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Research Article

Shallot distribution model under hydroclimatic extremes and soil physical properties in Sleman, Yogyakarta

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ABSTRACT

Global climate change significantly affects the agriculture sector, including reducing crop productivity and potential distribution through the frequency of hydrometeorological disasters. Despite its economic importance, limited research has explored the effects of such hydroclimatic extremes on shallot (Allium cepa var. *aggregatum) cultivation. This study aims to identify the soil-climate conditions, extreme events, variable contributions, and potential distribution areas of shallot in Sleman regency. The MaxEnt model was used herein to predict the suitable distribution area of shallot under hydroclimatic extremes and soil physical properties. The results show that shallot potential distribution in Sleman regency is governed by the synergistic action of climatic extremes and soil physical structure based on MaxEnt analysis. The dominance of Consecutive Dry Days (CDD) and soil moisture underscores the necessity of maintaining a stable soil–water equilibrium under intensifying hydroclimatic variability. These insights support the use of high-resolution soil and climate mapping to inform adaptive irrigation scheduling, precision tillage, and organic amendment strategies.*

Keywords: Climate change; extreme events, maximum entropy, soil properties, species distributions

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INTRODUCTION

Global climate change has become a phenomenon that is currently underway. Climate change has significant impacts on various sectors of human life, including agriculture (Sharma et al., 2021). This change is characterized by increasing rainfall variability as well as the frequency of extreme events and hydrometeorological disasters such as floods and drought (Zhao et al., 2020). Over the past decade, this region has faced challenges due to the rising frequency of hydrometeorological disasters triggered by extreme rainfall variability (Truong et al., 2022).

Extreme events and hydrometeorological disasters alter the current land suitability for certain crops and influence crop growth and production (Venkatappa et al., 2021). Assessing the impacts of extreme events and hydrometeorological disasters on crop production is a critical issue that must be addressed. Although the impact of extreme weather and hydrometeorological events has been studied in many crops, such as rice (Dulbari et al., 2017; Purwono et al., 2021), however, research on the effects of its disasters on shallot (*Allium cepa* var. *aggregatum*) remains relatively limited. Moreover, the consideration of land use change, land degradation, extreme events, and hydrometeorological disasters represents an important step in ensuring food security, through the quantitative analysis of ecological factors and a comprehensive assessment of the potential distribution of specific crops (Capitán-Moyano et al., 2025; Galanakis et al., 2025; Sopha et al., 2024).

Species Distribution Models (SDMs) are commonly used to predict the potential distribution of various crops (Miller, 2010). SDMs involve collecting species occurrence data, correlating them with soil-climatic variables, and generating distribution maps (Early et al., 2022). Based on occurrence data and the environmental variables affecting the target species, the relationship between them can be analyzed through statistical algorithms embedded in SDMs (Zhang & Wang, 2023). MaxEnt is currently the most widely used model (Phillips et al., 2006), which has the highest entropy and is closest to geographic uniformity, thereby ensuring prediction accuracy (Wang et al., 2024). MaxEnt has also demonstrated excellent predictive performance in comparative studies of various modeling approaches (Li et al., 2020; Qin et al., 2017).

Global bioclimatic changes are expected to have a major impact on shallot cultivation. To meet the growing global demand, identifying potential areas currently suitable for shallot cultivation has become an urgent issue in supporting global food security (Ali et al., 2023; Khalaf et al., 2024). Therefore, the objectives of this study are to: (1) identify the condition of soil, climate, and extreme events; (2) identify the main environmental factors affecting the geographic range; and (3) determine which regions are more suitable for shallot cultivation under prevailing soil and climatic conditions.

MATERIALS AND METHODS

The research was conducted in Sleman Regency, Special Region of Yogyakarta, which is located between 110° 33′ 00″ and 110° 13′ 00″ East Longitude, and 7° 34′ 51″ and 7° 47′ 30″ South Latitude as shown in Figure 1.

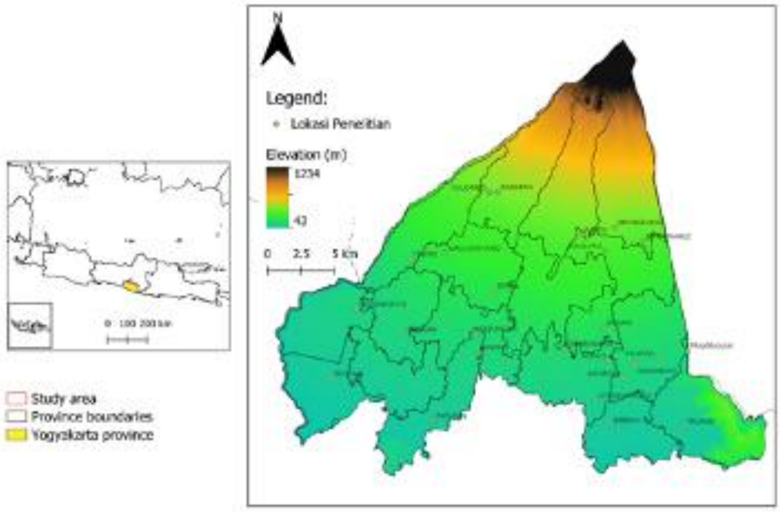

Figure 1. Study site

Sleman Regency has an area of approximately 574.82 km^2, which is divided into 17 districts and 86 villages/urban villages. The regency lies at an elevation ranging from 100 to 1,000 meters above sea level. Sleman Regency covers about 18.04% of the total area of the Special Region of Yogyakarta Province. This region has a tropical climate influenced by monsoonal rainfall patterns, resulting in considerable variation between the rainy and dry seasons. Shallot cultivation in Sleman is carried out by creating beds, using high-quality seeds, balanced fertilization, and regular watering. Average productivity reaches around 5-8 tons per hectare. With superior varieties and the right techniques, potential yields can be increased to around 9-10 tons per hectare (BPS-Statistic Indonesia)

In this study, we estimated distribution models using BPS-Statistics Indonesia (Badan Pusat Statistik) databases, collecting current distribution data for shallots in the Sleman Regency, Yogyakarta, Indonesia. For the SDM of shallot, we initially considered soil properties, climate conditions, and extreme events based on observation and Meteorology, Climatology, and Geophysics Agency (BMKG). Climate and extreme events analysis variables derived from monthly rainfall and temperature that define seasonal and yearly trends, which are important than the existence as a species in a place. All analyses, calculations, and transformations were performed in QGIS. To identify highly correlated variables (|r| > 0.74) and minimize the effects of multicollinearity and model overfitting, the Pearson correlation coefficient method was used.

The MaxEnt (Maximum Entropy) model is a machine-learning approach widely used for ecological niche and habitat suitability analysis, especially effective with presence-only data. It integrates environmental predictors, both categorical and continuous, to identify suitable habitats and crop distributions. In this study, MaxEnt version 3.4.4 was used to model shallot (*Allium cepa* var. *aggregatum*) suitability in Sleman Regency, Yogyakarta, Indonesia. Occurrence data and environmental variables (temperature, rainfall, soil type, land cover) were analyzed using optimized parameters (regularization multiplier = 3, 10,000 background points). Model performance was evaluated using ROC-AUC values, jackknife tests, and response curves, producing a robust, high-accuracy suitability map.

RESULTS AND DISCUSSION

Soil properties

Bulk density is a primary integrative index of soil compaction, texture, organic matter, and pore space arrangement (Robinson et al., 2025). Based on Figure 2, variations in soil bulk density across different regions can be observed. Areas with a soil bulk density of less than 1.2 g cm^{-3} are generally located in the southwestern part, covering an area of 102.3 km^2 or 17.5% of the total region. Regions with a bulk density below 1.2 g cm^{-3} tend to have looser soils, which may be attributed to a more porous soil structure. Meanwhile, areas with a bulk density ranging from 1.2 to 1.3 g cm^{-3} are distributed in the central part and several smaller surrounding areas. Regions indicated by light blue and dark blue colors represent areas with higher soil bulk density, ranging from 1.3 to 1.4 g cm^{-3} and exceeding 1.4 g cm^{-3}, respectively.

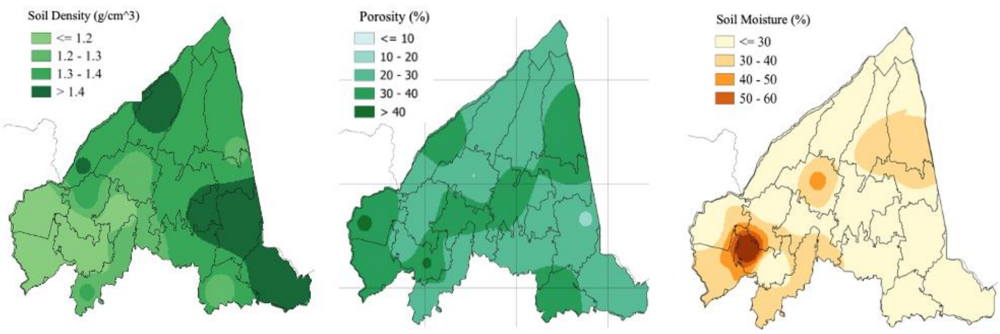

Figure 2. Soil properties in the study site

These areas are mostly found in the eastern and northwestern parts of Sleman Regency. It is noted that regions with a bulk density greater than 1.4 g cm^{-3} cover an area of 126.6 km^2 or 21.7% of the total region. Higher soil bulk density indicates denser soil characteristics and lower water content. In addition, porosity, being the complement of the solid fraction, is inherently related to density (i.e., porosity ≈ 1 – (ρ_bulk/ρ_particle), ignoring structural porosity). The map shows a range from very low (<10 %) to very high (>40 %) porosities. Regions with >40 % porosity are suggestive of well-structured, loosely packed soils with significant macro- and meso-pore volume. The spatial coincidence of high porosity with lower bulk density reinforces this interpretation.

The soil moisture distribution map of Sleman Regency shows significant variation across different areas. In general, regions with higher soil moisture content (>60%) are located in the northwestern part, covering an area of 6.7 km^2 or 1.2% of the total region. Meanwhile, areas with lower soil moisture content (<30%) are more dominant in Sleman Regency, covering an area of 404.4 km^2 or 69.3% of the total region. Previous study shows that a strong linear correlation ($r \approx 0.96$) exists between total porosity and soil moisture in field conditions, emphasizing that porosity governs soil water storage capacity by determining the ratio of macro- and micropores (Ghosh et al., 2022; Meng et al., 2020). Our findings are consistent with this relationship: the observed co-location of high-porosity zones with elevated soil moisture (50–60%) indicates enhanced infiltration and water retention, whereas compacted, low-porosity zones exhibit relatively depleted moisture (≤30%). This pattern reflects the well-known inverse relationship between bulk density and porosity, a fundamental driver of soil hydraulic behavior (Kravchenko & Guber, 2017). Based on the soil conditions described above, which generally have low soil density and porosity, thereby maintaining groundwater availability at 40%, shallot cultivation is suitable for development in the Sleman region, provided that proper drainage and aeration are taken into consideration (Sopha et al., 2024).

Climate and extreme events

Based on the spatial distribution map of total rainfall, as shown in Figure 3, the rainfall pattern across Sleman Regency can be clearly observed. The northwestern part of the region exhibits the highest total rainfall, covering approximately 30.26 km^2, while the southeastern area records the lowest total rainfall, around 37.72 km^2. This spatial contrast is likely influenced by topographical variation, where orographic effects cause greater cloud formation and precipitation in the northern and higher-elevation zones. The spatial distribution of annual extreme rainfall (R95PTOT) shown in Figure 3 further illustrates substantial spatial variability across the study area. The dark blue region in the northwest (100.8 km^2) represents zones with higher extreme rainfall, indicating more frequent events exceeding the 95th percentile threshold of annual precipitation. Conversely, green-colored regions show lower intensity of extreme rainfall, reflecting more stable or less variable precipitation regimes.

The implications of such spatial rainfall extremes on soil physical properties are significant. Areas experiencing high rainfall extremes are more prone to soil erosion, especially on sloped terrain or in soils with light texture. In highly porous soils, intense infiltration can prolong water saturation, increasing the risk of waterlogging that adversely affects rice growth (Pais et al., 2022). Conversely, regions with low extreme rainfall are more susceptible to drought, particularly where soil water-holding capacity is limited. The distribution of more intense rainfall events based on R99PTOT reveals a similar spatial trend, with the northwestern region (37 km^2) showing the highest rainfall intensity, while the southern and eastern parts record lower values. Areas with high rainfall extremes often experience prolonged saturation, especially in soils with low porosity and limited infiltration capacity, leading to poor aeration and reduced rice productivity. In contrast, sandy soils with high porosity may better absorb intense rainfall but face elevated erosion risks (Furtak & Wolińska, 2023).

Additionally, the spatial distribution of consecutive wet days (CWD) is presented in Figure 3. Most areas show relatively uniform values, ranging from 20 to 21 days annually, though some northwestern areas (46.7 km^2) record fewer wet days. High CWD values indicate more consecutive rainy days, increasing the likelihood of prolonged soil saturation, whereas low CWD values suggest infrequent rainfall and longer dry phases (Wu et al., 2021). From a soil physical perspective, areas with high CWD are more susceptible to waterlogging, especially in low-porosity soils with poor drainage, which can hinder aeration and root development in rice. Conversely, low-CWD regions face extended dry periods that may reduce soil moisture content. Soils with high clay content can retain water longer (Lal, 2020), mitigating drought risk, while sandy soils lose moisture rapidly through evaporation and percolation. In such contexts, soils with greater water-holding capacity help sustain soil moisture and reduce irrigation requirements (Abdallah et al., 2021). Conversely, areas with long CDD (>57 days) highlight pronounced dry spells that could trigger water-stress for vegetation, increased fire risk, or agricultural drought (Zaki et al., 2020). Extreme events will certainly have an impact on shallot productivity, as was the case in 2018 when a prolonged drought and El Niño caused shallot production to decline to 149 quintals from the normal level of between 250 and 300 quintals.

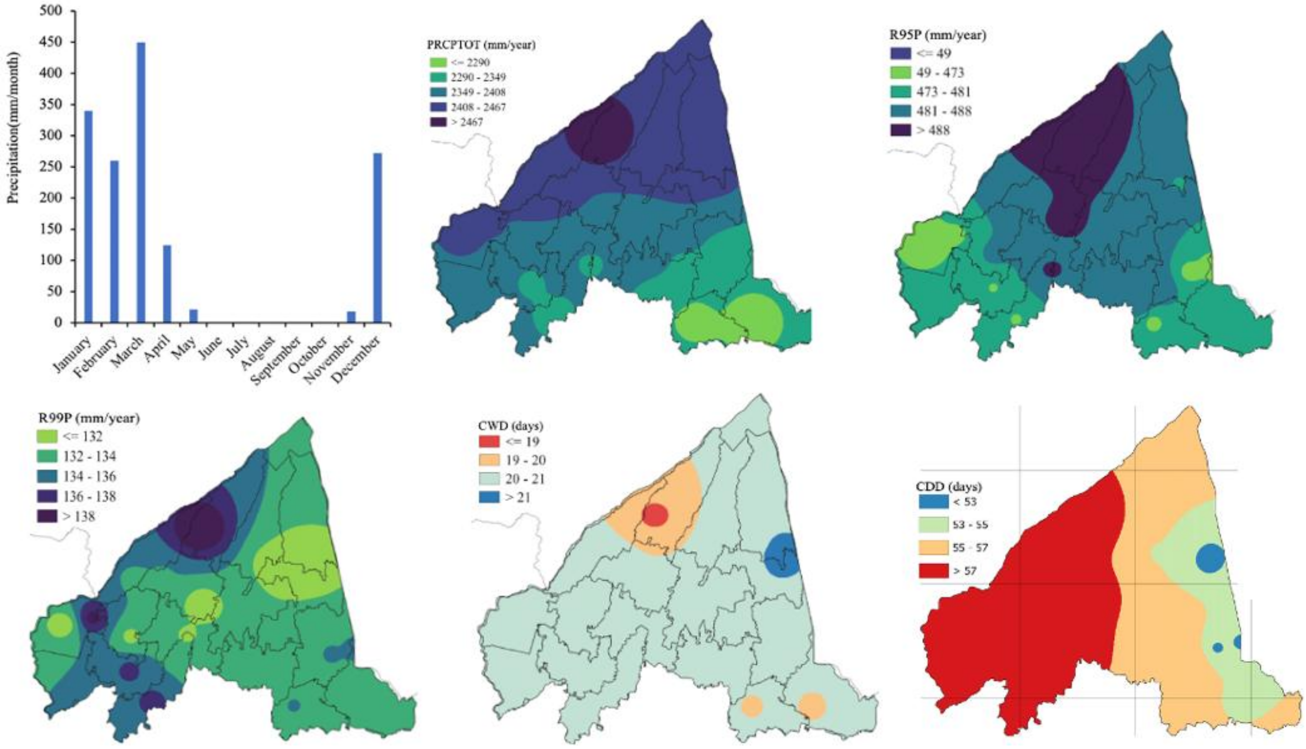

Figure 3. Precipitation trends and extreme events

Maximum entropy analysis

The Maximum Entropy (MaxEnt) model identified a distinct hierarchy of environmental variables influencing the spatial suitability of *Allium cepa* var. *aggregatum* across the study area. The results showed that the model produced AUC (Area Under the Curve) values ranging from 0.622 to 0.882. In the context of species distribution modeling, AUC values between 0.6 and 0.7 are generally categorized as moderate performance, particularly when presence-only data are limited or when environmental variables exhibit high levels of correlation. Nevertheless, AUC values greater than 0.6 are still considered suitable for exploratory purposes or initial habitat suitability mapping, especially in studies of cultivated crops that are influenced by numerous anthropogenic factors (Fitzgibbon et al., 2022; Li et al., 2023). Based on the percent contribution and permutation importance as shown in Table 1, climate-related factors, particularly consecutive dry days (CDD), and soil moisture, emerged as the most influential predictors. CDD accounted for 80.1% of the total percent contribution, followed by soil moisture (52%), soil density (33%), and total annual precipitation (PRCPTOT, 19.5%).

In such areas, infiltration capacity and capillary rise synergistically sustain favorable root-zone moisture, buffering crops against short-term droughts. Conversely, soils characterized by high density (>1.4 g cm^{-3}) often exhibit limited pore connectivity, reduced infiltration, and accelerated surface runoff, which collectively restrict water availability and increase desiccation risk (Joos & de Tender, 2022). The spatial juxtaposition of these zones—looser, high-porosity soils versus compacted, low-porosity soils—therefore delineates distinct hydrological and ecological niches that govern shallot viability (Finch-Savage & Bassel, 2016).

Table 1. Primary contribution percentage and permutation importance of the soil properties, extreme events, and climate variables impacting shallot distribution (%)

Variable	Percent contribution	Permutation importance
CDD	80.1	16.8
Soil moisture	52	51.4
Soil density	33	34.8
PRCPTOT	19.5	38.9
R95P	0.3	44.3
R99P	0	0
Porosity	0	0

The remaining precipitation intensity indices (R95P and R99P) and soil porosity contributed negligibly (<1%), suggesting their relatively minor role in determining shallot habitat suitability. Moreover, the jackknife results (Figure 4) show that when CDD was used in isolation, it generated the highest regularized training gain, suggesting that the model gained substantial predictive power solely from this variable. Conversely, removing CDD from the model caused a marked reduction in gain, confirming that dry spell persistence is the primary limiting factor for shallot cultivation in the region. The jackknife test reinforces this pattern: exclusion of soil moisture led to a substantial reduction in model gain, confirming that soil water retention capacity serves as a key buffering factor mitigating the effects of prolonged dry spells. Consequently, spatial regions maintaining moderate moisture levels during the driest months appear as high-probability zones for shallot cultivation.

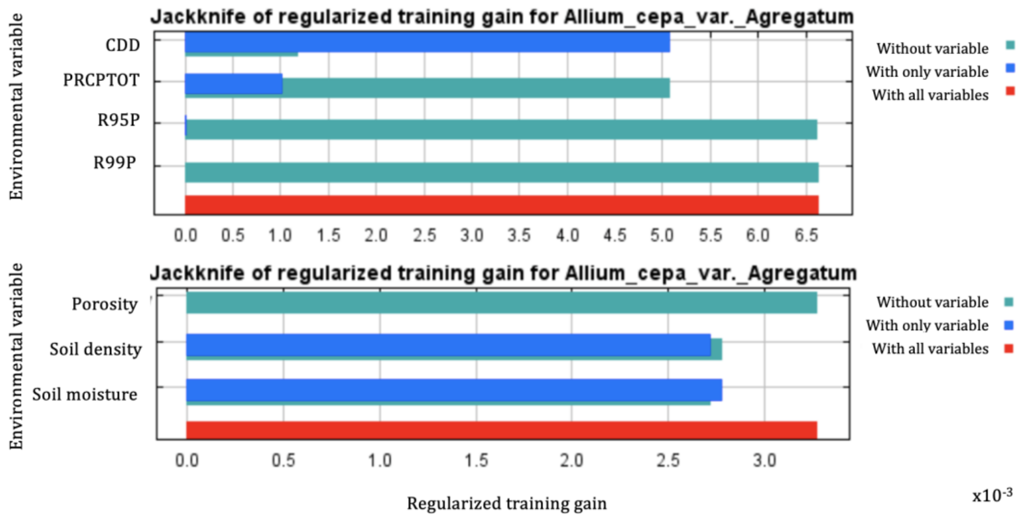

Figure 4. Results of the Jackknife AUC test of the MaxEnt model for evaluating the relative importance of soil, climate, and extreme events variables for shallot cultivations

The jackknife test of regularized training gain offers a robust validation of individual variable importance. When variables were used independently, CDD and soil moisture produced the highest training gains, underscoring their individual explanatory strength. Conversely, exclusion of these variables significantly reduced model gain, confirming their indispensable role in defining shallot suitability.

The Maximum Entropy (MaxEnt) model outputs shown in Figure 5 illustrate the predicted habitat suitability of *Allium cepa* var. *aggregatum* across the study region. The probability distribution (ranging from 0.0 to 0.92) demonstrates spatial variation in suitability, with several distinct high-suitability hotspots concentrated in the central and southern regions. These areas correspond to locations with moderate soil density, optimal soil moisture, and favorable climatic regimes characterized by balanced precipitation and moderate cumulative dry days (CDD).

The model performance, evaluated through percent contribution and permutation importance (Table 1), indicates that climatic and edaphic parameters jointly shape shallot distribution. CDD (80.1%) and soil moisture (52%) were the most influential predictors, highlighting that *Allium cepa* var. *aggregatum* exhibits strong sensitivity to drought stress and water availability. The ROC-AUC value is used to measure the model's ability to distinguish between suitable and unsuitable locations for crops. If the AUC value in the MaxEnt model for shallots in Sleman is in the range of 0.6–0.88, then the model has good to very good accuracy, making it reliable for predicting land suitability. Thus, the prediction of shallot suitability distribution from this model can be trusted as a basis for cultivation planning and production area development. However, further research is needed, and the dynamics of environmental conditions such as climate and extreme events must be continuously monitored. The use of real-time monitoring data, by adding projections of extreme events, can be a good input for a decision support system to support crop productivity.

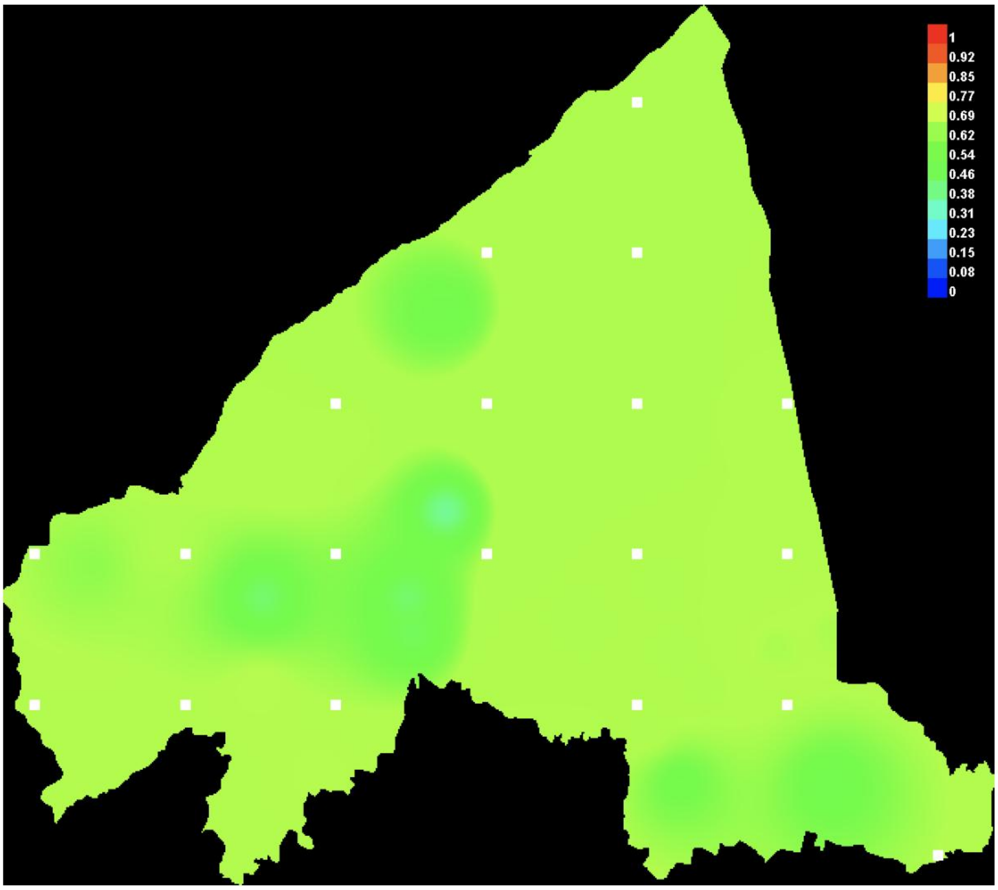

Figure 5. The suitable area for shallot cultivation under soil-climate conditions

CONCLUSIONS

This study concludes that the spatial suitability of *Allium cepa* var. *aggregatum* (shallot) in Sleman Regency is primarily shaped by the combined influence of soil physical properties and hydroclimatic extremes. The MaxEnt model identified consecutive dry days (CDD) and soil moisture as the most influential variables controlling shallot distribution, revealing a strong soil–climate coupling. Extended dry periods significantly reduce shallot suitability, while adequate soil moisture (35–50%) supports optimal physiological performance and yield stability. Moderate soil bulk density (1.1–1.3 g cm^{-3}) enhances mechanical stability and water retention, whereas higher densities (>1.4 g cm^{-3}) restrict infiltration and increase drought risk. Although total annual rainfall and extreme precipitation events exerted secondary effects, their irregular distribution intensifies soil moisture fluctuations and stress conditions for shallow-rooted crops. The model's robust predictive accuracy (AUC = 0.622–0.882) confirms its reliability for agroecological zoning. Suitable areas, particularly in Kalasan and Prambanan, display balanced interactions between soil structure, porosity, and rainfall–dry spell dynamics. In contrast, drought-prone and flood-susceptible zones require site-specific adaptation measures such as supplemental irrigation, improved drainage, and optimized planting schedules. Overall, the integrated MaxEnt approach highlights that managing soil–water balance under increasing climate variability is essential to sustain shallot productivity and regional food security.

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