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Understanding the impact of within-field Olsen P variation on common wheat production in Olsen P deficient soils

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ABSTRACT

This study investigates the influence of Olsen phosphorus (Ps) within-field variability on common wheat production in Ps-deficient soil. It covers a comprehensive investigation conducted over two growing seasons in Tuscany, Italy, aiming to evaluate the impact of within-field Ps variation on common wheat production and crop responses to different agronomic treatments. Field experiments were undertaken, employing 24 treatments, including 4 wheat varieties, 2 seeding densities, and 3 nitrogen fertilization levels. Soil samples were collected to determine within field variability of main soil properties. At harvesting, aboveground biomass was collected to determine grain yield, straw, and total protein content. Firstly, an ANOVA was performed to account for the effect of the agronomical treatments on crop parameters, namely the Agronomical Input Model (AIM). Then, soil total nitrogen (Ns) and Ps, were added as covariates in a new model, namely the Agronomical and Soil Input Model (ASIM). Results showed a significant spatial variability of Ps within the fields, ranging between 13.7 and 17.4 mg kg^{-1}. Despite this minimal variation in Ps, we observed a linear increase in GY of about 1430 kg ha^{-1} for each increase of 1 mg kg^{-1} in Ps. Further studies should be conducted to account for non-linear responses at both lower and higher Ps levels. The ASIM model outperformed AIM, indicating a notable increase in predictive accuracy for both grain yield and protein concentration due to its incorporation of soil parameters. The variance explained by ASIM in predicting the grain yield and protein concentration in grain increased by about 11.0 % and 17.3 %, respectively, with respect to AIM. The study emphasizes the necessity of managing within-field Ps variability through targeted fertilization strategies to enhance wheat production in Ps-deficient soils. By addressing soil nutrient variability, this research aims to contribute to more precise and efficient common wheat production systems.

1. Introduction

Soil fertility is a critical factor determining crop growth and yield, whereas nutrient availability is one of the most important factors affecting agricultural productivity. Among the various elements present in the soil, Olsen phosphorus (Ps) [1] and total soil nitrogen (Ns) are two of the most limiting nutrients for plant growth and crop yield. Nitrogen (N) and phosphorous (P) influence all aspects essential for the growth of wheat, including tissues components, protein content, the regulation of biochemical processes occurring in crops, the structural function of macromolecules, and energy exchange, respectively [2]. N and P affect also many aspects of plant physiology, such as photosynthesis, flowering, seed maturity, and seed development [3]. However, the scarcity of phosphorus, especially Ps, often proves to be a limiting factor for plant growth and crop yield. Ps-deficient soils account for more than 40 % of the world's agricultural land, which seriously limits crop yield [4,5]. Soil Ps deficiency is frequent and problematic in alkaline soils, which are common in arid and semi-arid regions with little rainfall [6]. In these soils, P ions quickly react with calcium (Ca), forming calcium phosphate which is not available for plant uptake [7]. Under these conditions, crop production losses related to the unavailability of Ps often occur [8,9]. In Ps-deficient soil conditions, growth is generally more reduced than the rate of photosynthesis per unit of leaf area, affecting crop growth [10]. Deng et al. (2018) [11] reported that under deficient soil Ps, overall plant growth was depressed due to limited photosynthesis, thereby affecting yield. In conditions where P fertilization does not meet the crop

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nutrient demand, the presence of soil Ps influences growth, development, and yield [12,13]. In general, Ps deficiency is a constraint to crop production, including common wheat (*Triticum aestivum*, L.), a staple food around the world, and a major crop requiring P fertilizer.

Generally, in Ps-deficient soils, most farmers use high doses of P fertilizer in an attempt to create a uniform availability of Ps within the field during crop development. However, according to several studies [4,14,15], the depletion of the world's P reserves within the next 50 to 100 years poses a significant risk to future agricultural production and food security. Therefore, it is crucial to generate significant efforts to ensure the effective and efficient use of P fertilizers to conserve the finite P resources in rock, to protect the environment [16], and to simultaneously meet the increasing demand for food [17]. Further, conventional nutrient application is often deemed inefficient, due to the high spatial variability in nutrient distribution. In particular, the spatial variability of soil chemical-physical-biological properties influences the availability of Ps in soil, resulting in extreme variability [18,19]. Spatial variability in soil Ps has been found at various scales, ranging from regional to field levels [20,21]. Agronomic practices, particularly the application of phosphorus fertilizers over time, appear to significantly influence the spatial variability of soil Ps [12,22]. The intricate spatial variability of Ps in fields with extensive cropping and fertilization histories has long been acknowledged [23]. Presently, smart farmers are mainly interested in within-field variability of nutrients, as well as variations across their farmland [21]. However, to date, the focus of nutrient fertilization has mainly centered on meeting the crop's nitrogen demand [24,25]. While supplementing nitrogen fertilizer can enhance grain yield when crop growth is impeded by nitrogen deficiencies, the yield may reach a plateau if factors other than nitrogen become limiting [26]. Therefore, optimization of soil fertilization must be pursued through the study of the heterogeneity of soil properties, especially Ps, becomes imperative [27]. However, the current emphasis on nitrogen, as opposed to a more holistic consideration of soil heterogeneity, is identified as a gap that needs to be addressed for future research and agricultural practices. In particular, there is the need for a more comprehensive and focused exploration of within-field Ps variability.

The research aims to evaluate the influence of within-field Ps variation on common wheat production in Ps-deficient soil. Furthermore, it seeks to examine how this variation affects crop responses to specific agronomic treatments, including wheat varieties, seeding densities, and N fertilization levels. The overarching goal of this investigation is not only to underscore the significance of Ps in P-deficient soils but also to emphasize the necessity for precise and efficient nutrient application, tailored to specific soil conditions, to optimize crop performance while mitigating environmental impacts.

The research is innovative in its in-depth exploration of within-field Ps variation's impact on common wheat production, especially in Ps-deficient soils. It introduces a new perspective, prompting readers and researchers to reassess within-field Ps variation's significance in common wheat production. The study spans two complete cycles, utilizing diverse treatments, including multiple common wheat varieties, seeding densities, and nitrogen fertilization levels. This comprehensive approach enhances findings' reliability and robustness and adds sophistication to the investigation. Importantly, the research contributes to precision agriculture, highlighting the crucial need to understand and manage within-field Ps variability for optimizing agricultural production. This novel approach has the potential to reshape our understanding of Ps dynamics in common wheat cultivation and guide precision agriculture practices for sustainable, improved common wheat yields.

2. Materials and methods

2.1. Description of the study fields

Field experiments were conducted for two consecutive growing seasons (GS) from September 2016 to August 2018 under rainfed conditions at the Giuseppe Chiarion farm, in Monteroni d'Arbia, Tuscany, Italy (43.2007 N, 11.4182 E, 160 m a.s.l.). The climate is sub-Mediterranean, characterized by humid, rainy, and relatively cold winters, and warm and dry summers. The mean annual temperature was approximately 13.5 °C and the cumulative rainfall 750 mm, respectively [28]. A meteorological station located near the experimental field was used to monitor meteorological parameters (rainfall, temperature, humidity). The cumulated rainfall (from November to June), during the 1st and 2nd GSs, was 332.8 and 679.2 mm, respectively. The monthly rainfall experienced during the two growing seasons is reported in Table 1. The highest amount of rainfall was shown in November and March during the 1st GS and 2nd GS, respectively. On the other hand, the lowest rainfall was detected in June in both GSs. The number of rainy days was also different in the two GSs, varying from 86 to 118 during the 1st GS and 2nd GS, respectively. During the two GSs, the monthly cumulated rainfall, and the growing degree day (GDD) [29] data were computed and analyzed as reported in Soofizada et al. [30]. The phenological development of the plants was monitored twice a week following the BBCH scale [31]. The monthly GDD ranged from 22 to 568 and from 37 to 489, during the 1st and the 2nd growing season, respectively.

The 0 –0.3 m soil layer was silty clay loam (Fluventic Haplustepts, fine silty, mixed, mesic), sub-alkaline (pH 7.9), and contained on average 12.0 g kg^{-1} total organic carbon (OCs), 1216 mg kg^{-1} Ns, 15.4 mg kg^{-1} Ps, and 265 mg kg^{-1} potassium. The experimental plan included 24 treatments (1250 m^2 each), replicated three times in a strip-plot design (Fig. 1).

Each strip was sown with a different variety (Gen) and, respectively, subdivided longitudinally in two different seeding densities (Sd: 90 and 180 kg of seed ha^{-1}) and transversally, in the three N fertilization levels (Nf: 35, 85, and 135 kg N ha^{-1}). A total of 4 common wheat varieties (Var) were tested, comprising one registered dwarf variety (Bologna) and three old, non-dwarf landraces (Andriolo, Sieve and Verna). Egyptian clover (*Trifolium alexandrinum*, L.) and sunflower (*Helianthus annuus*, L.) were the previous crops in the first and second growing seasons, respectively. In both seasons, the fields were plowed, and then the disk harrowed in late October. Then, a total of 100 kg ha^{-1} triple superphosphate (P_2O_5: 46 %) was distributed homogeneously on the soil surface and incorporated into the soil by disk harrowing at a 0.2 m depth ten days before sowing. The seedbed preparation for sowing was performed using a spike tooth harrow the day before sowing. Common wheat seeds were sown on December 19, 2016, and on November 21, 2017, respectively, with an inter-row distance of 13 cm. Total nitrogen dose was scheduled in three different applications: 20 % by spreading urea (N: 46 %) at seeding, 40 % by spreading ammonium nitrate (N: 26 %) at tillering, and 40 % by spreading ammonium nitrate (N: 26 %) at stem elongation. In both growing seasons, herbicide treatment was performed at tillering by spraying 0.75 L ha^{-1} of Axial Pronto 60 (Syngenta, Basel, Switzerland; containing: 60 g L^{-1} Pinoxaden and 15 g L^{-1} and Cloquintocet-mexyl) and 0.75 L ha^{-1} of Marox SX (Cheminova Agro Italia, Rome, Italy; containing 333 g L^{-1} of thifensulfuron-methyl and 167 g L^{-1} of tribenuron-methyl). Furthermore, fungicide treatments were performed at booting by spraying 0.8 L ha^{-1} Amistar Xtra (Syngenta, Basel, Switzerland; containing Azoxystrobin 18.2 % and Cyproconazole 7.3 %) and 1.2 L ha^{-1} Sakura (Sumitomo Chemical Co., Tokyo, Japan; containing Bromuconazole 167 g L^{-1} and Tebuconazole pure 107 g L^{-1}). No water logging, disease, pest, or weed problems were observed during the experiment.

2.2. Soil and crop sampling and physicochemical analysis

The common wheat samples were collected at commercial maturity (kernel moisture lower than 13 %) on July 10th, 2017, and on July 13th, 2018, respectively. Sampling was randomly performed in 3 replicates within each treatment by collecting aboveground biomass from sampling areas of 0.5 m^2. For each aboveground biomass sample, grains and

Table 1
Data of monthly precipitation, number of rainy days, and growing degree days (GDD) recorded at Monteroni D'Arbia meteorological station during the growing season (GS) 2016-2017 and 2017-2018 (1st GS and 2nd GS) respectively.

Parameter	GS	Month							
		Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Precipitation (mm)	1st GS	138.4	11.2	13.6	56.2	29.2	54.4	23.4	6.4
	2nd GS	87	77.8	36.4	128	138.4	55.8	126	29.8
Rainy days (N°)	1st GS	16	17	6	13	6	11	13	4
	2nd GS	13	22	12	15	15	9	18	14
GDD (°C)	1st GS	174	67	22	116	208	252	372	568
	2nd GS	156	59	101	37	130	305	416	489

straws were separated utilizing a small thresher plot (Cicoria 2375, Cicoria S.r.l., Palazzo San Gervasio, Italy). The grains and straw samples were oven-dried at 105 °C until constant weight and then weighed to calculate grain yield (GY; kg ha^{-1}) and straw yield (SY; kg ha^{-1}), both expressed as dry weight. Grains were milled using a grinder with a 0.5 mm screen (Cyclotec 1093 lab mill, FOSS Tecator, Höganäs, Sweden). Then, wholegrain flour samples (5 mg) were analyzed with a CHNS analyzer (CHN-S Flash E1112, Thermo-Finnigan LLC, San Jose, CA, USA) to determine total grain N content (GNC), and straw N content (SNC). The grain protein content (GPC) was determined as reported by Guerrini et al. (2020) [32].

Before sowing, a total of 3 soil samples for each treatment and year, respectively, were collected from a depth of 0-20 cm. The soil samples were air-dried, ground, and sieved (2 mm), and then analyzed for the determination of Ns and Ps. As the soil was only collected before sowing, we analyzed the total N as it is more related to the production parameters (grain and straw yield) than mineral N. On the opposite, the available soil N is subjected to high variability during the growing season, and is, therefore, representative of only a specific moment in time. Ns was determined using a CHNS analyzer, while Ps was determined by the colorimetric method based on extraction with $NaHCO_3$, as reported by Olsen et al. (1954) [1].

2.3. Soil data spatialization and statistical analysis

The Ns and Ps maps were created by interpolating the point data from soil test results with the regularized spline with the tension method, using ArcGIS software (ESRI, USA). The map cell size was 1 m^2. We conducted the statistical analyses using the R 4.1.1 version. Data were grouped for the two growing seasons (GS) in order to take into account, the environmental variance derived from the different meteorological conditions and unexplained soil characteristics. Two different linear models were built for each dependent variable and were then compared.

2.3.1. Agronomical Input Model (AIM)

The first model was the Agronomical Input Model (AIM) which includes the agronomic inputs Gen, Nf, SD, and GS, which were considered independent variables. The normality of data distributions was assessed using the Shapiro-Wilk test, while homogeneity of variances was examined with the Levene test. As both normality and homogeneity assumptions were met, the dataset was deemed suitable for Analysis of Variance (ANOVA). ANOVA was employed to examine the main effects of agronomic inputs and their interactions. Gen, SD, and GS were considered fixed effect variables in the model, while Nf was considered a random effect variable, resulting in a mixed effect ANOVA model.

2.3.2. Agronomical and Soil Input Model (ASIM)

The second model was the Agronomical and Soil Input Model (ASIM), which improved the AIM by adding Ns and Ps as a covariate in the model. The interactions between the Ps and Ns with the factors already present in the AIM model were only considered in the event of a statistically significant effect ($p<0.05$). Otherwise, these interactions were dropped into residuals, as suggested by Dunn and Smyth (2018) [33]. The considered dependent variables were GY, SY, GNC, SNC, and GPC. A correlation matrix was used to check for redundancy among covariates in order to eliminate collinear variables, using a threshold of 0.8.

To comprehend and quantify the impact of nitrogen and phosphorus already present in the experimental soils, a comparative analysis was undertaken between the AIM and ASIM models, focusing on the amount of variance explained by each model. Prior to commenting on observed differences in terms of explained variance, an additional ANOVA was conducted to compare the two models [33]. Comments were provided only when the ASIM model exhibited a statistically significant improvement over the AIM model ($p < 0.05$).

3. Results

3.1. Distribution of soil properties and their correlation with common wheat yield and quality parameters

For both GSs, all parameters were almost normally distributed, with all averages being close to all medians, with a low negative excess of kurtosis (platikurtic), and with a low positive skewness, respectively (Table 2). Considering both fields used in the two GSs, Ns and Ps values varied between 1010.0 and 1499.0 mg N kg^{-1}, and between 13.7 and 17.4 mg P kg^{-1}, respectively. The variation ranges for Ps were 3.3 mg P kg^{-1} and 2.7 mg P kg^{-1} in the first and second GS, whereas those for Ns were 428 mg N kg^{-1} and 465 mg N kg^{-1}. The Ns exhibited a 1.8 and 2.1 times larger variation than Ps in the first and second fields, respectively. The Ns and Ps spatialization highlighted the spatial variability of these nutrients within the two experimental fields (Fig. 2). The spatial distribution was shown to be discontinuous with no trends being observed for both nutrients in the two fields.

3.2. Production analysis

The GY and SY measured in the 1st GS were significantly different from that in the 2nd GS (Table 3). The GY production for each variety was significantly different. The highest and lowest productions were shown for the modern variety BO and AN, respectively, with the latter not being statistically different from VE. The GY value was significantly positively correlated ($R = 0.994$, $p < 0.01$) to the variety year of release (1933, 1953, 1960, and 2002 for AN, VE, SI, and BO, respectively). During the two GS, the highest SY was measured in VE, followed by SI, BO, and AN, respectively. Considering all varieties, no significant differences were detected between the two SD levels in terms of both GY and SY. Both GY and SY significantly increased as the Nf increased. The average GY increased by about 23 % from 35 to 80 kg ha^{-1} and by about 40 % from 80 to 135 kg N ha^{-1}. At the same time, the SY increased by about 28 % and 36 % from 35 to 80 kg ha^{-1} and from 80 to 135 kg N ha^{-1}, respectively. The ANOVA showed that GY and SY were not affected by seed density. On the other hand, GY and SY were significantly affected by the interaction GS × Gen and Gen × SD, whilst no interactions between GS × SD, GS × Nf, and SD × Nf, were found to be statistically

Table 2
Statistics for total soil nitrogen (Ns) and Olsen phosphorus (Ps) measured in the two experimental fields; average (standard errors – SE - are reported in brackets), minimum (Min), maximum (Max), coefficient of variability (CV%), skewness and excess kurtosis values are reported.

Parameter	Field	Average (SE)	Min	Max	CV%	Skewness	Excess kurtosis
OCs (%)	1^{st}	1.21 (0.01)	1.03	1.46	8.38 %	0.20	-0.69
	2^{nd}	1.19 (0.01)	1.00	1.45	8.96 %	0.51	-0.46
Ns (mg kg^{-1})	1^{st}	1215.1 (12.82)	1010.00	1438.00	8.95 %	0.15	-0.85
	2^{nd}	1217.29 (12.25)	1034.00	1499.00	8.54 %	0.51	-0.54
Ps (mg kg^{-1})	1^{st}	15.61 (0.09)	14.10	17.40	5.02 %	0.10	-0.53
	2^{nd}	15.09 (0.07)	13.70	16.40	4.15 %	0.18	-0.56
OCs:Ns	1^{st}	9.96 (0.04)	9.06	10.60	3.24 %	-0.57	-0.39
	2^{nd}	9.79 (0.04)	9.17	10.49	3.37 %	0.14	-0.45

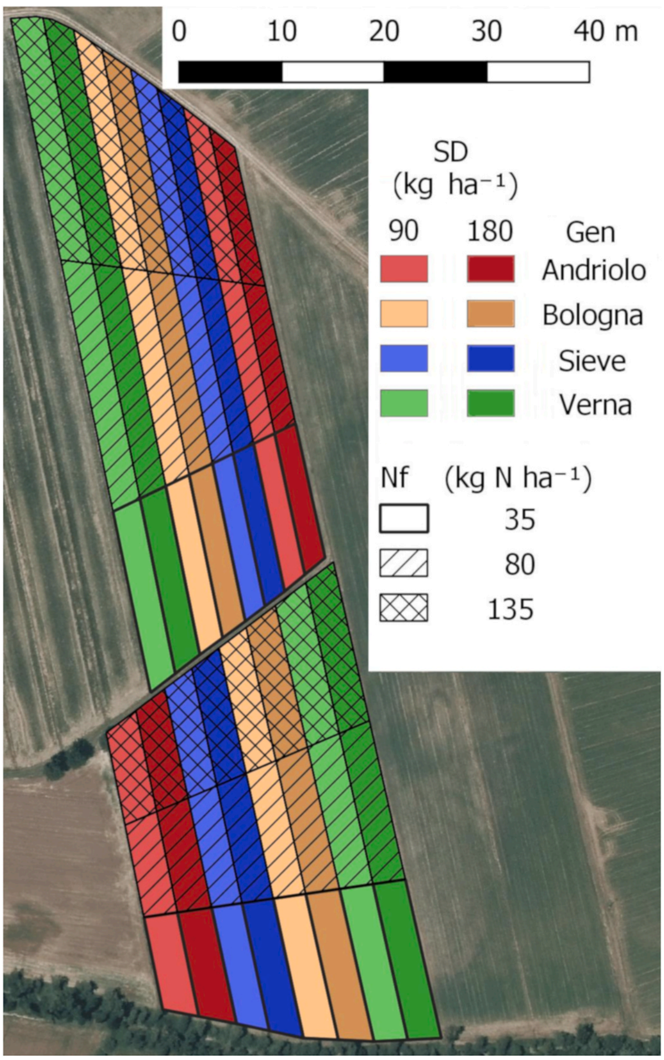

Fig. 1. Layout of the study fields for the 1^{st} and 2^{nd} growing season (GS), in the top and the bottom respectively. The two seed densities (SD), three nitrogen levels (Nf), and the four genotypes (Gen) are reported.

significant. The Gen × SD and Gen × Nf interactions were significant and attributable to the different fertilization responses of AN with respect to the remaining varieties. The GY in BO, SI, and VE increased as the SD and Nf increased. Although AN showed a higher GY at SD090 than at SD180, the GY increased from Nf35 to Nf135 and then Nf80.

According to the ANOVA, the GNC and SNC were not affected by SD, but were slightly affected by Gen. However, a strong influence was detected in the GNC parameter by Nf, GS, and the GS × Gen interaction. Similar results were also detected for GPC, but in this case, the Gen effect was highly significant ($p < 0.01$), with GS × SD, GS × Nf, and Gen × Nf

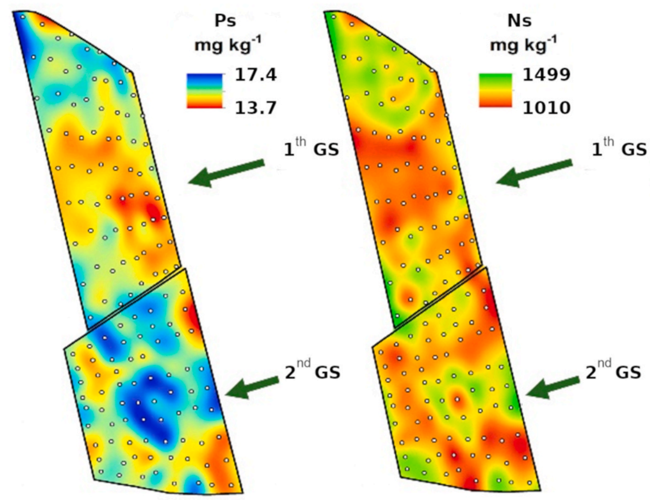

Fig. 2. Spatial distribution of the Olsen phosphorus (Ps) and total nitrogen (Ns) concentration in the soil within the experimental fields for the two growing seasons of common wheat.

also being significant, respectively. GNC and GPC were highest for 135 kg N ha^{-1} and the Verna variety. Moreover, significant differences were found between the Nf135 level and the two lower levels, while no significant difference was found between Nf35 and Nf80. In addition, the GS also significantly affected GNC and GPC. Results indicated that NU was not significantly affected by SD, while it was significantly affected by Gen, Nf, GS, and the GS × Gen interaction. The highest NU was found in BO, followed by VE and SI, and AN, respectively. The lowest fertilization level (35 kg N ha^{-1}) failed to meet the nitrogen demand for the 4 cultivars (NU: 42.7, 65.9, 50.7, and 42.1 kg N ha^{-1} for AN, BO, Si, and VE, respectively). Instead, the intermediate fertilization level (80 kg N ha^{-1}) was insufficient to meet the N demand for BO, sufficient for SI and VE, and in excess of the requirement for AN (NU: 54.3, 88.4, 68, and 76 kg N ha^{-1} for AN, BO, SI, and VE, respectively). Finally, the highest fertilization level (135 kg N ha^{-1}) met the nitrogen demand for BO, SI, and VE (NU: 127.2, 125.6, 129.0 kg N ha^{-1}, respectively) while it was in excess for AN (NU: 91 kg N ha^{-1}).

3.3. Effect of Ns and Ps and agronomical inputs on grain yield and grain protein concentration

The degree of correlation between the considered soil properties is shown in Fig. 3. Ns and Ps were significantly positively correlated with each other. The Pearson correlation analysis showed that GY, SY, GNP, and GPC were strongly correlated with Ns and Ps. Instead, the SNC values were weakly correlated with Ns, and no correlation was found with Ps.

The AIM model was able to explain a large part of the SY variance ($R^2 = 0.7723$, $p < 0.01$). In this model, the growing season effect on SY

Table 3
Average values of grain and straw yield (GY; SY) of nitrogen concentration in grain and straw (GNC and SNC), of grain protein concentration (GPC), and of nitrogen removed at harvesting with the above-ground biomass (NU) as a function of genotype (Gen), seed density (SD), nitrogen fertilization level (Nf), growing season (GS) and first-order interactions. The sig columns report the ANOVA results (* = 0.05, ** = 0.01, *** = 0.001, ns = not significant), while the lowercase letters represent the Tukey HSD post hoc test results.

Variability sources	GY (t ha^{-1})		SY (t ha^{-1})		GNC (%)		SNC (%)		GPC (%)		NU (kg ha^{-1})	
	Average	Sig.	Average	Sig.	Average	Sig.	Average	Sig.	Average	Sig.	Average	Sig.
Gen		***		***		*		***		***		***
AN	2.55 (0.93)	b	4.47 (1.34)	b	1.96 (0.33)	ab	0.23 (0.10)	b	11.13 (1.86)	ab	62.68 (3.29)	c
BO	3.84 (1.21)	a	4.56 (1.10)	b	1.96 (0.32)	ab	0.33 (0.14)	a	11.09 (1.81)	ab	93.86 (5.05)	a
SI	3.17 (1.35)	ab	5.61 (2.23)	ab	1.85 (0.35)	b	0.32 (0.12)	ab	10.53 (1.97)	b	81.46 (5.56)	b
VE	3.01 (1.14)	b	5.8 (2.52)	a	2.00 (0.45)	a	0.29 (0.15)	ab	11.39 (2.56)	a	82.44 (4.96)	b
SD												
SD90	3.08 (1.12)		5.15 (1.69)		1.93 (0.38)		0.29 (0.13)		10.97 (2.18)		77.12 (7.23)	
SD180	3.21 (1.31)		5.07 (2.22)		1.96 (0.41)		0.30 (0.13)		11.12 (2.30)		83.09 (8.66)	
Nf		***		***		***		***		***		***
Nf35	2.39 (0.87)	c	3.81 (1.24)	c	1.78 (0.29)	b	0.24 (0.10)	b	10.36 (1.70)	b	53.25 (3.17)	c
Nf80	2.94 (1.13)	b	4.89 (1.75)	b	1.81 (0.23)	b	0.28 (0.12)	b	10.27 (1.29)	b	68.84 (3.77)	b
Nf135	4.11 (1.06)	a	6.63 (1.78)	a	2.24 (0.38)	a	0.36 (0.15)	a	12.67 (2.14)	a	118.23 (5.23)	a
GS		***		***		***		***		***		***
1st GS	3.67 (1.22)	a	5.7 (1.86)	a	2.15 (0.37)	b	0.23 (0.10)	b	12.16 (2.09)	a	95.39 (3.29)	a
2nd GS	2.62 (1.04)	b	4.52 (1.92)	b	1.74 (0.24)	a	0.35 (0.14)	a	9.90 (1.37)	b	64.82 (5.05)	b
Second order interaction												
GS × Gen		***		***		***		***		***		***
GS × SD										*		
Gen × SD		**		**				*				
GS × NL										**		**
Gen × NL		***		***						**		**
SD × NL												

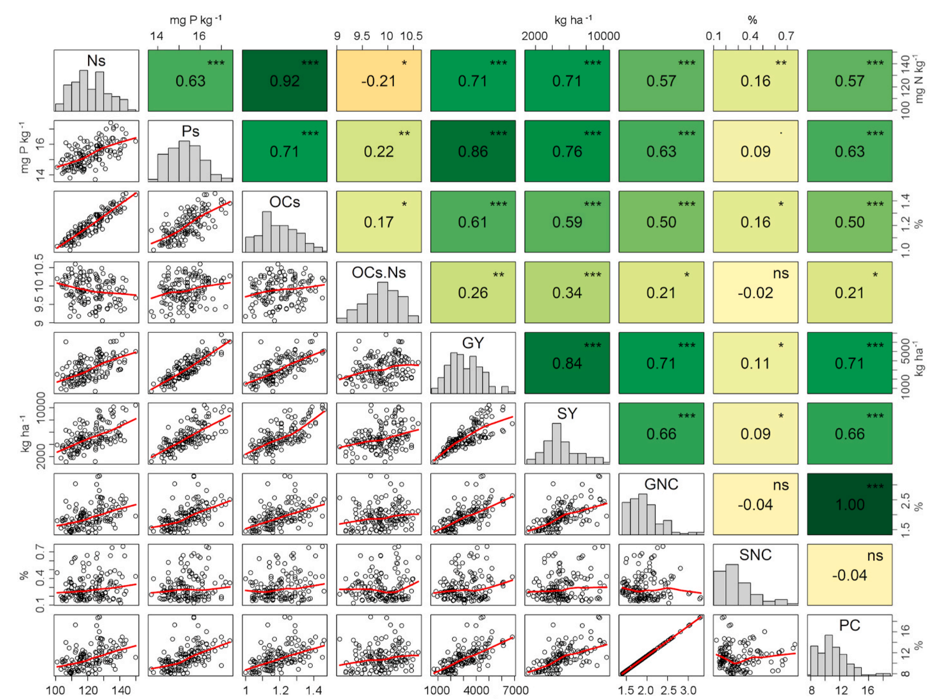

Fig. 3. Correlation heat map of total soil nitrogen (Ns), Olsen phosphorous (Ps), grain and straw yield (GY; SY), soil nutrients, the nitrogen concentration in the grain and straw (GNC; SNC), and grain protein concentration (PC).

was highly significant. Among all the agronomic variables, Nf was found to be the most important, capable of explaining approximately 60 % of the model variance. In contrast, Var was able to explain only 5 % of the model variance, while no significant influence of SD on SY was found. The addition of soil information allowed ASIM to explain the variance more adequately ($R^2 = 0.8726$, $P < 0.01$) with respect to the AIM improvement of the model. The ASIM model improved the capacity (approximately 10 %) to explain the GPC variance compared to AIM. In ASIM, Nf was still the most influential agronomical factor, followed by Gen, explaining 45 % and 4 % of the total variance, respectively, while the SD had no significant effect. In SY, Ps and Ns were able to explain 29 % and 4 % of the total variance, respectively. In both models, the interaction GS × Gen was highly significant (p < 0.01). As regards the remaining first-level interactions, Gen × SD and Gen × Nf, were highly significant (p < 0.01) in AIM, but not significant in ASIM. Instead, Ps × SD and GS × Ns were highly significant in ASIM, but not significant in AIM.

The AIM model was able to explain 55 % of SNC variance ($R^2 =$

0.5505, $p < 0.01$). In this model, the effect of GS, Nf, and Var, was highly significant and able to explain the 44.1 %, 28.3 %, and 5.9 % of the model variance, while no significant influence of SD on SNC was detected. The ASIM explains a larger part of the variance ($R^2 = 0.595$, $P < 0.01$) with respect to AIM. As in AIM, Nf and Gen in ASIM were the sole agronomic factors significantly affecting SNC. The soil parameters, Ps, and Ns were not significant. In both models, the interactions Gen × SD and GS × Gen were significant ($p < 0.05$) and highly significant ($p < 0.01$), respectively. As regards, the remaining first level interactions, Var × Ps, GS × Ps, and Nf × Ps were significant in ASIM.

In AIM, the agricultural practices (Nf, Sd, Gen) and the growing season (GS) were able to explain roughly 80 % of the observed variance in GY ($p < 0.01$). Considering the agronomic factors, GY was significantly affected by Nf ($p < 0.01$), which accounted for about 51 % of the variance explained by the model, and by Gen ($p < 0.01$), accounting for 7.2 % of the model-explained variance (Fig. 4). The model indicated that SD did not significantly affect the GY ($p > 0.05$). The GS significantly affected GY ($p < 0.01$), able to explain 28 % of the total variance, thereby affecting GY less than Nf in this trial. The addition of soil information allowed the ASIM model to explain a larger part of the variance ($R^2 = 0.9144$, $p < 0.01$) with respect to AIM. In ASIM, the agronomic inputs, Nf and Gen, were both still highly significant ($p < 0.01$) as in AIM. Interestingly, the additional variance explained by Ns and Ps led to the effect of both SD on GY becoming significant ($p < 0.05$). Nf, Gen, and SD were able to explain 40 %, 6 %, and 0.3 % of the variance, respectively (Fig. 4). The effect of the three environmental factors on GY was highly significant ($p < 0.01$). Among the considered environmental factors, Ps showed the largest influence on GY, explaining 26 % of the variance, followed by GS, explaining 22 % of the total variance. Instead, although significant, Ns was less influential. Despite the range of Ps values being narrow, between 13.7 and 17.4 mg kg^{-1}, the results indicated a strong covariance with GY. Under the experimental condition, it was observed that for each increase of 1 mg kg^{-1} in Ps there was an average rise in GY of approximately 1430 kg ha^{-1} ($R^2 = 0.7551$ $p < 0.01$). In both models, the interaction GS × Gen was highly significant ($p < 0.01$). As reported in Table 3, the effect of the different environmental conditions experienced during the two GS had a significant effect on the yield of the common wheat varieties. In the AIM model, GY was significantly ($p < 0.01$) affected by the interaction Gen × GS and GS × SD, and was also significantly ($p < 0.05$) affected by Gen × SD and Nf × SD. On the contrary, in the ASIM model, Ps × SD and Ns × GS were the sole second-order interactions significantly affecting GY ($p < 0.05$), while the above-mentioned interactions of SD with other factors had no significant effect on GY ($p > 0.05$). As previously mentioned, the main factor SD in the ASIM model is significant because of the part of variance explained by Ns and Ps.

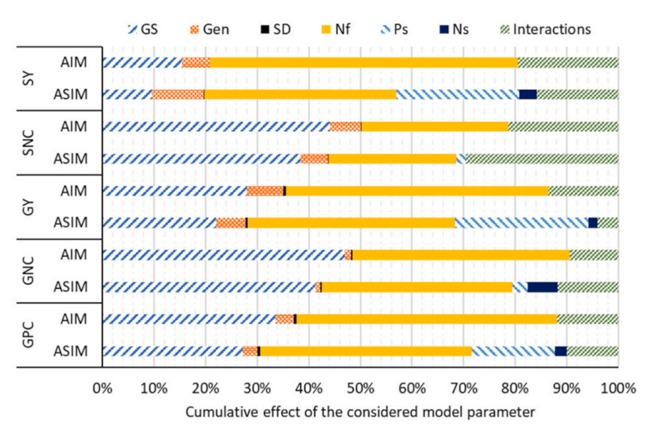

Fig. 4. Cumulative effect of the agronomical and environmental parameters in determining the quality and quantity of common wheat as considered by the Agronomical Input Model (AIM) and the Agronomical and Soil Input Model (ASIM).

AIM was able to explain a significant part of the GNC variance ($R^2 = 0.6568$, $p < 0.01$). In this model, the effect of GS and Nf were highly significant and the effect of Var was significant. GS, Nf, and Var were able to explain the 47 %, 42.1 %, and 1.2 % of the model variance. ASIM was shown to explain a larger part of the variance ($R^2 = 0.7313$, $P < 0.01$) with respect to AIM. As in AIM, Nf and Gen in ASIM were the sole agronomic factors significantly affecting SNC. The effect of soil parameters, Ps, and Ns were highly significant ($P < 0.01$) explaining 3 % and 5.8 % of the model variance, respectively. In AIM no first-order interactions were detected, while in ASIM, SD × Ps and GS × Nf were highly significant ($p < 0.01$) and the effect of SD × Ns was significant ($p < 0.05$).

The AIM model was able to explain 80 % of the total variance in GPC ($R^2 = 0.8025$, $p < 0.01$). Among the agronomic factors, Nf was the main factor affecting the GPC, accounting for about 50 % of the total variance ($p < 0.01$), followed by Gen accounting for about 3 % of the model-explained variance ($p < 0.01$), while SD was not significant ($p > 0.05$). The GS effect on GPC was highly significant ($p < 0.01$) being able to explain about 33.5 % of the total variance. The GPC variance explained by ASIM was higher ($R^2 = 0.9757$, $p < 0.01$) than that explained by AIM. Ps and Ns accounted for 16 % and 2 % of the total variance, respectively, thereby improving the capacity of ASIM to explain the GPC variance, by about 17.3 % with respect to AIM. The environmental variance explained by GS still accounted for a large part of the total variance (27 %). In ASIM, all agronomic inputs were highly significant ($p < 0.01$), able to explain 41 %, 3 %, and 1 % of total variance for Nf, Gen, and SD, respectively. As observed for GY, while the SD effect in AIM was masked by the unexplained variance, the higher effect of SD in ASIM was detected. This result was attributable to the amount of explained variance by adding Ps and Ns. In both models, the interactions GS × Gen, GS × Nf, and Gen × Nf were highly significant ($p < 0.01$), GS × SD was significant ($p < 0.05$), while SD × Nf was not significant. In the ASIM model, GPC was highly significant ($p < 0.01$), affected by the interactions Ps × SD. It was also significant ($p < 0.05$) by the interactions Gen × SD, Ns × SD, Ps × Nf. In contrast, the interactions did not significantly affect AIM.

4. Discussion

4.1. Distribution of soil properties

As suggested in Usowicz and Lipiec (2017) [34], CV values were low (<15 %) for all the considered soil parameters. The complex spatial variability of soil Ns and Ps in fields with long histories of cropping and fertilization has long been documented [23].

According to common guidelines used in Italy for the agronomic evaluation of soil nutrient content [35], the values of Ns in the present study were classified as average bordering rich, while the values of Ps were poor bordering very poor. In particular, the Ps values, ranging between 13.7 and 17.4 mg P kg^{-1}, were in the range commonly reported in the literature as limiting for the growth of common wheat. The literature reports that Ps amounting to less than 20 mg kg^{-1} soil appears to influence production, even if other nutrients are widely available [36]. It was recommended that for cereals grown on silty-clay loam soils, the Olsen P be maintained at about 20 mg P kg^{-1} soil in the plow layer to prevent P from becoming a limiting factor to production in the near future [37]. However, the threshold Ps values may vary depending on the soil properties [15]. On a sandy clay loam derived from chalky boulder clay at Saxmundham (UK), Johnston et al. (2013) [38] found limiting values varying from 6 to 34 mg P kg^{-1} soil. Ps values between 16 and 25 mg P kg^{-1} were the recommended levels to grow crops [38], with common wheat yield reaching the plateau for soil Olsen P levels between 8 and 12 mg kg^{-1} [12]. Cadot et al. (2018) [39] detected limiting values of 14.7 mg P kg^{-1} soil on a clay soil (Gleyic Cambisol according to the FAO classification system). Recently, Recena et al.

(2022) [15] proposed an equation to estimate the threshold Ps values for fertilizer response based on soil properties (Ps threshold = 49-0.016*Clay [mg kg^{-1}] - 3.81*pH). According to their findings, it was expected that the threshold Ps values in our soils would be on average 14.5 mg P kg^{-1} (with a range of 13.1 to 15.1 mg P kg^{-1}) and 14.7 mg P kg^{-1} (with a range of 14.3 to 15.2 mg P kg^{-1}) for the 1st GS and 2nd GS, respectively. These results suggest that the availability of Ps is not sufficient to satisfy the growth of the crop in both fields.

4.2. Production analysis

According to Dar et al. (2018) [40], the difference measured in GY between the two GSs was probably due to the higher amount of growing degree days calculated during the 1st GS with respect to that calculated for the 2nd GS. The low amount of rainfall experienced during the second GS probably determined the lower above-ground biomass production compared to the 1st GS.

Litke et al. (2018) [41] found a significant increase in wheat yield production by increasing the N rate from 0 to 180 kg ha^{-1}, which was then followed by a plateau. Our results confirmed the findings of Baloch et al. (2010) [42], showing no significant effect in grain yield when varying seeding density from 100 to 200 kg ha^{-1}, probably due to a higher competition for nutrients with higher seed density and consequently a lower nutrient availability. The interaction Gen and GS has also been previously [43], showing that temperature was the main factor influencing the GY. Furthermore, it was also reported that rainfall in the growing season was able to influence soil water, which changed the quantitative and qualitative traits of different wheat varieties with specific water crop requirements [44]. Valério et al. (2013) [45] tested different wheat varieties under different environments and seeding densities. It was shown that genotypes with reduced tillering ability showed higher production with an increase in seeding densities, but demonstrated a reduction in ear weight, justifying the significant interaction Gen x SD. In contrast to our results, a significant interaction between N fertilization level and seed density on yield and protein content was reported in North China [46]. In our experiment, the 3 old varieties produced a lower GY than the new variety. These results were consistent with Migliorini et al. (2016) [47], indicating that GY harvested in modern common wheat varieties is generally higher than that harvested in old varieties.

The GPC results corroborated previous results showing that a higher GPC value in common wheat can be obtained when supplied with 35 to 125 kg N ha^{-1} in a Mediterranean environment [48]. The GS significantly affected GY, attributable to the different weather conditions occurring during the two GSs. In particular, the GDD cumulated in 2017 was significantly higher than in 2018. The higher temperature during grain filling probably accelerated the rate of grain N accumulation, affecting the translocation of N in the grain [49]. Our results indicated that the modern common wheat variety (BO), has a better NU than the three old varieties used in this experiment. The selection carried out for old wheat varieties changed the efficiency for N-use of the cultivars and the capacity to store N in grain proteins. Modern wheat varieties have a higher yield potential than the older varieties, thereby affecting the protein concentration in the grain due to a dilution effect for the increase in the number of carbohydrates [50]. The NU results were consistent with previous findings showing that the wheat cultivars exhibited a progressive rise in demand for N supply in relation to the date of release, in order to maximize yields accompanied by the upgraded capacity for N use [50].

4.3. Effect of Ns and Ps and agronomical inputs on grain yield and grain protein concentration

The results from the study underscore the pivotal role of Ps and in soil fertility, showcasing their significant influence on the chemical, physical and biological properties of the soil, thereby influencing crop growth [51,52]. The comparison between the AIM and ASIM results highlighted the substantial impact of Ps on common wheat yield components under two specific conditions. Firstly, when Ps levels in the field are below the critical threshold for common wheat production and secondly, when the application of P fertilizer fails to entirely satisfy the common wheat's P requirement. Ps has a known significant influence on plant growth and above-ground biomass [53,54]. In phosphorus-deficient fertilization conditions, even minor Ps variations have been reported as a crucial factor affecting GY [12,36]. When Ps falls below the critical level, the common wheat's ability to absorb adequate phosphorus for growth diminishes, resulting in severe GY reductions [13]. This critical level varies based on the crop type, location, soil characteristics, climate, the availability of other elements, and the target production [12,13]. In our experiment, within the Ps range from 13.7 to 17.4 mg kg^{-1}, we observed a linear increase in grain yield associated with each mg kg^{-1} rise in Ps. However, it's important to note that this trend may not be universally applicable. Therefore, further studies should be conducted to account for non-linear responses at both lower and higher nutrient levels. The ASIM results suggest that when P fertilization is inadequate to meet the nutrient demands of the common wheat, a higher SD is associated with increased covariance between soil nutrients and GY. However, increasing SD is a common agronomic measure to increase P fertilizer use efficiency, it results in a reduced space for root growth. Hence, the more the SD increases, the more the dependent the plants become on the availability of nutrients near their roots [55–57]. This dependency exposes the crop once more to disparities in growth and productivity within the field due to the spatial variability for macro and micro nutrients.

Both AIM and ASIM models highlight Nf as the primary factor in determining GNC and GPC in common wheat. Several studies emphasize the dependence of GNC and GPC in cereals on N fertilization and N use efficiency [30,58]. Effective N management practices are essential to achieve optimal grain protein concentrations and yields. Additionally, seasonal weather variations, especially severe heat stress during the final grain filling stage, significantly impact Nitrogen remobilization, thus affecting GNC [59]. Furthermore, ASIM indicates that Ps also significantly impacts GPC due to unmet fertilization requirements, aligning with prior studies that revealed positive productivity responses with increased Phosphorus levels in tandem with various N levels [60]. To bolster these findings, further studies expanding on the specific ways Ps interact with Nf to influence common wheat's productivity, would contribute significantly to optimizing common wheat cultivation strategies.

In summary, our study demonstrates that understanding the spatial distribution of Ps in low Ps soils can allow farmers to make strategic decisions about the application of both P and N fertilizers. Precision application of fertilizer can significantly enhance overall fertilizer use efficiency, especially in contexts with low Ps levels.

5. Conclusions

In conclusion, the availability of Ps in soil plays a crucial role in determining common wheat yield and quality, particularly when fertilization rates do not match with crop requirements. This study conducted in Monteroni d'Arbia, central Italy, over two growing seasons, aimed to assess the impact of Ps concentrations in the soil on both common wheat yield and protein content. The results revealed that Ps availability, exhibited significant variability even within small fields. To analyze the data, two models were employed: the Agronomical Input Model (AIM), which considered common wheat varieties, nitrogen fertilization and seeding rates, and the Agronomical and Soil Input Model (ASIM), which also incorporated soil variables (Ns and Ps) as covariates. Comparative analysis demonstrated that ASIM outperformed AIM by improving the prediction accuracy of grain yield and protein concentration. ASIM accounted for the spatial variability of Ps and Ns within the fields, leading to a 11.0 % increase in the variance explained for grain yield prediction and a 17.3 % increase for protein concentration prediction compared to AIM, respectively. According to the ASIM model, Ps accounted for 25.9 and 16.2 % of the total variance in GY and GPC, respectively. These findings highlight the significance of considering soil parameters like Ps, especially in Ps-deficient soils, where large variability exists. Despite minimal variation in Ps, ranging range from 13.7 to 17.4 mg kg^{-1}, a notable trend was observed under our experimental conditions: for each increase of 1 mg kg^{-1} in Ps, there was an average rise in GY of approximately 1430 kg ha^{-1}. However, it's important to note that this trend may not be universally applicable outside from our experimental condition. Therefore, further studies should be conducted to account for non-linear responses at both lower and higher Ps levels. Managing within-field Ps variability through site-specific fertilization is crucial for optimizing wheat production. By incorporating soil information into nutrient management strategies, farmers can better tailor fertilization practices to match the specific needs of the crop and ensure optimal yield and quality. In summary, this study underscores the importance of understanding soil nutrient variability and its impact on crop performance. Integrating soil variables into predictive models can enhance the precision of nutrient management, ultimately contributing to sustainable and efficient common wheat production systems. However, additional trials including more years and different pedo-climatic conditions are required to evaluate the interaction between Ps and the agronomical treatments. Moreover, our study primarily focuses on Ps, and the results may not fully capture the interactions and effects of other soil nutrients. A broader analysis including multiple soil nutrients could provide a more holistic understanding of nutrient management.

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CRediT authorship contribution statement

Marco Mancini: Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft. **Lorenzo Guerrini:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Carolina Fabbri:** Investigation, Writing – original draft. **Simone Orlandini:** Funding acquisition, Supervision. **Marco Napoli:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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References

[1] S.R. Olsen, C. V Cole, F. Watandbe, L. Dean, Estimation of Available Phosphorus in Soil by Extraction with Sodium Bicarbonate, U.S. Government Printing Office, Washington D.C., 1954.
[2] S.L. Tisdale, W.L. Nielson, J.D. Beaten, J.L. Halving, Elements required in plant nutrition, in: S.L. Tisdale, W.L. Nelson, J.D. Beaton (Eds.), Soil Fertil. Fertil., McMillan Publishing Co., New York, 1993, pp. 48–49.
[3] H. Malhotra, Vandana, S. Sharma, R. Pandey, Phosphorus nutrition: plant growth in response to deficiency and excess, Plant Nutr. Abiotic Stress Toler (2018) 171–190, https://doi.org/10.1007/978-981-10-9044-8_7/COVER.
[4] D. Cordell, J.O. Drangert, S. White, The story of phosphorus: global food security and food for thought, Global Environ. Change 19 (2009) 292–305, https://doi.org/10.1016/J.GLOENVCHA.2008.10.009.
[5] T. Balemi, K. Negisho, Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review, J. Soil Sci. Plant Nutr. 12 (2012) 547–562, https://doi.org/10.4067/S0718-95162012005000015.
[6] B.G. Hopkins, J.W. Ellsworth, Phosphorus availability with alkaline/calcareous soil, West. Nutr. Manag. Conf. 6 (2005) 88–93.
[7] W.L. Lindsay, P.L.G. Vlek, S.H. Chien, Phosphate minerals, in: B. Dixon, S.B. Weed (Eds.), Miner. Soil Environ., John Wiley & Sons, Ltd, Madison, WI, USA, 2018, pp. 1089–1130, https://doi.org/10.2136/SSSABOOKSER1.2ED.C22.
[8] C.J. Penn, J.J. Camberato, A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants, Agriculture 9 (2019) 1–18, https://doi.org/10.3390/AGRICULTURE9060120.
[9] N.K. Fageria, Use of Nutrients in Crop Plants, CRC Press, Boca Raton (FL), 2019. https://www.routledge.com/The-Use-of-Nutrients-in-Crop-Plants/Fageria/p/book/9780367386887. (Accessed 22 May 2023).
[10] D. Rodríguez, W.G. Keltjens, J. Goudriaan, Plant leaf area expansion and assimilate production in wheat (Triticum aestivum L.) growing under low phosphorus conditions, Plant Soil 200 (1998) 227–240, https://doi.org/10.1023/A:1004310217694/METRICS.
[11] Y. Deng, W. Teng, Y.P. Tong, X.P. Chen, C.Q. Zou, Phosphorus efficiency mechanisms of two wheat cultivars as affected by a range of phosphorus levels in the field, Front. Plant Sci. 871 (2018) 1614, https://doi.org/10.3389/FPLS.2018.01614/BIBTEX.
[12] A.E. Johnston, P.R. Poulton, P.E. Fixen, D. Curtin, Phosphorus: its efficient use in agriculture, Adv. Agron. 123 (2014) 177–228, https://doi.org/10.1016/B978-0-12-420225-2.00005-4.
[13] A.E. Johnston, P.R. Poulton, Phosphorus in agriculture: a review of results from 175 years of research at rothamsted, UK, J. Environ. Qual. 48 (2019) 1133–1144, https://doi.org/10.2134/JEQ2019.02.0078.
[14] D. Cordell, T.S.S. Neset, Phosphorus vulnerability: a qualitative framework for assessing the vulnerability of national and regional food systems to the multi-dimensional stressors of phosphorus scarcity, Global Environ. Change 24 (2014) 108–122, https://doi.org/10.1016/J.GLOENVCHA.2013.11.005.
[15] R. Recena, A.M. García-López, J.M. Quintero, A. Skyttä, K. Ylivainio, J. Santner, E. Buenemann, A. Delgado, Assessing the phosphorus demand in European agricultural soils based on the Olsen method, J. Clean. Prod. 379 (2022) 134749, https://doi.org/10.1016/J.JCLEPRO.2022.134749.
[16] B. Kronvang, G.H. Rubaek, G. Heckrath, International phosphorus workshop: diffuse phosphorus loss to surface water bodies–risk assessment, mitigation options, and ecological effects in river basins, J. Environ. Qual. 38 (2009) 1924–1929, https://doi.org/10.2134/JEQ2009.0051.
[17] G. Tóth, R.A. Guicharnaud, B. Tóth, T. Hermann, Phosphorus levels in croplands of the European Union with implications for P fertilizer use, Eur. J. Agron. 55 (2014) 42–52, https://doi.org/10.1016/J.EJA.2013.12.008.
[18] A. Roger, Z. Libohova, N. Rossier, S. Joost, A. Maltas, E. Frossard, S. Sinaj, Spatial Variability of Soil Phosphorus in the Fribourg Canton, Switzerland, Geoderma, vols. 217–218, 2014, pp. 26–36, https://doi.org/10.1016/J.GEODERMA.2013.11.001.
[19] A. Delgado, Critical nutrients in mediterranean environments as affected by agricultural management in the long-term, in: G. Seddaiu, P. Benincasa (Eds.), Proc. XLVIII Conf, Ital. Soc. Agron., Perugia, 2019, pp. 30–31.
[20] K. Senthilkumar, T. Nesme, A. Mollier, S. Pellerin, Regional-scale phosphorus flows and budgets within France: the importance of agricultural production systems, Nutrient Cycl. Agroecosyst. 92 (2012) 145–159, https://doi.org/10.1007/S10705-011-9478-5/FIGURES/6.
[21] W. Fu, K. Zhao, P. Jiang, Z. Ye, H. Tunney, C. Zhang, W. Fu, K. Zhao, P. Jiang, Z. Ye, H. Tunney, C. Zhang, Field-scale variability of soil test phosphorus and other nutrients in grasslands under long-term agricultural managements, Soil Res. 51 (2013) 503–512, https://doi.org/10.1071/SR13027.
[22] W.X. Sun, B. Huang, M.K. Qu, K. Tian, L.P. Yao, M.M. Fu, L.P. Yin, Effect of farming practices on the variability of phosphorus status in intensively managed soils, Pedosphere 25 (2015) 438–449, https://doi.org/10.1016/S1002-0160(15)30011-4.
[23] R.G. Petersen, L.D. Calvin, Sampling, methods soil anal. Part 1, Phys. Mineral. Prop. Incl. Stat. Meas. Sampl. (2015) 54–72, https://doi.org/10.2134/AGRONMONOGR9.1.C5.
[24] C. Fabbri, M. Napoli, M. Mancini, G. Brandani, R. Vivoli, S. Orlandini, Adopting precision agriculture to improve the cultivation of old wheat varieties in Tuscany (Italy), in: Precis. Agric. 2019 - Pap. Present. 12th Eur. Conf. Precis. Agric. ECPA 2019, Wageningen Academic Publishers, 2019, pp. 461–467, https://doi.org/10.3920/978-90-8686-888-9_57.

[25] C. Fabbri, B. Basso, M. Napoli, A. Dalla Marta, S. Orlandini, R.A. Martinez-Feria, Developing a tactical nitrogen fertilizer management strategy for sustainable wheat production, Eur. J. Agron. 144 (2023) 126746, https://doi.org/10.1016/J.EJA.2023.126746.
[26] T.L. Wilson, M.J. Guttieri, N.O. Nelson, A. Fritz, M. Tilley, Nitrogen and sulfur effects on hard winter wheat quality and asparagine concentration, J. Cereal. Sci. 93 (2020) 102969, https://doi.org/10.1016/J.JCS.2020.102969.
[27] M.R. Karaman, S. Ersahin, A. Durak, Spatial variability of available phosphorus and site specific P fertilizer recommendations in a wheat field, Plant Nutr (2001) 876–877, https://doi.org/10.1007/0-306-47624-X_427.
[28] L. Massetti, C. Grassi, S. Orlandini, M. Napoli, Modelling hydrological processes in agricultural areas with complex topography, Agronomy 10 (2020) 750, https://doi.org/10.3390/agronomy10050750.
[29] M.R. Salazar-Gutierrez, J. Johnson, B. Chaves-Cordoba, G. Hoogenboom, Relationship of base temperature to development of winter wheat, Int. J. Plant Prod. 7 (2013) 741–762.
[30] Q. Soofizada, A. Pescatore, R. Atefi, C. Grassi, S. Orlandini, M. Napoli, Evaluation of nitrogen and phosphorus responses on yield, quality and economic advantage of winter wheat (Triticum aestivum, L.) under four different agro-climatic zones in Afghanistan, Agronomy 13 (2023) 345, https://doi.org/10.3390/AGRONOMY13020345/S1.
[31] U. Meier, Growth Stages of Mono- and Dicotyledonous Plants, Federal Biological Research Centre for Agriculture and Forestry, Bonn, 2001, https://doi.org/10.5073/20180906-074619.
[32] L. Guerrini, M. Napoli, M. Mancini, P. Masella, A. Cappelli, A. Parenti, S. Orlandini, Wheat grain composition, dough rheology and bread quality as affected by nitrogen and sulfur fertilization and seeding density, Agronomy 10 (2020), https://doi.org/10.3390/agronomy10020233.
[33] P.K. Dunn, G.K. Smyth, Generalized Linear Models with Examples in R, 2018, https://doi.org/10.1007/978-1-4419-0118-7.
[34] B. Usowicz, J. Lipiec, Spatial variability of soil properties and cereal yield in a cultivated field on sandy soil, Soil Tillage Res. 174 (2017) 241–250, https://doi.org/10.1016/j.still.2017.07.015.
[35] E.A.C. Costantini, Metodi di valutazione dei suoli e delle terre, Cantagalli, Firenze, 2006.
[36] E. Lichtfuse, Alternative Farming Systems, Biotechnology, Drought Stress and Ecological Fertilisation, Springer, Dodrecht, the Netherlands, 2011, https://doi.org/10.1007/978-94-007-0186-1.
[37] P.R. Poulton, A.E. Johnst, R.P. White, Plant-available soil phosphorus. Part I: the response of winter wheat and spring barley to Olsen P on a silty clay loam, Soil Use Manag. 29 (2013) 4–11, https://doi.org/10.1111/j.1475-2743.2012.00450.x.
[38] A.E. Johnston, P.R. Poulton, R.P. White, Plant-available soil phosphorus. Part II: the response of arable crops to Olsen P on a sandy clay loam and a silty clay loam, Soil Use Manag. 29 (2013) 12–21, https://doi.org/10.1111/J.1475-2743.2012.00449.X.
[39] S. Cadot, G. Bélanger, N. Ziadi, C. Morel, S. Sinaj, Critical plant and soil phosphorus for wheat, maize, and rapeseed after 44 years of P fertilization, Nutrient Cycl. Agroecosyst. 112 (2018) 417–433, https://doi.org/10.1007/s10705-018-9956-0.
[40] E.A. Dar, A.S. Brar, A. Yousuf, Growing degree days and heat use efficiency of wheat as influenced by thermal and moisture regimes, J. Agrometeorol. 20 (2018) 168–170, https://doi.org/10.54386/JAM.V20I2.535.
[41] L. Litke, Z. Gaile, A. Ruza, Effect of nitrogen fertilization on winter wheat yield and yield quality, Agron. Res. 16 (2018) 500–509, https://doi.org/10.15159/AR.18.064.
[42] M.S. Baloch, I.T.H. Shah, M.A. Nadim, M.I. Khan, A.A. Khakwani, Effect of seeding density and planting time on growth and yield attributes of wheat, J. Anim. Plant Sci. 20 (2010) 239–242.
[43] F. Chairi, N. Aparicio, M.D. Serret, J.L. Araus, Breeding effects on the genotype x environment interaction for yield of durum wheat grown after the Green Revolution: the case of Spain, Crops J 8 (2020) 623–634, https://doi.org/10.1016/J.CJ.2020.01.005.
[44] V. Spanic, D. Horvat, K. Dvojkovic, Comparison of quantitative traits of old and modern wheat varieties, Cereal Res. Commun. 36 (2008) 1283–1286, https://doi.org/10.2307/90002946.
[45] I.P. Valério, F.I.F. de Carvalho, G. Benin, G. da Silveira, J.A.G. da Silva, R. Nornberg, T. Hagemann, H. de S. Luche, A.C. de Oliveira, Seeding density in wheat: the more, the merrier? Sci. Agric. 70 (2013) 176–184, https://doi.org/10.1590/S0103-90162013000300006.
[46] Y. Zhang, X. Dai, D. Jia, H. Li, Y. Wang, C. Li, H. Xu, M. He, Effects of plant density on grain yield, protein size distribution, and breadmaking quality of winter wheat grown under two nitrogen fertilisation rates, Eur. J. Agron. 73 (2016) 1–10, https://doi.org/10.1016/J.EJA.2015.11.015.
[47] P. Migliorini, S. Spagnolo, L. Torri, M. Arnoulet, G. Lazzerini, S. Ceccarelli, Agronomic and quality characteristics of old, modern and mixture wheat varieties and landraces for organic bread chain in diverse environments of northern Italy, Eur. J. Agron. 79 (2016) 131–141, https://doi.org/10.1016/j.eja.2016.05.011.
[48] O. Parenti, L. Guerrini, B. Cavallini, F. Baldi, B. Zanoni, Breadmaking with an old wholewheat flour: optimization of ingredients to improve bread quality, Lebensm. Wiss. Technol. 121 (2020), https://doi.org/10.1016/j.lwt.2019.108980.
[49] R. Osman, Y. Zhu, W. Cao, Z. Ding, M. Wang, L. Liu, L. Tang, B. Liu, Modeling the effects of extreme high-temperature stress at anthesis and grain filling on grain protein in winter wheat, Crops J 9 (2021) 889–900, https://doi.org/10.1016/j.cj.2020.10.001.
[50] G. Guarda, S. Padovan, G. Delogu, Grain yield, nitrogen-use efficiency and baking quality of old and modern Italian bread-wheat cultivars grown at different nitrogen levels, Eur. J. Agron. 21 (2004) 181–192, https://doi.org/10.1016/j.eja.2003.08.001.
[51] S.K. Behera, R.K. Mathur, A.K. Shukla, K. Suresh, C. Prakash, Spatial variability of soil properties and delineation of soil management zones of oil palm plantations grown in a hot and humid tropical region of southern India, Catena 165 (2018) 251–259, https://doi.org/10.1016/J.CATENA.2018.02.008.
[52] M.S. Metwally, S.M. Shaddad, M. Liu, R.J. Yao, A.I. Abdo, P. Li, J. Jiao, X. Chen, Soil properties spatial variability and delineation of site-specific management zones based on soil fertility using fuzzy clustering in a hilly field in Jianyang, Sichuan, China, Sustain. Times 11 (2019), https://doi.org/10.3390/su11247084.
[53] H. Gong, Y. Xiang, B.K. Wako, X. Jiao, Complementary effects of phosphorus supply and planting density on maize growth and phosphorus use efficiency, Front. Plant Sci. 13 (2022) 3731, https://doi.org/10.3389/FPLS.2022.983788/BIBTEX.
[54] P.N. Nkrumah, G. Echevarria, P.D. Erskine, R.L. Chaney, S. Sumail, A. van der Ent, Contrasting phosphorus (P) accumulation in response to soil P availability in 'metal crops' from P-impoverished soils, Plant Soil 467 (2021) 155–164, https://doi.org/10.1007/S11104-021-05075-9/FIGURES/3.
[55] Q. Jia, L. Sun, S. Ali, Y. Zhang, D. Liu, M. Kamran, P. Zhang, Z. Jia, X. Ren, Effect of planting density and pattern on maize yield and rainwater use efficiency in the Loess Plateau in China, Agric. Water Manag. 202 (2018) 19–32, https://doi.org/10.1016/J.AGWAT.2018.02.011.
[56] H. Shao, T. Xia, D. Wu, F. Chen, G. Mi, Root growth and root system architecture of field-grown maize in response to high planting density, Plant Soil 430 (2018) 395–411, https://doi.org/10.1007/S11104-018-3720-8/TABLES/6.
[57] Y. Zhang, Z. Xu, J. Li, R. Wang, Optimum planting density improves resource use efficiency and yield stability of rainfed maize in semiarid climate, Front. Plant Sci. 12 (2021) 752606, https://doi.org/10.3389/FPLS.2021.752606/BIBTEX.
[58] V. Mandic, V. Krnjaja, Z. Tomic, Z. Bijelic, A. Simic, D.R. Muslic, M. Gogic, Nitrogen fertilizer influence on wheat yield and use efficiency under different environmental conditions, Chil. J. Agric. Res. 75 (2015) 92–97, https://doi.org/10.4067/S0718-58392015000100013.
[59] N. Akter, R.M. Islam, Heat stress effects and management in wheat, A review, Agron. Sustain. Dev. 375 (37) (2017) 1–17, https://doi.org/10.1007/S13593-017-0443-9, 2017.
[60] M. Irfan, M. Abbas, J.A. Shah, M.Y. Memon, Grain yield, nutrient accumulation and fertilizer efficiency in bread wheat under variable nitrogen and phosphorus regimes, J. Basic Appl. Sci. 14 (2018) 80–86. https://setpublisher.com/index.php/jbas/article/view/1784.