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Delineation of Management Zones for Site-Specific Management of Potato Crop in Some Areas in Western Nile Delta, Egypt

Omnia Hassan[1], Ayman F Abou-Hadid[2], Mohamed Z. El-Shinawy[2], Abdel-Aziz Belal [3] and **Ehab Hendawy[3]**

[1] *Institute of Postgraduate Studies and Agricultural Research in Arid Regions, Ain shams University, Cairo*
[2] *Horticulture Department, Faculty of Agriculture, Ain shams University, Cairo*
[3] *National Authority for Remote Sensing and Space Sciences, Cairo, Egypt*

SITE SPECIFIC is a farming management practice with the potential to address management challenges, this approach leverages precise and timely information on agricultural resources to observe and measure variability in field crops. Site -Specific management zones one of the most important pillars of precision agriculture. This technology is designed to enhance management practices by tailoring agricultural treatments to specific production zones within a field, thereby conserving resources, protecting the environment, and improving crop quality. This paper aims to developed spatial modeling for Site-Specific Management Zones based on soil and plant parameters. This work was done in Agrofood Company with an area approximately 18.69 hectares (ha) planted with potato crop (DITTA variety) in winter session 2019. 21 soil samples were taken before planting the crop and 21 plant samples were taken during the three growth stages based on the grid system, Soil and plant variability maps were produced based on Geostatistical Analysis of laboratory analyses of the samples. Spatial Model was developed to delineate site-specific management zones using ArcGIS 10.8, the input factors to developed this model were soil maps for Nitrogen (N), Phosphors (P), Potassium (K), pH, electrical conductivity (ECe), calcium carbonate ($CaCO_3$) and soil organic carbon (SOM), plant maps for NPK, Chlorophyll a, Chlorophyll b, Carotenoids (Car) yield data maps and normalized difference vegetation index (NDVI) to create Site -Specific management zones for the study area. The results showed that management zones were classified into two zones, which zone (I) with an area 10.94 Hectares and its was characterized by high crop yield and good soil parameters, on the other hand zone (II) with an area 7.75 hectares and it was characterized by low crop yield, low soil and plants parameters.

Keywords: Site-Specific Management, Western Nile Delta, Potato, Spatial Modeling.

1. Introduction

Precision agriculture (PA) is a farming management strategy designed to boost crop production and protect the environment through the use of precise and timely practices like accurate seeding, fertilizer application, irrigation, and pesticide use. This approach is especially advantageous for high-value crops, addressing management challenges by observing and measuring field crop variability and leveraging advanced information about agricultural resources. The ultimate goal of precision farming is to enhance grower revenue while ensuring sustainable agricultural practices (Cambouris et al., 2014; El-Sharkawy et al., 2013; Oliver et al., 2013; Blackmore et al., 1999).

The origins of precision agriculture date back to the mid-1980s. Initially, remote sensing applications in this field concentrated on sensors for soil organic matter, but they have since expanded to include a diverse array of technologies such as satellite, aerial, and handheld or tractor-mounted sensors. Over time, there has been significant advancement in both the spatial resolution and temporal frequency of aerial and satellite remote sensing imagery. Spatial resolution has improved from several hundred meters to sub-meter accuracy, allowing for more detailed assessment of soil and crop properties. Although this progress has increased demands on data storage and processing, it represents a substantial enhancement in remote sensing capabilities of yield limiting factors (Lowenberg, 2022; Teboh et al., 2012).

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*Corresponding author e-mail: Ehab.hendawy20@gmail.com
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The global food landscape is experiencing rapid transformation. With limited arable land resources, the pressure on existing productive land has reached unprecedented levels. Per capita arable land is projected to decrease from around 0.23 hectares in 2000 to approximately 0.15 hectares by 2050 (Campanhola & Pandey, 2018, Rao et al., 2010). At the same time, the global need for food is expected to increase by 1.5 to 2 times (Fischer, 2009). In response to the instability caused by fluctuating costs of agricultural inputs and farm product income, the adoption of modern technologies has become essential. These technologies aim to enhance crop yields, provide data for improved in-field management decisions focus on lowering chemical and fertilizer costs by ensuring more efficient application, facilitate accurate farm record-keeping, maximize profit margins and reduce environmental pollution. Essentially, precision farming is vital for optimizing both inputs and outputs on the farm (Friedman et al., 2024, Buick, 1997).

Potato is a critical staple crop in many countries and ranks fourth globally in production volume, following wheat, rice, and corn, with a total global output of about 360 million metric tons (Londhe, 2016). In 2018, Egypt emerged as the fifth-largest potato exporter, generating potato exports valued at 205 million US dollars. The country exported over 724,200 thousand tons of potatoes, mainly to Russia and the European Union, underscoring the crop's significant contribution to Egyptian vegetable exports (El-Basioni & Abd El-Kader,2024; EL-Basioni et al., 2022). To meet the increasing demand for potatoes and bolster global food security, enhancing productivity per unit area is essential. This requires the precise application of farming inputs, including site-specific seeding, fertilization, and crop protection products. However, despite these advancements, many potato growers continue to use the uniform rate seeding (URS) method, which is inadequate for managing the typical in-field soil variations found in most arable fields (Šarauskis et al., 2022).

This work is adoption of Precision Agriculture (PA) on potato Ditta variety due to their significant economic importance and their sensitivity to crop management practices and environmental conditions. This sensitivity, combined with the substantial costs associated with inputs, underscores the value of precision management for optimizing their production (Madison et al., 2019; Cambouris et al., 2014).

Site-specific management zones (SSMZs) are delineating a sub region within crop fields where specific yield-limiting factors consistently occur homogeneously (Méndez et al., 2019). Precision These zones are homogeneous with similar attributes. The success in terms of profitability and environmental protection of PA depends on agricultural practices are tailored to local conditions (Jalhoum et al., 2022; El-Sharkawy et al., 2013). The development of effective SSMZs is a key aim of Site-Specific Crop Management (SSCM), facilitating improved decisions related to various soil or crop properties such as soil fertility, plant parameters and crop yield (Paccioretti et al., 2020; Grunwald, 2009).

The challenge in delineating SSMZs stems from the complex interplay of edaphic (soil-related), anthropogenic (human-related), biological, and meteorological factors that influence crop yield. Despite this complexity, accurately defining effective soil zones can significantly enhance soil sampling and nutrient management practices. Establishing such zones is crucial, given the variability in the frequency and intensity of plant growth-limiting factors across a field (Fassa et al., 2022).

This work aimed to develope spatial modeling for Site-Specific Management Zones based on soil and plant parameters using remote sensing, GIS, field work and Laboratory analyses.

2. Materials and Methods

Figure 1 represents the material and methodological implemented in this studied and it could be viewed in three subsections: image interpretation, field survey and laboratory analyses, as well as site-specific management zones model.

2.1. Discerption of the study area

The study area is located in Western of Nile Delta, Egypt, which is located in Beheira Governorate Abu El Matamir District, between latitude 30° 39´ 52″, 30 40 10 N and longitude 29° 57´ 30″, 29° 57´ 54″ E.. The region is characterized by a Mediterranean climate, with hot, dry summers and mild, wet winters, which further contributes to its agricultural viability. Experiment held at Agrofood Company and the total area of the concerned area was approximately 18.69 ha. The farm is irrigated by center pivot system using fresh water and soil texture is sandy as shown in Fig 2.

2.2. Remote sensing Data

Three Sentinel-2 images were acquired on 16/2/2019, 3/3/2019 and 27/4/2019 within tile id (36RTV), with spatial resolution 10 meters, it were used to monitoring the potato crop growth in different three stages (vegetation growth, potato initiation and potato building) in the studied area. A shuttle radar topography mission (ALOS PALSAR) was used to created digital elevation model (DEM) with spatial resolution 12.5 m, as shown in Fig 2. NDVI were computed from Sentinel-2 images to display the condition of vegetation and the stages of crop growth. NDVI was computed as follows (Groten, 1993, Huete, 1988 and Rouse et al., 1974), Equation (1) reveals that this index is represents the crop healthy and density based on red and NIR reflectance.

$$\mathrm{NDVI}=\frac{(\rho NIR-\rho red)}{(\rho NIR+\rho red)} \qquad (1)$$

Where: NIR = Reflectance in the near infrared band, ρ red = Reflectance in the red band.

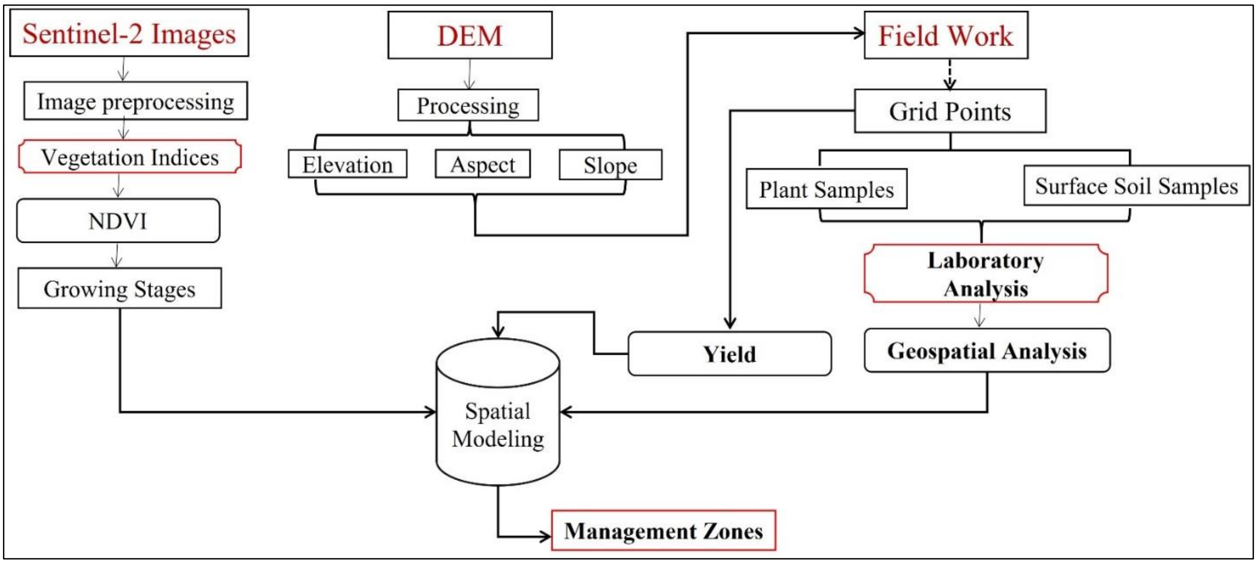


Fig. 1. Flowchart of material and methodological approach for the studied area.

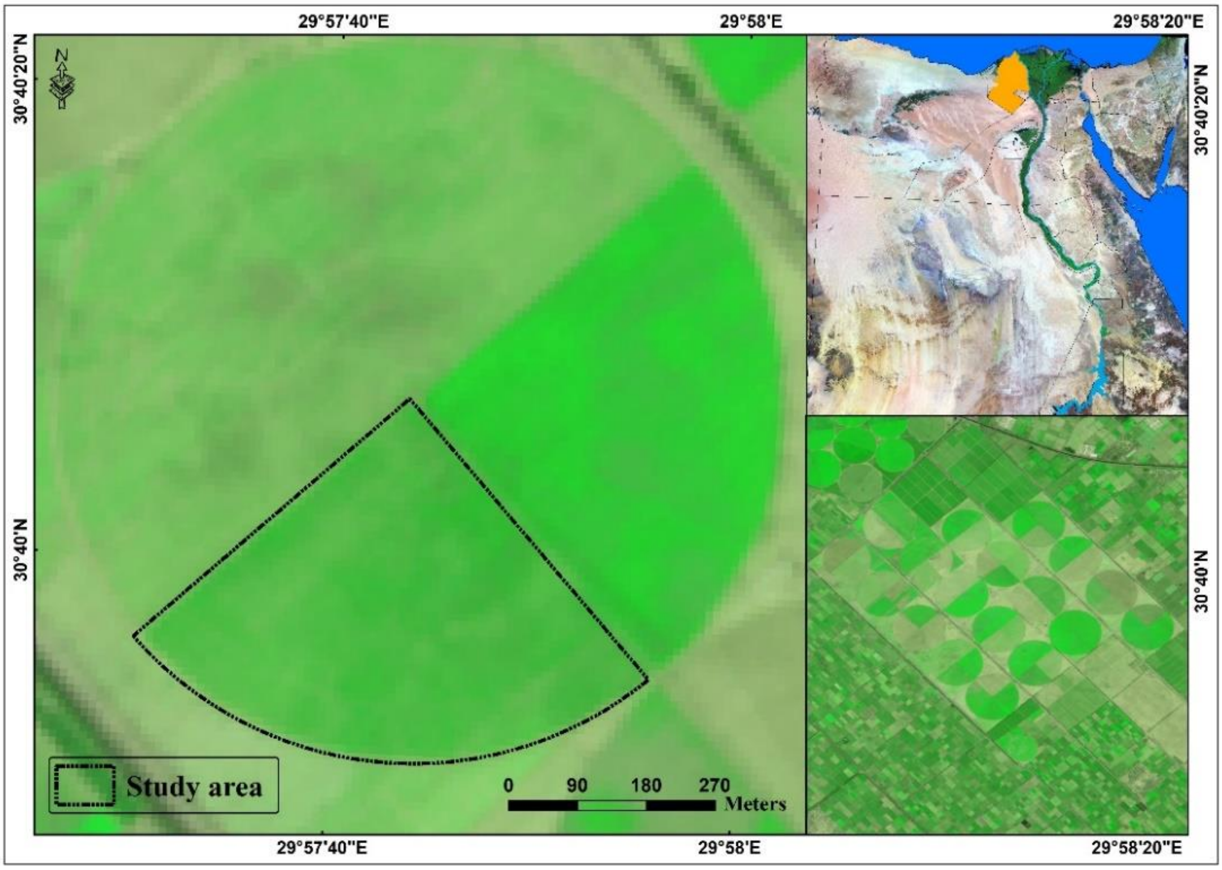


Fig. 2. Location map of the study area.

2.3. Field work and laboratory analyses

For a comprehensive analyses, 21 surface soil samples were collected throw grid system across the study area before planting activities. Physical and chemical analyses of these soil samples included, soil texture, pH, electrical conductivity content (ECe), calcium carbonate content (CaCO3), soil organic matter content (SOM), available nitrogen (N), phosphorus (P) and potassium (K), in accordance with guidelines (USDA, 2004). Additionally, 21 plant samples were meticulously collected from the study area using the grid system during three growth stages of the potato crop as shown in Fig 2. These plant samples were then subjected to detailed chemical laboratory analyses to determine the concentrations of essential nutrients, including N, P, K, and chll (a and b).

2.4. Geospatial for variability maps of soil and plant parameters

Utilizing the Inverse distance weighted (IDW) interpolation method, which determines the value of a specific cell by utilizing a linearly weighted combination of a collection of sample points (Aldabaa & Yousif, 2020; Shokr et al., 2022; El-Aziz et al., 2024) the findings acquired for the 21 surface soil samples and plant samples were used in the ArcGIS 10.8 environment to build soil and plant properties maps, according to (Philip & Watson, 1982) the following Equation (2).

$$\mathbf{Zp} = \sum_{I}^{n} = 1\ (Zi/di)/\ \sum_{i}^{n} = 1(d/di) \qquad \mathbf{(2)}$$

Where Zp = value predicted at point P, *Zi* = z value at the measured point i, and *di* is the= distance between point 0 and the point ‘i’.

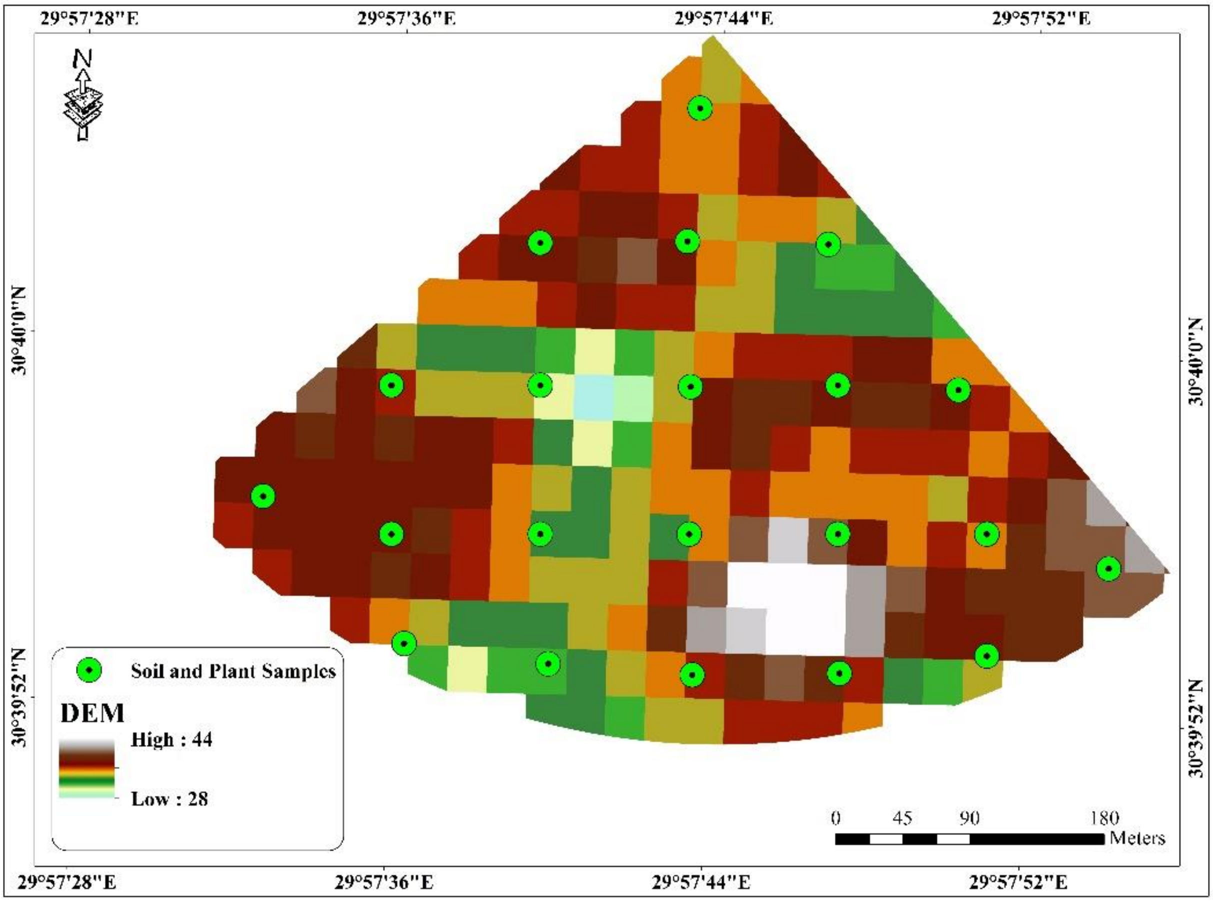


Fig. 3. Location of the collected soil and plant samples.

2.5. Spatial modeling for site specific management zones ($SSMZ_S$)

A model for spatial statistical prediction was developed using the ArcGIS environment's model builder tool to estimate the weighted average and (SSMZs) in the studied area. This model builder processes all incoming data in raster format to create thematic maps (Fig. 4). The initial step involves identifying and preparing the necessary datasets in raster format (moghanm et al.,2018). These inputs included (1) NDVI, (2) soil parameters (soil texture, pH, electrical conductivity (ECe), calcium carbonate content ($CaCO_3$), soil organic matter content (SOM), and available nitrogen (N), phosphorus (P), and potassium (K)), and (3) plant parameters from three stages of the potato crop's growth, including nitrogen (N), phosphorus (P), potassium (K), chlorophyll (a and b), carotene content, and crop yield.

The second step reclassifies all datasets, scaling each one to a consistent value range from 1 to 5, where more favorable attributes receive higher values. Finally, each input dataset was assigned a percentage impact according to its significance for soil and crop productivity, ensuring that the total influence across all datasets sums to 100%. The cell values in each dataset were multiplied by the respective dataset's weight, and the resulting values were summed to generate the final output dataset. This output dataset identified areas more suitable for soil productivity based on the combined impact of all the input

variables.

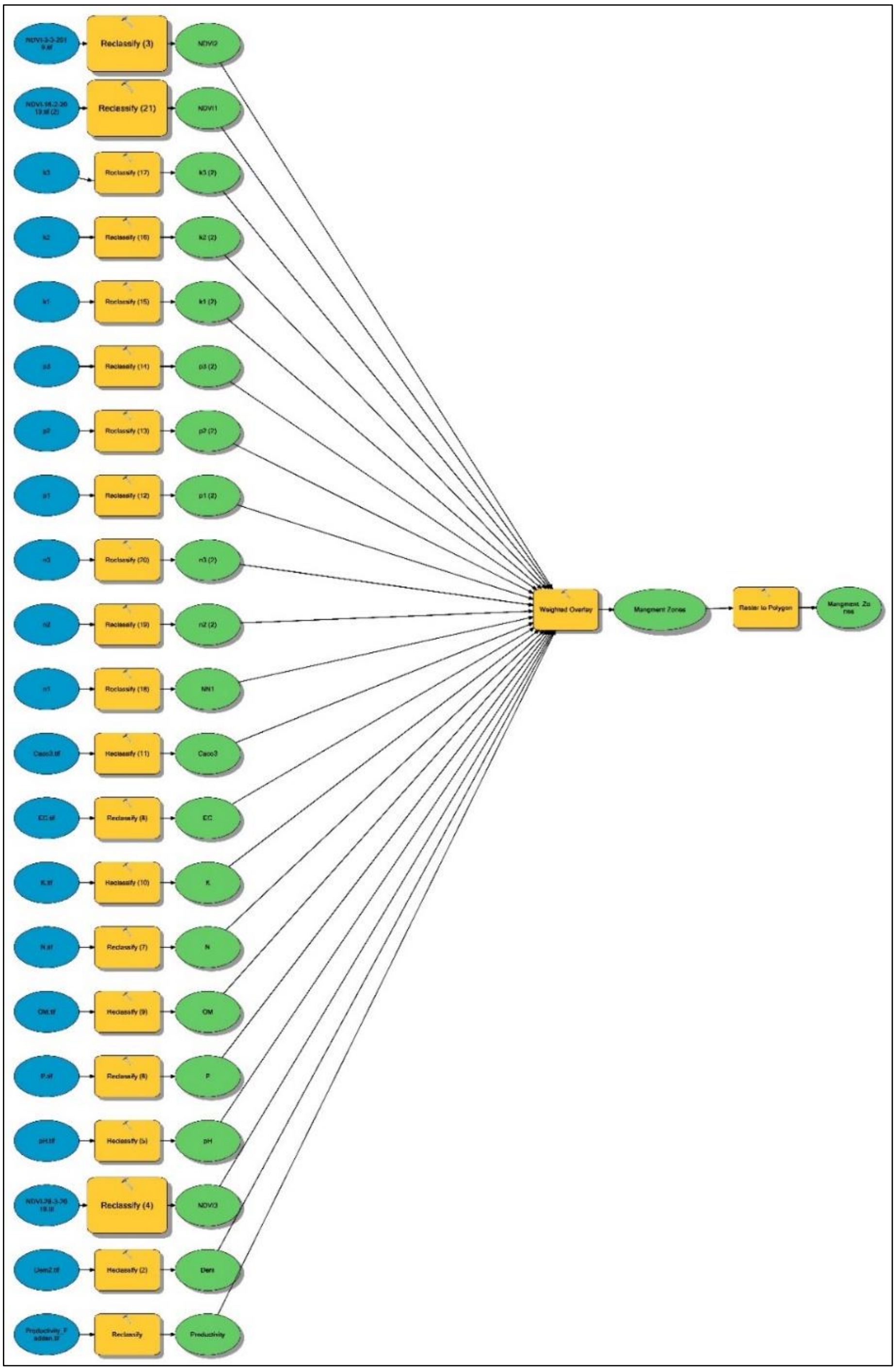


Fig. 4. Model Builder diagram for management zones based on plant and soil parameters.

3. Results

3.1. Geospatial analysis for Soil and plant variability

The statistical characteristics of the soil properties examined are summarized. The maximum values for pH, calcium carbonate content (ECe), calcium carbonate content ($CaCO_3$), soil organic matter content (SOM), N, P and K were found to be 8.7, 1.57 dS m^{-1}, 8.6 %, 0.47 %, 103 mg kg $^{-1}$, 38 mg kg $^{-1}$, and 101.3 mg kg $^{-1}$, respectively. In contrast, the minimum values recorded were 8.21, 0.7 dSm^{-1}, 5.17%, 0.08 %, 12.88 mg kg $^{-1}$, 22 mg kg $^{-1}$, and 33.47 mg kg $^{-1}$, respectively as shown in Figure 5 and 6. On other hand the statistical characteristics of plant in the first stage of N content in plant ranged from 5.3% to a 7.0%, P content varied between 0.3% and 0.4%, and K content was between 0.2% and 0.3%. Chll-A concentrations ranged from 0.261 mg/lg to 0.419 mg/lg, Chll-B from 0.129 mg/lg to 0.202 mg/lg, and Car levels were between 0.068 mg/lg and 0.104 mg/lg. In contrast, during the third stage, N content decreased to a range of 3.2% to 4.3%, P content in the same of the first stage, and K content increased, ranging from 3.4% to 5.8%. Chll-A levels decreased to 0.181 mg/lg to 0.311 mg/lg, Chll-B ranged from 0.081 mg/lg to 0.142 mg/lg, and Car levels were between 0.046 mg/lg and 0.078 mg/lg. This indicates a general decline in N, Chll-A, Chll-B, and Car from the first to the third growth stage, while K content increased, as depicted in table 1 and Figure 7, 8 and 9. The data were subsequently employed in ArcGIS utilizing the IDW interpolation technique. The resulted maps, illustrating spatial variability through the studied area, These maps provide a visual representation of the variability and distribution patterns of the plant properties analyzed.

Table 1. Statistical parameters of growing stages for plant.

Growing stages	N (%)		P (%)		K (%)		**Chlorophyll -A** (mg/1g)		**Chlorophyll -B** (mg/1g)		**Carotenoids** (mg/1g)	
	Max	Min	Max	Min	Max	Min.	Max.	Min.	Max.	Min.	Max.	Min.
First Stage	7.0	5.3	0.4	0.3	0.3	0.2	0.419	0.261	0.202	0.129	0.104	0.068
Second Stage	6.2	4.4	0.6	0.2	6.8	3.7	0.391	0.261	0.185	0.125	0.088	0.054
Third Stage	4.3	3.2	0.3	0.2	5.8	3.4	0.311	0.181	0.142	0.081	0.078	0.046

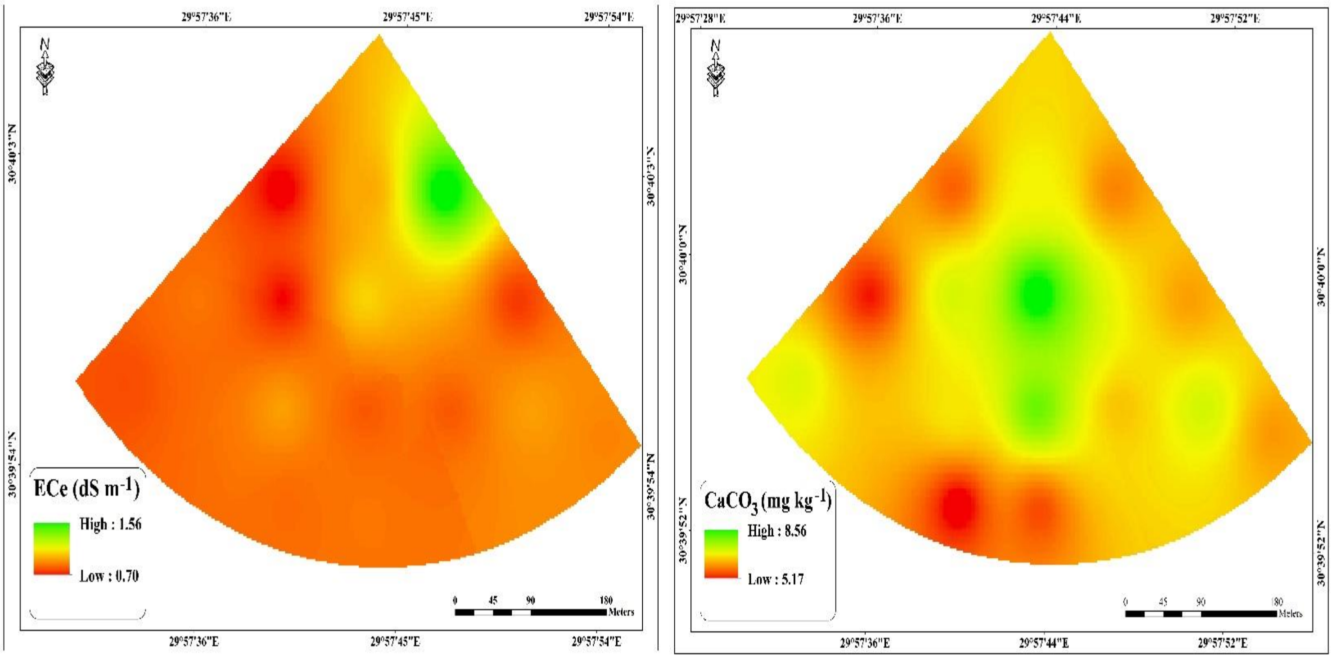


Fig. 5. Spatial distribution of soil ECe and $CaCO_3$ in study area.

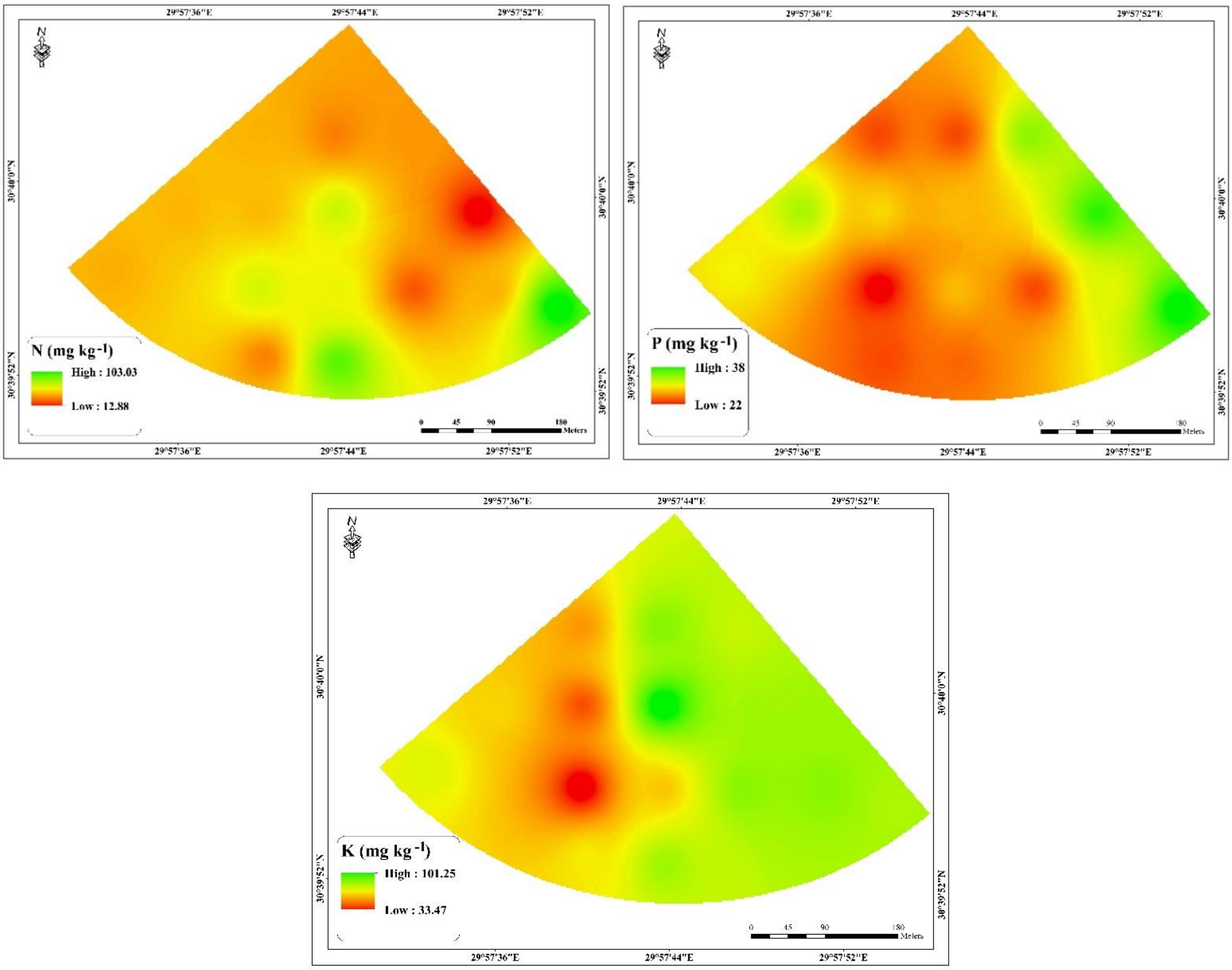
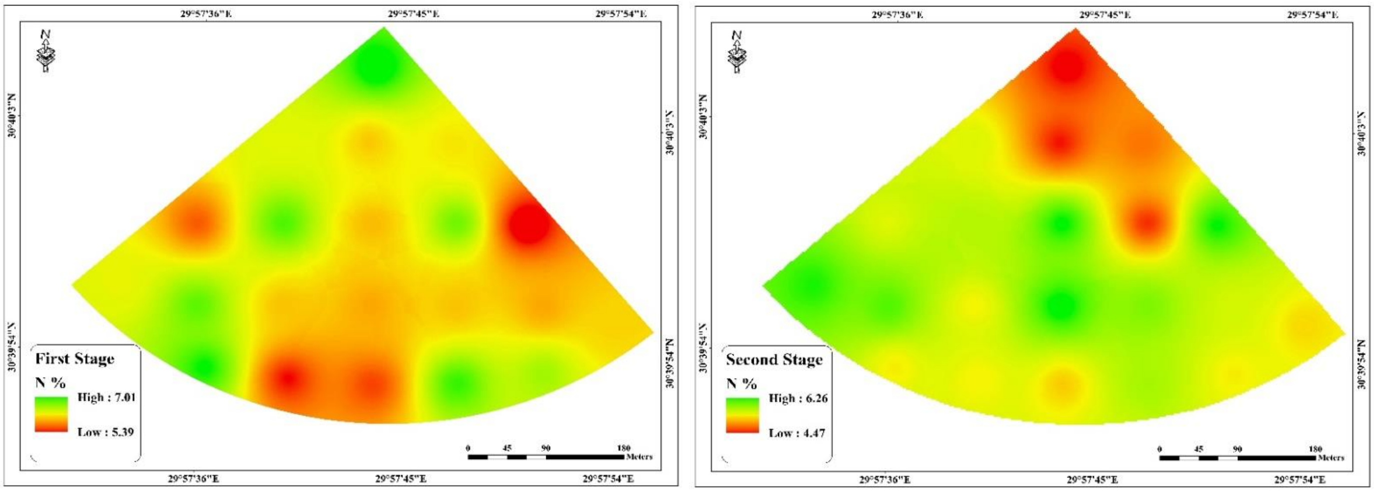


Fig. 6. Spatial distribution of soil N, P and K in study area



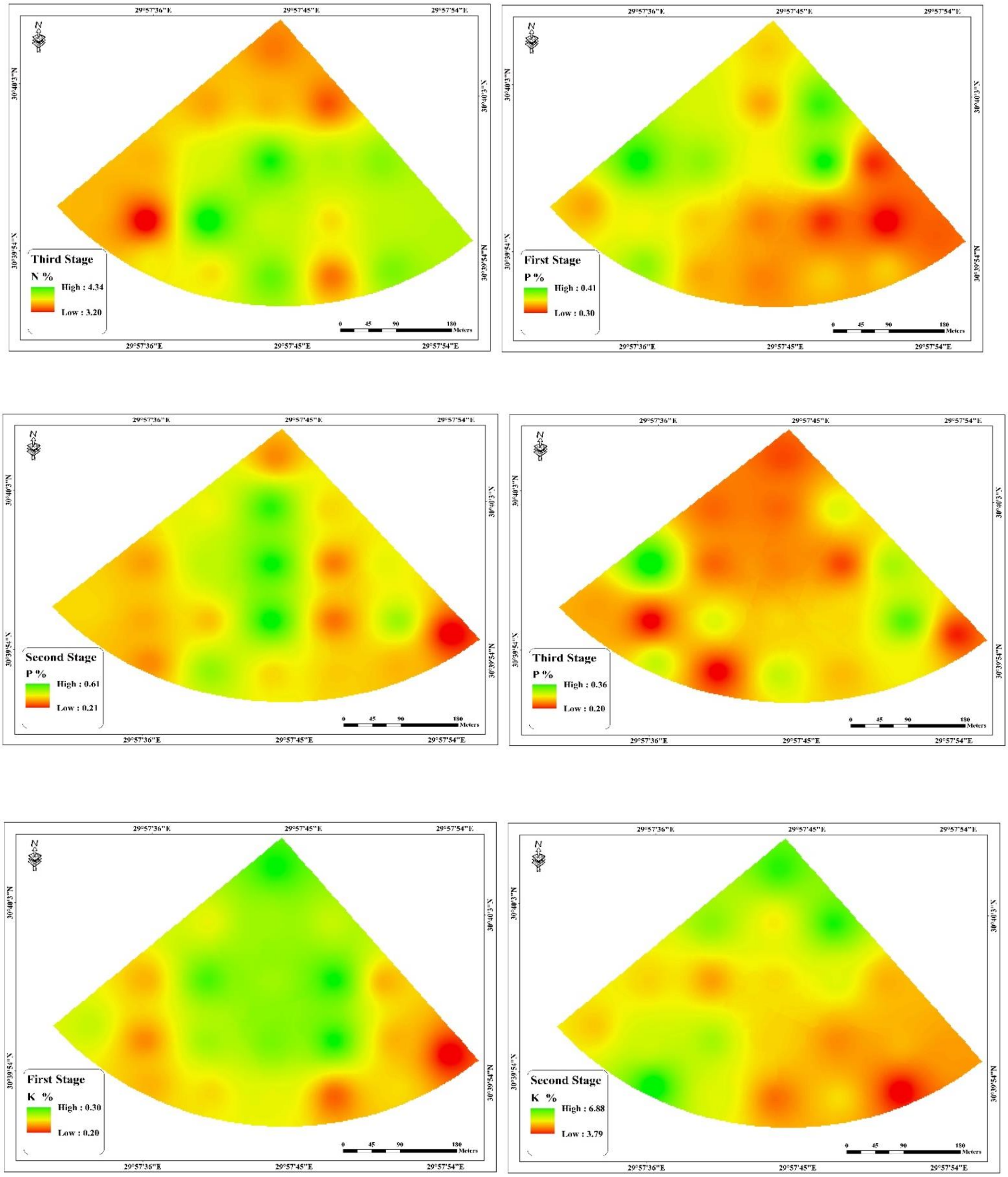


Fig. 7. Spatial distribution of N, P and K for growing stages.

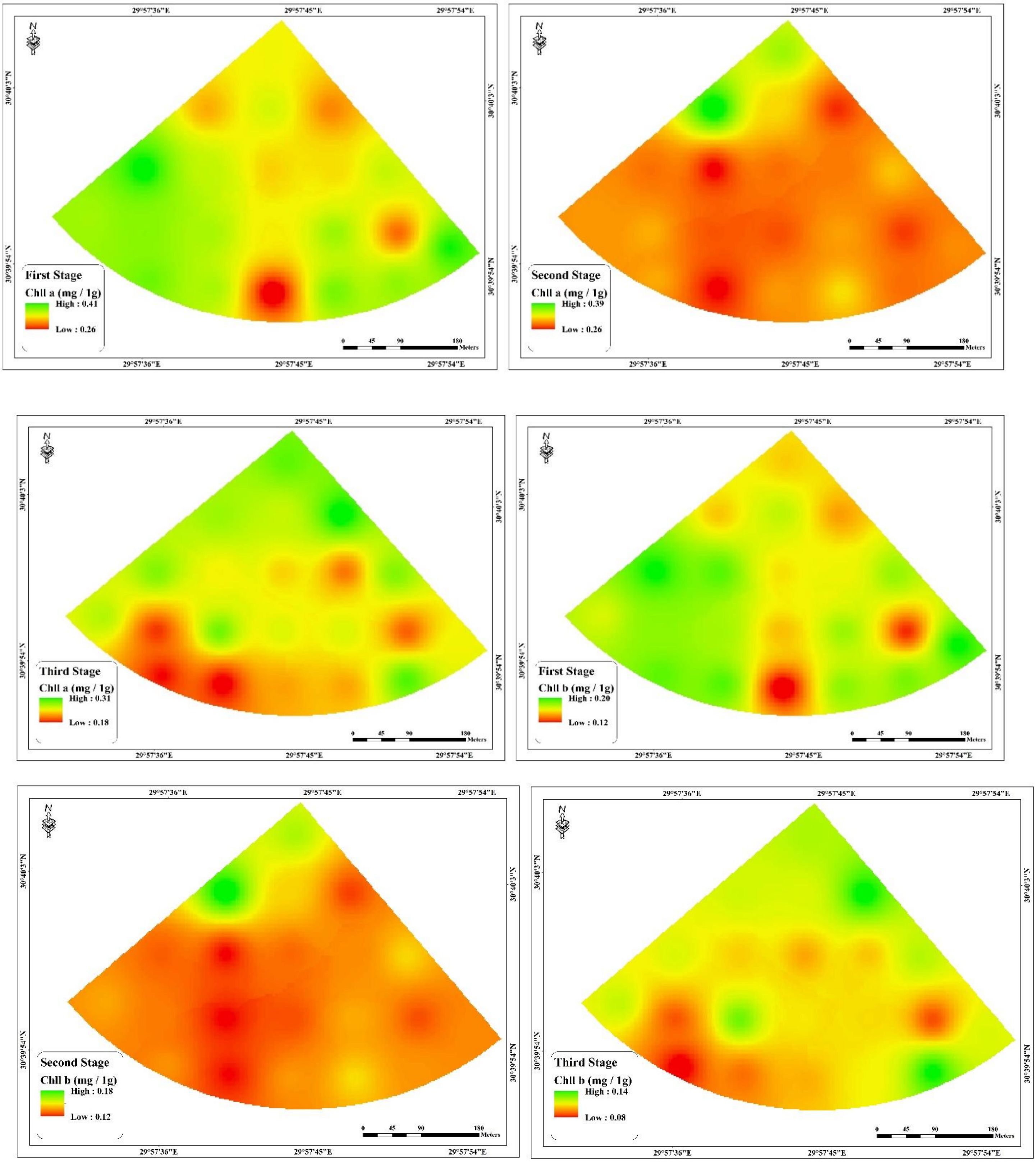


Fig. 8. Spatial distribution of Chlorophyll A and B for growing stages

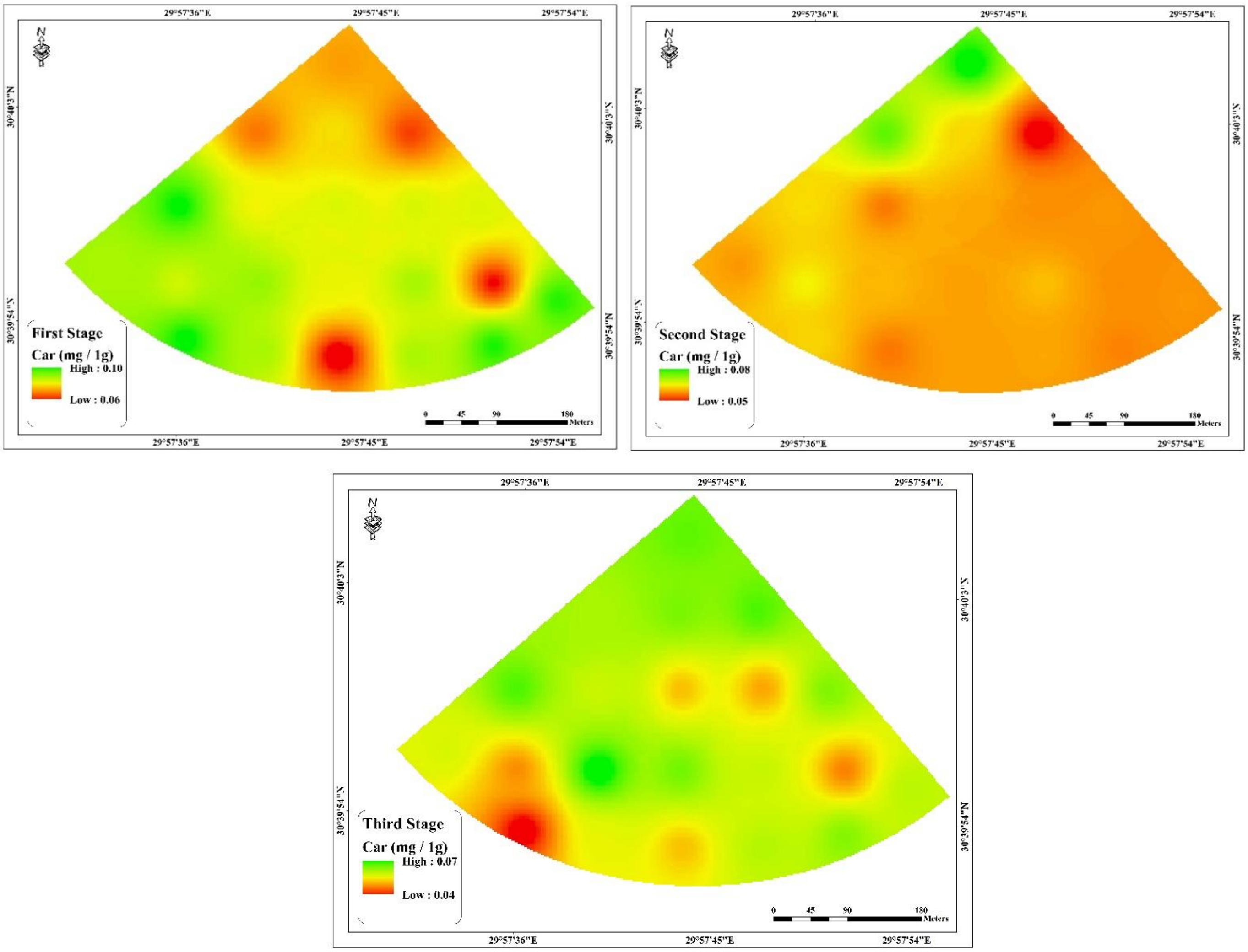


Fig. 9. Spatial distribution of Carotenoids (Car) for growing stages.

3.3. Estimation of NDVI from Sentinel-2 images

Sentinel-2 is instrumental in Earth observation, providing high-resolution multispectral imagery essential for monitoring various aspects of the Earth's surface. One of its key applications is the calculation of vegetation indices such as the NDVI. NDVI is widely recognized for its ability to quantify the greenness and health of vegetation based on satellite data, making it invaluable for assessing crop health, monitoring land cover changes, and evaluating ecosystem dynamics.

During the middle growth stage, NDVI showed a significant peak value of 0.6, indicative of vigorous vegetative growth. This stage is critical as it reflects optimal conditions for plant development, characterized by enhanced photosynthetic activity and biomass accumulation. Figure 10 visually represents this peak in NDVI, highlighting the spatial distribution of vegetation health throughout the study area.

The data derived from Sentinel-2 and NDVI analysis not only enhance our understanding of vegetation dynamics but also support informed decision-making in agriculture, forestry, and environmental management. These insights contribute to sustainable land use practices and facilitate responses to environmental changes at local and global scales.

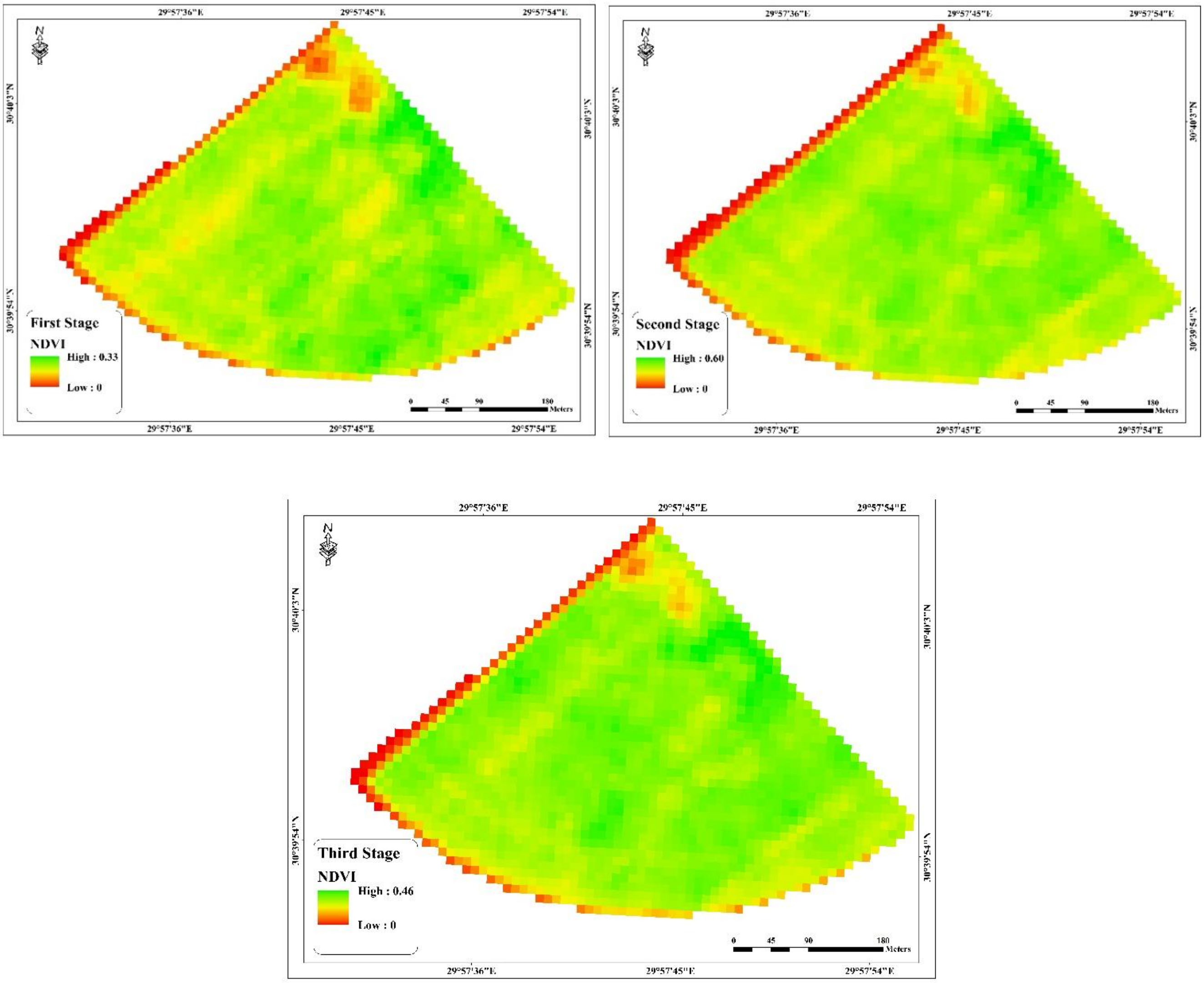


Fig. 10. NDVI for growing stages.

3.4. Yield mapping

The productivity map for the study area reveals significant spatial variability in potato yield across the analyzed region, depicted through a color gradient where green areas indicate higher productivity and red areas denote lower productivity. Yield values, measured in hectares, range from a low of 3520.2 (red) to a high of 7814.4 (green). The map shows scattered high-yield zones amidst lower-yield regions, reflecting a complex spatial distribution of potato productivity as shown in Figure 11.

Understanding this variability is crucial for targeted agricultural interventions. High productivity areas, benefiting from optimal conditions such as fertile soil and adequate water supply, can serve as benchmarks for best practices. In contrast, low productivity areas, possibly facing challenges like poor soil quality, water scarcity, or pest infestations, may require soil enhancement, improved water management, or the introduction of more resilient potato varieties. Intermediate productivity zones, shown in yellow and orange, represent regions where slight improvements in environmental conditions or agricultural practices could lead to significant yield increases. This map provides a comprehensive visual overview of potato yield variation, underscoring the need for localized strategies to enhance agricultural productivity throughout the region.

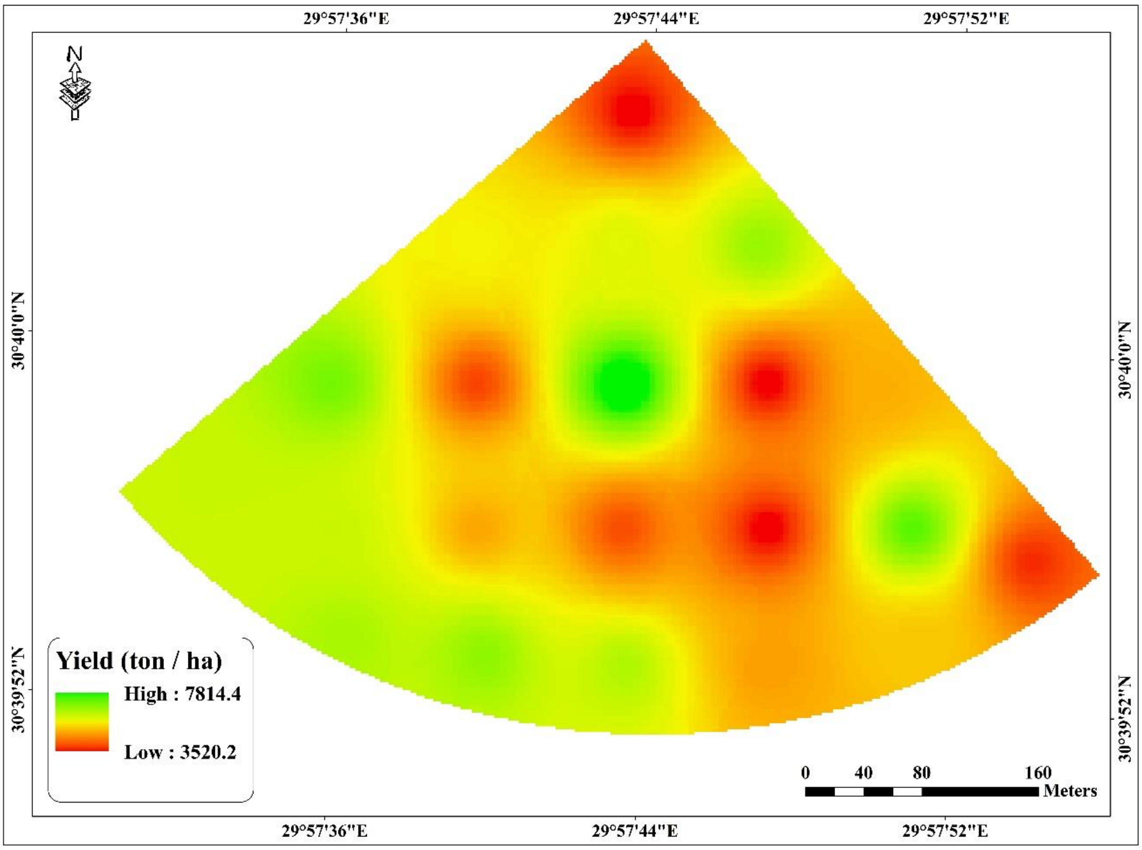


Fig. 11. Yield mapping in study area.

3.5. Spatial Modeling for site specific management zones

Currently, most crop models include information relevant to a certain place. Consequently, the creation of a biophysical crop model that is raster- or spatially-based will be very helpful in comprehending the various complexities involved in modeling big areas. A new document (a model window similar to the view, layout, and other document types already present in Arc-GIS) is added to Arc-GIS via Model Builder. Users develop models as process flow diagrams, as shown in figure 12, within the model document.

All input shape files, yield productive, soil variables (pH, ECe, $CaCO_3$, SOM, available N, P, and K), and plant variables (NPK content, Chlorophyll A, B and Carotenoids) were converted to discrete grid formats. These values are processed by the Model Builder to create prediction maps. Based on the impact of every variable in the model, each category in the grid themes utilized in the models was given a numerical value or influence value ranging from 0 to 100. By assigning a value to each category, one can convert its level of significance into a format that assigns low value to categories and vice versa. Each category was given these values using the Model Builder's Weight Overlay function.

After applying the model to the base layer of yield management and prioritizing only the yield within it, two management zones were produced Figure 10. The following is how the model was used on the layer of management zones:

Zone (I) High: It is excellent and appropriate. In instances where it has very little restrictions that need for solid ongoing management techniques. Its yield productivity is good. It encompasses approximately 10.94 ha, or 58.5 % of the entire region.

Zone (II) Low: It has one minor restriction in addition to good and appropriate qualities. It has had a moderate impact on low salinity, alkaline soils, and crop productivity. This zone encompasses around 7.75 ha, or 41.5 % of the entire region.

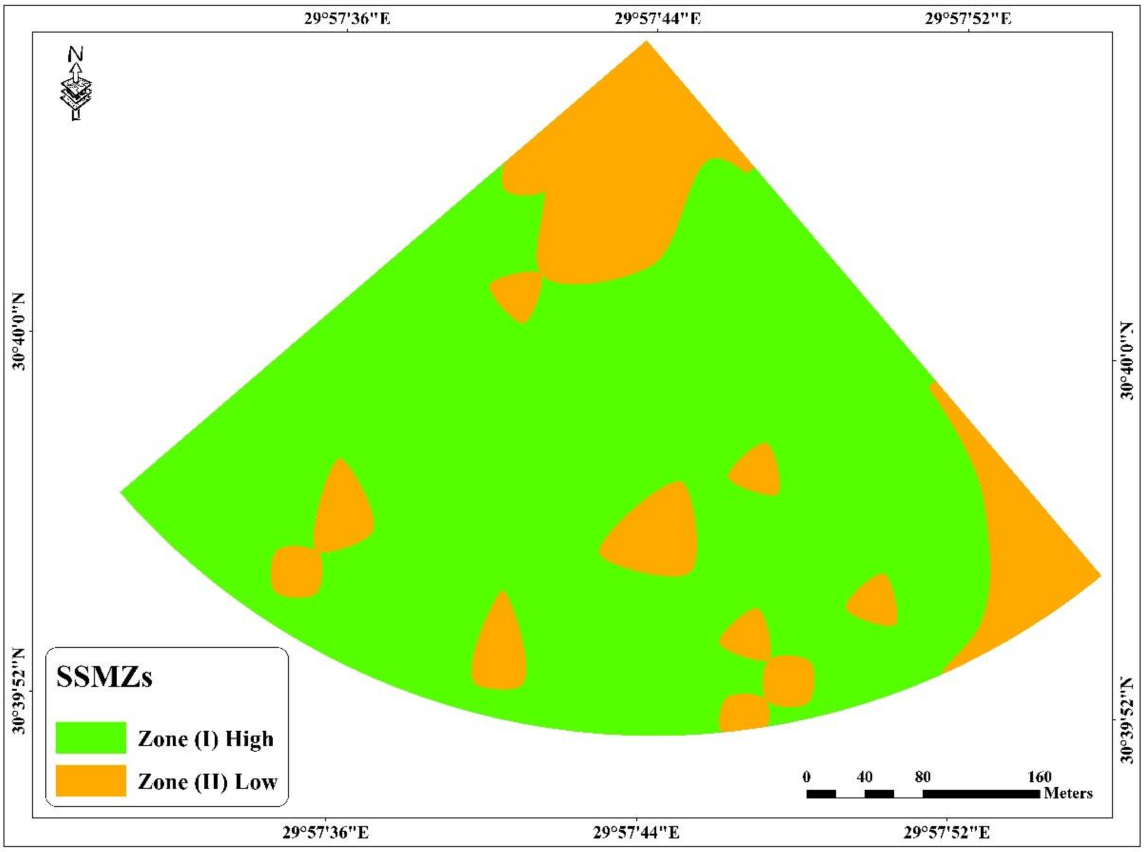


Fig. 12. Site specific management zones management zones map for the study area .

4. Discussion

Selecting the appropriate potato variety is vital for enhancing yield, quality, and disease resistance in potato farming. The Ditta variety is especially beneficial due to its adaptability, high yield, and resistance to diseases. Bradshaw, (2016) found that Ditta thrives across diverse climates and soil types, showing strong growth and productivity even in varying environmental conditions. Ditta's inherent resistance to common potato diseases, reduces the necessity for chemical treatments, thereby supporting more sustainable farming practices (Fry, 2008). Additionally, Ditta potatoes satisfy market demand with their desirable tuber shape, smooth skin, and firm flesh, enhancing their economic value and appeal to consumers (Amare, 2016). By selecting the Ditta variety, farmers can align with best agricultural practices, leveraging its high yield potential and resilience to boost productivity and profitability (Devaux et al., 2014).

The study area was chosen as for evaluating the Ditta potato variety due to its optimal agricultural conditions. The region's fertile alluvial soils, moderate Mediterranean climate, and well-established irrigation infrastructure from the Nile River create an ideal environment for potato cultivation, supporting robust growth and high yield potential of the Ditta variety (Roushdi, 2024).

The grid sampling technique involves collecting soil samples from uniformly distributed grids across a field. However, variability in soil types within each grid complicates soil characterization for crop management. Using smaller grids can reduce variability but requires more samples, increasing workload and costs. To address this, management zones were employed in this study to reduce sample numbers and analyses costs, as noted by Rains and Thomas (2009) in the context of precision farming expenses.

Management zones offer an alternative to grid sampling, where soil samples are taken from homogeneous zones rather than uniformly spaced grids (Searcy, 1997). These zones are defined using satellite-derived remote sensing data and NDVI classification, also exploring methods for classifying soil and plant properties.

A novel agricultural management approach involves using site-specific management zones. This method employs ArcGIS Spatial Analyst to incorporate soil variability, NDVI-based plant health, and crop yield. Soil and crop parameters, converted into grid files, involve rasterization by overlaying a grid on prediction maps with polygonal areas, sampling assigned values at regular intervals. Model specification includes defining and weighting factors for calibration, evaluating crop yield, NDVI, and soil-plant variables systematically. Zones, irregular polygonal areas with defined boundaries (ESRI, 1997; Blonn et al., 2001), reflect complex spatial interactions influencing crop yield. Precision farming tools like spatial models, remote sensing, and yield mapping are critical (Corwin, 2005; Kroot & Longsworth, 2005).

Defining site-specific management (SSM) zones in potato fields enables uniform soil management to enhance crop yield. This study utilized ArcGIS spatial modeling to integrate NDVI, soil and plant analyses, and standard crop yield, delineating management zones. Zone classification was based on cumulative yield performance, distinguishing zones needing varying management attention (Basnet et al., 2003). Whelan and McBratney (2003) described methods for delineating management zones based on yield, soil, and crop variations. Other approaches involve classifying soil fertility, plant parameters, or using standard deviation and frequency distribution for partitioning yield in soil maps or imagery. Management zones can also consider soil and field characteristics (Fridgen et al., 2000).

5. Conclusion

This paper identifies significant spatial variability within potato crop fields, underscoring the need for precision agricultural inputs. Geospatial analysis of soil and plant characteristics revealed that many of these parameters exhibit strong spatial dependencies. The results indicate that management zones (MZs) for site-specific management in potato fields can be effectively delineated based on four key factors: NDVI, yield, soil, and plant variability. The study emphasizes the importance of management zones, which provide a more effective approach to addressing site-specific spatial variability of soil and plant properties and optimizing potato yield across the farm. Implementing site-specific management zones (SSMZs) can help farmers and the private sector reduce production costs while increasing farm productivity and profitability. However, challenges arise when attempting to account for variability in soil and plant properties using new technologies to develop SSMZ maps. These services can be facilitated through commercial providers or governmental institutions, assisting farmers and the private sector in generating variable maps of plant, soil, and yield for their fields. These maps are essential for making informed decisions in precision agriculture management planning.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

Competing interests: The authors declare that they have no conflict of interest in the publication.

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Authors' contributions: Authors OH, AA, ME, AB and E H write the original draft and OH, AA, ME, AB and E H edit and finalize the manuscript. All authors read and agree for submission of manuscript to the journal.

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