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Agricultural land optimization to supports sustainable shallot production on fluvial and structural landforms

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ABSTRACT

As shalot land decreases annually, it is crucial to take deliberate measures to boost production on current agricultural land. This study aimed to formulate a strategy for optimizing shallot agricultural land in two different landscapes in the tropics. A rapid scan approach was used to identify land characteristics, while linear regression analysis was used to identify land limiting factors on shallot productivity. Literature and DPSIR (Driving Forces, Pressures, States, Impacts, and Responses) were used to develop a land optimization strategy. Typically, the pedogeomorphology analysis showed that both landscapes studied had initial alkaline conditions. Specifically, the fluvial landscape experienced a drastic acidification range (pH 4.55-7.39) due to anthropogenic factors, while the structural landscape maintained its alkaline conditions (pH 6.58-7.74). The regression results showed that the anthropogenic modifications made soil pH and EC limiting factors for productivity ($R^2 = 0.61$ for pH; $R^2 = 0.68$ for EC). Optimal results were consistently at pH conditions approaching neutral, with EC approaching one dS/m. Finally, land and water management is the best response to land optimization, accompanied by policies favoring local farmers. These findings can be used in policy-making to manage shallot agricultural land in other tropical areas.

Keyword: agricultural, land optimization, sustainable production, shallot, fluvial, structural.

INTRODUCTION

Indonesia's food security and economic stability continually face complex challenges, particularly in producing vital commodities like shallots. Over the past decade, national shallot production strategies have predominantly focused on expanding harvested areas rather than improving productivity (Sutardi et al., 2022; Ministry of Agriculture, 2022), creating significant pressure on available agricultural land resources. This approach has enhanced productivity but also caused unsustainable land management and agriculture sector vulnerability.

Another primary concern is the accelerated loss of agricultural land brought on by urbanization, land use conversion, and competition with other commodities (Warlina & Pradana, 2021; Setiawan et al., 2022; Pramesti, 2023). Recent data indicate a 4.93% reduction in shallot harvesting area, equivalent to 9.95 thousand hectares by 2022 (Ministry of Agriculture, 2022). This trend is particularly alarming given that Indonesia's average shallot productivity remains at 10.05 tons/ha, significantly below the optimal potential of 20 tons/ha (Widodo & Rembulan, 2010; Aldila et al., 2015; Bawarta et al., 2022). Systemic errors in land usage and farming methods cause the yield gap, which prevents the agriculture industry from meeting rising demand.

Shallot is grown in fluvial and structural landscapes across Indonesia. These landscapes exhibit distinct pedological characteristics resulting from complex interactions between parent materials, topography, and environmental factors (Sartohadi, 2011; Chai et al., 2015; Elwan, 2023). Fluvial landscapes, characterized by alluvial deposits and varying drainage patterns, present different cultivation challenges compared to structural landscapes with distinct geological formations and slope characteristics (Notebaert et al., 2011; Barančoková et al., 2017; Maulana et al., 2017; Kabala., 2022). While previous studies have extensively documented shallot production challenges (Sembiring et al., 2021; Fitriani et al., 2022; Adiyoga, 2023; Sari et al., 2023), limited attention has been given to the relationship between pedogeomorphological characteristics and crop productivity. Furthermore, the interplay between land attributes and farming practices has to be clarified despite its importance in influencing agricultural productivity.

Multiple approaches are used to formulate strategies to address environmental issues. The DPSIR (Driver, Pressure, State, Impact, Response) approach is one of the most commonly used approaches. DPSIR is a framework used to identify cause-and-effect relationships and formulate solutions to the problems studied (EEA, 2000). DPSIR has proven effective in identifying and solving problems related to agricultural or environmental issues (Gobin et al., 2004; Chen et al., 2024; Wardhani et al., 2024). Referring to the effectiveness of DPSIR in identifying agricultural issues, this study adopts the DPSIR framework to formulate strategies for optimizing shallot production.

Due to the issues' complexity, a comprehensive systems approach is required to enhance shallot output. This approach involves analyzing both geomorphological factors and agricultural practices. Finally, this study explores land-use constraints and suggests optimization solutions to enhance sustainable shallot cultivation. Furthermore, this strategy is anticipated to substantially aid in closing the disparity between potential productivity and its actualization in the sector while providing tangible solutions to enhance food security.

MATERIAL AND METHODS

Study site

The study was conducted in Bantul Regency, Indonesia. Specifically, the locations studied were Parangtritis, Kretek (-8.0057635 S and 110.3094543 E) and Selopamioro, Imogiri (-7.9623869 S and 110.4123023 E). The two locations are centers of shallot farming that have different landform typologies. Parangtritis was formed from the origin of the fluvial process with a relatively flat relief. Selopamioro has a hilly relief and is composed of structural processes. Differences in landforms cause differences in the process and strategy of shallot cultivation (Figure 1). It is intriguing to explore this distinctiveness further to develop the most effective strategy for optimizing shallot cultivation.

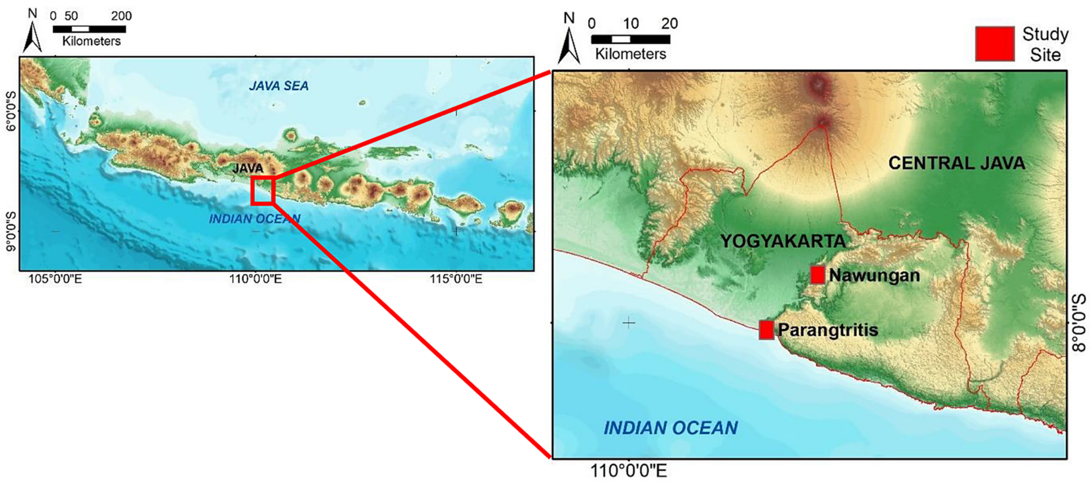


Figure 1. Study site

Data collection

Purposive sampling was implemented for the sampling process, incorporating into consideration the variety of shallots (Bima) and irregular sampling distances. Notably, the pedogeomorphology approach highlights the geomorphic process that contributes to soil formation by examining the reciprocal relationship between the landscape (geomorphology) and the soil formation process (pedologic). We used a rapid assessment approach to gather data on the characteristics of shallot cultivation areas. Land morphology data was acquired employing standardized measurements, including slope gradient using a clinometer and elevation using GPS with ± 3 m precision.

Composite sampling was used at 0–20 cm depth with five points per unit at each site to characterize soil physicochemically. Soil chemical characterization includes pH measurement (1:2.5 soil: water), qualitative organic matter test (H_2O_2 10%), $CaCO_3$ presence test (10% HCl), and EC measurement (1:5 soil: water). Soil physical characterization includes a texture test (feel method), visual color test (Munsell Soil Color Chart), visual structure test, and visual consistency test based on the USDA-NRCS guideline (NRCS, 2021).

Shallot productivity data were obtained using the tiling method with a 1x1 m sampling plot systematically determined on the cultivated land. In-depth interviews with the farmers who responded were used to augment the data collection process. A semi-structured guide that addressed technical aspects of cultivation, productivity restrictions, and farmer opinions of development potential was employed to conduct the interviews. Finally, the information obtained was analyzed descriptively to identify DPSIR that affect environmental carrying capacity for the sustainability of shallot cultivation. This analysis provides an empirical basis for formulating strategic recommendations in optimizing the development of shallot production centers that are adaptive to local conditions.

Data analysis

A descriptive-exploratory approach was employed to characterize and identify the terrain suitable for shallot farming. Specifically, the pedogeomorphology approach was used to describe the the findings. Each parameter is linked to the local pedo geomorphology typology, and the findings are presented in a matrix format. Quantitative analysis, such as boxplot and simple linear regression, is used to determine the relationship and determine the factors of the soil's physical-chemical characteristics on the level of shallot productivity. The simple linear regression model used is:

$$Y = \beta_0 + \beta_1 X + \varepsilon \quad (1)$$

where: Y is the productivity of shallots (tons/ha), β_0 is the intercept or regression constant, β_1 is the regression coefficient, X is the variable of physical-chemical characteristics of the soil, and ε is the error term. In addition, the coefficient of determination ($R2$) establishes the correlation intensity between the variables. In addition, the F-test was used to evaluate the relationship's significance at a genuine 5% level ($\alpha = 0.05$). The elements that drive shallot productivity are soil characteristic variables that substantially impact productivity (p-value <0.05). A quantitative analysis was conducted using SPSS 24.0 software.

The development of land optimization strategies is accomplished by implementing the DPSIR approach. Several modification factors include seed selection, cultivation practices, land management, fertilization techniques, pest-disease control, and irrigation techniques. Considering the typology of study site, the final DPSIR analysis results offer numerous options for managing shallot cultivation areas.

RESULT AND DISCUSSION

Land features for shallot production

Pedogeomorphological analysis of shallot cultivation areas in Parangtritis and Nawungan, Yogyakarta, revealed distinct patterns of soil development influenced by two major landscape types: fluvial and structural. These landscapes demonstrate unique characteristics shaped by their geological setting, depositional processes, and anthropogenic influences, ultimately affecting their suitability for shallot cultivation. Table 1 provides comprehensive details about the features of the area utilized for shallot cultivation.

Typically, the fluvial landscape of Parangtritis serves as a complex depositional zone at low elevations (5±15 m asl) with gentle relief (0-8% slope). Clay texture dominates the foothill plains, floodplains, and former back swamp areas. This clay dominance emerges from the convergence of two primary sediment sources: weathered andesitic materials from Mount Merapi and limestone-derived materials from Baturagung hills, both transported and sorted through the Opak-Oyo River system (Pramono, 2007; Sartohadi, 2011). However, the buried back swamp exhibits a distinctive sandy clay loam texture owing to the incorporation of aeolian sand deposits from nearby coastal dunes (Saputro et al., 2017). This situation illustrates the unique interaction between fluvial and aeolian processes (Gao et al., 2020; Malawani et al., 2024).

Nawungan's structural landscape is mostly clay due to its higher elevation (51–255 meters above sea level) and steeper slopes (0–27%). In-situ weathering of the parent materials from the Wonosari Formation (Tmwl) with limestone and the Nglanggran Formation (Tmn) with volcanic andesitic breccia has enabled the development of the clay texture in the structural landscape (Riyanto et al., 2022; Nurcholis et al., 2023). This culminated in the formation of the clay texture in the structural landscape. Furthermore, the intensive weathering of feldspar-rich minerals from these formations, combined with the landscape's slope characteristics, has promoted clay formation while allowing sufficient drainage to prevent waterlogging (Saikia et al., 2015; Tawfik et al., 2015; Qodri & Sopamena, 2023; Maulana et al., 2023). Nayyef (2022) states that this combination of clay texture and good drainage conditions often creates favorable environments and provides appropriate management practices for bulb crop cultivation.

Soil structure development showed transparent relationships with landscape position and parent material. However, the fluvial landscape transitions from a subangular blocky structure at higher positions to angular blocky and granular structures at lower positions, reflecting the influence of hydrogeomorphic processes. This soil structure facilitates aeration and drainage while maintaining moisture levels, which are vital for root crops. Following Nunes et al. (2021), the soil's physical quality directly influences root growth, with structural characteristics affecting soil drainage.

Variations in soil consistency across the study area revealed important patterns in the soil's physical conditions and their implications for root development. In the fluvial landscape, consistency ranged from firm in most areas to friable in the buried back swamp, reflecting the influence of textural and drainage variations on soil physical properties. Furthermore, the structural landscape maintains firm consistency throughout, combined with clay texture and angular blocky structure, indicating stable soil development influenced by the base mineral of the parent material. These consistency patterns, as observed by Yu et al. (2016), significantly influence the root penetration capacity and water retention properties, which are crucial factors for crop cultivation.

Soil color variations across the study area provide crucial insights into organic matter dynamics and oxidation-reduction conditions. In the fluvial landscape, colors ranged from 10 YR 2/2 to 10 YR 4/3, with darker colors corresponding to higher organic matter content in the back swamp areas. The structural landscape exhibited a distinctive reddish-brown color (7.5 YR 5/4), indicating significant iron oxide formation through weathering processes. These color variations, as noted by Juwanda et al. (2020), reflect the different stages of soil development and organic matter accumulation that influence soil fertility.

Table 1. Characteristics of shallot cultivation land

Landscape	Landform	Slope	Elevation	Texture	Color	Structure			Consistency	pH	Organic matter	$CaCO_3$	EC
		(%)	(m asl)			Type	Grade	Size					(dS/m)
Fluvial	Foothill plains	3±8	10±12	Clay	10 YR 4/3	Subangular blocky	Moderate	Medium	Firm	5.55±7.30	Very low	Negative	0.14±0.75
	Floodplains	0±8	7±11	Clay	10 YR 4/3	Subangular blocky	Moderate	Medium	Firm	4.55±7.39	Very low	Negative	0.13±0.74
	Former back swamp	0±3	5±10	Clay	10 YR 3/3	Angular blocky	Moderate	Coarse	Firm	7.12±7.54	Moderate	Moderate	0.88±1.09
	Buried back swamp	3±8	6±15	Sandy clay loam	10 YR 2/2	Granular	Weak	Medium	Friable	7.30±7.62	Moderate	Moderate	0.75±0.88
Structural	Structural	0±27	51±255	Clay	7.5 YR 5/4	Angular blocky	Moderate	Medium	Firm	6.58±7.74	High	Moderate	0.44±1.16

Anthropogenic impacts have caused large pH fluctuations in both landscapes, which naturally have base soil conditions. Typically, the foothill plains and floodplains exhibit notably acidic conditions (pH 4.55–7.30) with negative CaCO3, primarily attributed to intensive pesticide application in shallot cultivation. This finding aligns with the observations of Hathout et al. (2021), who documented similar pH alterations in intensively managed agricultural soils. Also, the low electrical conductivity (EC) values (0.13–0.75 dS/m) in these areas further reflect the impact of intensive pesticide use on soil chemical properties. Similar conditions have been mentioned by Maznah et al. (2016) and Akhter et al. (2017).

Limiting factors in shallot cultivation

It was shown that there were notable differences in shallot productivity across various landforms. On average, structural landscapes had 17.81% higher productivity than fluvial landscapes (Figures 2 and 3). Within the fluvial landscape, former back swamp areas showed superior productivity, exceeding that of other fluvial landforms by 5-25%. These productivity differences can be attributed to distinct soil physical and chemical properties, limiting factors in shallot cultivation.

Soil physical properties, particularly texture and consistency, have emerged as critical factors influencing shallot productivity (Figure 2). Clay-textured soils in structural landscapes achieved the highest productivity (20.34 tons/ha), attributed to moisture retention and nutrients. This finding aligns with that of Firmansyah and Bhermana (2019), who documented optimal shallot growth in well-structured clay soils. However, the sandy clay loam texture in the buried back swamp areas showed moderate productivity (14.19 tons/ha) with notably more stable yields, suggesting a trade-off between maximum productivity and yield stability.

Soil consistency significantly affects bulb formation and water movement patterns. Areas with firm consistency (structural landscape, former back swamp, floodplains) showed varying productivity levels, whereas friable consistency in the buried back swamp demonstrated more stable yields. According to Olivares et al. (2024), excessive soil firmness can lead to compaction, potentially restricting bulb formation and nutrient uptake. This relationship is particularly evident in floodplain areas, where firm consistency and poor drainage reduce productivity.

Soil structure analysis revealed that angular blocky structures, particularly those of medium size and moderate grade, provided optimal conditions for shallot cultivation. These characteristics allow better drainage, root elongation, and nutrient uptake (Nunes et al., 2021; Tomar et al., 2023). Conversely, coarse size structure in former backswamp area, tend to be less stable than smaller ones and are more susceptible to physichal and biophysichal disturbances (Totsche et al., 2018)

Typically, the structural landscape was dominated by soils with high chroma values (5). High chroma values indicated lighter soil color, suggesting a more intensive oxidation process. This condition is generally associated with improved soil drainage (Kafoor, 2017; Turk & Young, 2020). Optimal soil drainage is crucial for supporting shallot growth and productivity, as this bulb crop requires good soil aeration to avoid bulb rot (Hadiwiyono et al., 2020; Hawayanti et al., 2024). Consistent with this, structural landforms with high chroma values show higher shallot productivity than floodplains and foothill plains, which tend to have lower chroma values.

Productivity patterns were strongly correlated with organic matter and $CaCO_3$ levels (Figure 3). Structural landscapes, characterized by high organic matter content and moderate $CaCO_3$ levels, demonstrated superior productivity. Mamondol and Meringgi (2022) noted a significant relationship between organic matter, which improves the soil structure and provides essential nutrients, leading to optimal shallot productivity. However, the positive influence of moderate $CaCO_3$ levels on soil pH buffering capacity appears to create favorable conditions for nutrient availability and uptake (Motior et al., 2011; Luo et al., 2015).

Chemical properties, particularly pH and EC, have emerged as crucial limiting factors (Figure 4). Statistical analysis revealed strong correlations between these parameters and shallot productivity (R^2 = 0.61 for pH; R^2 = 0.68 for EC). Optimal productivity was observed in soils with near-neutral pH (average 7.16) and EC values approaching one dS/m. This finding aligns with those of Bintang et al. (2018) and Girsang et al. (2021), which indicated that lands with base pH and EC <2 dS/m have highly suitable class compatibility for shallot cultivation. Areas with pH below 6.0, particularly in floodplains, showed markedly reduced productivity, confirming observations by Rahayu et al. (2021) regarding the impact of pH on shallot productivity.

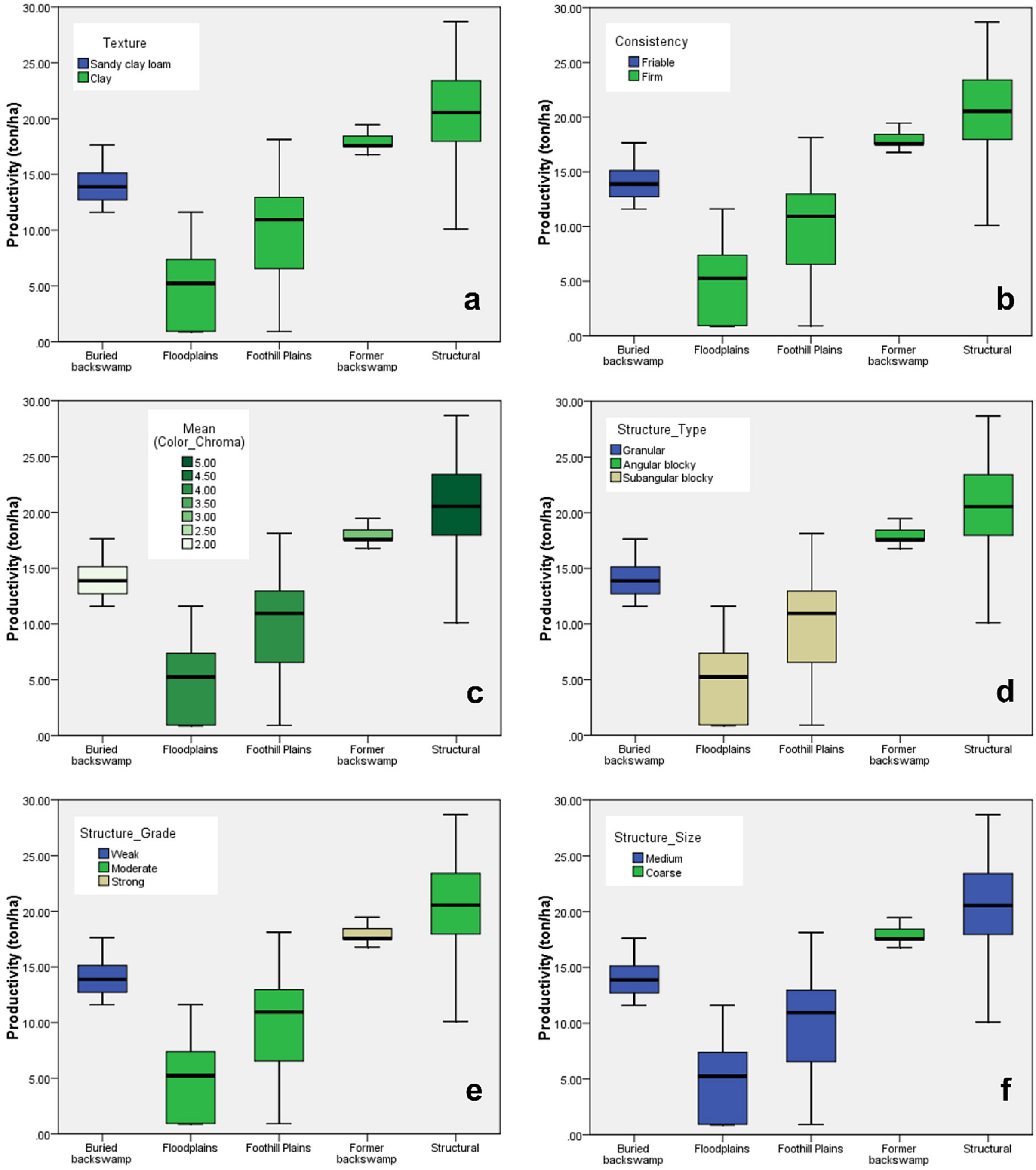


Figure 2. The relationship between soil physical properties and shallot productivity

Land optimization strategy

These findings suggest that the primary factors (D) that motivate the planting of shallots are the high market demand, the relatively brief planting duration, and the favorable prices. Furthermore, access to information related to other plant options as an alternative to shallots is also relatively limited. Also, both communities believe the farmed land is ideal for shallots. It is essential to provide and manage surface air to cultivate shallot successfully. Different landscape conditions cause the pressure factor (P) in the two locations to be different. Agricultural development in Parangtritis tends to have easier access to air during the dry season, while in Nawungan, the opposite is true. Wells in Nawungan can reach depths of more than 80 m. Interestingly, when weather anomalies occur during the rainy season, agriculture in Parangtritis is more vulnerable to flooding than Nawungan, which has a hilly relief. Other P factors include fertilizers and pesticides

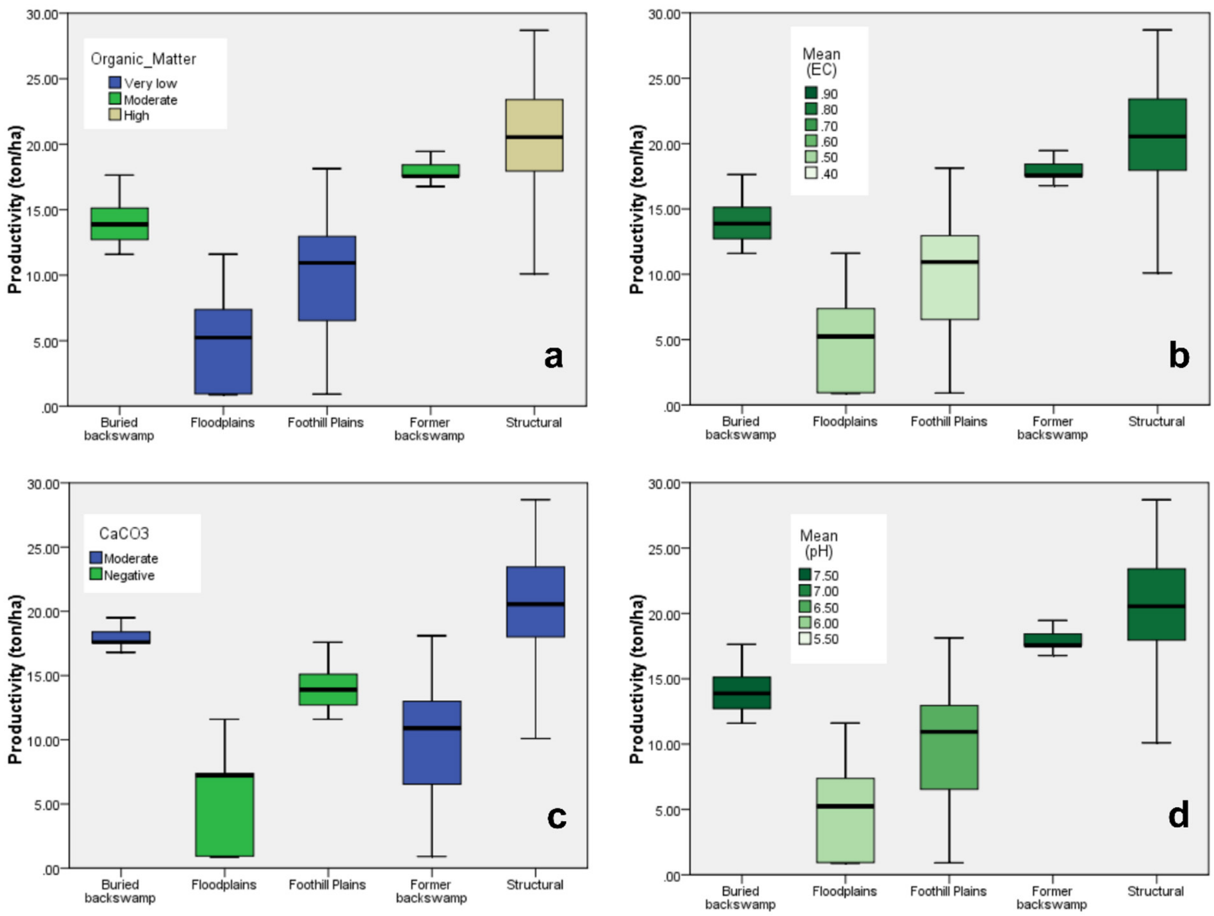


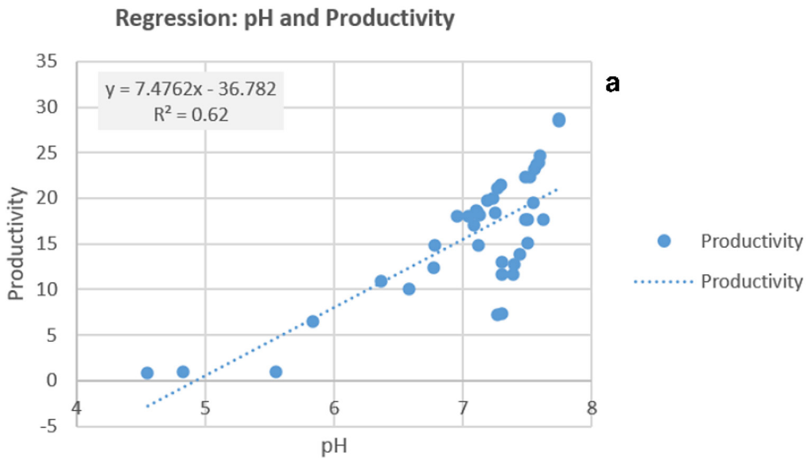
Figure 3. The relationship between soil chemichal properties and shallot productivity

in specific seasons. Furthermore, due to high product demand, intensification occurs in several plots of land, which harms land sustainability.

State component (S) demonstrates the conditions that result from the pressure that occurs. This study has demonstrated that the integrity of soil, water, and ecosystems tended to deteriorate. An increase followed this decline in the development of diseases and pests. Specifically, the analysis of limiting factors showed that soil pH and EC were the main limiting factors in shallot cultivation. Optimal productivity was observed in soil with a pH close to neutral (average 7.16) and an EC value close to 1 dS/m, generally found in structural landforms. In contrast, areas with a pH below 6.0, especially in flood plains, showed much lower productivity. Interestingly, to overcome this issue, farmers prefer to increase the dose of fertilizer and pesticides so that the impact component (I) tends to be stable or even increase. Almost all key informants said that productivity and income tend to be stable or even increase. However, they know that increasing chemical use to boost agricultural yield could lower environmental quality.

Policy strengthening is crucial to sustainable agriculture. Based on the cases in the two locations studied, regulating land management practices, water management, and using fertilizers and pesticides is necessary. Through strong regulations, villages and agricultural offices can allocate budgets for water management and hold training to increase farmers' capacity in sustainable land management practices (Maulana et al., 2023; Maulana et al., 2025). Land management can be focused on mechanical efforts using environmentally friendly fertilizers and pesticides while paying attention to local land characteristics. Furthermore, regular soil quality monitoring must be carried out to evaluate the relationship between soil properties and characteristics and their effect on shallot productivity. Water management must also be improved in Nawungan because water deficits occur in the dry season (Putranti et al., 2023).

Typically, both locations use different seeds from Brebes (Central Java) and Kediri (East Java). According to key informants, seeds from Brebes tend to be better, and not all farmers have access



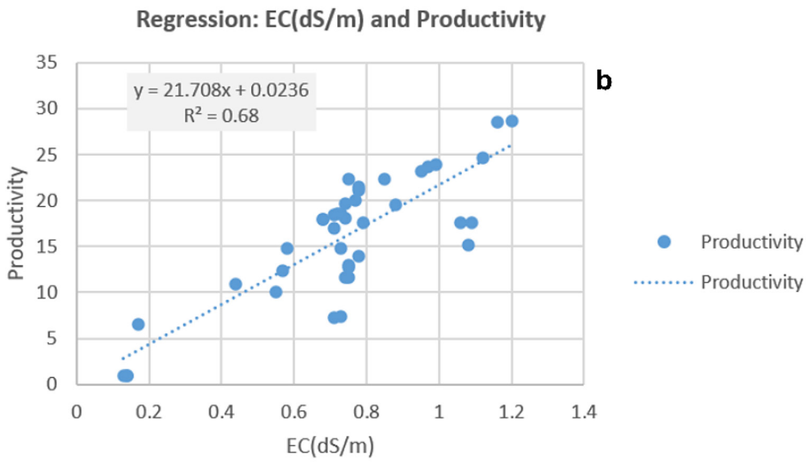


Figure 4. Linear regression of pH and EC on shallot productivity

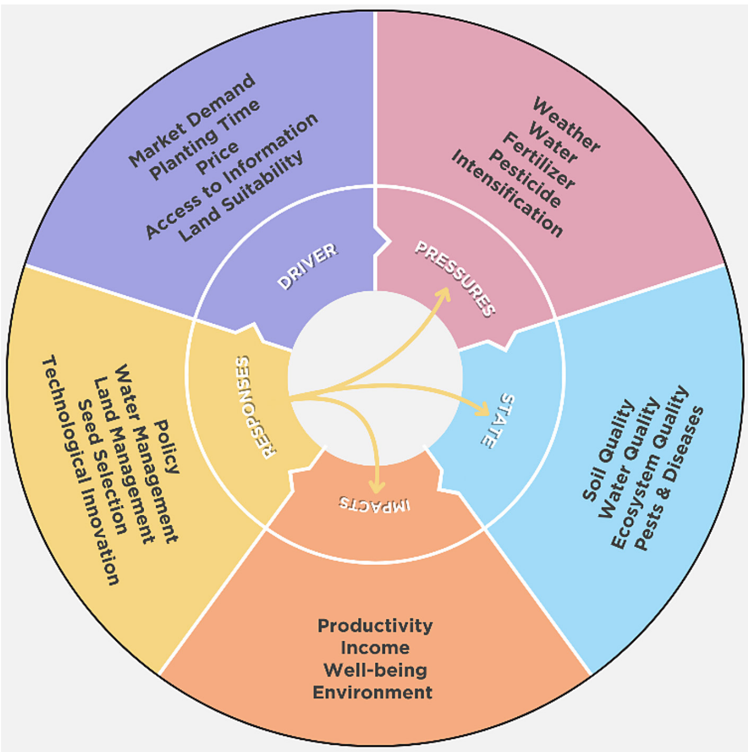


Figure 5. DPSIR analysis

and information to obtain these seeds. Through strengthening regulations, cooperation to increase land productivity can be improved. Regarding technology, several plots in Parangtritis have also started implementing agro-electrifying (AE) to carry out automatic watering. This model can also be adopted in Nawungan to save time and energy and make the watering dose more measurable. Finally, the DPSIR analysis is presented in Figure 5 in detail.

CONCLUSIONS

This study highlights the significant role of pedogeomorphological factors in determining soil suitability for crop production. Parangtritis' fluvial landscape and Nawungan's structural landscape affect soil properties and agricultural productivity. Typically, the fluvial landscape in Parangtritis, with clay soils from volcanic and limestone materials, is ideal for moisture retention, though the back swamp areas have slightly lower but stable productivity. In Nawungan, the structural landscape, with clay-rich soils from weathering, shows higher productivity due to better drainage and moisture retention. Firmer soil in the structural landscape and friable soil in the back marshes affect root growth and water retention, which are crucial to shallot production.

A comprehensive land optimization strategy should consider soil properties and water management in addition to pedogeomorphological factors. DPSIR analysis helps identify key factors such as high market demand, fluctuating prices, and short planting cycles that drive land use decisions. Parangtritis benefits from better water access during dry seasons, while Nawungan faces challenges with deeper water tables and steeper slopes, limiting water availability. Policy responses should focus on sustainable land management, efficient irrigation, and environmentally friendly farming inputs to address environmental concerns like soil degradation and pesticide accumulation.

Furthermore, soil pH in Parangtritis is more acidic due to pesticide use, highlighting the need for regulations to reduce chemical reliance and promote sustainable practices. Encouraging organic fertilizers, integrated pest management, and new technologies like automated irrigation can improve soil health and productivity. Strengthening farmer organizations through training and knowledge sharing will help farmers adopt sustainable practices and increase resilience to climate and market changes. Tailoring soil management to the specific conditions of each landscape can optimize shallot production while maintaining environmental sustainability.

Finally, this study confirms that pedogeomorphological analysis can be relied on to predict an area's land potential. Differences in pedogeomorphological characteristics will cause different land productivity. To further our understanding of land potential analysis, similar studies in different regions will be necessary in the future.

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