreover, Si influences the accumulation of C, N, and P, potentially altering ecological stoichiometry in vegetation and litter decomposition [33]. While these properties suggest possible benefits for crop production on marginal soils, recent studies indicate that the effectiveness of Si in such environments can be inconsistent and context-dependent. For example, [34] reported limited effects of foliar Si fertilization on crop growth, water use, and carbon dynamics under simulated future climate conditions on marginal soils. In this study, field trials were conducted in one of Lithuania’s poorest soil regions, characterized by predominantly sandy textures, low nutrient and water retention capacities, and high acidity—conditions that typify marginal agricultural land and pose significant challenges for sustainable crop production.

Our 3-year field study aimed to: (i) evaluate the effects of organic fertilizers - applied alone and paired with ammonium nitrate and soil additives (selenium and silicon) - on crop yield; (ii) quantify nutrient (N, P, K, and selenium) uptake by various cereal crops; and (iii) assess the potential of silicon (Si) application to mitigate abiotic stress effects in crop rotation systems on marginal soils.

2. Materials and methods

2.1. Site description

According to the environmental stratification of Europe, Lithuania lies within the Nemoral climate zone, characterized by a continental, relatively cool climate and a short vegetation period. This zone also includes southern Scandinavia, the Baltic States, and Belarus [35]. Lithuania's landscape shows notable variation in air temperature, precipitation, and soil types. The mean annual temperature ranges from 5.8 to 7.6 °C, with annual precipitation between 550 and 910 mm [36]. The dominant soil types are Luvisols (28.5 %), Cambisols (15.9 %), Gleysols (14.6 %), and Arenosols (13.2 %).

The field trials were conducted in agro-climatic zone IIIB of southeastern Lithuania [37], characterized by distinct seasons, relatively warm conditions, moderate precipitation, and marginal soils. The mean annual temperature is 7.2 °C, with 678 mm of precipitation (1991–2020). The soil at the study site is classified as Endocalcaric Eutric Brunic Arenosol (Geoabruptic, Aric) [38], a type commonly found in southeastern Lithuania (see Supplementary Fig. S1).

In the upper Ap soil horizon (0–30 cm) the dominant textural class is sandy silt loam, consisting of 45.2 % sand, 44.3 % silt, and 10.5 % clay. In the deeper horizons, sand predominates, comprising more than 81.9 % (see Supplementary Table 1). The SOC content in the Ap-horizon ranges from 1.16 to 1.34 %, which corresponds to average values for sandy soils in Lithuania. The soil is slightly acidic, with high levels of phytoavailable phosphorus (P_2O_5) and potassium (K_2O) (see Table 1).

2.2. Experimental design and crop management

A crop rotation field experiment with barley, oats, and winter rye with different types of fertilization and fertilizer levels was conducted at the Lithuanian Research Centre for Agriculture and Forestry, Vokė Branch (54.588029° N, 25.135752° E), over a 3-year period (2020–2023) (see Fig. 1). The treatment plots location remained unchanged throughout the experiment, despite the rotation of different crops.

Table 1
Soil properties at the experimental site and management practices for barley, oats, and winter rye.

Year	2020	2021	2022	2022–2023
Soil (FAO classification)	Endocalcaric Eutric Brunic Arenosol (Geoabruptic, Aric)			
Soil pH_{KCl} (1 N KCl extraction)	5.5	6.0	6.3	5.9
Soil P_2O_5 (mg kg^{-1}) (Egner-Riehm-Domingo (A-L))	170	205	192	269
Soil K_2O (mg kg^{-1}) (Egner-Riehm-Domingo (A-L))	324	174	180	149
Soil organic carbon (%) (Tjurin)	1.34	1.16	1.21	1.35
Soil N total (%) (Kjeldahl)	0.103	0.101	0.103	0.101
Previous crop	Buckwheat	Barley	Barley	Oats
Crop and cultivar	Barley, KWS Fantex	Barley, KWS Fantex	Oats, Symphony	Winter rye, VB Duoniai
Seeding date	27 April 2020	10 May 2021	04 May 2022	10 October 2022
Seeding density (grains m^{-2})	450	450	450	450
Plot size	3 × 10 m = 30 m^2	3 × 10 m = 30 m^2	3 × 10 m = 30 m^2	3 × 10 m = 30 m^2
Pesticides, fungicides, insecticides	–	–	–	–
Harvesting dates	12 August 2020	13 August 2021	9 August 2022	16 August 2023

Pelletized compost (PC), composed of spent mushroom growing substrate (48 %), sludge (33 %), green manure (12 %), and sawdust (7 %), was produced by the Warsaw University of Life Sciences. The primary characteristics of the organic fertilizers used are presented in Table 2.

During the 2020–2021 growing seasons, spring barley was cultivated and harvested at physiological maturity using a combine harvester. The cultivar was selected for its high yield potential, resistance to lodging, and strong resistance to major barley diseases (net blotch, spot blotch, scald, and mildew), as well as nematodes. All agricultural practices and crop details are provided in Table 1. Barley was harvested mechanically with a combine harvester upon reaching physiological maturity (12th of August 2020; 13th of August 2021), from a plot area of 1.68 m × 8 m (13.44 m^2) per plot.

The barley field experiments were conducted using a randomized block design with four replicates, comprising four treatments in 2020 and 13 treatments in 2021 (see Table 3). Due to strict logistical restrictions during the COVID-19 pandemic, pelletized compost could not be produced in 2020. Thus, only four treatments with mineral fertilizers were established: 1) No fertilization (CON), 2) $N_{100}P_{80}K_{140}$ (AN100), 3) $N_{100}P_{80}K_{140}$ + Se (AN100+Se), and 4) $N_{100}P_{80}K_{140}$ + Si (AN100+Si). The mineral fertilizers were in the form of ammonium nitrate (34.4-0-0), superphosphate (0-20-0), and potassium chloride (0-0-60). In 2021, the same treatments were repeated and expanded to include additional treatments with lower mineral fertilizer rates ($N_{60}P_{45}K_{90}$), pelletized compost at 170 kg N ha^{-1} (PC170), and a combined treatment of compost at 120 kg N ha^{-1} with mineral fertilizers at 30 kg N ha^{-1} (PC + AN). Mineral fertilizers (superphosphate and potassium chloride) and organic fertilizers were manually applied once and incorporated into the soil prior to barley sowing. Half of the mineral N dose was applied before sowing, while the remaining half was applied during barley tillering.

Barley was sprayed twice with selenium in the form of the preparation JOSEK™ (INTERMAG, Poland), which contains 9.7 g Se per 1 dm^3 as sodium selenate (Na_2Se0_4). Applications were made at a rate of 0.5 L ha^{-1} at growth stages BBCH 21–25 and BBCH 31–33. Silicon was applied three times at the same rate (0.5 L ha^{-1}) at BBCH 21–25, 31–33, and 47–59, using the liquid preparation OPTYSIL (INTERMAG, Poland), which contains 200 g SiO_2 per 1 dm^3, (equivalent to soluble orthosilicic acid stabilized with potassium salt) as active silicon from.

In the 2022 growing season, the oats cultivar 'Symphony' was sown on 4th of May 2022 at a density of 450 seeds m^{-2} and a depth of 3–5 cm. This cultivar was selected for its superior grain quality and high yields, excellent grading, high kernel content, and moderate to high lodging resistance, making it suitable for organic farming. The oats was harvested mechanically with a combine harvester on 9th of August 2022 upon reaching physiological maturity from plots measuring 1.68 × 8 m (13.44 m^2 each). The oats field experiments employed a randomized block design with four replicates and included ten treatments (Table 4). These ones involved different fertilizations (mineral, organic fertilizers, and combinations of both). The same mineral and organic fertilizers were used as in the 2020–2021 barley seasons. However, after observing limited yield effects from the PC170 treatment in barley, the pelletized compost (PC) rate was reduced from 170 kg N ha^{-1} to 100 kg N ha^{-1} in 2022. The fertilization strategy remained consistent: mineral fertilizers (superphosphate and potassium chloride) and organic fertilizers were manually applied once and incorporated into the soil before oats sowing. Half of the mineral N dose was applied prior to sowing, and the remaining half during the oats tillering stage. Selenium and Si fertilization of oats followed the same protocol and timing described previously for barley.

In the 2022–2023 growing season, the winter rye cultivar 'VB Duoniai' was sown on 10th of October 2022 at a density of 450 seeds m^{-2} and a depth of 3–5 cm. This Lithuanian cultivar, bred by the Lithuanian Research Centre for Agriculture and Forestry, was selected for its

Fig. 1. Aerial views of the crop rotation field experiment (2020–2023). The experiment included barley (top left: 2020; top right: 2021), oats (bottom left: 2022), and winter rye (bottom right: 2022–2023).

Table 2
Comprehensive chemical composition of pelletized compost (PC) used in the growing seasons 2020–2024.

Parameter	Amount (g kg^{-1})	Amount (%)	Value
pH			6.7
Total nitrogen (N)	12.80	1.28	
Total phosphorus ($P_2 0_5$)	11.05	1.11	
Total potassium ($K_2 0$)	10.71	1.07	
Sulfur (S)	1.49	0.15	
Sodium (Na)	1.02	0.10	
Calcium (Ca)	84.57	8.45	
Magnesium (Mg)	5.39	0.54	
Lead (Pb)	0.010	0.0010	
Copper (Cu)	0.080	0.0080	
Cadmium (Cd)	0.002	0.0002	
Zinc (Zn)	0.459	0.0458	
Manganese (Mn)	0.287	0.0287	

excellent winter hardiness, high resistance to lodging and diseases, and high yield potential. Winter rye was harvested mechanically with a combine harvester on 16th of August 2023 upon reaching physiological maturity, from plots measuring 1.68 × 8 m (13.44 m^2 each). The experimental design was identical to that used for barley and oats, employing a randomized block design with four replicates and ten treatments. Application rates for mineral, organic, and combined fertilizers are detailed in Table 5. The fertilization strategy remained consistent with previous years: mineral fertilizers (superphosphate and potassium chloride) and organic fertilizers were manually applied once and incorporated into the soil before winter rye sowing. Half of the mineral N dose was applied prior to sowing, with the remaining half applied during rye tillering. Selenium and Si fertilization of winter rye followed the same protocol and timing previously described for barley.

2.3. Soil measurements

2.3.1. Soil physics and hydraulic properties

In 2020, before the barley growing season, a soil pit was dug at the central experimental site. Ten undisturbed 250 cm^3 samples were collected in duplicate from depths of 15–20, 40–45, 60–65, 90–95, and 110–115 cm. Soil hydraulic properties were determined using the HYPROP® system and WP4® Dewpoint Potentiometer [39], while saturated hydraulic conductivity (Ks) was measured with the K_{SAT} system. Estimated van Genuchten parameters for the 0–120 cm profile are reported in a previous study [18].

2.3.2. Soil water content

From 2020 to 2023, soil volumetric water content (SWC) was monitored hourly at five depths (15, 40, 60, 90, and 110 cm) using a wireless sensor network SoilNet [40], installed before seedbed preparation. Daily average SWC values were calculated from the hourly data.

2.3.3. Soil agrochemical properties

Before each growing season, the soil nutrient status was assessed. Therefore, composite samples were collected from the ploughed layer (0–30 cm) at 12 field locations. Chemical analyses included pH, SOC, total nitrogen (N_{total}), and plant-available P_2O_5 and K_2O (Table 1). Soil chemical analyses were performed at the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry. pH was measured using an XS Instruments pH-meter (Italy) in 1 M KCl solution (1:5 vol/vol ratio). SOC was determined by dry combustion using a Liqui TOC II (Elementar, Germany) after HCl treatment to remove inorganic carbon. All measurements were performed in triplicate. N_{total} was assessed via the Kjeldahl method with a Velp Scientifica™ UDK 139 (Italy), followed by manual titration with 0.1 M NaOH. P_2O_5 and K_2O was measured using the Egner-Riehm-Domingo (A-L) method—P_2O_5 with a Shimadzu UV 1800 spectrophotometer and K_2O with a JENWAY PFP7 flame photometer (766 nm, Thermo Scientific, UK).

2.4. Plant measurements

Cereal growth stages from emergence to maturity were assessed weekly using the BBCH scale, a universal decimal code system that standardizes and homogenizes the description of plant development stages across different species [41]. A stage was recorded when 50 % or more of plants reached the corresponding stage. At physiological maturity (BBCH93), each fertilization treatment plot was harvested over an area of 1.68 × 8 m (13.44 m^2). Grain yield moisture content was measured using a Wile-200 grain moisture meter (Farmcomp, Finland). Additionally, samples were collected from a 0.25 m^2 area within each plot to assess straw and grain yields (GY) for calculating total above-ground biomass (TAB). Subsamples of straw and GY collected at harvest were analyzed to determine N, P, K, and Se concentrations in the plant parts. Se concentrations were determined according to the standardized methology outlined in LST EN 14627:2005. Nitrogen

Table 3
Fertilization rates applied across different treatments for barley.

Treatments	Codes	Macro nutrient rate (kg ha-1)			Micro nutrient rate (L ha^{-1})	
		N	P	K	Se	Si
Control	(CON)	–	–	–	–	–
Ammonium nitrate N60 + P + K	(AN60)	60	45	90	–	–
Ammonium nitrate N60 + P + K + Se	(AN60+Se)	60	45	90	2 × 0.5	–
Ammonium nitrate N60 + P + K + Si	(AN60+Si)	60	45	90	–	3 × 0.5
Ammonium nitrate N100 + P + K	(AN100)	100	80	140	–	–
Ammonium nitrate N100 + P + K + Se	(AN100+Se)	100	80	140	2 × 0.5	–
Ammonium nitrate N100 + P + K + Si	(AN100+Si)	100	80	140	–	3 × 0.5
Pelletized compost N170	(PC170)	170	147	142	–	–
Pelletized compost N170 + Se	(PC170+Se)	170	147	142	2 × 0.5	–
Pelletized compost N170 + Si	(PC170+Si)	170	147	142	–	3 × 0.5
Pelletized compost N120 + Ammonium nitrate N30	(PC + AN)	150	104	100	–	–
Pelletized compost N120 + Ammonium nitrate N30 + Se	(PC + AN + Se)	150	104	100	2 × 0.5	–
Pelletized compost N120 + Ammonium nitrate N30 + Si	(PC + AN + Si)	150	104	100	–	3 × 0.5

Note: In 2020, only four treatments were conducted (CON, AN100, AN100+Se, and AN100+Si), whereas in 2021, all treatments listed in the table were implemented.

concentration was measured using the Kjeldahl method [42]. The P and K concentrations were determined following the standardized methodology outlined in LST EN 15510:2017.

For each crop (barley, oats, and winter rye) and treatment, nutrient uptake (N, P, K, and Se) was calculated separately based on dry matter. This was done by multiplying the nutrient concentration by the corresponding yield as follows:

$$Nutrients\ uptake\ \left(kg\ ha^{-1}\right) = \frac{Nutrients\% \times dry\ matter\ \left(kg\ ha^{-1}\right)}{100} \quad (1)$$

The recovery efficiency of applied nitrogen (RE_N), phosphorus (RE_P), potassium (RE_K), and selenium (RE_{Se}) was calculated according to Dobermann [43] by:

$$RE_x = \frac{U_x - U_0}{F_x} \times 100 \quad (2)$$

where U_x is the crop yield with applied N, P, K or Se (kg ha^{-1}), U_0 is the crop yield (kg ha^{-1}) in a treatment with no fertilization, and F_x is the amount of N, P, K or Se applied (kg ha^{-1}).

Table 4
Fertilization rates applied across different treatments for oats.

Treatments	Codes	Macro nutrient rate (kg ha-1)			Micro nutrient rate (L ha-1)	
		N	P	K	Se	Si
Control	(CON)	–	–	–	–	–
Ammonium nitrate N75 + P + K	(AN75)	75	60	100	–	–
Ammonium nitrate N75 + P + K + Se	(AN75 + Se)	75	60	100	2 × 0.5	–
Ammonium nitrate N75 + P + K + Si	(AN75 + Si)	75	60	100	–	3 × 0.5
Pelletized compost N100	(PC100)	100	86.0	84.0	–	–
Pelletized compost N100 + Se	(PC100 + Se)	100	86.0	84.0	2 × 0.5	–
Pelletized compost N100 + Si	(PC100 + Si)	100	86.0	84.0	–	3 × 0.5
Pelletized compost N100 + Ammonium nitrate N30	(PC + AN)	130	86.0	84.0	–	–
Pelletized compost N100 + Ammonium nitrate N30 + Se	(PC + AN + Se)	130	86.0	84.0	2 × 0.5	–
Pelletized compost N100 + Ammonium nitrate N30 + Si	(PC + AN + Si)	130	86.0	84.0	–	3 × 0.5

Table 5
Fertilization rates applied across different treatments for winter rye.

Treatments	Codes	Macro nutrient rate (kg ha^{-1})			Micro nutrient rate (L ha^{-1})	
		N	P	K	Se	Si
Control	(CON)	–	–	–	–	–
Ammonium nitrate N75 + P + K	(AN75)	75	60	100	–	–
Ammonium nitrate N75 + P + K + Se	(AN75 + Se)	75	60	100	2 × 0.5	–
Ammonium nitrate N75 + P + K + Si	(AN75 + Si)	75	60	100	–	3 × 0.5
Pelletized compost N100	(PC100)	100	86.0	84.0	–	–
Pelletized compost N100 + Se	(PC100 + Se)	100	86.0	84.0	2 × 0.5	–
Pelletized compost N100 + Si	(PC100 + Si)	100	86.0	84.0	–	3 × 0.5
Pelletized compost N100 + Ammonium nitrate N45	(PC + AN)	145	86.0	84.0	–	–
Pelletized compost N100 + Ammonium nitrate N45 + Se	(PC + AN + Se)	145	86.0	84.0	2 × 0.5	–
Pelletized compost N100 + Ammonium nitrate N45 + Si	(PC + AN + Si)	145	86.0	84.0	–	3 × 0.5

2.5. Meteorogical data

The weather data for this study were obtained from the Vilnius meteorological station, located 5.3 km away from the experimental site.

2.6. Statistical analyses

Statistical analyses were performed using SAS 9.4 (SAS Institute Inc., 2016). Analysis of variance (ANOVA) for a randomized complete block design was used to evaluate yield, yield components, quality parameters, nutrient uptake, and nutrient use efficiency. Treatment means were compared using Tukey's test at the 0.05 and 0.01 significance levels. Linear correlation and regression analyses were conducted to assess relationships between plant traits and yield.

3. Results

3.1. Environmental conditions

The barley growing period lasted 108 days in 2020 and 96 days in 2021, while oats were grown for 97 days in 2022. In contrast, the winter rye growing season extended to 166 days (excluding overwintering). Mean air temperatures from sowing to harvest were 15.9 °C in 2020, 18.6 °C in 2021, 15.9 °C in 2022, and 12.5 °C in 2022–2023 — representing deviations of −0.3 °C, +1.9 °C, −0.8 °C, and +0.8 °C from the 1990–2020 average, respectively.

Daily soil temperatures during the respective growing seasons also varied by year and depth (Fig. 2). Average soil temperatures followed expected depth-dependent gradients. The warmest year was 2021 (e.g., 18.4 °C at 15 cm), while the coldest was the 2022–2023 season, with temperatures dropping to ~9 °C across all depths. Detailed temperature profiles are shown in Fig. 2.

Precipitation also varied between years. In 2020, total precipitation amount during the barley season was 225.4 mm (94.7 % of the long-term average), while in 2021 and 2022 it increased to 327.8 mm (147.7 %) and 346.2 mm (145.5 %), respectively. During the winter rye season, total precipitation reached 338.6 mm, which accounted for 86 % of the long-term average. Variations in precipitation had a clear impact on soil water content (SWC) across all depths (Fig. 3). The driest conditions were observed in 2020, with the lowest SWC values recorded throughout the profile. In contrast, 2021 and 2022 showed more stable and comparable SWC patterns, consistent with similar rainfall levels. The highest SWC variability occurred during the winter rye season, particularly in the upper soil layers. Detailed temporal and depth-specific fluctuations are presented in Fig. 3. Notably, throughout all years and depths measured, SWC did not reach either the permanent wilting point or full saturation.

3.2. Yields, yield components and quality

3.2.1. Barley

At harvest in August 2020, TAB ranged from 1.98 to 4.38 t ha^{-1}, grain yield from 0.93 to 2.12 t ha^{-1}, and straw biomass from 1.05 to 2.22 t ha^{-1}, accounting for approximately 50 % of the barley harvest index (Table 6). Combined analysis of the 2-year data revealed significant ($p < 0.01$) differences between treatments. Treatments with higher nutrient inputs consistently outperformed the control (CON) in terms of TAB and grain yield. As expected, the 1000-grain weight was also highest under fertilization treatments and lowest in the CON. A similar pattern was found for grain protein content, with significantly ($p < 0.01$) higher values in fertilized plots compared to the control.

In 2021, at harvest, TAB in barley ranged from 2.49 to 4.97 t ha^{-1}, grain yield from 0.88 to 1.95 t ha^{-1}, and straw biomass from 1.55 to 3.02 t ha^{-1} (Table 6). Compared to 2020, TAB yield was higher, but

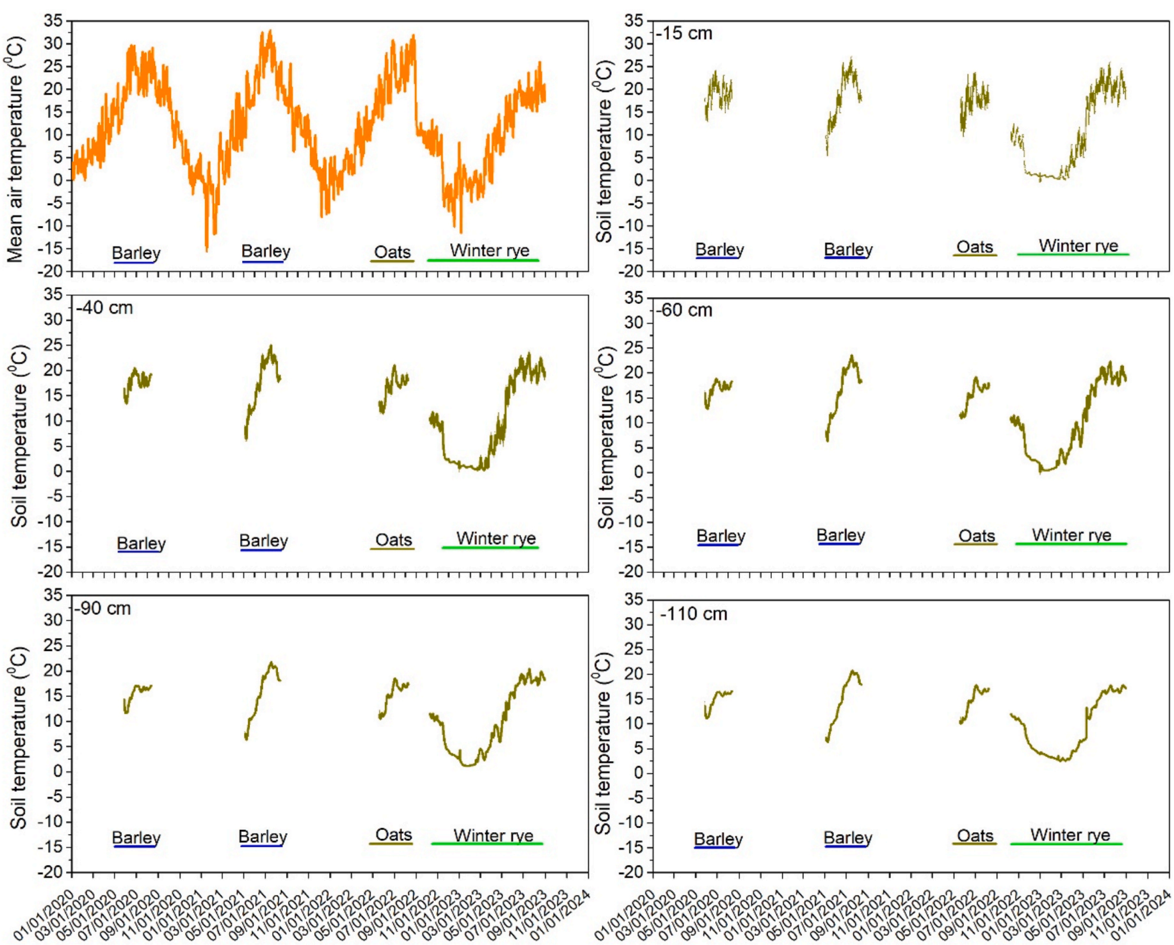

Fig. 2. Seasonal dynamics of air and soil temperatures measured at multiple depths during the different cereal crop growing periods (2020–2023). Note that soil temperature has been only measured over the main growing periods.

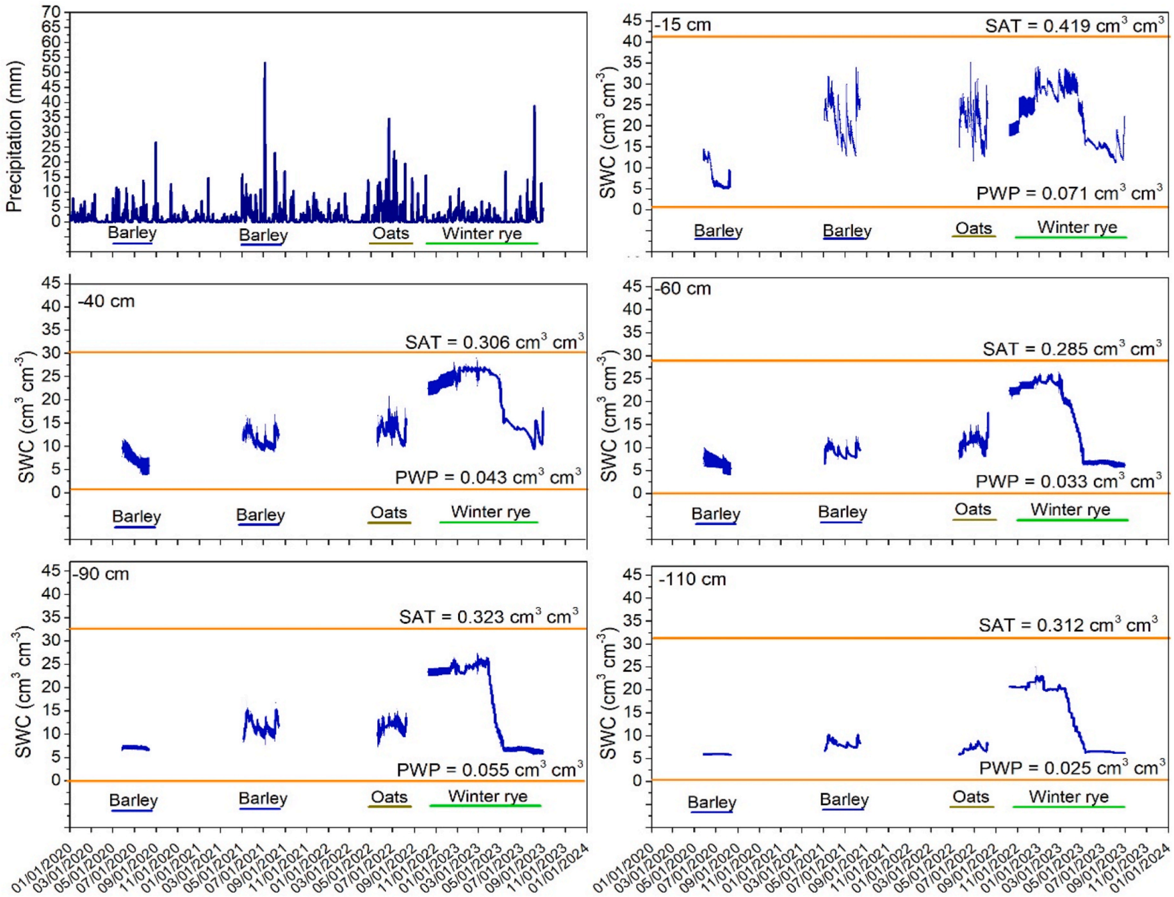

Fig. 3. Daily precipitation patterns and soil water contents measured at various depths across teh different cropping seasons (2020–2022). SAT is the saturated water content, PWP is the permanent wilting point, and SAT-WP is the plant available water (all in cm^3 cm^{-3}).

Table 6
Total above-ground biomass, yield components, and grain protein content of barley in 2020–2021. Different letters (A, B) indicate statistically significant differences ($p < 0.05$, Tukey's test).

Treatments	TAB (t ha^{-1})		Grain yield (t ha^{-1})		Straw biomass (t ha^{-1})		1000-grain-weight (g)		Protein content (%)	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
CON	1.98 B	2.49 B	0.93 B	0.88 B	1.05 B	1.61 B	43.4 B	29.7 BA	9.58 B	12.65 A
AN60	–	3.25 BA	–	1.23 BA	–	2.02 BA	–	29 BA	–	12.73 A
AN60 + Se	–	3.56 BA	–	1.41 BA	–	2.15 BA	–	30.1 BA	–	12.93 A
AN60 + Si	–	3.76 BA	–	1.29 BA	–	2.47 BA	–	29.2 BA	–	13.03 A
AN100	4.15 A	4.66 A	2.10 A	1.91 A	2.05 A	2.75 BA	47.1 A	34.4 A	14.43 A	13.2 A
AN100 + Se	4.38 A	4.75 A	2.21 A	1.85 BA	2.16 A	2.90 A	46.8 A	34 A	13.78 A	12.9 A
AN100 + Si	4.34 A	4.97 A	2.12 A	1.95 A	2.22 A	3.02 A	46.2 BA	32.4 A	14.23 A	13.03 A
PC170	–	2.69 BA	–	1.04 BA	–	1.65 B		28.2 B	–	12.18 A
PC170 + Se	–	3.29 BA	–	1.23 BA	–	2.06 BA		28.1 B	–	12.63 A
PC170 + Si	–	2.6 BA	–	1.05 BA	–	1.55 B		29.8 BA	–	12.63 A
PC + AN	–	3.45 BA	–	1.49 BA	–	1.96 BA		31 BA	–	12.33 A
PC + AN + Se	–	3.26 BA	–	1.29 BA	–	1.97 BA		30.2 BA	–	12.73 A
PC + AN + Si	–	3.89 BA	–	1.57 BA	–	2.32 BA		31 BA	–	12.5 A
Mean over all treatments	3.67	3.59	1.84	1.40	1.87	2.19	45.88	30.5	13.01	12.73
Significance level	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	NS

grain yield was lower, resulting in a harvest index of only ≈39 % in 2021. These inter-annual differences were strongly influenced by contrasting weather conditions. From sowing to harvest, the mean air temperature was 15.9 °C in 2020, while it increased to 18.6 °C in 2021. Total precipitation also substantially differed with 225.4 mm in 2020 (94.7 % of the long-term average) versus 327.8 mm in 2021 (147.7 % of the long-term average). In addition, barley grown in 2021 experienced severe heat stress during the flowering and grain filling stages, with an average air temperature of 20.8 °C and ten days exceeding maximum temperatures of 30 °C. In contrast, during the same period in 2020, the average temperature was 18.2 °C and only two days exceeded 30 °C. The impact of heat stress in 2021 was clearly reflected in the reduced 1000-grain weight, indicating impaired grain development under high-temperature conditions.

Combined statistical analysis of the 2021 data revealed highly significant ($p < 0.01$) differences among treatments. In general, despite a few exceptions, the treatments' effects on TAB, grain yield, and straw biomass could be grouped into three distinct performance tiers: (1)

$N_{100}P_{80}K_{140} \approx N_{100}P_{80}K_{140} + Se \approx N_{100}P_{80}K_{140} + Si$; (2) $N_{60}P_{35}K_{60} \approx N_{60}P_{35}K_{60} + Se \approx N_{60}P_{35}K_{60} + Si \approx PCN_{170} + N_{30} \approx PCN_{170} + N_{30} + Se \approx PCN_{170} + N_{30} + Si \approx PCN_{170} \approx PCN_{170} + Se \approx PCN_{170} + Si >$ and (3) CON. This grouping reflected the strong positive impact of higher mineral fertilization rates on biomass and yield formation, while lower-inputs or compost-based treatments resulted in lower plant productivity.

A very similar pattern occurred for the effect of treatments on 1000-grain weight, with the exception that the lowest grain weights were recorded in treatments that received only organic fertilization. In 2021, grain protein content varied only slightly, ranging from 12.3 to 13.2 %, and no statistically significant differences among treatments were detectable. However, combining organic with mineral fertilizers (e.g., $PCN_{170} + N_{30}$) produced results similar to those achieved using only mineral fertilizers ($N_{60}P_{35}K_{60}$), demonstrating that a portion of mineral fertilizers can effectively be replaced by slower-acting organic alternatives.

Foliar Si application had only a few effect on barley productivity and it was not statistically significant. Therefore, no definitive conclusions can be drawn. For example, in 2021 the highest total TAB (4.97 t ha^{-1}) and grain yield (1.95 t ha^{-1}) were found for the $N_{100}P_{80}K_{140} + Si$ treatment, slightly outperforming the $N_{100}P_{80}K_{140}$ and $N_{100}P_{80}K_{140} + Se$ treatments. A similar trend was determined when combining organic and mineral fertilizers. The $PCN_{170} + N_{30} + Si$ treatment resulted in the highest TAB (3.89 t ha^{-1}) and grain yield (1.57 t ha^{-1}) within that group. However, as in the mineral treatments, these differences were not statistically significant, suggesting that the overall effect of Si was limited under the conditions of this study.

3.2.2. Oats

At harvest in 2022, oats TAB ranged from 3.97 to 5.95 t ha^{-1}, grain yield varied from 2.63 to 3.70 t ha^{-1}, and straw biomass ranged from 1.34 to 2.25 t ha^{-1} (Table 7). Analysis of the one-year data revealed significant differences between fertilization treatments. In most cases, significantly higher TAB, grain yield, and straw biomass were determined in mineral fertilizer treatments with the highest fertilization rates. Intermediate yields were recorded when mineral fertilizers were combined with organic amendments, whereas the lowest yields were found in treatments with only organic fertilizers and in the unfertilized control. For example, the average TAB in the mineral fertilization treatments ($N_{75}P_{60}K_{100}$ and its combinations with Se and Si) reached 5.66 t ha^{-1}, with a corresponding grain yield of 3.53 t ha^{-1} and straw biomass of 2.13 t ha^{-1}. Slightly lower yields were obtained when mineral fertilizers were combined with organic amendments ($PC_{N100} + N_{30}$; $PC_{N100} + N_{30} + Se$; $PC_{N100} + N_{30} + Si$), with an average TAB of 5.24 t ha^{-1}, grain yield of 3.44 t ha^{-1}, and straw biomass of 1.81 t ha^{-1}. Lowest yields occurred in plots with only organic fertilizers and the unfertilized control. In these cases, the TAB yield averaged 4.17 t ha^{-1} compared to 4.15 t ha^{-1} in the control, grain yield was 2.76 t ha^{-1} versus 2.74 t ha^{-1}, and straw biomass was 1.41 t ha^{-1} in both treatments.

Table 7
Total above-ground biomass, yield components, and grain protein concentration of oats in 2022. Different letters (A, B,C) indicate statistically significant differences ($p < 0.05$, Tukey's test).

Treatments	TAB (t ha^{-1})	Grain yield (t ha^{-1})	Straw biomass (t ha^{-1})	1000-grain-weight (g)	Protein concentration (%)
CON	4.15C	2.74C	1.41C	34.4 A	11.4 A
AN75	5.64 A	3.60 A	2.04 A	33.1 A	10.5 BC
AN75 + Se	5.95 A	3.70 A	2.25 A	32.6 A	10.5 BC
AN75 +Si	5.38 BA	3.28 BA	2.10 A	32.6 A	10.2C
PC100	4.39 BAC	2.92 BAC	1.47 BAC	33.2 A	11.0 BA
PC100 + Se	3.97C	2.63C	1.34C	32.9 A	11.0 BA
PC100 +Si	4.16C	2.74C	1.42C	33.9 A	10.8 BAC
PC + AN	5.28 BA	3.45 BA	1.83 BA	32.6 A	10.8 BAC
PC + AN + Se	5.07 BAC	3.32 BA	1.75 BA	32.2 A	10.6 BC
PC + AN + Si	5.38 BA	3.54 A	1.84 BA	33 A	10.1C
Mean over all treatments	4.94	3.19	1.75	33.0	10.7
Significance level	$p < 0.01$	$p < 0.01$	$p < 0.01$	ns	$p < 0.01$

In contrast to barley, the 1000-grain weight in oats was not significantly influenced by fertilization treatments (Table 7). Across all treatments, 1000-grain weight values ranged narrowly from 32.2 to 34.4 g, indicating a high degree of stability for barley growth under varying fertilization regimes. The highest value was displayed by the control (34.4 g), while the lowest was recorded in treatments combining mineral and organic fertilization, e.g., $PC_{N100} + N_{30} + Se$ with 32.2 g. Despite substantial differences in TAB and grain yield, the 1000-grain weight remained relatively consistent, suggesting that changes in oat yield were primarily driven by variations in grain number rather than grain weight. Oat grain protein content was significantly affected by fertilization treatments (Table 7), which contrasts with the response of barley. The highest protein content was for the control treatment (11.4 %), followed closely by treatments with only organic fertilizers (PC_{N100} and $PC_{N100} + Se$, approximately 11.0 %). Mineral fertilization generally resulted in lower protein content, ranging from 10.1 to 10.8 %, with the lowest values determined in treatments supplemented with Si ($PC_{N100} + N_{30} + Si$ and $N_{75}P_{60}K_{100} + Si$, both around 10.1–10.2 %). Overall, an inverse relationship (R^2 – 0.53) between grain yield and protein concentration was evident, suggesting that increased biomass production under higher fertilization rates led to a dilution of grain protein content.

Similar to the results for barley, the foliar Si application had an unclear effect on oat productivity, with differences often being statistically insignificant. The minor changes between treatments with and without Si supplementation were likely due to field heterogeneity rather than a true effect of Si application. This suggests that the rates of Si used in our study were insufficient to produce a consistent or meaningful increase in yields.

3.2.3. Winter rye

At harvest in 2023, winter rye TAB ranged from 4.39 to 8.71 t ha^{-1}, grain yield from 1.83 to 3.84 t ha^{-1}, and straw biomass from 2.56 to 4.96 t ha^{-1}, resulting in an average harvest index of ~42.5 % (Table 8). Analysis of the one-year data revealed significant differences between fertilization treatments, similar to trends observed in barley and oat. In most cases, significantly higher TAB, grain yield, and straw biomass were found in mineral fertilizer treatments with the highest fertilization rates. However, treatments combining mineral and organic fertilizers showed only slightly lower performance. As with the other crops, the use of organic fertilizers alone had only limited effect, with only marginal improvements over the unfertilized control. For instance, the average TAB in mineral fertilizer treatments ($N_{75}P_{60}K_{100}$ and its combinations with Se and Si) reached 8.62 t ha^{-1}, with a corresponding grain yield of 3.73 t ha^{-1} and straw biomass of 4.89 t ha^{-1}. Slightly lower values were evidenced in treatments combining mineral and organic fertilization ($PC_{N100} + N_{45}$, with or without Se or Si), where the average TAB was 7.86 t ha^{-1}, grain yield 3.35 t ha^{-1}, and straw biomass 4.51 t ha^{-1}. The lowest productivity occurred in treatments with only organic fertilizers, which performed similarly to the unfertilized control. In these treatments, average TAB was 4.67 t ha^{-1} versus 4.39 t ha^{-1} in the control, grain yield was 1.95 t ha^{-1} versus 1.83 t ha^{-1}, and straw biomass was 2.72 t ha^{-1} versus 2.56 t ha^{-1}, respectively.

Again, the fertilization treatments had a significant effect on the 1000-grain weight of winter rye ($p < 0.01$) (Table 8). The highest 1000 grain weight was recorded in the N_{75}P60K100 + Se treatment (36.1 g), followed by N75P60K100 + Si (35.4 g). In contrast, the 1000 grain weight values were lowest in treatments receiving only organic

Table 8
Total above-ground biomass, yield components, and grain protein concentration of winter rye in 2022–2023. Different letters (A, B, C, D) indicate statistically significant differences ($p < 0.05$, Tukey's test).

Treatments	TAB (t ha^{-1})	Grain yield (t ha^{-1})	Straw biomass (t ha^{-1})	1000-grain-weight (g)	Protein concentration (%)
CON	4.39 D	1.83 D	2.56C	32.9 BA	9.3C
AN75	8.64 A	3.81 A	4.83 A	34.3 BA	10.8 BA
AN75 + Se	8.51 A	3.55 BA	4.96 A	36.1 A	11.2 A
AN75 +Si	8.71 A	3.84 A	4.87 A	35.4 BA	11.4 A
PC100	4.45 DC	1.85 DC	2.60C	32.8 BA	9.3C
PC100 + Se	4.64 DC	1.94 BDC	2.70C	32.3 B	9.2C
PC100 +Si	4.91 BDC	2.05 BDC	2.86 BC	31.8 B	9.2C
PC + AN	8.30 A	3.46 BAC	4.84 A	34.6 BA	9.4C
PC + AN + Se	7.40 BAC	3.09 BDAC	4.31 BA	34.6 BA	9.6 BC
PC + AN + Si	7.88 BA	3.49 BA	4.39 A	34.1 BA	9.9 BC
Mean over all treatments	6.78	2.89	3.89	33.9	9.9
Significance level	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$

fertilization, particularly PCN100 + Si (31.8 g) and PCN100 + Se (32.3 g). The unfertilized control and PCN100 treatment also showed relatively lower 1000 grain weight values (32.9 and 32.8 g, respectively).

Fertilization significantly influenced winter rye grain protein content (Table 8), contrasting with the barley response but aligning with that of oats. The highest protein levels were recorded in mineral fertilization treatments with added Si or Se, particularly $N_{75}P_{60}K_{100}$ + Si (11.4 %) and $N_{75}P_{60}K_{100}$ + Se (11.2 %), followed by $N_{75}P_{60}K_{100}$ alone (10.8 %). In contrast, treatments with only organic fertilizers showed significantly lower protein content (9.2–9.3 %), similar to the unfertilized control (9.3 %). These results suggested that mineral fertilization—especially when combined with micronutrients—enhances grain protein content in winter rye, while organic fertilization alone was insufficient to reach similar quality levels.

In contrast to the barley and oats results, the foliar Si application often had a positive effect on winter rye productivity, particularly in terms of TAB and grain yield. However, the yield increases in Si-treated plots were not statistically significant when compared to treatments without Si application.

3.3. Nutrients uptake

3.3.1. Barley

Different fertilization treatments significantly influenced the uptake of N, P, K, and Se by barley in both years. Total N uptake and removal with grains and straw at physiological maturity (Figs. 4 and 5) were similar across both years.

In 2020, N uptake by TAB ranged from 16.1 to 72.2 kg ha^{-1}, while in 2021 it varied from 24.6 to 64.5 kg ha^{-1}. Correspondingly, N uptake by grains ranged from 11.8 to 55.1 kg ha^{-1} in 2020 and from 17.7 to 40.6 kg ha^{-1} in 2021. N uptake by straw varied from 4.3 to 20.1 kg ha^{-1} in 2020 and from 6.9 to 23.9 kg ha^{-1} in 2021. In 2020, as expected, plots treated with AN and soil additives significantly increased N uptake by TAB, grains, and straw compared to the CON. For example, in the AN100, AN100 + Se, and AN100 + Si treatments, N uptake by TAB increased by 75.6–78.3 %, grain N uptake increased by 76.2–78.6 %, and straw N uptake increased by 73.8–78.6 % compared to the CON, respectively. In 2021, the combined analysis revealed significant differences between treatments. With a few exceptions, the general trend in N uptake by TAB, grains, and straw followed this approximate order: AN100 ≈ AN100 + Se ≈ AN100 + Si > AN60 ≈ AN60 + Se ≈ AN60 + Si ≈ PC + AN ≈ PC + AN + Se ≈ PC + AN + Si > PC170 ≈ PC170 + Se ≈ PC170 + Si ≈ CON. Compared to the unfertilized control plots, treatments with higher mineral N inputs resulted in substantial increases in N uptake:

TAB uptake increased by 59.7–61.9 %, grain uptake by 53.7–56.4 %, and straw uptake by 67.0–71.7 %. These results suggested that the more favorable environmental conditions in 2021—particularly higher temperatures and higher precipitation - reduced the gap in N uptake between the control plots and the AN100 treatments, compared to 2020.

In 2020, P uptake was approximately 2.8–5.3 times lower than N uptake. P uptake by TAB ranged from 5.8 to 13.7 kg ha^{-1}, while in 2021 it ranged from 7.0 to 13.8 kg ha^{-1}. P uptake by grains varied from 4.0 to 10.5 kg ha^{-1} in 2020 and from 3.8 to 8.9 kg ha^{-1} in 2021. Meanwhile, P uptake by straw ranged from 1.8 to 3.3 kg ha^{-1} in 2020 and increased to 3.2–5.7 kg ha^{-1} in 2021. In 2020, P uptake by TAB, grains, and straw was significantly higher in plots receiving mineral fertilization compared to the unfertilized control. A similar trend was found in 2021, with significant differences in P uptake by TAB and grains among fertilization treatments. However, no statistically significant differences in straw P uptake were evidenced between treatments in 2021. Compared to the unfertilized control, the treatments with the highest mineral fertilizer input resulted in considerable increases in P uptake: TAB uptake increased by 54.7–57.7 % in 2020 and 46.9–49.3 % in 2021, Grain uptake increased by 58.3–61.9 % in 2020 and 55.3–57.3 % in 2021, Straw uptake increased by 35.7–45.5 % in 2020 and 25.6–38.5 % in 2021.

In 2020, K uptake by TAB ranged between 9.8 and 33.8 kg ha^{-1}, while in 2021 it increased, ranging from 13.9 to 45.0 kg ha^{-1}. Potassium uptake by grains was between 4.4 and 12.0 kg ha^{-1} in 2020 and ranged from 4.1 to 11.3 kg ha^{-1} in 2021. In the case of straw, K uptake varied from 5.4 to 22.1 kg ha^{-1} in 2020 and from 9.8 to 33.7 kg ha^{-1} in 2021. In 2020, similar to N and P, K uptake by TAB, grains, and straw was significantly higher in plots receiving mineral fertilization at the AN100 rate compared to the unfertilized control. In 2021, a greater number of treatment groups showed variation in K uptake. However, in all cases, the three treatments with the highest mineral N input (AN100 rate) consistently resulted in significantly larger K uptake. Conversely, the CON and treatments with compost alone showed the lowest K uptake values. The application of the highest mineral fertilizer rates AN100 led to a marked improvement in K uptake compared to the unfertilized control. In 2020, K uptake by TAB was nearly 70 % higher, while in 2021 the increase was close to 68 %. Potassium accumulation in the grain rose by approximately 61–63 % in both years. Similarly, straw K uptake showed a substantial rise — about 75 % in 2020 and 61–63 % in 2021 — highlighting the consistent positive effect of intensive mineral fertilization on K dynamics across plant components and years.

In 2020, as expected, the highest Se uptake was evidenced in the AN100 + Se treatment, with 1.09 g ha^{-1} (505 μg kg^{-1}) in straw and 1.19 g ha^{-1} (538 μg kg^{-1}) in grain, resulting in a total of 2.28 g ha^{-1} (1043 μg kg^{-1}) taken up by the whole plant (TAB). Compared to the AN100 and AN100 + Si treatments, foliar Se application increased total Se uptake by 71–80 %. Similar trends were found in 2021, when a greater number of treatments included Se application. Once again, the AN100 + Se treatment showed the highest Se uptake, with 1.11 g ha^{-1} (383 μg kg^{-1}) in straw and 0.86 g ha^{-1} in grain (465 μg kg^{-1}), totaling 1.97 g ha^{-1} (848 μg kg^{-1}) - which was 71–78 % higher than in the comparable treatments AN100 and AN100 + Si. With a lower mineral N rate, the AN60 + Se treatment resulted in 0.83 g ha^{-1} (386 μg kg^{-1}) in straw and 0.52 g ha^{-1} (369 μg kg^{-1}) in grain, totaling 1.35 g ha^{-1} (737 μg kg^{-1}), representing a 73–78 % increase in Se uptake compared to AN60 and AN60 + Si. In combined fertilization treatments, PC + AN + Se achieved 0.70 g ha^{-1} (355 μg kg^{-1}) in straw and 0.44 g ha^{-1} (341 μg kg^{-1}) in grain (total 1.14 g ha^{-1} (696 μg kg^{-1})), which was approximately 70 % higher than PC + AN and PC + AN + Si. Even in treatments with compost alone, Se application had a strong effect. The PC170 + Se

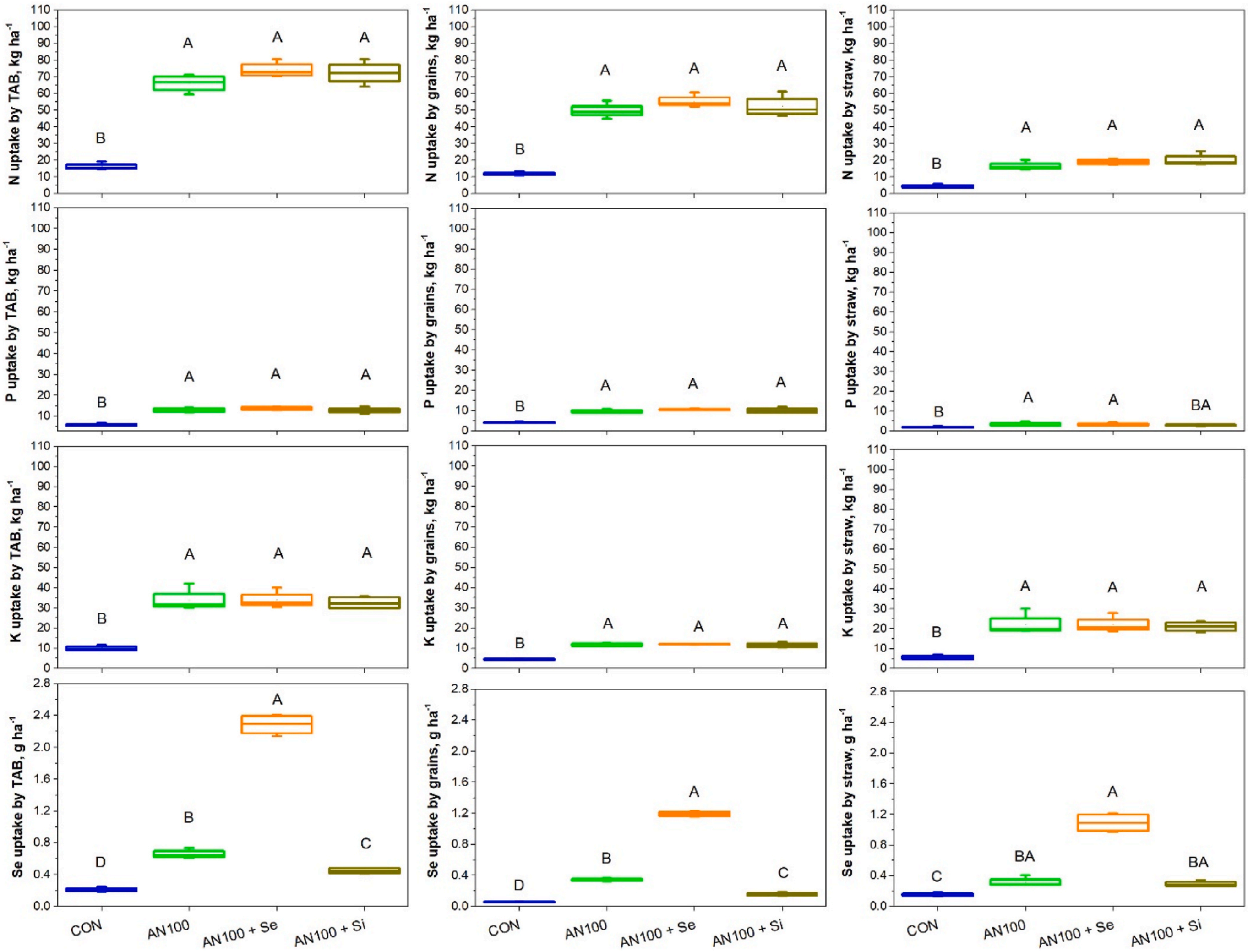

Fig. 4. Effect of fertilization treatments (CON, AN100, AN100 + Se, AN100 + Si) on N, P, K, and Se uptake by barley total aboveground biomass (TAB), grains, and straw in 2020. Different letters above bars indicate statistically significant differences between treatments (Tukey's HSD, $p < 0.05$).

treatment resulted in 0.63 g ha^{-1} (306 μg kg^{-1}) in straw and 0.32 g ha^{-1} (260 μg kg^{-1}) in grain, for a total of 0.95 g ha^{-1} (566 μg kg^{-1}), which was about 74 % more than in the PC170 and PC170 + Si treatments.

3.3.2. *Oats*

In 2022, N uptake by oats TAB at physiological maturity (Fig. 6) ranged from 56.5 to 72.3 kg ha^{-1}. Of this, N uptake by grains accounted for 46.3–62.2 kg ha^{-1}, representing 75–86 % of total uptake. In contrast, N uptake by straw was considerably lower, ranging only from 8.1 to 18.8 kg ha^{-1}, or 14–25 % of the total. With a few exceptions, and based on statistical analysis of N uptake by TAB, grains, and straw, treatments can be ranked in the following order: AN75 + Se > AN75 ≈ AN75 + Si ≈ PC + AN ≈ PC + AN + Se ≈ PC + AN + Si > PC100 ≈ PC100 + Se ≈ PC100 + Si ≈ CON.

In 2022, P uptake by oat TAB at physiological maturity ranged from 11.9 to 16.8 kg ha^{-1}. Of this, P uptake by grains varied between 8.7 and 11.5 kg ha^{-1}, accounting for approximately 68–73 % of the total. At the same time, straw P uptake ranged from 3.2 to 5.3 kg ha^{-1}, contributing 27–32 % of the total uptake. Regarding P uptake by TAB and grains, the AN75 and AN75 + Se treatments resulted in significantly higher P uptake compared to the PC100 + Se and PC100 + Si treatments, while the remaining treatments fell into an intermediate group. In contrast, straw P uptake did not differ among the treatments.

At physiological maturity, K uptake by oat TAB ranged from 32.7 to 53.2 kg ha^{-1}. Of this, 10.1–13.2 kg ha^{-1} (24–32 %) was accumulated in the grains and 22.5–40.5 kg ha^{-1} (68–76 %) in the straw. Similar trends were evidenced for TAB and straw K uptake, with the highest values recorded under the AN75 + Se treatment (TAB: 53.2 kg ha^{-1}; straw: 40.5 kg ha^{-1}), followed by AN75 and AN75 + Si (TAB: 50.8 and 48.1 kg ha^{-1}; straw: 37.6 and 36.5 kg ha^{-1}, respectively). The lowest K uptake was determined under CON, PC100 + Se, and PC100 + Si treatments (TAB: 32.7–33.5 kg ha^{-1}; straw: ~22.5 kg ha^{-1}). The remaining treatments fell into an intermediate group. Notably, grain K uptake were similar among treatments.

The highest Se uptake by oats was occurred in the three treatments with Se foliar application. For example, in the AN75 + Se treatment, Se uptake reached 1.03 g ha^{-1} (314 μg kg^{-1}) in grains and 0.86 g ha^{-1} (410 μg kg^{-1}) in straw, totaling 1.89 g ha^{-1} (724 μg kg^{-1}). Slightly lower values were recorded in the PC + AN + Se treatment (grains: 0.99 g ha^{-1} (298 μg kg^{-1}); straw: 0.62 g ha^{-1} (354 μg kg^{-1}); total: 1.61 g ha^{-1} (652 μg kg^{-1})), followed by the PC100 + Se treatment (grains: 0.77 g ha^{-1} (293 μg kg^{-1}); straw: 0.53 g ha^{-1} (396 μg kg^{-1}); total: 1.30 g ha^{-1} (689 μg kg^{-1})). Across all fertilizer types, Se application increased Se content by approximately 70–75 % compared with the same treatments without Se. No significant differences in Se uptake were found among the remaining treatments without Se application.

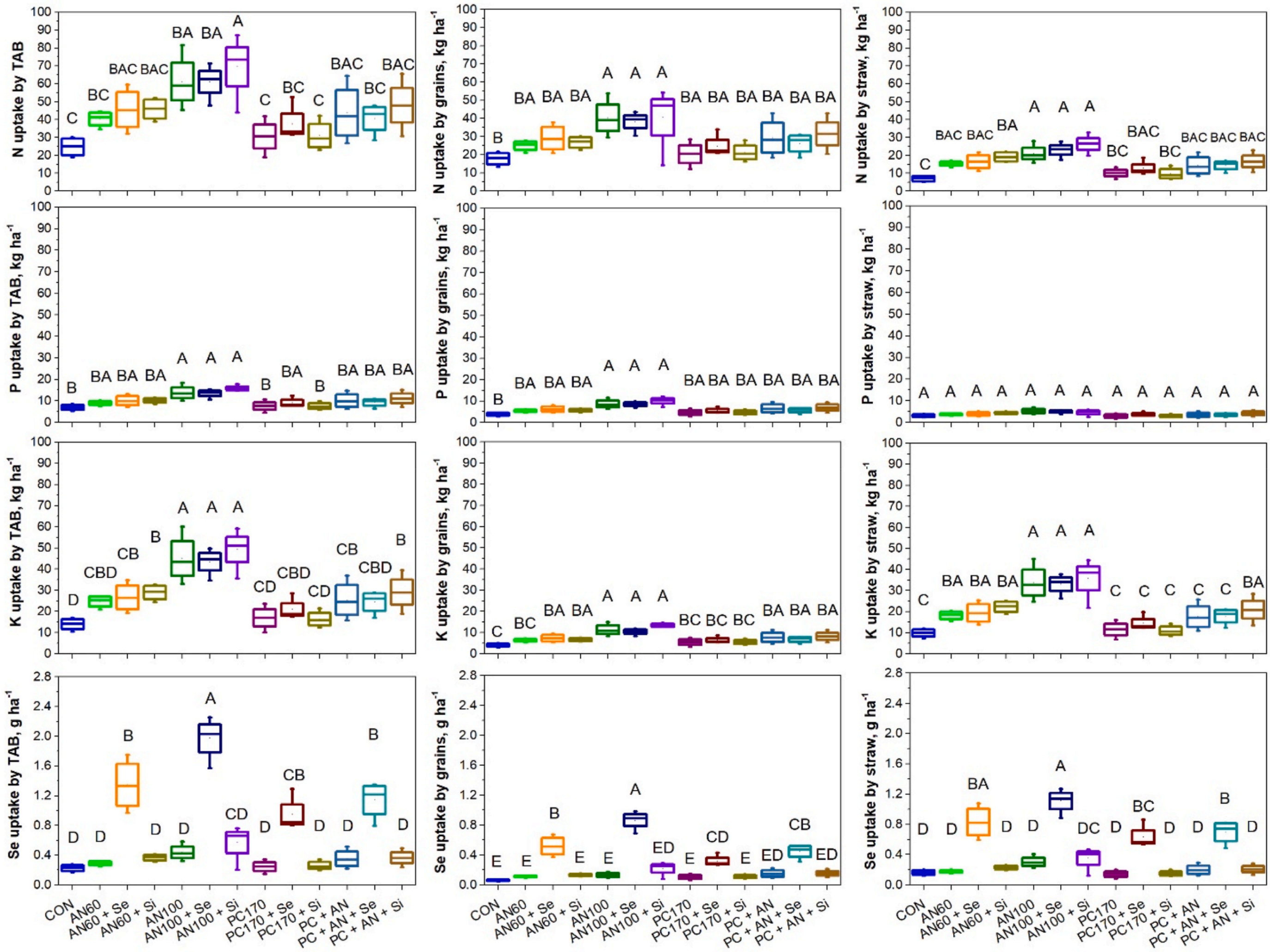

Fig. 5. Effect of fertilization treatments (mineral, organic, and combined) on N, P, K, and Se uptake by barley total aboveground biomass (TAB), grains, and straw in 2021.

3.3.3. *Winter rye*

In the 2022–2023 season, N uptake by winter rye TAB at physiological maturity (Fig. 7) was the highest among all crops grown in the experiment, ranging from 39.1 to 99.0 kg ha^{-1}. Of this total, N uptake by the grains accounted for 29.6–75.6 kg ha^{-1}, representing 72–78 % of the total crop uptake. Similar to other crops, N uptake by the straw was considerably lower, ranging from only 9.5–23.4 kg ha^{-1}, or 22–28 % of the total. Nitrogen uptake by TAB was significantly the lowest and remained at a similar level in the CON and all three compost treatments (PC100, PC100 + Se, and PC100 + Si), with values ranging from 29.6 to 32.9 kg ha^{-1}. In contrast, significantly higher N uptake values were evidenced in the remaining treatments.

P uptake by winter rye TAB at physiological maturity ranged from 29.9 to 50.4 kg ha^{-1} and P uptake by the grains varied between 6.6 and 13.7 kg ha^{-1}. Interestingly, in all three treatments with the highest N75 fertilization rate, grain P uptake accounted for 27–33 % of the total crop uptake, whereas in the remaining treatments, this proportion dropped to 19.5–25.6 %. Meanwhile, straw P uptake was relatively high, ranging from 23.3 to 36.7 kg ha^{-1}, contributing 63.3–76.7 % of the total uptake.

At physiological maturity, K uptake by winter rye TAB ranged from 15.0 to 33.1 kg ha^{-1}. Of this amount, approximately half - 6.8 to 15.6 kg ha^{-1} (41–55 %) - was accumulated in the grains, while the remaining 8.2–17.5 kg ha^{-1} (45–59 %) was taken up by the straw. Similar trends were observed in K uptake by both TAB and grains, with significantly higher values recorded under all three AN75 treatments, followed by the PC + AN treatment group. Statistically, the lowest K uptake occurred under the CON, PC100 + Se, and PC100 + Si treatments.

As with the other crops in the experiment, the highest Se uptake by winter rye was determined in the three treatments with foliar Se application. For example, in the AN75 + Se treatment, Se uptake reached 1.27 g ha^{-1} (358 μg kg^{-1}) in the grains and 0.61 g ha^{-1} (123 μg kg^{-1}) in the straw, totaling 1.88 g ha^{-1}(481 μg kg^{-1}). Slightly lower values were recorded in the PC + AN + Se treatment (grains: 1.06 g ha^{-1} (343 μg kg^{-1}); straw: 0.50 g ha^{-1} (116 μg kg^{-1}); total: 1.56 g ha^{-1} (459 μg kg^{-1})), followed by the PC100 + Se treatment (grains: 0.68 g ha^{-1}; straw: 0.40 g ha^{-1}; total: 1.08 g ha^{-1}). Independent of fertilizer type, applying Se resulted in roughly 46–67 % higher Se content than in the corresponding treatments without Se. In the treatments without Se application, Se concentrations were similar, and Se uptake showed only minor statistical differences, mainly influenced by fertilization rate.

3.4. *Crop nutrient recovery efficiency*

The recovery efficiency of nutrients across the crops during the field experiments 2020–2023 varied notably, influenced by both crop type and fertilizer treatments (Fig. 8). As expected, N had the highest recovery efficiency (RE_N), though values fluctuated depending on fertilizer type. When only mineral fertilizers were applied, RE_N reached ~55

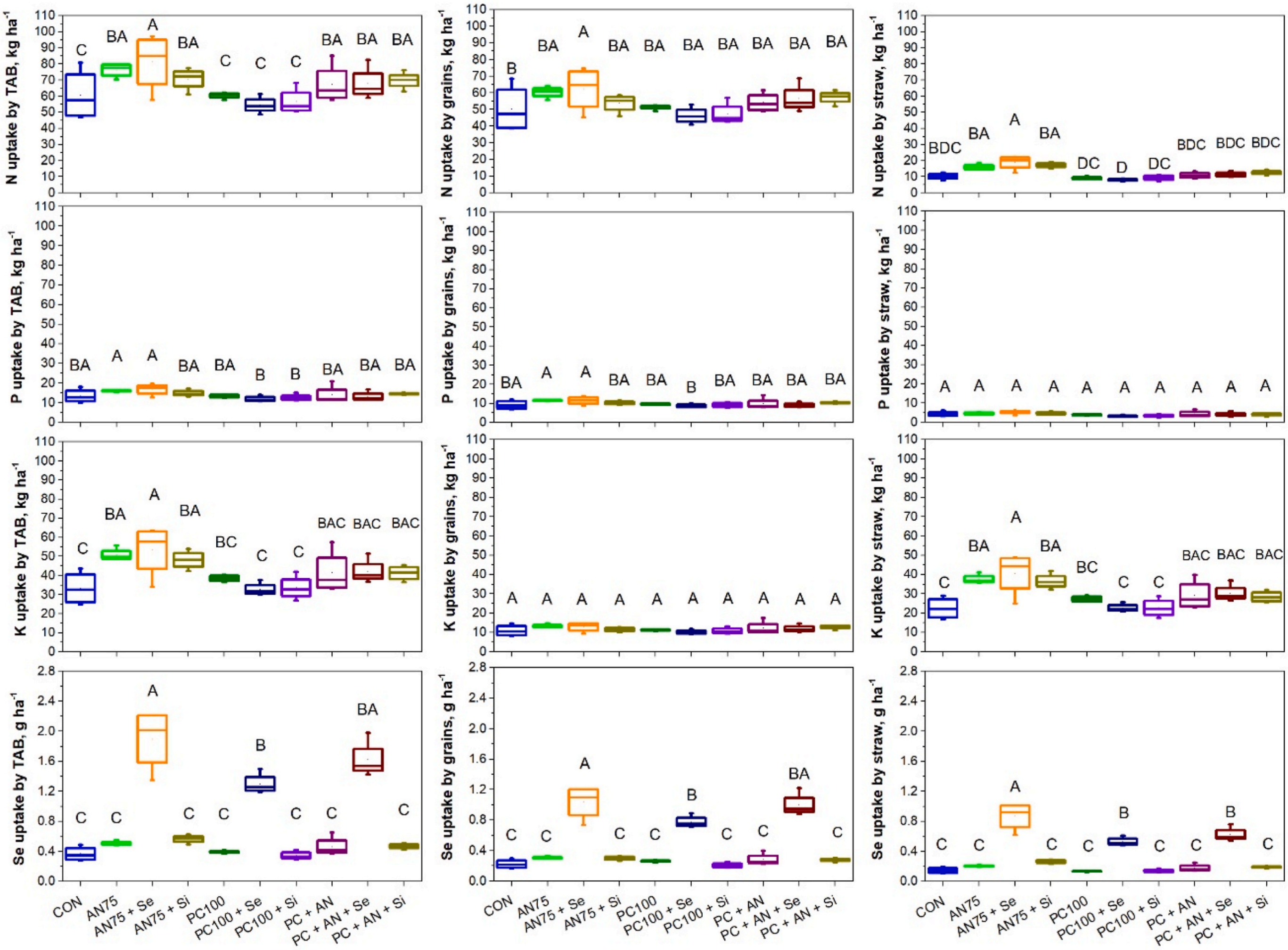

Fig. 6. Effect of fertilization treatments on N, P, K and Se uptake by oat total aboveground biomass (TAB), grains, and straw. Different letters above boxplots indicate significant differences between treatments ($p < 0.05$, Tukey's HSD test).

% for barley in 2020, 39 % in 2021, 33 % for oats in 2022, and up to 70 % for winter rye in 2022–2023. The RE_N values were significantly lower under combined fertilization (mineral + organic), with RE_N around 13 % in both 2021 and 2022, and 24 % in 2022–2023. The lowest RE_N values were calculated for treatments using solely organic fertilizers—5 % in 2021 and 2022, and just 4 % in 2022–2023.

P efficiency was generally low, especially in spring cereals (Fig. 8). Three statistically distinct groups were identified based on fertilization type. The P efficiency (RE_P) was highest with mineral fertilizers (9 % in 2020–2021, 7 % in 2022, and 22 % in 2022–2023). Moderate values were found when combining mineral and organic fertilizers (4 % in 2021, 3 % in 2022, 17 % in 2022–2023), while the lowest RE_P was recorded with organic fertilizers alone (1–2 % in 2021–2022, and 5 % in 2022–2023). These results indicated limited P availability from organic sources under short-term field experiments.

The trends in K use efficiency (RE_K) remained relatively consistent over the years. The RE_K values were highest when only mineral fertilizers were used, with efficiencies of approximately 17 % in 2020, 23 % in 2021, 22 % in 2022, and around 15 % in 2022–2023. Moderate RE_K values were recorded when mineral and organic fertilizers were combined, reaching 12 % in 2021, 13 % in 2022, and 15 % in 2022–2023. The lowest RE_K values were consistently evidenced with the use of organic fertilizers alone: 4 % in 2021, 7 % in 2022, and only 3 % in 2022–2023.

Although, the foliar Se application rate was the same across all treatments, Se use efficiency (RE_{Se}) differed significantly depending on the crop and fertilization treatment. In 2022, RE_{Se} for oats averaged around 22 % and showed no significant differences among treatments. However, in 2021, barley displayed the highest RE_{Se} at the highest mineral fertilizer rate (AN100), reaching 28 %. In contrast, other treatments showed significantly lower RE_{Se} values, averaging around 16 %. A similar trend was detected during the 2022–2023 season, where the highest RE_{Se} (22 %) was recorded in the AN75 + Se treatment, while the average RE_{Se} in the remaining two treatments dropped to 13 %.

4. Discussion

4.1. Effects on yield and soil fertility

The 3-year field study with three cereal crops was carried out under variable weather conditions that strongly influenced crop performance and fertilization effects (Figs. 2 and 3). Only barley was grown in two consecutive years, while oats and winter rye were each cultivated for one year only. Inter-annual differences in precipitation and air temperature likely contributed to changes in yield, nutrient uptake, and nutrient use efficiency, aligning with long-term findings that year-to-year climate variability can significantly affect cereal yields and responses to fertilization [44].

All three cereal species – spring barley (Table 6), spring oats (Table 7), and winter rye (Table 8) – showed grain yield improvements

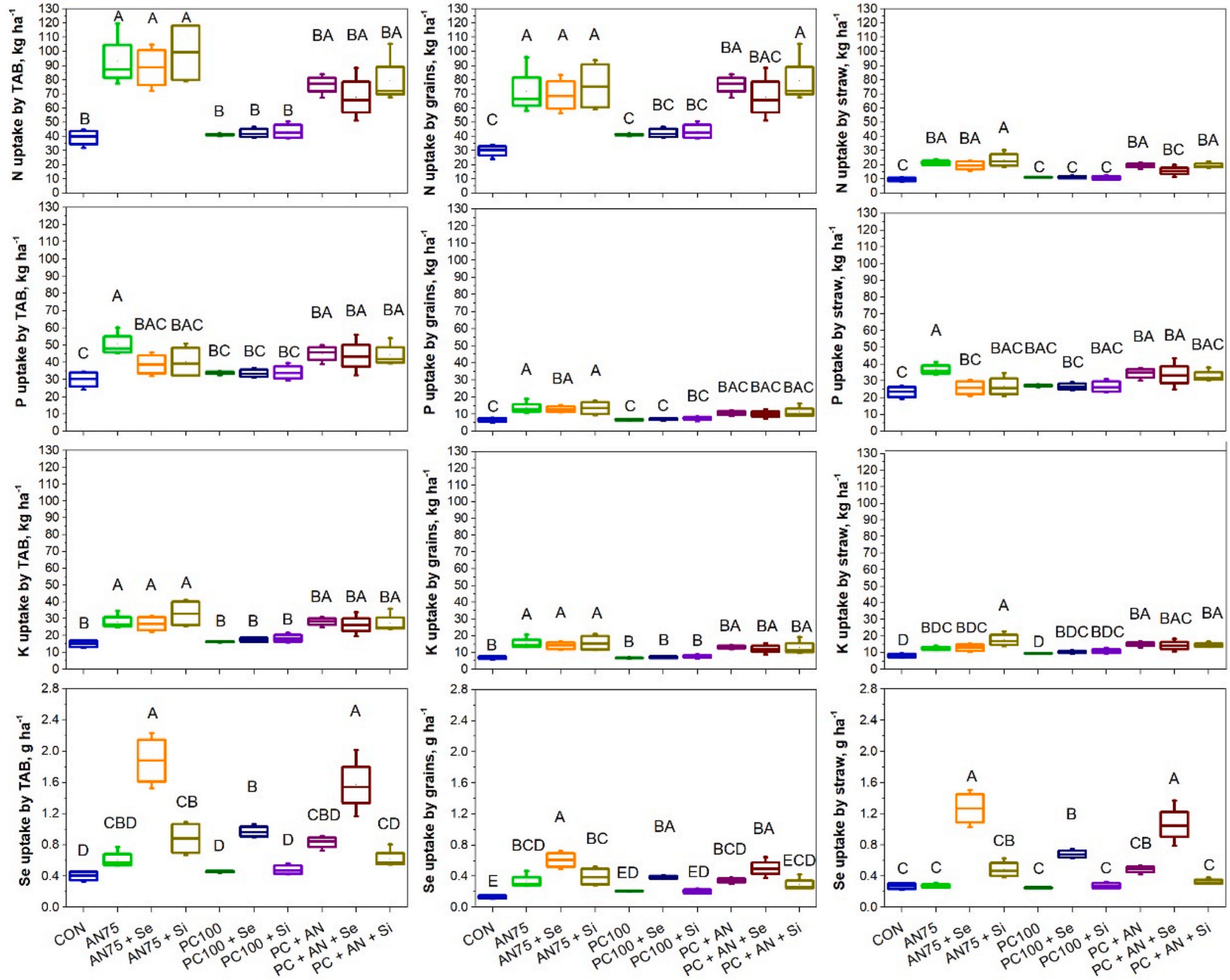

Fig. 7. Effect of fertilization treatments on N, P, K and Se uptake by winter rye total aboveground biomass (TAB), grains, and straw. Different letters above boxplots indicate significant differences between treatments ($p < 0.05$, Tukey's HSD test).

from nutrient enrichment on marginal soil, although the magnitude and nature of responses varied. For example, mineral fertilization alone substantially increased grain yields compared to the unfertilized controls. In contrast, we confirmed that nutrient availability from organic fertilization (pelletized compost) was significantly lower than from mineral sources. This aligns with previous findings showing limited effects of organic fertilization on cereals yields [45].

However, combining mineral and organic fertilizers can achieve yields similar to mineral fertilization alone, and in some cases even higher (Table 7). This was particularly evident for oats during the 2022 growing season and suggests that a portion of mineral inputs can be effectively substituted with slower-releasing organic sources without compromising productivity. While this may point a synergistic effect, it could also reflect a short-term response. In marginal soils with low fertility and organic matter, the addition of pelletized compost likely contributed to improved soil structure and water retention. However, such benefits are typically more pronounced in the long term, as nutrient release, microbial activity, and physical soil improvements accumulate gradually with repeated applications.

In long-term studies, organic amendments alone can sustain high yields once a nutrient cycling equilibrium is established [46]. In contrast, when compost is applied as a one-time input, N may be mineralized later in the season—at a time when cereal crops are no longer able to absorb it efficiently. Similarly, Erhart et al. [47] comparing compost and mineral fertilizer treatments in cereals, found that compost supplied sufficient N during early growth and after flowering, but not during stem elongation in spring—a critical period for N uptake in wheat. Barley and oats, as shorter-season spring crops, showed greater year-to-year yield variability in response to weather and fertility, whereas winter rye proved to be the most resilient, producing more stable yields – consistent with its known tolerance of poor, sandy soils. Nevertheless, all three cereals responded positively to nutrient management strategies, highlighting the practical importance of improving soil fertility to boost productivity on marginal land.

An inverse relationship ($R^2 = 0.53$) between oat grain yield and protein concentration occurred, with the highest protein content found in the unfertilized control. Although this may be counterintuitive, similar patterns have been reported in cereals and are often explained by the "dilution effect," where higher biomass and starch accumulation reduce the relative protein concentration [48]. Accordingly, grain quality may decline as yield increases, not due to limited N, but due to altered source–sink dynamics.

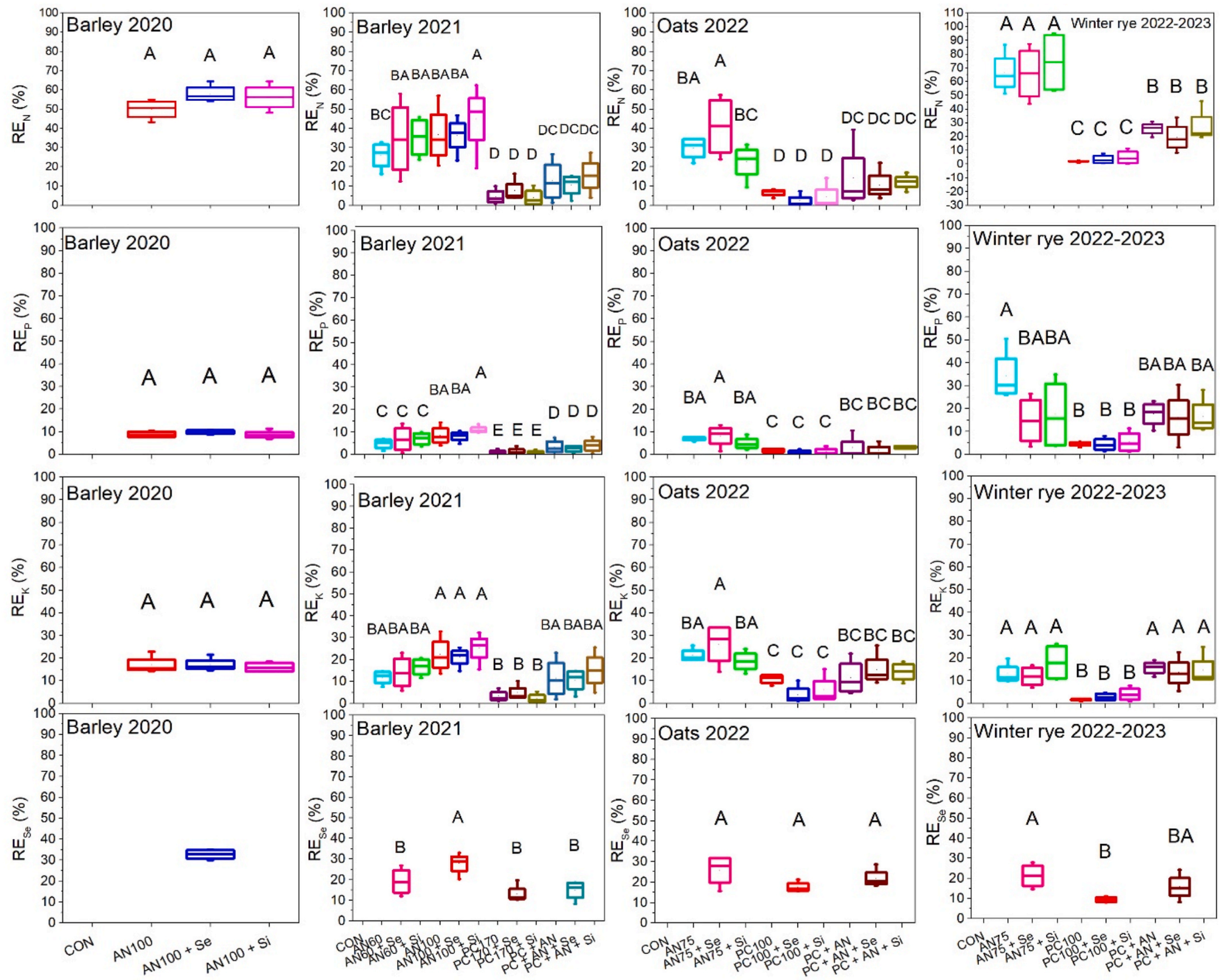

Fig. 8. Crop recovery efficiency of applied N, P, K, and Se (RE_N, RE_P, RE_K, RE_{SE}) under different treatments in barley, oats, and winter rye (2020–2023). Different letters above boxplots indicate statistically significant differences between treatments ($p < 0.05$, Tukey's HSD test).

4.2. Effects on nutrient use and N, P, K efficiency

Nutrient use efficiency depended on crop, fertilizer type, and treatment (Fig. 8). Mineral fertilizers offer rapidly available nutrients and high short-term efficiency but may pose greater loss risks if not well timed. Organic fertilizers released nutrients more slowly and improved soil nutrient retention [49], with potential long-term benefits—although these could not be fully assessed within our three-year study.

Among the tested cereals, winter rye consistently showed the highest N use efficiency (RE_N), with up to ~70 % of applied N recovered in aboveground plant biomass under mineral fertilization. This greater performance is likely due to rye's deeper and more extensive root system combined with its longer growing season [50]. These properties enable rye to access N from deeper soil layers more effectively than barley and oats, particularly in leaching-prone sandy soils. This aligns with long-term field trials in Germany, where RE_N roughly reached 66 % for winter rye and 46 % for spring barley under similar fertilization regimes, although those trials were conducted on contrasting Cambisol soils, unlike our sandy soils [6]. Here, average barley RE_N values ranged between 39 and 55 % across 2020–2021 and all treatments, which were lower than the ranges typically reported across Europe. For instance, Norwegian farm-scale data show that barley recovered 61–71 % of applied N, while oats achieved even higher recovery rates of 67–82 % [51]. However, in our experiment, both the N fertilization rates were slightly lower than those used in the referenced studies, and also the soil types differed considerably. Consequently, our oats data exhibited much lower N use efficiency (~33 %) compared to those reported values. Global estimates indicate that only 30–50 % of applied N is typically recovered by cereals [52]. In well-managed systems, N use efficiency can exceed 60–70 %, especially when employing practices such as split N application and cultivating deep-rooted crops like rye. In our trials on sandy soils, RE_N was relatively high considering the elevated risk of N leaching typically associated with such soil types.

In contrast to N, P recovery efficiency (RE_P) was considerably lower. In our trials, cereal P uptake was only ~5–50 kg P ha^{-1}, corresponding to ~7–22 % of the applied P. Notably, RE_P values were slightly higher in the winter rye experiment compared to summer cereals. These findings align with general estimates that cereals typically recover only 15–20 % of applied P in the first year, with much of it becoming fixed in the soil [53]. For instance, in Ethiopian trials, balanced P application increased barley yields by 11–30 % on Cambisols but only 7–14 % on Vertisols, largely due to P fixation [54]. Here, the sandy soils—with low fertility and poor buffering capacity—likely limited immediate P availability, highlighting the need for long-term P buildup strategies in such marginal soils. Organic P may also contribute to phytoavailable P if hydrolyzed under favorable conditions—namely, when substrate is available and soil pH remains buffered [55]. However, such conditions are unlikely to be consistently met in low-buffering sandy soils, as in our case.

Potassium recovery efficiency (RE_K) followed a similar pattern. In our trials, the crops accumulated between 9.8 and 53.2 kg K ha^{-1}, corresponding to approximately 3–23 % of the applied potassium. These values are consistent with global averages for cereals, where K recovery typically reaches ~19 % (Dhillon et al., 2019).

4.3. Se uptake and efficiency

Micronutrient uptake shifted notably under the biofortification treatments. Selenium uptake increased significantly with Se fertilization – barley, oats, and rye all accumulated much more Se in their tissues and grains than untreated plants. Here foliar Se application increased Se recovery efficiency (RE_{Se}) by approximately 16–28 % depending of plant species, indicating effective translocation from foliar spray to grain. Notably, Se was distributed almost evenly between grains and leaves, suggesting that crop residues—particularly leaves—could serve as a valuable Se source if returned to the soil through post-harvest composting. This aligns with other field trials showing that 20–30 % of applied Se can be absorbed and stored in cereal grains [56]. Winter rye showed particularly high RE_{Se}, highlighting its potential for biofortification. Interestingly, Se fertilization had no negative effect on N, P, or K uptake at the foliar application levels used. In fact, there were indications of enhanced N uptake in Se-treated plots. This effect may be explained by Se-induced activation of antioxidant systems, protection of photosynthetic capacity, and improved membrane integrity, which help maintain root function and nutrient transport under stress [27]. In addition, Se can interact with sulfur metabolism, influencing the synthesis of sulfur-containing amino acids and indirectly supporting N assimilation [57]. This agreed with findings in rice, where Se applications improved N assimilation, likely due to healthier root systems and beneficial microbial interactions [58].

The fertilization strategy applied in the experiment strongly influenced crop yields, nutrient uptake, and use efficiency under nutrient-poor sandy soil conditions. Organic fertilizers alone were insufficient to meet cereal nutrient demands over the short term, resulting in low nutrient recovery and limited yields. In contrast, mineral fertilizers provided immediate nutrient availability and led to the highest yields. Integrated fertilization strategies - combining organic and mineral sources - offered a balanced approach by supporting both short-term productivity and long-term soil improvement. In our marginal sandy soils, integrated treatments produced yields close to those of mineral-only fertilization, despite lower short-term nutrient recovery due to slow compost mineralization. Over time, we expect improvements as soil organic matter builds up. Overall, balanced fertilization tailored to crop and soil conditions is key to achieving efficient nutrient use and sustainable productivity, particularly on marginal land.

5. Conclusions

This 3-year field experiment on marginal sandy soils demonstrated that both cereal species and fertilization strategy strongly influenced yield performance, nutrient uptake, and nutrient recovery efficiency. The study was carried out within a rotational cropping system, which reflects realistic farm management practices and allows assessment of cumulative effects across different cereal species and fertilization regimes. Based on the analysis conducted, the key findings are as follows:

1. Winter rye outperformed oats and barley in terms of N recovery efficiency (RE_N), reaching values of up to ~70 % under mineral fertilization. This high recovery rate was attributed to its deep root system and longer vegetative period. In contrast, oats showed the lowest RE_N (~33 %), reflecting both species-specific traits and limited N availability under organic or low-input treatments.
2. Phosphorus (RE_P) and K (RE_K) recovery efficiencies were lower than for N, as expected in sandy soils with low buffering capacity. Across treatments, RE_P ranged from 7 % to 22 %, and RE_K from 3 % to 23 %.
3. Foliar Se application significantly enhanced Se uptake and recovery efficiency (RE_{Se}), increasing Se use efficiency by 16–28 % compared to untreated controls. Notably, Se accumulated nearly equally in grains and leaves, indicating both successful grain biofortification and the potential for Se-enriched crop residues to be recycled into the soil through composting.
4. Fertilization strategy had a major influence on both short- and medium-term productivity. Mineral fertilizers produced the highest yields and nutrient recovery rates, while organic fertilizers alone were insufficient to meet immediate crop demands. However, integrated treatments (mineral + compost) delivered similar yields to mineral-only treatments and hold promise for long-term soil quality improvements, despite slower nutrient mineralization.
5. Overall, balanced fertilization tailored to crop type and soil limitations is essential to optimize yield and nutrient efficiency in low-fertility systems. For marginal soils, management should combine balanced mineral and organic fertilization with targeted micronutrients (e.g. selenium, silicon) to enhance nutrient uptake and stress resilience. Given the relatively low P and K recovery, further targeted experiments are needed to isolate and evaluate the specific effects of phosphorus and potassium under different management strategies and soil types.

CRediT authorship contribution statement

R. Žydelis: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **V. Povilaitis:** Writing – review & editing, Methodology, Investigation. **L. Weihermüller:** Writing – review & editing. **A. Kazlauskaitė-Jadzevičė:** Writing – review & editing. **E. Loit:** Writing – review & editing, Project administration, Methodology. **W. Szulc:** Writing – review & editing, Resources, Methodology. **P. Schröder:** Writing – review & editing, Methodology. **M. Mench:** Writing – review & editing, Methodology. **F. Rineau:** Writing – review & editing, Methodology. **E. Bakšienė:** Writing – review & editing, Investigation. **B. Rutkowska:** Writing – review & editing, Methodology. **A. Povilaitis:** Writing – review & editing, Supervision.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2025.102277.

Data availability

Data will be made available on request.

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