Identification and mapping of yield-limiting factors of potato (*Solanum tuberosum* L.) using proximal sensing and geostatistical techniques

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Abstract: Potato is one of the key crops for ensuring food security and can be a potential substitute for cereal crops due to its high yielding nature and nutritional value. Crop nutrient management practices within potato fields are implemented uniformly without considering crop requirements and soil variability, causing uneven and low yield. However, yield can be increased by identifying growth and yield-limiting factors. Geospatial tools are robust and effective in identifying the spatial variations within the field. Proximal sensing allows quick analysis of soil and plant characteristics, decreases the need for laborious and expensive soil and plant sampling, and strengthens precision agriculture techniques. The aim of the study was to quantify the soil spatial variability and identify potato crop growth and yield limiting factors for the optimization of inputs. Two fields were selected in the subtropical region of Pakistan (Koont, Rawalpindi), and each field was cultivated with two different potato varieties. A grid sampling approach was developed to collect soil samples and tuber yields. The soil was tested for nitrogen (N), phosphorus (P), potassium (K), pH, electrical conductivity (E.C), temperature, and moisture content (M.C) by using a soil proximal sensor. Normalized difference vegetation index (NDVI) was recorded using a handheld GreenSeeker, and chlorophyll was estimated using a chlorophyll meter. Descriptive statistics and correlation analysis for soil and crop parameters were performed in Minitab 21, while geostatistical analysis was performed in Arc Map 10.8 to show spatial variability and to generate kriged maps of different soil properties. The coefficient of variation of soil properties and plant parameters showed moderate to high variability within the field, except for pH and temperature. The correlation matrix suggested that N, P, K, E.C., chlorophyll, NDVI, plant height, and leaf area had a significant relationship with potato yield. Most of the soil and plant parameters had a medium to high range of influence (20 to 90 m) and varied greatly within the field. Kriged maps of plant and soil parameters also showed spatial variations and were aligned with descriptive statistics and correlations. Quantification of soil spatial variability within potato fields can assist in measuring yield-limiting soil characteristics to establish management zones for variable rate fertilization for optimum tuber yield and low environmental impact.

Keywords: precision agriculture, potato, proximal sensing, variable rate fertilization, geostatistics, geospatial analysis, soil variability

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1 Introduction

Potatoes are widely recognized as a major non-cereal food crop on an international scale, and it is the fourth most important food crop in the world, following rice, wheat, and maize. The potato is a key crop for ensuring food security and can be an acceptable substitute for cereal crops due to its high yielding nature and nutritional value[1]. The cultivation of potato crops promotes a viable and sustainable solution to address the growing global threat of hidden hunger[2]. In most of the continents, the growth in potato production is mainly achieved by expanding the cultivated land area dedicated to this crop. This expansion has resulted in more than a twofold increase since 1994[3]. The projected growth of the global population, particularly in developing countries, highlights the significance of potatoes in ensuring food security[4].

Agriculture is the foundation of Pakistan's economy, contributing 23% to GDP, and 44% of employment is associated with this sector[5]. Pakistan has diverse agro-climatic conditions, suitable for the cultivation of various crops including wheat, rice, cotton, sugarcane, maize, potatoes, chilies, onions, and fruit orchards. Production of these crops fluctuate due to numerous factors such as weather conditions, water availability, and pest attacks[6,7]. The total cultivated area of Pakistan is approximately

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22.1 million hectares (hm^2), including both irrigated and rain-fed areas[8]. Pakistan is one of the major producers of potato in South Asia, and the area under potato cultivation in Pakistan is 220 thousand hectares with an annual production of 3.5 to 4 million metric tons[9]. Potato productivity fluctuates due to issues like weather conditions, disease outbreaks, and market dynamics. Pakistan's per acre yield of potato is not satisfactory as compared to advanced and neighbor countries[10].

Potatoes are one of the major crops grown in the sub-tropical dryland (Potohar) region of Pakistan, especially in districts of Jhelum (Pind Dadan Khan), Attock (Hazro), and Rawalpindi (Taxila)[11]. The Potohar region of Pakistan has diverse agricultural characteristics due to its semi-arid climate, moderate rainfall, limited water resources, and unique soil. This region is known for rain-fed agriculture and cultivation of crops like wheat, maize, barley, pulses, oilseeds, and vegetables[12]. Potohar region has a variety of soil types, including loamy, sandy, and clayey soils and low organic matter content. The cooler climate and well-drained soils of this region make it an ideal location for potato cultivation. However, proper fertilization practices need to be adopted to address soil fertility limitations and achieve optimal crop yields[13]. Potato production in this region both serves the local consumption needs and contributes to the national potato market. It plays a vital role in ensuring food security, providing economic opportunities for farmers, and supporting the overall agricultural landscape of Potohar. Due to colder climate, farmers in this region obtain earlier production in comparison to other districts of Punjab, resulting in higher market rates and increased farm profitability.

Pakistan faces challenges in achieving higher potato crop production because of various abiotic and biotic factors[14-18]. Among these factors, soil fertility is vital in determining both yield and quality of potatoes[19]. Injudicious application of nitrogen and phosphorus contribute to uneven and low potato yields[20]. Several researchers have studied the correlations between the uptake of fertilizer usage, plant nutrient concentrations, tuber yield, and quality of tubers[21-24]. Farmers in Pakistan are still applying fertilizers through conventional techniques, which is not recommended because of over- or deficit application of nutrients[25]. Uniform fertilizer application (UFA) of inputs without identifying the spatial variation of soil properties is one of the main limitations in achieving higher yields[26], and UFA could also lead to environmental contamination through nutrient leaching[27,28]. Therefore, precision agriculture and site-specific nutrient management (SSNM) can play a vital role in increasing potato production by optimizing resource utilization and addressing crop variability[29].

Spatial variability in soil parameters and crop yield can be observed within individual fields, among different fields, as well as over multiple years on an agricultural field. Several elements, such as site conditions, soil characteristics, crop management practices, and climate have the potential to influence both crop yield and quality[30-33]. Spatial variability of soil parameters must be characterized to better understand complex soil-environmental interactions and to choose appropriate management practices. The objective of spot-specific management is to efficiently manage the spatial variations of soil by providing inputs in a manner that fulfills the particular needs of the soil and crop[24,34]. Soil fertility and agricultural yield are largely attributed to variations in soil chemical, physical, and biological traits[35]. However, the determination of these parameters requires an examination of various indicators of soil properties, including nitrogen (N), phosphorus (P), potassium (K), electrical conductivity (E.C), pH, moisture content (M.C), and soil organic matter (SOM).

Numerous studies have been conducted to identify and quantify the geographical variability in soil parameters, leaf nutrient levels, and yield across various cultivation practices[26,27], and authors also distinguished between productive and unproductive regions by using the spatial information of soil attributes[25,34,36]. Termin et al.[37] developed a spatiotemporal cluster of five different variables to delineate Nitrogen MZs for citrus crop. Detailed research on soil spatial variation in wild blueberry fields showed that variation within the same field can affect the production of crops[26,27]. Haroon et al.[25] examined the variability of different soil parameters and their impact on wheat yield using principal component analysis. Khan et al.[34] delineated the management zones for site-specific fertilization in the potato crop of Prince Edward Island, which is characterized by cold temperatures and sandy soil with high drainage. Limited research has been conducted on the soil and plant characterization and their interlinkages for potato production system in any soil condition in Pakistan. Therefore, this study was designed to evaluate the relationships between different soil and crop parameters and their impacts on potato yield, especially considering the unique soil and environment setting of the Potohar region as a case study. Various statistical and geostatistical tools and techniques were implemented to quantify and characterize the soil and crop parameters and their potential impacts on yield for both table and processing potato varieties. The results and techniques implemented in this research could be adopted across the world for potato crop management.

2 Materials and methods

2.1 Site description

This research was conducted at University Research Farm, Koont, Rawalpindi (33.1166°N, 73.0111°E), classified as semi-arid region, with an average annual rainfall of 370 mm. The soil of the study area is sandy loam with low organic matter[38]. Two potato fields were selected for this study, and both fields have been utilized for field crops, such as potatoes, peanuts, and wheat, in previous years. Two potato cultivars, the table variety (Kuroda) and processing variety (Musica), were cultivated in each field, and variety selection was based on high market demand and widespread cultivation across the globe. Characteristics of these varieties are well described by the European Cultivated Potato Database (ECPD)[39,40]. Potatoes seeds were sown on 5 October 2022 in Field 1 and 6 October 2022 in Field 2. Surface irrigation is used to irrigate most of Pakistan's potato growing areas. However, due to the lack of canal irrigation and low groundwater levels in the Potohar region, high efficiency irrigation techniques are being used to address the issue of water scarcity. Soil moisture was measured by sensors (JXCT, China) installed within the experimental area. Due to the sensitivity of potato plants to water stress, the threshold for initiating irrigation was chosen at 60% moisture content depletion. Field 1 (33.11°N, 73.01°E) was irrigated using the drip irrigation method with an application rate of 4.9 mm/h, and Field 2 (33.11°N, 73.01°E) was irrigated using raingun with the application rate of 32.02 mm/h. Standard agronomic practices were adopted for potato cultivation excluding irrigation. 120 sampling points and field boundaries were demarcated using real-time kinematics global positioning system (RTK-GPS) (ComNav Technology Ltd., Shanghai, China) to ensure accuracy and precision.

2.2 Sampling strategy and analysis

A 10 m×10 m grid pattern was established in ArcGIS 10.8 (ESRI, Redlands, California) to collect soil- and crop-related samples. Soil characteristics such as Nitrogen (N), Phosphorus (P), Potassium (K), temperature, electrical conductivity (E.C), and moisture content (M.C.) were measured twice during this study: before and after fertilization (September 2022 and December 2022) using a soil proximal sensor. Properly calibrated soil proximal sensors can measure the soil physical and chemical properties rapidly and efficiently with high accuracy[41–44]. Five readings were taken from each grid, and their mean values were used to minimize errors and to increase the accuracy of data.

2.3 Plant parameters

Plant growth parameters were calculated during the tuber bulking stage to observe the relationship between soil properties and relative chlorophyll content, normalized difference vegetation index (NDVI), plant height (Plant Ht), number of leaves (NoL), and leaf area (LA). Plant growth parameters from each grid were measured using a 1×1 meter steel quadrant in the first week of December 2022 for both fields. Eight plants were randomly selected within the quadrant from each grid to measure plant height, number of leaves, and leaf area. Data for yield was obtained during the end of the growing season. NDVI was measured utilizing a handheld GreenSeeker™ device (Trimble Inc., USA), while chlorophyll content was determined using a portable chlorophyll meter (FieldScout CM 1000 Chlorophyll Meter, Spectrum Technologies, 3600 Thayer Court, Aurora, Canada). Potatoes were harvested in mid-January (2023), and yield was derived from each grid using a 1×1 m quadrant. The harvested tubers were weighed using an electronic weighing scale.

2.4 Statistical analysis

2.4.1 Descriptive statistics

Shapiro-Wilk test normality suggested that all parameters were normally distributed (p>0.05) except E.C, M.C, and N for both fields. Parkin and Robinson[45] stated that many characteristics of soil with uneven distributions are actually log-normally distributed. Management strategies and temporal impacts may cause normal and non-normal distributions of several of these soil parameters of both fields. Statistical analyses were carried out using Minitab 21 (Minitab Ltd., Coventry, West Midlands) to determine the mean, minimum, maximum, coefficient of variation (CV), and standard deviation for crop and soil parameters. Descriptive statistical analysis provides a comprehensive understanding of the variability in soil properties, but it does not distinguish the spatial trends present in the data. Variability can be assessed by the coefficient of variation (CV), and it serves as an initial step to detect variability[46]. If CV exceeds 35%, it indicates a high degree of variability in the parameter. When CV falls between 15% and 35%, it suggests a moderate level of variability for the parameter, while if CV is less than 15%, it indicates that the parameter being assessed is characterized by low variability. The Pearson's correlation coefficient (R^2) was calculated using Minitab 21 Statistical software to determine the correlation between soil properties and tuber yield.

2.4.2 Geostatistical analysis

Geostatistical analysis was performed using ArcGIS 10.8 to examine the spatial dependencies of soil and crop parameters. The characterization of spatial relationships was achieved through semi-variogram modeling. Geostatistical analysis was conducted on soil physical and chemical properties, plant growth parameters, and potato yield to investigate the spatial dependence (SpD) within these datasets. Geostatistical analysis considered variogram parameters such as nugget (C_0), representing the error at a distance of 0; the sill (C_0+C), indicating the highest value on the y-axis, which increases with the increase in lag distance (h); and the range (a), representing the maximum distance at which sampling points remain correlated. The degree of SpD was determined by calculating the nugget-sill ratio, following the interpretation provided by Cambardella[47]. SpD was classified as strong if the ratio was less than 25%, intermediate when falling within the range of 25-75%, and weak when exceeding 75%. An iterative cross-validation technique was employed to achieve high prediction accuracy. This approach aimed to maximize the coefficient of determination (R^2) while minimizing the root mean square error (RMSE). Stable, circular, spherical, exponential, Gaussian models were evaluated to select the most appropriate semi-variogram model based on prediction accuracy. These semi-variogram models can be used for quantifying and characterizing the crop and yield[48]. Spatial variability of soil properties and crop yield was analyzed by using a combination of geostatistics and geographical information system (GIS). Interpolated maps were generated in ArcGIS 10.8 (ESRI) to visually examine the relationship between these variables using ordinary kriging interpolation technique. Pusch et al.[49] observed a high degree of similarity between the kriged estimations and the measured estimates. Kriging interpolation method is recognized as accurate and reliable compared to other approaches such as inverse distance weighting or trend surface models. The resulting maps were standardized on a similar scale and had the same number of classes to facilitate comparison.

3 Results and discussion

3.1 Descriptive statistics of soil properties of Field 1

Soil and plant data were tested for normality using the Shapiro-Wilk test[50] at a significance level of 5%, and non-normal data were normalized by using the Box-Cox method (Box and Cox, 1964). Mean values of the three most essential macronutrients, nitrogen (N), phosphorus (P), and potassium (K), before fertilization in the Musica region were 8.49, 4.91, and 139.77 mg/kg, respectively, and the mean values for N, P, and K were 8.24, 4.88, and 137.35 mg/kg, respectively, for the Kuroda region (Table 1). Mean values showed significant increase in both regions after fertilization, reaching 9.32, 5.85, and 144.02 mg/kg in Musica, and 9.35, 5.81, and 145.24 mg/kg in Kuroda.

N and K exhibited low variation, whereas P showed moderate variation for both samplings in the Musica region. Conversely, high variation was found in the Kuroda region for N and P, and moderate variation in K. CV of pH were consistently low, ranging from 4.27 to 3.26 in Musica and 3.98 to 2.35 in Kuroda. This suggested that the pH levels remained relatively stable throughout the study, with a decrease in variability observed during the second sampling period. M.C and E.C displayed low variation in the first sampling, but M.C showed higher variation in the second sampling in both regions. Incorporation of fertilizers via uniform rate fertilizer has the potential to induce variations in soil nutrient levels, salt levels, and growth of plants. Similar trends of pH and E.C in this research support the findings of [25,51]. Regarding skewness, all parameters, except K and pH, exhibited positive skewness during the first sampling, indicating that the data were skewed towards higher values. However, the skewness patterns changed during the second sampling, with N and K displaying lower and negative skewness. These findings highlighted the difference of variability in soil parameters observed before and after fertilization in both the Musica and Kuroda fields. Results suggested that fertilization influenced the mean values and variability of the soil parameters, emphasizing the importance of understanding soil dynamics for effective agricultural management. Potatoes need a high concentration of nutrients to produce maximum yield[52].

Table 1 Results of descriptive statistics for soil properties of Field 1

Variables	Mean	S.D	C.V/%	Min	Max	Skewness	Kurtosis
Before fertilization, Musica region							
N/mg·kg⁻¹	8.469	1.635	19.31	4.5	12.154	0.160	0.540
P/mg·kg⁻¹	4.912	1.243	25.30	2.949	8.000	0.610	0.170
K/mg·kg⁻¹	139.770	17.950	12.84	83.92	179.99	–0.940	2.720
pH	6.80	0.29	4.27	6.00	7.00	–1.50	1.40
Temp/°C	33.99	5.39	15.88	6.10	37	–5.06	26.91
M.C/%	25.44	4.91	19.30	18.30	33.20	0.10	–1.51
E.C/dS·m⁻¹	0.130	0.02	17.36	0.102	0.193	0.72	–0.09
After fertilization, Musica region							
N/mg·kg⁻¹	9.32	1.39	14.87	7.29	12.49	0.64	–0.06
P/mg·kg⁻¹	5.85	1.31	22.43	3.74	8.24	–0.08	–0.84
K/mg·kg⁻¹	144.02	18.21	12.64	110.46	189.27	0.15	0.14
pH	6.90	0.22	3.26	6.29	7.4	–0.65	1.18
Temp/°C	21.80	0.78	3.62	20.50	23.60	0.19	–0.26
M.C/%	25.39	9.16	36.10	8.00	46.00	0.62	0.61
E.C/dS·m	0.130	0.010	19.830	0.112	0.183	0.810	0.040
Before fertilization, Kuroda region							
N/mg·kg⁻¹	8.245	2.850	34.580	3.830	14.950	0.530	–0.480
P/mg·kg⁻¹	4.88	1.59	32.57	1.73	8.50	0.25	–0.59
K/mg·kg⁻¹	137.35	23.45	17.07	80.60	181.54	–0.34	0.20
pH	6.82	0.27	3.98	6.00	7.10	–1.67	2.74
Temp/°C	36.23	1.82	5.03	34.00	40.00	0.69	–0.77
M.C/%	24.96	3.72	14.92	20.10	33.20	0.40	–1.00
E.C/dS·m	0.130	0.020	16.490	0.110	0.191	1.560	1.860
After fertilization, Kuroda region							
N/mg·kg⁻¹	9.35	2.44	26.10	5.47	14.32	0.23	–0.72
P/mg·kg⁻¹	5.80	1.64	28.28	2.65	10.42	0.48	1.00
K/mg·kg⁻¹	145.24	22.72	15.64	91.94	187.40	–0.36	–0.04
pH	6.86	0.16	2.35	6.60	7.41	1.17	2.95
Temp/°C	21.416	2.040	9.530	18.500	29.700	2.300	8.760
M.C/%	24.56	8.10	32.96	8.00	40.80	0.23	–0.03
E.C/dS·m	0.140	0.020	17.890	0.101	0.195	0.350	–0.800

3.2 Descriptive statistics of crop growth parameters of Field 1

Plant growth parameters and yield showed less variation for both varieties except NDVI, as listed in Table 2. CV value of NDVI in Kuroda and Musica was 10.55% and 16.49%, respectively. Yield of Kuroda (CV=13.33%) showed higher variation as compared to Musica (CV=9.86). Chlorophyll content and NDVI of Kuroda is slightly higher (241.35 and 0.73) compared to Musica (237.37 and 0.66). NDVI is an indicator of plant health and vigor, with higher values typically associated with increased photosynthetic activity[53]. Almost similar NDVI values were found in potato crop when different rates of N were applied, as reported by Az et al.[54]. This difference may be attributed to variations in genetic traits and pigment synthesis pathways between the two varieties. Several variables displayed negative skewness for both regions except number of leaves, leaf area, tuber weight, and yield of Musica, and tuber weight and yield for Kuroda. Results showed that the Kuroda plants are taller (46.48 cm) than Musica plants (38.53 cm). Kuroda results show a higher mean number of leaves and leaf area compared to Musica. Plant height, number of leaves, and leaf area are influenced by genetic traits and may also be influenced by factors such as nutrient availability and plant density. Leaf area is an important indicator of photosynthetic potential, and the larger leaf area in Kuroda indicates that Kuroda has a high capacity of capturing light and conducting photosynthesis[55]. Kuroda exhibited slightly lower tuber weight and yield compared to Musica. Tadesse & Mulugeta[56] reported that higher plant density and canopy increased the number of small-size tubers, as is evident from the Kuroda's yield. The higher yield in Musica, despite having slightly lower plant growth parameters as compared to Kuroda, may be attributed to genetic factors such as higher tuber density or larger total tuber production per unit area. Overall yield of potato tuber was higher in drip irrigation system as compared to raingun irrigation because drip systems deliver water directly to the root zone of plants, ensuring a more even and targeted distribution[57].

Table 2 Results of descriptive statistics crop growth parameters and yield of Field 1

Variable	Mean	S.D	C.V/%	Min	Max	Skewness	Kurtosis
Kuroda							
Chlorophyll content (SPAD)	241.35	20.11	8.33	189.00	275.00	–0.45	0.55
NDVI	0.73	0.07	10.55	0.59	0.86	–0.34	–1.0
Plant ht/cm	46.480	3.294	7.090	38.100	51.00	–1.210	0.670
NoL	109.22	8.35	7.64	88.00	124.00	–0.82	0.68
LA/cm²	128.81	10.26	7.96	105.23	141.23	–0.97	0.03
Yield/kg·hm⁻²	27 883.00	3717.00	13.33	22 208.00	34 271.00	0.21	–1.26
Tuber weight/g	330.00	20.09	6.09	301.00	372.10	0.52	–0.60
Musica							
Chlorophyll content (SPAD)	237.37	16.29	6.86	208.00	264.00	–0.34	–0.80
NDVI	0.66	0.11	16.49	0.45	0.85	–0.31	–0.85
Plant ht/cm	38.570	3.530	9.170	32.272	44.972	–0.340	–0.760
NoL	98.57	4.99	5.07	91.00	108.00	0.21	–1.21
LA/cm²	121.86	7.09	5.82	111.00	132.00	0.16	–1.55
Yield/kg·hm⁻²	35 453.00	1367.00	9.86	33 000.00	37 500.00	–0.02	–1.08
Tuber weight/g	341.50	16.18	4.74	315.00	370.00	0.03	–1.04

3.3 Descriptive statistics of soil properties of Field 2

N, P, and K values were relatively low before fertilization, suggesting limited nutrient availability in soil (Table 3). However, these values displayed significant increase after fertilization, indicating the successful incorporation of nutrients into the soil. N displayed a high degree of variation before fertilization (24.63% and 26.18%) and after fertilization (28.18% and 26.17%) in Musica and Kuroda, respectively, while P and K showed relatively low variability in both regions (Table 3). These variations highlighted the dynamic nature of soil composition and its response to fertilization. CV of N showed an increase during the second sampling, indicating a greater dispersion of values within the dataset. Conversely, the CV of pH remained relatively constant for both the Musica and Kuroda fields, suggested a consistent pH level in the soil. M.C and E.C displayed moderate variation during the first sampling, while M.C exhibited greater variability during the second sampling. The same pH ranges from 6 to 8 were reported by Haroon et al.[25] for the soil of URF, Koont. Skewness provided further understanding about the shape and asymmetry of the distribution of data. Positive skewness was found during the first sampling in all parameters except temperature. However, several parameters showed negative skewness in the second sampling, deviating from the distribution found during first sampling. N, P, and pH had a different skewness pattern in Musica. First sampling in Kuroda showed negative skewness for all metrics except pH. Second sampling showed negative skewness in E.C and M.C, depicting how these properties change after fertilization. CV of temperature decreased significantly throughout both samplings in the Musica and Kuroda regions. Hence, suggested Field 2 maintains a more constant and steady temperature, which may affect plant growth and soil processes. Similar results of soil spatial variability were found in different crops[58,59], of which similar soil properties were investigated. Several factors were involved in the soil spatial variations such as incorporation of fertilizer, crop nutrient uptake efficiency, crop management practices, and spray-like distribution of water through raingun. These factors are essential in determining agricultural productivity and facilitating optimal plant growth. Raingun irrigation led to the dispersal of water in a spray-like manner, resulting in uneven distribution of water across the field. The lack of uniformity can lead to variations in the moisture content of the soil and the availability of nutrients[60].

Table 3 Results of descriptive statistics for soil properties of Field 2

Variables	Mean	S.D	C.V/%	Min	Max	Skewness	Kurtosis
Before fertilization, Musica region							
N/mg·kg^{-1}	7.16	1.76	24.63	3.58	13.48	1.25	4.90
P/mg·kg^{-1}	7.67	2.01	26.26	4.89	15.09	1.84	5.33
K/mg·kg^{-1}	113.27	16.81	14.84	89.22	148.82	0.51	–0.49
pH	7.74	0.08	1.16	7.58	7.98	0.26	0.33
Temp/°C	35.08	2.51	7.16	21.97	36.32	–5.24	28.20
M.C/%	25.24	5.61	22.23	12.53	34.01	–0.50	–0.31
E.C/dS·m	0.140	0.010	11.520	0.111	0.167	–0.610	–0.950
After fertilization, Musica region							
N/mg·kg^{-1}	8.73	2.46	28.18	6.27	18.30	2.27	6.96
P/mg·kg^{-1}	8.60	2.08	24.19	6.09	16.87	2.50	8.12
K/mg·kg^{-1}	121.14	15.26	12.60	93.44	149.74	–0.07	–0.51
pH	7.74	0.08	1.16	7.58	7.98	0.26	0.33
Temp/°C	25.78	0.27	1.05	25.32	26.34	–0.17	–0.72
M.C/%	21.65	1.12	5.21	20.00	23.01	–0.59	–1.34
E.C/dS·m	0.140	0.020	16.540	0.044	0.167	–2.610	10.210
Before fertilization, Kuroda region							
N/mg·kg^{-1}	6.65	1.74	26.18	3.13	11.80	0.72	1.66
P/mg·kg^{-1}	7.124	1.10	15.56	5.13	9.67	0.34	0.22
K/mg·kg^{-1}	110.91	19.11	17.23	60.65	143.61	–0.17	0.27
pH	7.78	0.10	1.40	7.58	8.03	0.36	0.19
Temp/°C	35.96	0.46	1.30	35.09	36.74	–0.35	–0.82
M.C/%	24.48	4.97	20.31	8.33	32.96	–1.27	3.02
E.C/dS·m	0.290	0.017	6.030	0.258	0.317	–0.270	–0.790
After fertilization, Kuroda region							
N/mg·kg^{-1}	8.059	2.109	26.170	4.580	12.780	0.540	–0.170
P/mg·kg^{-1}	8.383	1.822	21.730	5.890	14.180	1.640	3.050
K/mg·kg^{-1}	118.88	19.52	16.42	72.26	156.95	0.08	0.06
pH	7.78	0.10	1.40	7.58	8.03	0.37	0.21
Temp/°C	25.60	0.43	1.69	24.98	27.08	1.46	3.61
M.C/%	21.67	1.18	5.44	17.7	23.04	–1.78	3.39
E.C/dS·m	0.110	0.030	32.860	0.024	0.168	–0.620	–0.290

3.4 Descriptive statistics of crop growth parameters of Field 2

Kuroda exhibited less variation in most parameters, with CV ranges of 3.85% (leaf area) to 8.06% (chlorophyll) (Table 4). On the other hand, Musica showed slightly larger coefficients of variation than Kuroda, ranging from 4.1% for plant height to 14% for NDVI. Overall, Musica displayed greater coefficients of variation than Kuroda, indicating a relatively higher variability. This indicated that Musica may have more diverse responses within its plant density. On the other hand, Kuroda tends to have slightly lower coefficients of variation, indicating a relatively more consistent performance across the measured variables. Kuroda showed lower values for relative chlorophyll content, while Musica exhibited a lower NDVI. Plant height is slightly higher in Kuroda (38.454 cm) compared to Musica (39.065 cm). Similarly, Kuroda presented a higher mean number of leaves (94.073) compared to Musica (91.484) (Table 4). Both varieties displayed similar mean values for leaf area, with Kuroda at 113.49 (cm^2) and Musica at 114.5 (cm^2). However, Musica demonstrated a higher mean tuber weight (331.09 g) as compared to Kuroda (323.07 g) (Table 4). Tuber yield also differs significantly, with Musica having a much higher mean yield (27 639 kg/hm^2) compared to Kuroda (19 164 kg/hm^2). Results indicated that Kuroda showed slightly right-skewed distributions for plant height, number of leaves, and tuber weight, while Musica exhibited a moderately right-skewed distribution for NDVI. Similar findings were reported by Khan et al.[34], suggesting that soil properties and plant growth parameters have a significant relationship. Plant growth parameters were significantly higher in the Kuroda as compared to Musica because of the varietal and genetic factors. On the other hand, yield was higher in Musica as compared to Kuroda. This difference may be attributed to the fact that white-skinned potatoes have thicker skin, which provides better protection against biotic and abiotic stresses.

Table 4 Results of descriptive statistics crop growth parameters and yield of Field 2

Variable	Mean	S.D	C.V/%	Min	Max	Skewness	Kurtosis
Kuroda							
Chlorophyll content (SPAD)	233.33	18.81	8.06	193.00	268.00	0.06	–0.26
NDVI	0.67	0.07	11.13	0.52	0.82	–0.07	0.14
Plant ht/cm	38.454	1.940	5.050	35.800	42.560	0.570	–0.650
NoL	94.070	4.980	5.300	84.000	104.560	0.430	–0.200
LA/cm^2	113.490	4.370	3.850	104.590	121.450	–0.250	–0.340
Yield/ kg·hm^{-2}	19 164.00	1364.00	7.12	16 800.00	21 945.00	0.18	–0.66
Tuber weight/g	323.07	8.19	2.54	304.45	335.00	–1.01	0.33
Musica							
Chlorophyll content (SPAD)	241.87	13.41	5.55	211	265	0.01	–0.06
NDVI	0.62	0.08	14.00	0.48	0.80	0.71	–0.19
Plant ht/cm	39.06	1.60	4.10	36.60	41.85	0.27	–1.23
NoL	91.48	3.82	4.18	84.00	99.36	0.06	–0.55
LA/cm^2	114.50	5.65	4.93	104.00	125.00	0.00	–0.79
Yield kg·hm^{-2}	27 639.00	2563.00	9.27	24 000.00	32 100.00	0.13	–1.32
Tuber weight/g	331.09	6.36	1.92	321.23	341.00	0.05	–1.41

Overall results of the descriptive statistics showed variations in soil chemical characteristics and plant growth parameters in fields of potatoes irrigated with raingun. These variations can be attributed to the non-uniform water distribution, nutrient leaching, and soil compaction associated with applied irrigation. The precision and uniformity of water application in drip irrigation make it a more reliable method for minimizing soil and yield variability compared to raingun irrigation. This precision in water and nutrient delivery supports more uniform plant growth, resulting in comparable plant heights, number of leaves, and NDVI values across the field. Plant growth parameters were significantly higher in the Kuroda as compared to Musica, which could be due to the varietal and genetic factors. Though genetic and varietal factors are not studied in this research, they play a crucial role in variability in plant growth parameters according to the nutrient and water uptake efficiency.

3.5 Geostatistical analysis and spatial dependencies of soil and plant parameters

Descriptive statistics provide a comprehensive understanding of

Table 5 Semivariogram parameters of soil characteristics and crop parameters for Field 1

Parameters	Nugget (C_0)	Partial sill (C)	Sill (C_0+C)	Range	ASE	RMSE	Nugget sill ratio	N/S	Model
First sampling (before fertilization)									
N/mg·kg⁻¹	0.89	3.90	4.79	19.68	1.74	1.05	0.18	18.58	Gaussian
P/mg·kg⁻¹	1.94	0.36	2.30	43.24	1.52	0.99	0.84	84.34	Stable
K/mg·kg⁻¹	312.93	118.00	430.93	37.92	20.33	1.03	0.72	72.61	Exponential
pH	0.003	0.009	0.012	49.700	0.113	1.150	0.250	25.000	Stable
Temp/°C	0.46	1.00	1.46	18.28	1.13	1.01	0.31	31.50	Circular
M.C/%	0.34	2.26	2.60	23.19	1.34	1.03	0.13	13.07	Spherical
E.C/dS·m	0.000 21	0.000 29	0.000 50	22.620 00	0.020 00	0.950 00	0.420 00	42.000	Exponential
Second sampling (after fertilization)									
N/mg·kg⁻¹	2.37	3.68	6.05	26.44	2.21	1.02	0.39	39.17	Spherical
P/mg·kg⁻¹	0.83	1.26	2.09	54.84	1.40	1.01	0.39	39.71	Stable
K/mg·kg⁻¹	340.64	104.83	445.47	47.70	20.82	1.02	0.76	76.46	Stable
pH	0.05	0.00	0.05	84.00	0.24	1.006	1.00	100.00	Stable
Temp/°C	0.75	2.72	3.47	83.31	1.31	1.013	0.21	21.61	Exponential
M.C/%	1.47	2.51	3.98	19.05	1.79	0.93	0.36	36.97	Gaussian
E.C/dS·m	0.0005	0.000	0.0005	24.9600	0.0200	0.9500	1.0000	100	Stable
Crop parameters (Musica)									
Plant height/cm	8.37	3.96	12.33	32.2	3.46	1.04	0.67	67.88	Exponential
Chlorophyll (SPAD)	169.95	151.71	321.66	54.84	14.38	1.01	0.52	52.83	Stable
NDVI	0.006	0.007	0.013	52.420	0.090	0.990	0.460	46.150	Circular
Yield/kg·hm⁻²	1 677 376.56	243 389.00	1 920 765.00	25.05	1409.00	1.05	0.87	87.32	Stable
Crop parameters (Kuroda)									
Plant height (cm)	77.35	33.65	111.00	53.98	10.12	1.03	0.69	69.68	Exponential
Chlorophyll (SPAD)	346.04	200.21	546.25	100.96	21.09	0.99	0.63	63.34	Exponential
NDVI	0.002	0.004	0.006	28.370	0.070	0.990	0.330	33.330	Circular
Yield/kg·hm⁻²	13 614 697.00	1 098 613.00	14 713 310.00	28.96	3976	0.98	0.92	92.53	Stable

Table 6 Semivariogram parameters of soil characteristics and crop parameters for Field 2

Parameters	Nugget (C_0)	Partial sill (C)	Sill (C_0+C)	Range	ASE	RMSE	Nugget sill ratio	N/S	Model
First sampling (before fertilization)									
N/mg·kg⁻¹	3.82	0.79	4.61	31.38	2.16	0.97	0.82	82.86	Exponential
P/mg·kg⁻¹	1.75	1.066	2.816	34.33	1.59	0.96	0.62	62.14	Circular
K/mg·kg⁻¹	200.44	220	420.44	40.06	16.19	1.18	0.47	47.67	Gaussian
pH	0.007	0.003	0.01	30.01	0.1	0.94	0.70	70.00	Stable
Temp/°C	0.8	34.33	35.13	0.29	1.03	1.02	0.02	2.27	Exponential
M.C/%	1.6	1.2	2.8	45.65	1.4	0.98	0.57	57.14	Gaussian
E.C/dS·m	0.0007	0.0006	0.0013	43.27	0.02	1.00	0.53	53.84	Stable
Second sampling (after fertilization)									
N/mg·kg⁻¹	2.11	1.92	4.03	35.61	1.9	0.9	0.52	52.35	Exponential
P/mg·kg⁻¹	1.74	1.5	3.24	45.25	1.58	0.97	0.53	53.70	Spherical
K/mg·kg⁻¹	225.24	137.53	362.77	20.81	19.5	0.9	0.62	62.08	Exponential
pH	0.007	0.002	0.009	30.01	0.1	0.94	0.77	77.77	Stable
Temp/°C	0.97	0.32	1.29	97.64	1.07	1.01	0.75	75.19	Exponential
M.C/%	1.01	0.5	1.51	79.81	1.13	1.11	0.66	66.88	Exponential
E.C/dS·m	0.0002	0.0077	0.0079	97.64	0.04	0.67	0.02	2.53	Exponential
Crop parameters (Musica)									
Plant height/cm	1.17	1.53	2.7	43.2	1.498	1.1	0.43	43.33	Exponential
Chlorophyll (SPAD)	165.01	44.08	209.09	53.015	14.25	0.92	0.78	78.91	Exponential
NDVI	0.007	38.1	38.107	38.1	0.09	0.94	0.000 18	0.08	Spherical
Yield/kg·hm⁻²	4 567 985	3 020 718	7 588 703	33.39	2479	0.99	0.60	60.19	Gaussian
Crop parameters (Kuroda)									
Plant height/cm	2.16	1.23	3.39	20.24	1.82	1.15	0.63	63.71	Gaussian
Chlorophyll (SPAD)	250.49	55	305.49	20.95	18.06	1.08	0.81	81.99	Gaussian
NDVI	0.005	0.0003	0.0053	20.32	0.07	0.98	0.94	94.33	Spherical
Yield/kg·hm⁻²	1 165 889	749 706	1 915 595	18.1	1454	0.99	0.60	60.86	Exponential

soil variability within the field but do not offer any information about spatial patterns[26]. In light of this, the results of geostatistical analyses conducted in both fields are provided in Tables 5 and 6 to get insights of spatial trends of variability. These analyses aim to understand the spatial variability and dependency of various parameters within each field, using metrics such as Nugget (C_0), Partial Sill (C), Sill (C_0+C), Range, ASE (Absolute Standard Error), RMSE (Root Mean Square Error), Nugget Sill Ratio N/S, the spatial model used, and the SpD (Spatial Dependency) classification.

3.5.1 Geostatistical variations in soil and plant growth parameters of Field 1 & Field 2

Soil properties and plant parameters data from both samples were best fitted by Gaussian, spherical, exponential, and linear models. ASE and RMSE also indicated that all of the models exhibited the best fit, as listed in Table 5. Moderate to strong variance in the field was observed as demonstrated by the semivariogram range of effect for soil characteristics, except P for the first sampling and K for the second sampling. The nugget-to-sill ratio demonstrated that plant characteristics had moderate spatial dependency, except for yield. The nugget-to-sill ratio is an indicator of the spatial dependence of a parameter; a low nugget-to-sill ratio indicates a significant degree of spatial dependence. According to studies, a variable is considered to have high spatial dependency when the ratio is less than 25%, moderate spatial dependency when the ratio is between 25% and 75%, and weak spatial dependency when the ratio is greater than 75%[40,54]. Soil texture, mineralogy, and microorganisms are examples of intrinsic soil properties that may exert significant control over variables that are highly spatially dependent. The variability of moderate to weak spatially dependent variables may be influenced by extrinsic factors such as weather conditions, topography, and management strategies[61]. The first soil sampling displayed significant spatial dependency, while the second sampling demonstrated a moderate level of spatial dependency. The regulation of this phenomenon could potentially be influenced by external influences, such as the application of fertilizers[26]. N and M.C illustrated a strong spatial dependency, and Gaussian and spherical were the best fitted model, with ranges of influence of 19.68 and 23.19 m, respectively, during first sampling. K, pH, temperature, and E.C exhibited intermediate spatial dependency. The best fitted model for P was stable with the range of 43.24 m, and K and E.C were best described by the exponential model during second sampling. The best fitted model for P, K, pH, and E.C were stable, and spherical was the best semivariogram model for N, with the range 26.44 m during second sampling. All the plant parameters for both cultivars showed moderate spatial dependency except yield, which showed weak spatial dependency. The best fitted semivariogram model for the chlorophyll and yield for the Musica was stable, and the ranges of influence were 54.84 and 25.05 m, respectively. NDVI and plant height were best described by the circular and exponential models, respectively, for the Musica. Contrary to that, the best fitted model of chlorophyll and plant height for the Kuroda was the exponential model, with ranges of influence of 100.96 and 53.98 m, respectively. The potential causes of variation in soil parameters and crop production can be attributed to both external and intrinsic factors. The intrinsic variation in the field was a result of natural factors such as parent material, whereas extrinsic variation was attributed to the implementation of various management strategies[62,63].

N displayed a weak spatial dependency (82%) during first sampling, demonstrating that nearby data points have a limited influence on each other. N displayed an intermediate spatial dependency (52.35%) during second sampling, indicating moderate spatial correlation between nearby data points (Table 6). P, K, and M.C exhibited intermediate spatial dependencies for both fields. On the other hand, pH and temperature demonstrated strong spatial dependencies during first sampling and showed weak spatial dependencies during second sampling. Spatial models for soil properties were chosen on the basis of spatial characteristics. N and temperature were best described by an exponential model, while P and M.C were better represented by Gaussian models. pH was well-fitted with a stable model due to its heavy-tailed distribution. On the other hand, P, N, and M.C were best described by an exponential model, while P was represented by a spherical model. The soil properties were uneven because the influence range was greater than the grid size. The large spatial dependency and lower range of influence of soil properties in the field showing yield variability have been reported for different crops[64–66]. The best fitted models for chlorophyll and plant height were exponential, while Gaussian was best fitted for yield, and spherical for NDVI, with the range of influence from 33.39 to 53 m for the Musica. On the other hand, chlorophyll and plant height were best described by the Gaussian model, while NDVI and yield were best represented by spherical and exponential, respectively, for Kuroda. Plant height and yield exhibited moderate spatial dependency. On the other hand, chlorophyll and NDVI showed weak spatial dependency. According to Magro et al.[67], the study revealed a moderate level of spatial dependence in fruit yield, suggesting that the variability in fruit yield is influenced by soil parameters. According to Chen et al.[68], there is a considerable correlation between variations in soil characteristics and both soil fertility and crop productivity.

3.6 Correlation of soil properties and plant parameters

Correlation matrices provided the relationships between different soil properties and plant variables in two different cultivars for Field 1 (Tables 7 and 8). Nitrogen showed positive correlations with P and K in both cultivar regions, indicating that these nutrients are interrelated, and their availability affects each other in supporting plant growth. Positive correlation between N and plant growth parameters suggested that nitrogen plays a crucial role in promoting plant growth and development, as Koch et al.[52] reported that N is the important nutrient for plant growth and development. Phosphorus was positively correlated with all plant and soil variables except pH, temperature, M.C, and leaf area. K also exhibits positive correlations with P, pH, chlorophyll, NDVI, plant height, number of leaves, leaf area, tuber height, and yield. K is necessary for various physiological processes in plants, including enzyme activation, osmoregulation, and transportation of sugars and water. Adequate potassium levels in the soil support plant cell turgor and maintain a balance of ions within the plant, which contributes to healthy growth and higher yields[69]. Positive correlations between N, P, K, and plant parameters, except leaf area, suggested that optimal soil conditions favor nutrient absorption and utilization by plants, leading to improved growth and productivity. Temperature and M.C were negatively correlated (r=–80) with each other. E.C was significantly correlated with N, P, K, and tuber weight and tuber yield for both cultivars (Table 7). Yield was strongly correlated with N, P, and K in Kuroda (r=0.76, r=0.64, and r=0.80) (Table 7). In Musica, results were little different as yield was strongly correlated only with P and K (r=0.56 and r=0.88) (Table 8). Yield of Kuroda was significantly correlated with chlorophyll (r=0.748) and NDVI (r=0.69). Contrary to that, Musica was slightly less correlated with chlorophyll (r=0.593) and NDVI (r=0.530) as compared to Kuroda. Comparing the two cultivars, it is evident that both Kuroda and Musica show similar patterns of correlations between nutrients, chlorophyll, plant height, leaf attributes, and tuber weight. This indicates that these factors are important for growth and yield in both cultivars. However, there are some variations in the correlation strengths and associations between the two cultivars. These differences may arise from genetic variations, and from biotic and abiotic factors for each cultivar. Results indicated that factors promoting plant height, leaf development, and tuber weight also contribute to higher crop yields. Baye et al.[70] reported that plant height has a positive correlation with actual yields of crops, and Gondwe et al.[23] suggested that proper application of N, P, and K considering the crop requirements of potato could significantly increase potato yield. Potato fields irrigated by drip irrigation with proper fertilization enhanced potato tuber yield[71].

Similar correlations were observed between N, P, K, and plant parameters for both cultivars as observed for Field 1 (Tables 9 and 10). Liang et al.[72] reported that soil parameters showed significant correlation with plant growth parameters and varied with plant growth stages. These correlations suggested that primary nutrient availability positively influences soil nutrient status, plant physiology, and overall plant growth and productivity[73]. Adequate nutrient levels promote plant growth, enhance photosynthesis, improve water-use efficiency, and strengthen cell walls[52]. E.C showed positive correlations with N, P, and K in both cultivars. Higher E.C values indicated higher salt concentrations in the soil, which can impact nutrient availability and plant growth. M.C showed non-significant correlations with other variables in each

Table 7 Correlation Matrix among the soil properties and plant growth parameters of Kuroda (Field 1)

	N	P	K	pH	Temp	M.C	E.C	Chlorophyll (SPAD)	NDVI	Plant ht	NoL	LA	Tuber weight/g
P	0.61^{***}												
K	0.79^{**}	0.70^{***}											
pH	0.63^{***}	0.25^{NS}	0.37^{*}										
Temp	-0.01^{NS}	-0.05^{NS}	-0.04^{NS}	0.09^{NS}									
M.C	-0.06^{NS}	-0.01^{NS}	0.06^{NS}	-0.12^{NS}	-0.80^{***}								
E.C	0.61^{***}	0.51^{**}	0.54^{**}	0.34^{*}	0.02^{NS}	-0.05^{NS}							
Chlorophyll (SPAD)	0.74^{***}	0.43^{**}	0.59^{***}	0.53^{**}	0.07^{NS}	-0.08^{NS}	0.34^{*}						
NDVI	0.69^{***}	0.41^{**}	0.55^{***}	0.41^{**}	0.02^{NS}	-0.1^{NS}	0.39^{*}	0.52^{**}					
Plant height/cm	0.59^{**}	0.38^{**}	0.48^{**}	0.25^{NS}	0.13^{NS}	-0.22^{NS}	0.26^{NS}	0.8^{***}	0.44^{*}				
NoL	0.47^{**}	0.32^{**}	0.37^{**}	0.23^{NS}	0.00^{NS}	-0.04^{NS}	0.24^{NS}	0.68^{***}	0.30^{*}	0.83^{***}			
LA/cm^2	0.23^{NS}	0.20^{NS}	0.21^{NS}	0.02^{NS}	-0.13^{NS}	-0.03^{NS}	0.05^{NS}	0.47^{**}	0.20^{NS}	0.69^{***}	0.79^{***}		
Tuber weight/g	0.72^{***}	0.65^{***}	0.79^{***}	0.35^{*}	-0.13^{NS}	0.02^{NS}	0.45^{**}	0.44^{**}	0.47^{*}	0.46^{**}	0.33^{*}	0.22^{NS}	
Yield/kg·hm^{-2}	0.76^{***}	0.64^{***}	0.81^{***}	0.34^{*}	-0.10^{NS}	0.02^{NS}	0.52^{**}	0.59^{**}	0.53^{**}	0.53^{**}	0.45^{*}	0.32^{*}	0.92^{***}

Note: * Significance of correlation, p=0.05; ** Significance of correlation, p=0.01; *** Significance of correlation, p=0.001. Same as tables below.

Table 8 Correlation Matrix among the soil properties and plant growth parameters of Musica (Field 1)

	N	P	K	pH	Temp	M.C	E.C	Chlorophyll (SPAD)	NDVI	Plant ht	NoL	LA	Tuber weight/g
P	0.44^{**}												
K	0.53^{**}	0.50^{**}											
pH	0.37^{*}	0.18^{NS}	0.30^{*}										
Temp	0.00^{NS}	-0.14^{NS}	-0.01^{NS}	0.03^{NS}									
M.C	-0.04^{NS}	-0.04^{NS}	-0.15^{NS}	-0.01^{NS}	-0.53^{**}								
E.C	0.30^{*}	0.39^{*}	0.32^{*}	0.05^{NS}	0.08^{NS}	0.46^{**}							
Chlorophyll (SPAD)	0.80^{***}	0.34^{*}	0.41^{**}	0.32^{*}	-0.00^{NS}	0.57^{**}	0.30^{*}						
NDVI	0.79^{***}	0.38^{*}	0.34^{*}	0.32^{*}	0.06^{NS}	0.55^{**}	0.48^{**}	0.94^{***}					
Plant height/cm	0.89^{***}	0.33^{*}	0.46^{**}	0.37^{*}	0.00^{NS}	0.47^{**}	0.09^{NS}	0.80^{***}	0.81^{***}				
NoL	0.83^{***}	0.32^{*}	0.42^{**}	0.22^{NS}	-0.10^{NS}	0.36^{*}	0.12^{NS}	0.75^{***}	0.77^{***}	0.82^{***}			
LA/cm^2	0.83^{***}	0.19^{NS}	0.48^{**}	0.20^{NS}	-0.11^{NS}	0.27^{NS}	0.11^{NS}	0.70^{***}	0.72^{***}	0.82^{***}	0.93^{***}		
Tuber weight/g	0.48^{**}	0.52^{**}	0.93^{***}	0.23^{NS}	-0.29^{NS}	0.15^{NS}	0.43^{**}	0.29^{NS}	0.25^{NS}	0.44^{**}	0.36^{*}	0.44^{**}	
Yield/kg·hm^{-2}	0.34^{*}	0.56^{**}	0.88^{***}	0.16^{NS}	-0.33^{*}	0.34^{*}	0.51^{**}	0.27^{NS}	0.22^{NS}	0.34^{*}	0.24^{NS}	0.31^{*}	0.91^{***}

Table 9 Correlation Matrix among the soil properties and plant growth parameters of Kuroda (Field 2)

	N	P	K	pH	Temp	M.C	E.C	Chlorophyll (SPAD)	NDVI	Plant ht	NoL	LA	Tuber weight/g
P	0.40^{**}												
K	0.43^{**}	0.60^{***}											
pH	0.45^{**}	0.18^{NS}	0.37^{*}										
Temp	-0.05^{NS}	-0.29^{NS}	-0.17^{NS}	0.21^{NS}									
M.C	0.15^{NS}	0.04^{NS}	-0.00^{NS}	0.13^{NS}	-0.53^{**}								
E.C	0.39^{*}	0.45^{**}	0.30^{*}	0.56^{**}	0.52^{**}	0.45^{**}							
Chlorophyll (SPAD)	0.84^{***}	0.30^{*}	0.49^{**}	0.38^{*}	0.04^{NS}	0.06^{NS}	0.35^{*}						
NDVI	0.72^{***}	0.29^{NS}	0.48^{**}	0.20^{NS}	0.03^{NS}	0.14^{NS}	0.17^{NS}	0.81^{***}					
Plant height/cm	0.70^{***}	0.16^{NS}	0.35^{*}	0.12^{NS}	0.00^{NS}	-0.10^{NS}	0.18^{NS}	0.78^{***}	0.46^{**}				
NoL	0.89^{***}	0.32^{*}	0.39^{*}	-0.02^{NS}	-0.11^{NS}	0.20^{NS}	0.00^{NS}	0.79^{***}	0.78^{***}	0.57^{**}			
LA/cm^2	0.88^{***}	0.20^{NS}	0.50^{**}	0.23^{NS}	-0.01^{NS}	0.15^{NS}	0.34^{*}	0.83^{***}	0.65^{***}	0.65^{***}	0.82^{***}		
Tuber weight/g	0.50^{**}	0.47^{**}	0.84^{***}	0.34^{*}	-0.15^{NS}	0.01^{NS}	0.47^{**}	0.65^{***}	0.62^{***}	0.43^{**}	0.52^{**}	0.59^{**}	
Yield/kg·hm^{-2}	0.43^{**}	0.19^{NS}	0.61^{***}	0.35^{*}	-0.162^{NS}	0.24^{NS}	0.332^{*}	0.44^{**}	0.58^{**}	0.20^{NS}	0.46^{**}	0.52^{**}	0.66^{***}

Table 10 Correlation Matrix among the soil properties and plant growth parameters of Musica (Field 2)

	N	P	K	pH	Temp	M.C	E.C	Chlorophyll (SPAD)	NDVI	Plant ht	NoL	LA	Tuber weight/g
P	0.45^{**}												
K	0.33^{*}	0.36^{*}											
pH	0.36^{*}	0.06^{NS}	0.33^{*}										
Temp	0.03^{NS}	0.05^{NS}	$–0.02^{NS}$	0.00^{NS}									
M.C	$–0.1^{NS}$	$–0.08^{NS}$	$–0.00^{NS}$	$–0.06^{NS}$	$–0.88^{***}$								
E.C	0.37^{*}	0.31^{*}	0.44^{**}	0.02^{**}	0.1^{NS}	0.48^{**}							
Chlorophyll (SPAD)	0.82^{***}	0.52^{**}	0.34^{*}	0.32^{*}	0.05^{NS}	$–0.15^{NS}$	0.02^{NS}						
NDVI	0.88^{***}	0.54^{**}	0.31^{*}	0.33^{*}	0.15^{NS}	$–0.27^{NS}$	0.08^{NS}	0.94^{***}					
Plant height/cm	0.78^{***}	0.40^{**}	0.39^{*}	0.41^{**}	$–0.16^{NS}$	0.04^{NS}	0.14^{NS}	0.70^{**}	0.71^{***}				
NoL	0.70^{***}	0.38^{*}	0.24^{NS}	0.24^{NS}	-0.23^{NS}	0.18^{NS}	$–0.01^{NS}$	0.52^{**}	0.52^{**}	0.85^{***}			
LA/cm²	0.73^{**}	0.22^{NS}	0.28^{NS}	0.37^{*}	$–0.26^{NS}$	0.18^{NS}	0.17^{NS}	0.59^{**}	0.57^{**}	0.82^{***}	0.83^{***}		
Tuber weight/g	0.32^{*}	0.30^{*}	0.72^{***}	0.13^{NS}	$–0.07^{NS}$	$–0.03^{NS}$	0.13^{NS}	0.24^{NS}	0.36^{*}	0.42^{*}	0.32^{*}	0.22^{NS}	
Yield/kg·hm⁻²	0.65^{***}	0.35^{*}	0.45^{**}	0.25^{NS}	$–0.26^{NS}$	0.16^{NS}	0.03^{NS}	0.66^{**}	0.64^{**}	0.88^{**}*	0.71^{***}	0.70^{***}	0.46^{**}

cultivar. The lack of correlation occurred because readings were taken after 15 days of irrigation to allow sufficient time for fertilizers to dissolve in the field. M.C plays a critical role in plant growth, as water is essential for photosynthesis, nutrient transport, and cell expansion. Adequate soil moisture levels are crucial for optimal plant performance and crop productivity[74,75].

These correlations suggested that nutrient availability and soil conditions influence plant physiological processes and ultimately affect plant growth and productivity. Positive relationships between soil parameters and tuber yield indicated that soil properties play a significant role in limiting crop yield. Few variables that contributed to yield variability have not been addressed, and these include factors other than soil characteristics such as disease and insect damage. Potato production can also be negatively impacted by factors such as weed competition, weather extremes, and frosting. Significant correlations between the soil parameters and plant growth parameters and the effect of soil variability on the plant growth and yield were also reported by [25-27,34,37,51].

3.7 Interpolated maps

The interpolated maps of all the soil and plant parameters showed spatial variability with significant different values across both fields except pH (Figure 1 and Figure 2). Spatial patterns of variations for N, P, and K maps showed almost similar variation patterns with high values on the northern and northwest regions,

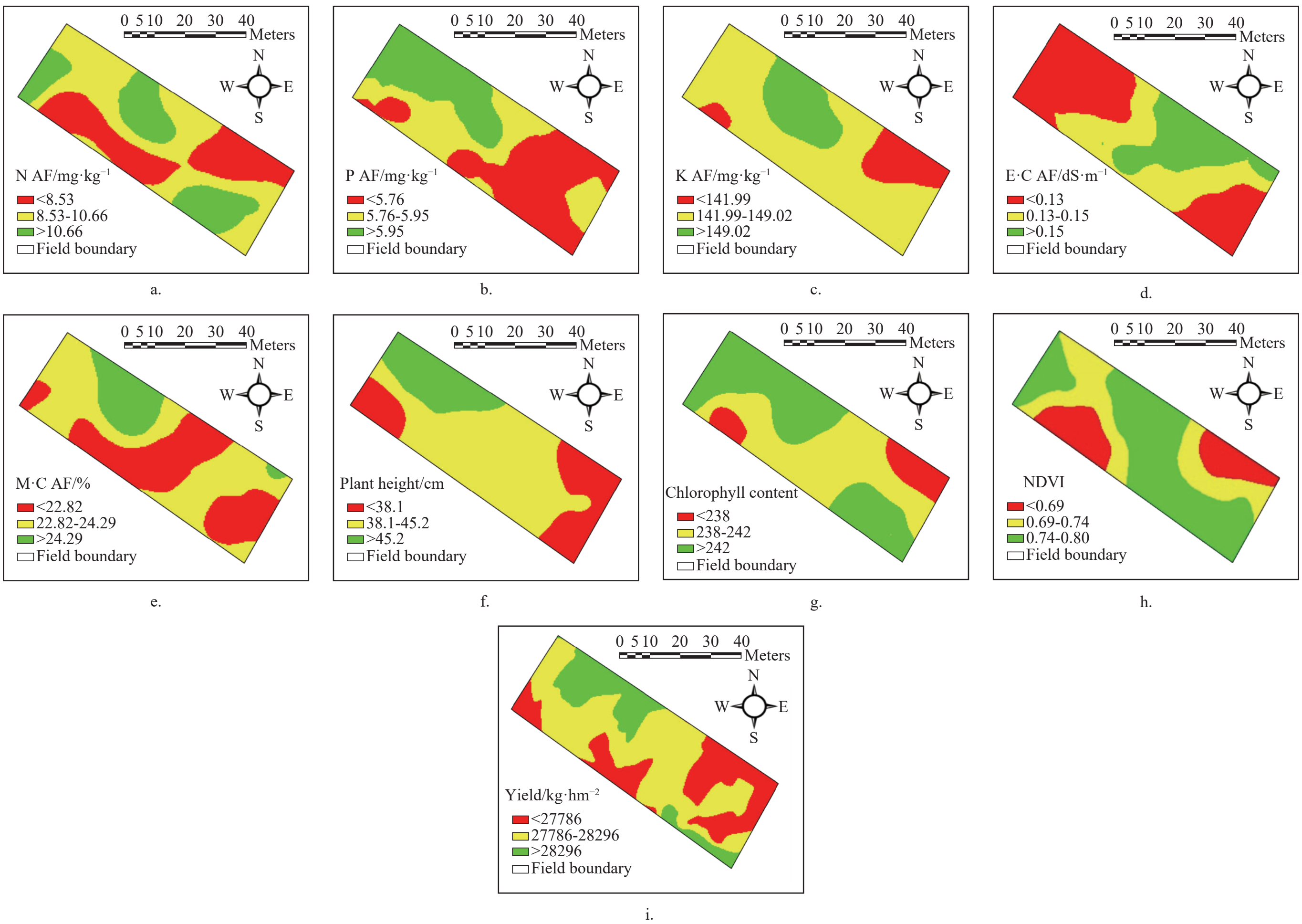

Figure 1 Kriged maps of soil and plant parameters of Kuroda (Field 1)

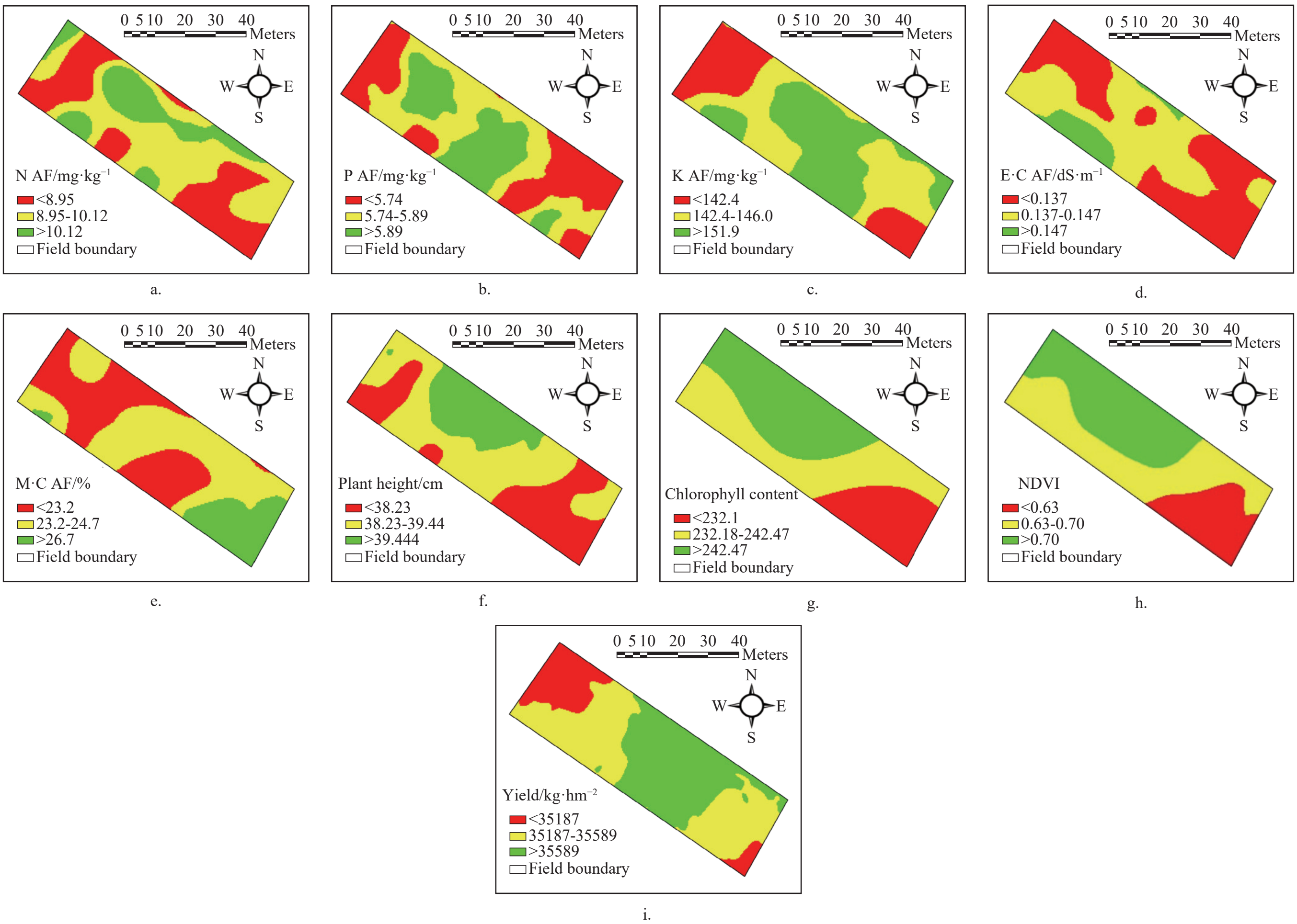

Figure 2 Kriged maps of soil and plant parameters of Musica (Field 1)

lower values in northeast and southern regions, and medium values in the center of the field (Figures 1a, 1b and 1c; 2a, 2b and 2c). M.C, E.C, N, P, and K maps revealed the high spatial variability within Field 1. Significant positive correlations and range of influence also suggested similar patterns of variation of these soil properties. Maps of soil pH, M.C, and E.C showed less variability as compared with other soil properties, as also suggested by the range of influence for these soil properties (Figures 1d and 1e; 2d and 2e). Similar patterns of variations for these soil properties were observed in the first sampling. Kriged maps of plant parameters showed that the NDVI variation pattern was high in the northern to southern regions, and low in eastern and western regions for the Kuroda cultivar (Figure 1h). On the other hand, NDVI values were low in the southern region and high in the northeastern region, and medium values were found in western regions for Musica. Chlorophyll content and NDVI maps showed almost similar patterns of variation for both cultivars (Figures 1g and 1h; Figure 2g and 2h). Plant height map for both cultivars showed that the plant height was low in the western and southern regions, high in northern regions, and medium plant height was found in the middle of the field (Figures 1g and 2g). Musica cultivar showed that the yield was poor in the northern side but good in the eastern and middle regions (Figure 2i). On the other hand, Kuroda yield was lower in the eastern and western regions, but yield was high in the northern side (Figure 1i). Kriged maps of plant parameters showed substantial variation across the field, which was also revealed by the range of influence and CV.

Kriged maps of soil properties of Field 2 suggested the spatial variability within the field. The spatial patterns of N, P, and K showed less values in northern and western regions, medium values in the middle of the field, and showed much less higher values within Field 2 on the northeastern part of the field (Figures 3a, 3b, 3c; 4a, 4b, 4c). Kriged maps discovered that Field 2 was less fertile as compared to Field 1. These spatial variations were also indicated by the CV, geospatial range of influence, and correlation. Chlorophyll content, NDVI, and plant height maps showed similar spatial patterns (Figures 3f, 3g, 3h; 4f, 4g, 4h). However, high values were observed in the middle of the field for Musica, and low values were found in the middle of the field for Kuroda. Kriged maps of Kuroda cultivar indicated that higher yield was present in the northwestern part and lower yield was present in between the western and eastern parts of the field (Figure 3i). On the other hand, Musica yield was high between the northern and eastern parts, and low yield was found in the southern and northwestern parts of the field (Figure 4i).

The overall findings indicated a significant degree of variability in both soil parameters and tuber yield, as evidenced by their coefficient of variation (CV) (Tables 1-4). The geostatistical range of influence, as well as the high to moderate spatial dependence, indicated that soil characteristics and tuber yield exhibited a significant degree of variability within the field, apart from soil pH and E.C, which had rather consistent values throughout both fields (Tables 5 and 6). The kriged maps of soil parameters and tuber yield exhibited alignment with results derived from both descriptive and geostatistical analyses, indicating the presence of considerable heterogeneity within the field. Significant positive relationships between soil characteristics and plant parameters were aligned with the patterns illustrated in the kriged maps.

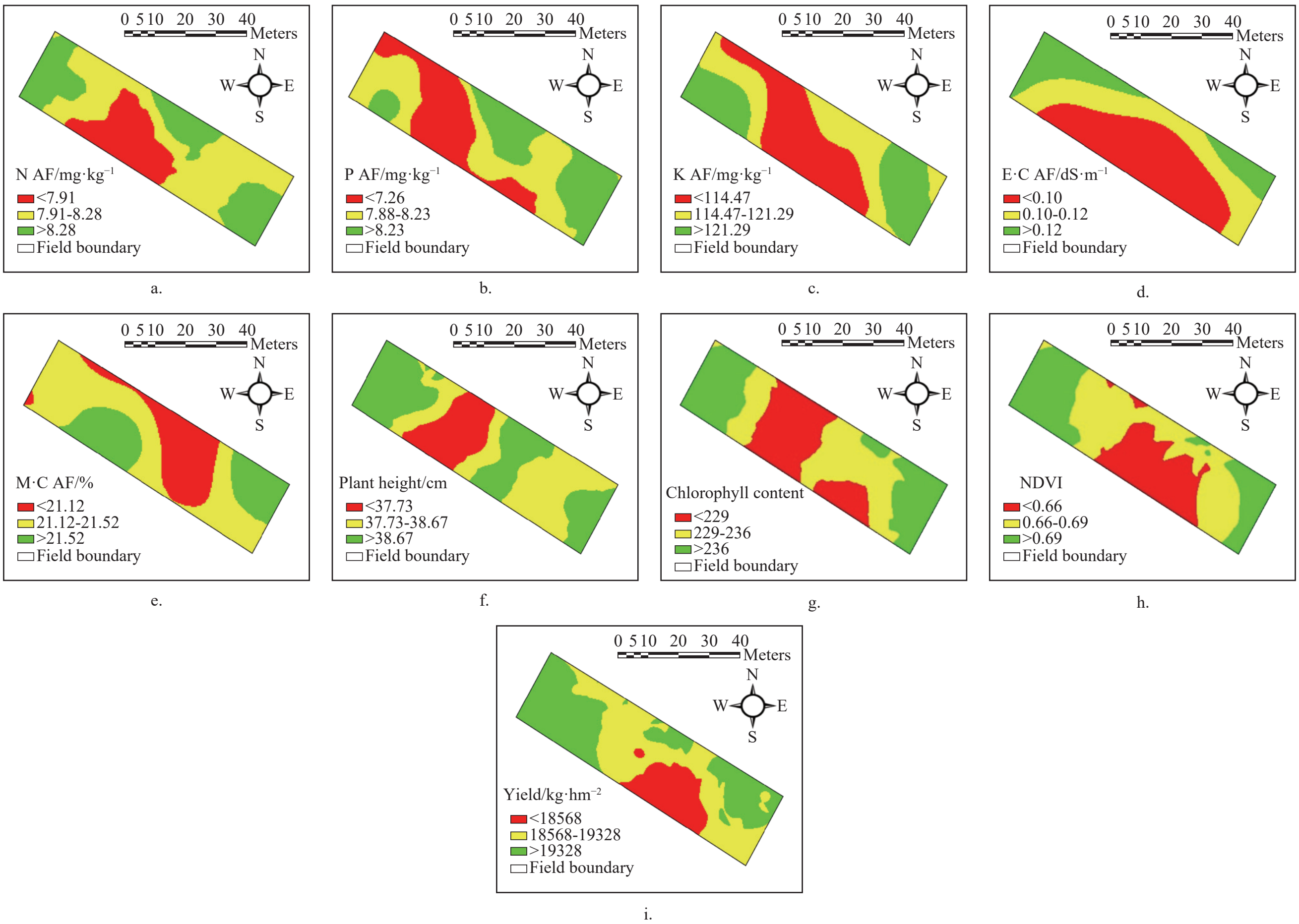

Figure 3 Kriged maps of soil and plant parameters of Kuroda (Field 2)

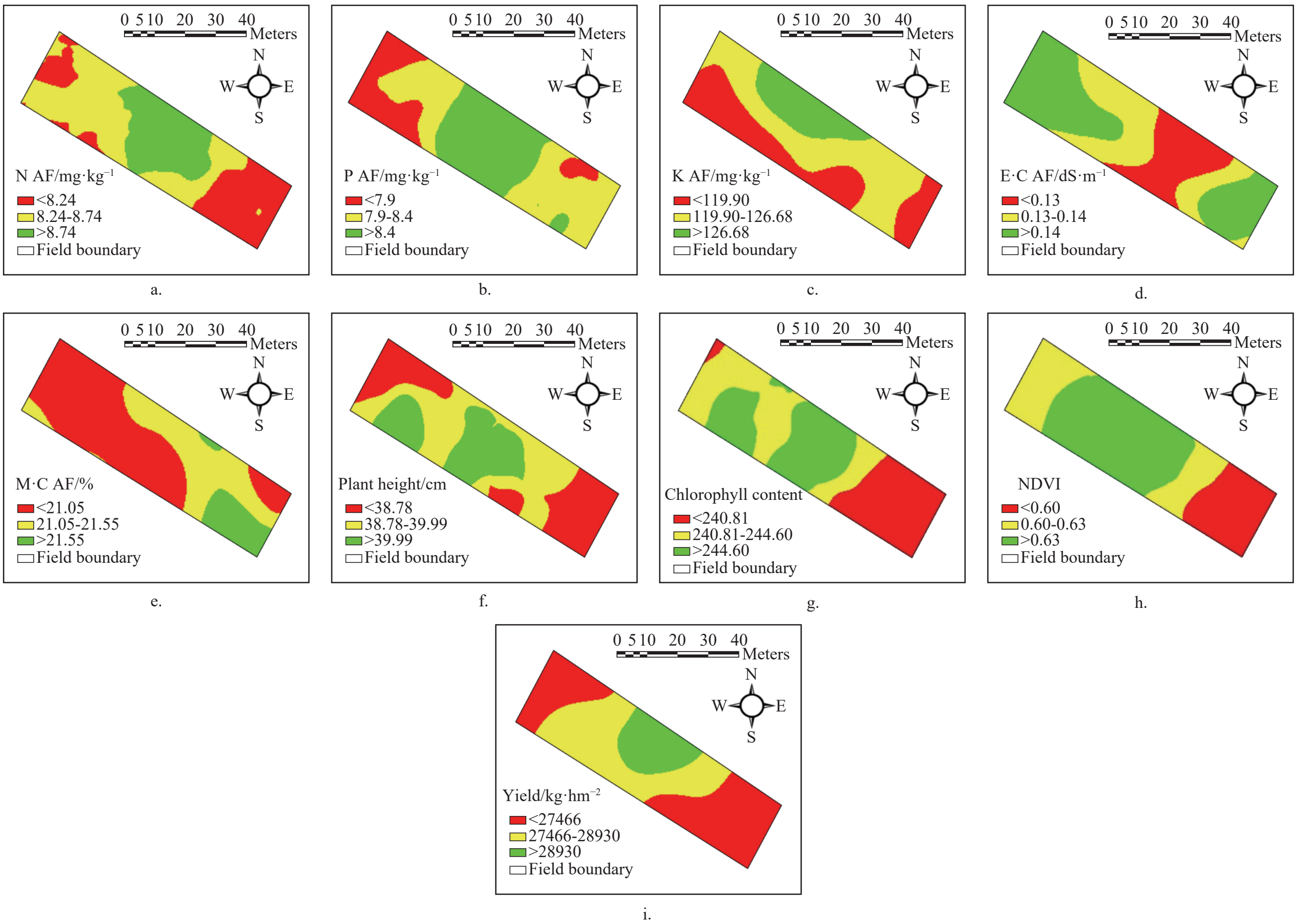

Figure 4 Kriged maps of soil and plant parameters of Musica (Field 2)

4 Conclusions and recommendations

The aim of this study was to identify the major soil and crop properties impacting the potato crop yield in rainfed areas. Results of descriptive statistical analysis showed a significant variation within the fields and suggested that spatial variation in soil is the key factor in limiting potato yield. Coefficient of variation (CV) values showed medium to high variation of Nitrogen (N), Phosphorus (P), Potassium (K), Moisture Content (M.C), and Electrical Conductivity (E.C) within the fields. Therefore, understanding the factors responsible for lower yields in certain areas may require a better description of the variation in soil fertility. Geostatistical analysis revealed that soil properties and plant parameters from both fields were best fitted by Gaussian, spherical, exponential, and linear models. Geostatistical analyses showed moderate to strong variance for various soil parameters in the fields and were aligned with descriptive statistical results. The correlation analysis showed that potato yield had a significant relationship with N, P, K, NDVI, chlorophyll, and plant height. The yield map highlighted the significance of several features in defining potato production, and the field can be split into distinct productivity zones by considering easily quantifiable soil variables such as N, P, and K. This categorization can facilitate the implementation of variable-rate fertilization. The findings of this study could provide guidance for mitigating the excessive or insufficient use of fertilizers in order to maximize crop production, enhance agricultural productivity, and minimize potential environmental effects within potato cultivation areas. Further research is needed to address the impacts of high efficiency irrigation systems on soil and crop variations and delineating the management zones accordingly, since the soil and water dynamics could significantly influence the soil and crop spatial variations. The results of this study also highlighted the significance of different varietal traits and their relationship with soil spatial variability. For more precise application of fertilizers, potato varietal characteristics can also be taken into consideration for the delineation of management zones.

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