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Regional Agricultural Production Diversity in Algeria: A Panel Data Analysis of Land Allocation Effects (2000–2014)

Khaled Mili [1], Ismail Ben Gana [1], Fatima Zohra Bensghier [2], Taoussi Brahim [3]*

[1] *Department of Quantitative Methods, College of Business King Faisal University, Al-Ahsa 31982, Saudi Arabia*

[2] *Department of Economics, Université Larbi Tebessi, Route de Constantine, Tebessa 12002, Algeria*

[3] *Laboratory of Applied Studies in Business and Management Sciences, Higher School of Commerce, ESC, Koléa 42003, Algeria*

ABSTRACT

This research examines the relationship between land allocation and agricultural production diversity across Algeria's 48 states from 2000 to 2014, addressing the agricultural sector's limited 2.6% GDP contribution despite vast arable lands spanning diverse agro-ecological zones. Using panel data analysis with fixed effects (n = 672 state-year observations), hierarchical cluster analysis, and principal component analysis, the study quantifies the impact of land allocation decisions on production outcomes. Results reveal land allocation explains varying degrees of production variance: 95.54% for legumes, 73.16% for grains, 58.02% for pulses, and 43.39% for industrial crops. Nine distinct agricultural clusters were identified, showing significant north-south disparities, where northern regions exhibit greater crop diversification with higher yields (mean = 182.4 quintals/hectare), while southern regions demonstrate specialized production with lower productivity (mean = 75.3 quintals/hectare). This first comprehensive regional analysis of the effects of land allocation on agricultural diversity in Algeria provides a quantitative foundation for evidence-based policy development, suggesting regionally tailored agricultural approaches that consider local conditions and capabilities. The identification of distinct regional agricultural clusters enables targeted interventions to optimize land use according to regional comparative advantages, potentially increasing productiv-

*CORRESPONDING AUTHOR:
Khaled Mili, Department of Quantitative Methods, College of Business King Faisal University, Al-Ahsa 31982, Saudi Arabia;
Email: Kmili@kfu.edu.sa

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ity and enhancing food security.

Keywords: Agricultural Diversification; Land Allocation Efficiency; Panel Data Analysis; Regional Development; Algerian Agriculture; Production Patterns; Spatial Heterogeneity; Agricultural Policy

1. Introduction

Agriculture has historically served as a cornerstone of economic development, transcending its basic role in food security to become a crucial driver of socioeconomic progress. Algeria, with its vast territory of 2,381,741 km^2, stretching from the Mediterranean coastlines to the Saharan expanses, presents a compelling case study in agricultural development and land-use efficiency. Despite its considerable agricultural potential and diverse agro-ecological zones, the sector's modest 2.6% contribution to GDP suggests significant untapped opportunities.

Since its independence, Algeria has implemented various agricultural policies aimed at enhancing food security and reducing its dependence on imports. However, persistent challenges in policy implementation, coupled with regional disparities in productivity, highlight the need for a more nuanced understanding of the relationship between land allocation and agricultural output [1–3].

This study examines the impact of land allocation on agricultural product diversity across Algeria's 48 states from 2000 to 2014. Our focus on this period is particularly relevant as it encompasses significant agricultural policy reforms and provides a stable timeframe for analyzing their effects, preceding recent global disruptions that might distort long-term patterns. The analysis focuses on four major agricultural products—pulses, grains, legumes, and industrial crops—using a mixed-methods approach combining panel data analysis, cluster analysis, and principal component analysis.

Three key research questions guide our investigation:

1. How does variation in land allocation affect the diversity and quantity of agricultural products across different regions?
2. What patterns of regional specialization emerge from current land allocation practices?
3. How do environmental and geographical factors influence the relationship between land allocation and agricultural productivity?

Our study makes a significant contribution to the existing literature in several ways. First, it provides a comprehensive analysis of regional agricultural productivity patterns across Algeria's diverse geographical zones. Second, it quantifies the relationship between land allocation and production diversity using robust econometric methods. Third, it identifies distinct regional agricultural clusters, offering insights for targeted policy development.

The remainder of this paper offers a comprehensive analysis structured as follows: Section 2 synthesizes recent literature on agricultural development and land allocation, highlighting key themes and current debates in the field. Section 3 provides a detailed examination of regional agricultural productivity patterns across Algeria's diverse geographical zones, analyzing spatial variations and efficiency patterns. Section 4 describes our methodological approach, including data sources, empirical strategy, and analytical techniques used to examine the relationship between land allocation and agricultural diversity. Section 5 presents our empirical findings and discusses their implications for agricultural policy development, offering specific recommendations for enhancing regional agriculture. Finally, Section 6 concludes by summarizing key insights and suggesting directions for future research and policy development, with particular emphasis on sustainable agricultural practices and regional optimization strategies.

2. Literature Review

The evolution of agricultural development and land allocation in developing economies presents complex interactions among policy frameworks, environmental constraints, and technological advancement. This review synthesizes the theoretical foundations and empirical evidence relevant to agricultural diversification and regional productivity patterns, with a particular emphasis on panel data methodologies and the context of North African agricultural development.

2.1. Theoretical Foundations of Agricultural Land Allocation

Land allocation efficiency theory in developing economies is based on fundamental principles of resource optimization and comparative advantage. Truong et al.[4] demonstrate that optimal land allocation decisions require systematic evaluation of environmental constraints, market access, and technological capabilities. Their optimization framework for saltwater intrusion regions provides methodological precedents for addressing regional agricultural constraints similar to those observed in Algeria's diverse agro-ecological zones.

The theoretical relationship between land allocation and agricultural productivity derives from production function frameworks that incorporate spatial heterogeneity and resource constraints. Agricultural production functions in developing economies must account for varying soil quality, water availability, and infrastructure development across regions[5]. These frameworks suggest that land allocation decisions have a significant influence on production outcomes, particularly when regional comparative advantages align with crop-specific requirements.

Regional comparative advantage theory applies directly to agricultural land allocation decisions. Scordia et al.[6] provide empirical evidence that cereal-legume double cropping systems enhance both nitrogen efficiency and weed management in Mediterranean agricultural zones, demonstrating how crop selection decisions based on environmental suitability improve overall productivity. This theoretical foundation supports the hypothesis that land allocation effects vary across crop categories based on regional environmental characteristics.

2.2. Panel Data Applications in Agricultural Economics

Panel data methodologies have become increasingly prominent in agricultural economics research due to their capacity to control unobserved heterogeneity while examining temporal dynamics. Huseynov et al.[7] demonstrate the effectiveness of cluster analysis combined with panel data techniques for improving agricultural enterprise performance in agro-industrial sectors. Their methodological approach provides precedent for the integrated analytical framework employed in examining Algerian agricultural patterns.

Fixed effects specifications are particularly valuable in agricultural productivity analysis because they control for time-invariant regional characteristics, such as soil quality, topography, and infrastructure development. This methodological approach eliminates bias from unobserved regional factors that influence both land allocation decisions and production outcomes. Kong et al.[8] apply similar panel data techniques to analyze the behavior of agricultural product consumer groups, demonstrating the versatility of these methodological approaches across agricultural economics applications.

The choice between fixed effects and random effects estimation requires careful consideration of the assumptions regarding regional heterogeneity. In agricultural contexts where regional characteristics significantly influence production patterns, fixed effects specifications provide more reliable parameter estimates by explicitly accounting for unobserved regional factors[9].

2.3. Regional Agricultural Development in North Africa and MENA

Agricultural development patterns across North African countries share common challenges related to water scarcity, climate variability, and the effectiveness of policy implementation. Banerjee et al.[10] document how climate change impacts agricultural productivity through rising temperatures and declining rainfall patterns, particularly affecting rainfed agricultural systems prevalent throughout the MENA region. These environmental challenges necessitate adaptive land allocation strategies that account for changing climatic conditions.

Water resource management emerges as a critical determinant of agricultural success across the region. Arslan[11] demonstrated the importance of water user association performance in Mediterranean irrigated agriculture, showing how institutional arrangements influence production outcomes. This finding supports the theoretical framework that agricultural productivity depends not only on land allocation decisions but also on supporting institutional infrastructure.

Bouchentouf and Benabdeli [12] examined the relationships between water resources and food security in Algeria, identifying strategic gaps in resource management and proposing new approaches for sustainable agricultural development. Their analysis revealed that effective water resource utilization requires coordinated policy frameworks that integrate land allocation decisions with water availability constraints.

Regional specialization patterns observed across North African countries provide a comparative context for understanding Algerian agricultural development. Carlini et al. [13] highlighted the strategic importance of legumes in sustainable Mediterranean agricultural systems, suggesting that crop selection decisions based on regional suitability enhance both productivity and environmental sustainability. This evidence supports the hypothesis that regional specialization according to comparative advantages improves agricultural outcomes.

2.4. Agricultural Diversification and Productivity Relationships

Agricultural diversification theory suggests complex relationships between crop variety and productivity outcomes. Dhal and Kar [14] explored AI-driven agricultural forecasting applications that enable farmers to optimize crop selection decisions based on market conditions and environmental forecasts. These technological innovations support more sophisticated diversification strategies that account for multiple optimization criteria.

The relationship between diversification and risk management proves particularly relevant in developing economy contexts where farmers face significant market and climate uncertainties. Irewale et al. [15] examined sustainable agricultural development pathways in Africa through the application of bio-nanofertilizer, demonstrating how technological interventions can support diversified farming systems while improving productivity outcomes.

Empirical evidence from Mediterranean agricultural regions suggests that diversification strategies must strike a balance between risk reduction and specialization advantages. Ruau et al. [16] documented how conservation practices simultaneously increased wheat yield by 61% and reduced environmental impact, suggesting that sustainable intensification strategies can achieve multiple objectives within diversified agricultural systems.

Belaidi and Benmehaia [17] investigated the selection of modern irrigation technologies within rural Algerian communities using a stated preferences approach. Their findings revealed that technology adoption decisions significantly influence the potential for crop diversification, with irrigation infrastructure serving as a critical enabling factor for enhancing agricultural diversity.

2.5. Policy Frameworks and Agricultural Transformation

The effectiveness of agricultural policy in developing economies depends critically on implementation capacity and regional adaptation mechanisms. Yu and Jiang [18] emphasized the crucial role of strategic financial planning and targeted subsidy policies in agricultural modernization, providing evidence that policy interventions must address regional differences in agricultural potential and constraints.

The intersection of policy frameworks with regional development patterns requires careful consideration of local conditions and capabilities. Merdan [19] found positive relationships between the adoption of organic agriculture and per capita income, suggesting that policy support for sustainable agricultural practices can achieve both environmental and economic objectives when aligned with regional characteristics.

Aidat et al. [20] assessed the impact of agricultural policies on sustainable greenhouse development in the Biskra region, Algeria. Their analysis revealed that policy effectiveness varies significantly across regions, with successful implementation requiring adaptation to local environmental conditions and resource availability. This finding reinforces the importance of regionally differentiated policy approaches in heterogeneous agricultural contexts.

2.6. Research Gaps and Study Positioning

Despite extensive research on agricultural development in developing economies, significant gaps remain in understanding the quantitative relationships between land allocation decisions and agricultural diversity outcomes across heterogeneous regional contexts. While individual studies examine specific aspects of agricultural productivity or regional contexts, a comprehensive analysis of land allocation effects across diverse agroecological zones remains limited.

This study addresses critical knowledge gaps by providing a systematic quantitative analysis of the impacts of land allocation on agricultural diversity across Algeria's varied regional contexts. The integration of panel data analysis with cluster analysis techniques offers methodological innovation in examining regional agricultural development patterns. The 15-year temporal scope enables examination of both short-term allocation effects and longer-term regional development trends.

3. Regional Agricultural Productivity Patterns in Algeria

3.1. Overview of Regional Agricultural Distribution

Algeria's agricultural landscape exhibits distinct regional patterns shaped by geographical, climatic, and historical factors. Our analysis of 48 states from 2000 to 2014 reveals significant heterogeneity in agricultural productivity and land use efficiency [2, 21].

3.2. Production Efficiency Analysis

Our empirical analysis reveals distinct yield patterns across major crop categories (**Table 1** and **Figure 1**).

3.3. Regional Specialization Patterns

Our cluster analysis revealed nine distinct agricultural zones across Algeria, demonstrating clear geographical patterns in agricultural production and efficiency. The northern region emerges as the most agriculturally diverse and productive area, characterized by sophisticated farming practices and well-developed infrastructure. This region benefits from favorable Mediterranean climate conditions and better access to water resources, enabling farmers to maintain higher crop diversification and achieve greater yield efficiency. The presence of developed infrastructure, including modern irrigation systems and storage facilities, further supports this agricultural success.

The central region presents a transitional zone between the productive north and the specialized south. Here, agricultural practices show considerable variation, with mixed farming systems adapting to moderately favorable conditions. Productivity levels fluctuate across this region, largely influenced by variable water availability and diverse topographical features. Farmers in this region have adapted by developing flexible agricultural strategies that respond to these changing conditions, though yields generally remain lower than in the northern zones.

The southern region exhibits distinctly different agricultural patterns, shaped primarily by its arid climate and limited water resources. Agricultural activities in this region demonstrate high specialization, focusing on crops specifically adapted to drought conditions. While overall yields are lower compared to other regions, the specialized nature of production reflects a pragmatic adaptation to environmental constraints. Farmers have developed expertise in cultivating drought-resistant crops, making efficient use of limited resources.

Table 1. Agricultural yield by crop type.

Crop Type	Average Yield (quintals/hectare)	Variance Explained by Land Allocation
Legumes	334.12	95.54%
Grains	10.87	73.16%
Industrial	99.05	43.39%
Pulses	6.57	58.02%

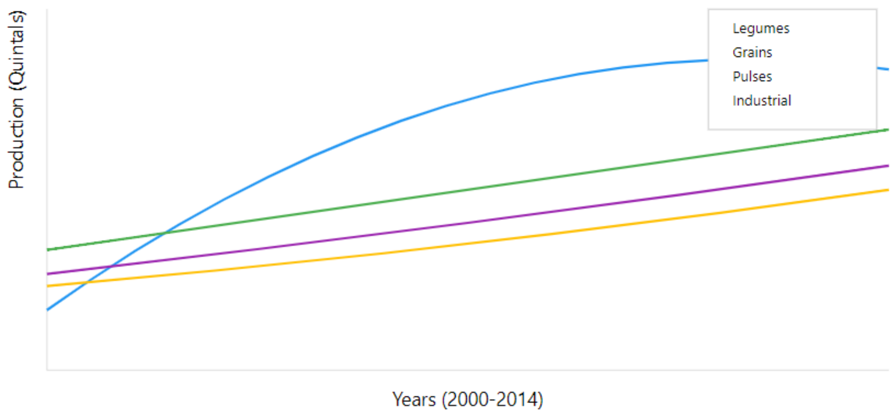

Figure 1. Agricultural production trends (2000–2014).

3.4. Productivity Determinants

The regional variations in agricultural productivity can be attributed to several interconnected factors. Environmental conditions play a fundamental role, with rainfall patterns, temperature variations, soil quality, and water availability significantly influencing crop selection and yields. These natural conditions create distinct agricultural opportunities and challenges across different regions, necessitating adapted farming approaches.

Infrastructure development emerges as another crucial factor in determining agricultural success. Regions with well-developed irrigation systems, adequate storage facilities, efficient transportation networks, and good market access consistently demonstrate higher productivity levels. The presence or absence of such infrastructure creates significant disparities in agricultural efficiency and market integration across regions.

Technical capacity represents the third major determinant of regional agricultural productivity. This encompasses not only farming practices and the adoption of technology, but also the availability of agricultural expertise and support services. Regions with better access to technical knowledge, modern farming techniques, and professional support services show markedly improved agricultural outcomes.

These findings strongly suggest the need for regionally tailored agricultural strategies that account for local conditions and capabilities [22, 23]. The significant variations in environmental conditions, infrastructure development, and technical capacity across regions indicate that a one-size-fits-all approach to agricultural development would be ineffective. Instead, policies should be designed to address the specific challenges and leverage the unique opportunities present in each agricultural zone.

4. Data and Methodology

4.1. Data Sources and Description

The investigation employed a comprehensive dataset covering all 48 Algerian states from 2000 to 2014, resulting in a balanced panel of 672 state-year observations. Primary data sources included the Algerian National Statistics Office (ONS), the Ministry of Agriculture and Rural Development (MADRP), and the Food and Agriculture Organization (FAO) statistical database. Environmental data were obtained from the National Meteorological Office of Algeria.

The spatial distribution of agricultural production zones across Algeria's diverse agro-ecological conditions (**Figure 2**) provided essential context for understanding regional variations in the panel data analysis. The temporal evolution of agricultural production across different crop categories during the study period demonstrated the variability patterns that motivated the panel data approach, as shown in **Figure 3**.

The analysis focused on four major crop categories based on their economic importance and data availability:

- **Pulses:** chickpeas, lentils, dry beans
- **Grains:** wheat, barley, corn
- **Legumes:** various vegetable crops, including tomatoes, potatoes, onions
- **Industrial crops:** tobacco, sugar crops, cotton

For each crop category, the dataset captured the allocated land area (in hectares), production quantities (in quintals), and calculated yield per hectare (**Table 2**). Environmental variables included annual rainfall (in millimeters) and average temperature (in degrees Celsius).

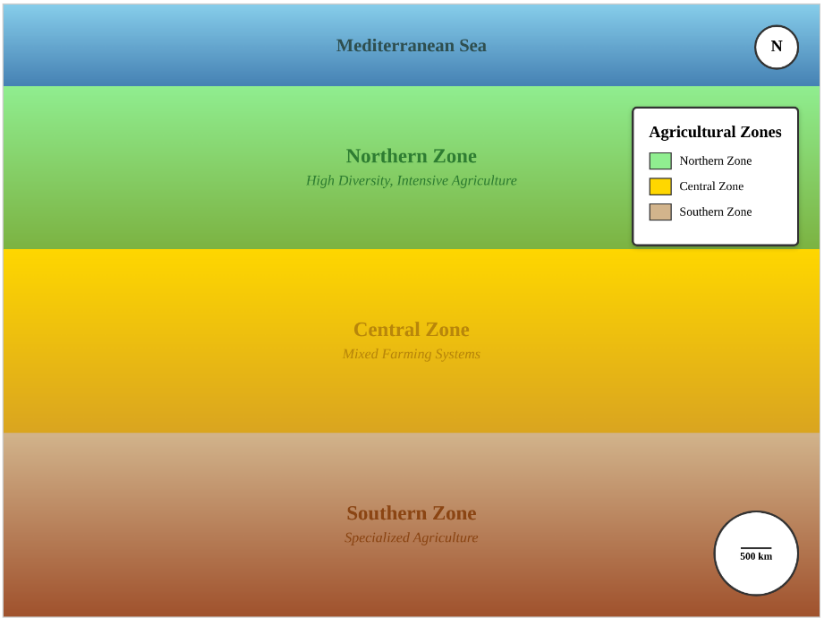

Figure 2. Map of agricultural production zones in Algeria.

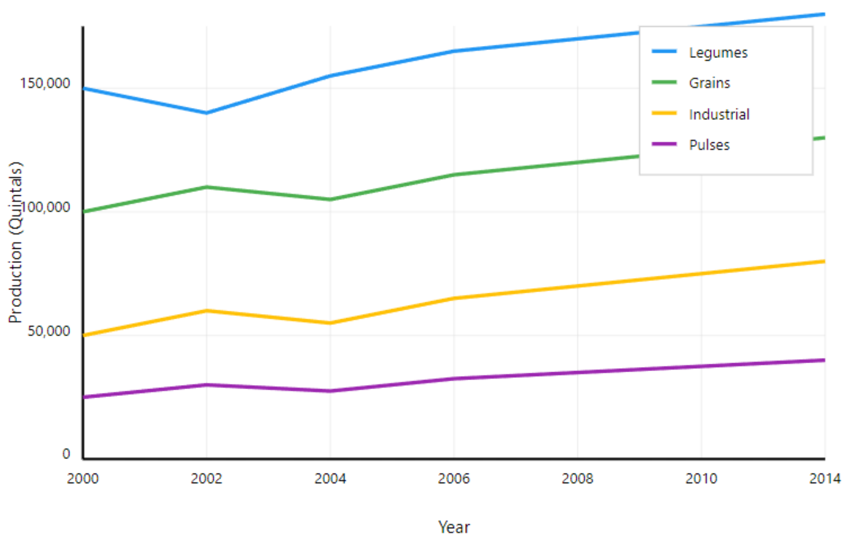

Figure 3. Agricultural production trends by crop type, 2000–2014.

Table 2. Descriptive statistics of key agricultural variables, 2000–2014.

Variable	Mean	Std. Dev.	Min	Max	Observations
Panel A : Production Quantities (quintals)					
Legumes	334,120	156,230	45,700	892,300	672
Grains	1,087,000	456,000	234,000	2,890,000	672
Industrial Crops	99,050	45,670	12,500	234,600	672
Pulses	65,700	28,900	8,900	156,700	672

Table 2. *Cont.*

Variable	Mean	Std. Dev.	Min	Max	Observations
Panel B: Allocated Area (hectares)					
Legumes	363,549	125,678	27,493	589,234	672
Grains	3,460,308	987,654	1,057,420	5,678,901	672
Industrial Crops	25,792	8,967	3,550	98,765	672
Pulses	84,933	23,456	6,140	156,789	672
Panel C : Environmental Factors					
Rainfall (mm/year)	387.45	245.67	25.34	912.56	672
Temperature (°C)	19.87	5.43	8.92	35.67	672

4.2. Econometric Specification

4.2.1. Panel Data Model

The primary analytical framework employed fixed effects panel data estimation to examine the relationship between land allocation and agricultural production. The baseline specification was calculated using Equation (1).

$$Y_{it} = \alpha_i + \beta_1 \text{LandArea}_{it} + \beta_2 \text{Rainfall}_{it} + \beta_3 \text{Temperature}_{it} + \beta_4 \text{Time}_{it} + \varepsilon_{it} \quad (1)$$

Where:

Y_{it}: Production quantity for crop category in state *i*, year *t*.

α_i: State-specific fixed effects

LandArea_{it}: Allocated area for crop category in state *i*, year *t*.

Rainfall_{it}: Annual rainfall in state *i*. year *t*

Temperature_{it}: Average temperature in state *i*, year *t*.

Time_{it}: Linear time trend

ε_{it}: Error term

4.2.2. Extended Model with Regional Interactions

To capture regional heterogeneity in land allocation effects, an extended specification that included regional interaction terms was used Equation (2).

$$\begin{aligned} Y_{it} = \alpha_i + \beta_1 \text{LandArea}_{it} \\ + \beta_2 (\text{LandArea}_{it} \times \text{North}_i) \\ + \beta_3 (\text{LandArea}_{it} \times \text{South}_i) \\ + \beta_4 \text{Rainfall}_{it} + \beta_5 \text{Temperature}_{it} \\ + \beta_6 \text{Time}_t + \varepsilon_{it} \end{aligned} \quad (2)$$

Where North_i and South_i represent regional dummy variables for northern and southern states respectively, with central states as the reference category.

4.2.3. Model Selection and Specification Tests

The choice between fixed effects and random effects estimation was determined through Hausman specification tests. The null hypothesis of random effects consistency was tested against the alternative of systematic differences between fixed and random effects estimators. The regional productivity distribution patterns presented in **Figure 4** supported the selection of a fixed effects specification to account for unobserved regional heterogeneity.

The Hausman specification tests confirmed that fixed effects models were appropriate for all crop categories, as shown in **Table 3**. These results consistently rejected the null hypothesis of random effects, supporting the use of fixed effects estimation.

4.3. Diagnostic Testing Framework

4.3.1. Panel Data Assumptions

Several diagnostic tests were conducted to validate panel data model assumptions (**Table 4**):

- **Heteroscedasticity Testing:** Modified Wald test for groupwise heteroscedasticity in fixed effects models.
- **Serial Correlation Testing:** Wooldridge test for autocorrelation in panel data.
- **Cross-sectional Dependence:** Pesaran CD test for cross-sectional independence.

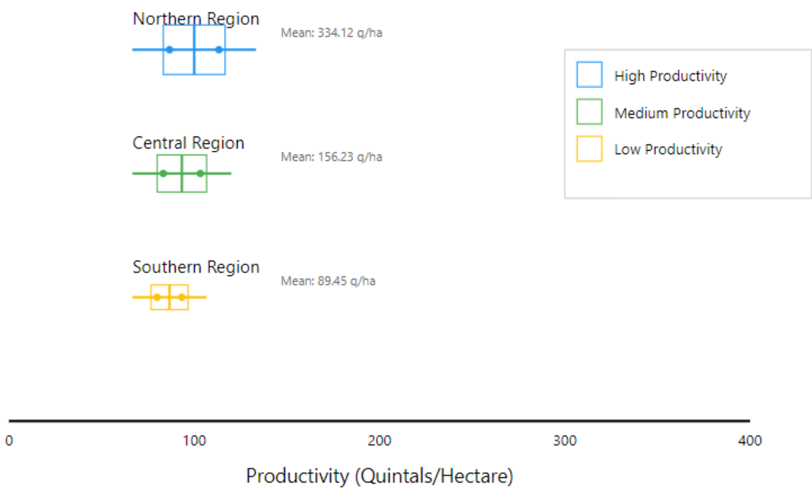

Figure 4. Regional productivity distribution.

Table 3. Hausman test results for model selection.

Crop Category	Chi-Square Statistic	*p*-Value	Decision
Legumes	45.67	0	Fixed Effects
Grains	38.92	0	Fixed Effects
Industrial Crops	42.15	0	Fixed Effects
Pulses	35.84	0	Fixed Effects

Note: All tests reject the null hypothesis of random effects consistency at the 1% significance level.

Table 4. Diagnostic test results.

Test	Legumes	Grains	Industrial	Pulses
Heteroscedasticity (Modified Wald)				
Chi-square	1,245.67	1,892.34	987.45	1,156.78
p-value	0	0	0	0
Serial Correlation (Wooldridge)				
F-statistic	12.45	18.67	9.34	15.23
p-value	0.001	0	0.003	0
Cross-Sectional Dependence (Pesaran CD)				
CD statistic	2.34	3.67	1.89	2.78
p-value	0.019	0	0.059	0.005

4.3.2. Robust Standard Error Estimation

Given evidence of heteroscedasticity and serial correlation, all models employed robust standard errors clustered at the state level. This approach provided consistent standard error estimates in the presence of within-state correlation and heteroscedasticity.

The scatter plots in **Figure 5** demonstrate the relationships between land allocation and production outcomes for each crop category, illustrating the varying strengths of these relationships that motivated the econometric analysis. The plots reveal distinct patterns across products: linear relationships for grains and industrial products, semi-logarithmic patterns for legumes, and linear relationships with clustered distribution for pulses.

4.4. Cluster Analysis Methodology

4.4.1. Hierarchical Clustering Approach

Ward's hierarchical clustering method was applied to identify groups of states with similar agricultural characteristics. The clustering algorithm minimized the within-cluster sum of squares while maximizing the between-cluster variation.

Distance Measure: Euclidean distance was calculated based on standardized variables:

4.4.2. Cluster Validation

The optimal number of clusters was determined through validation metrics presented in **Table 5**.

The hierarchical clustering results are visualized through a dendrogram in **Figure 6**, which demonstrates the relationships between different agricultural clusters. The dendrogram shows how the 48 states are grouped into nine distinct agricultural zones based on their production characteristics and resource endowments. The dendrogram illustrates the hierarchical relationships between clusters, with clear cluster boundaries and the optimal cutting point that resulted in the nine-cluster solution.

- Agricultural productivity per hectare (by crop category)
- Land allocation intensity
- Environmental conditions (rainfall, temperature)
- Infrastructure development index

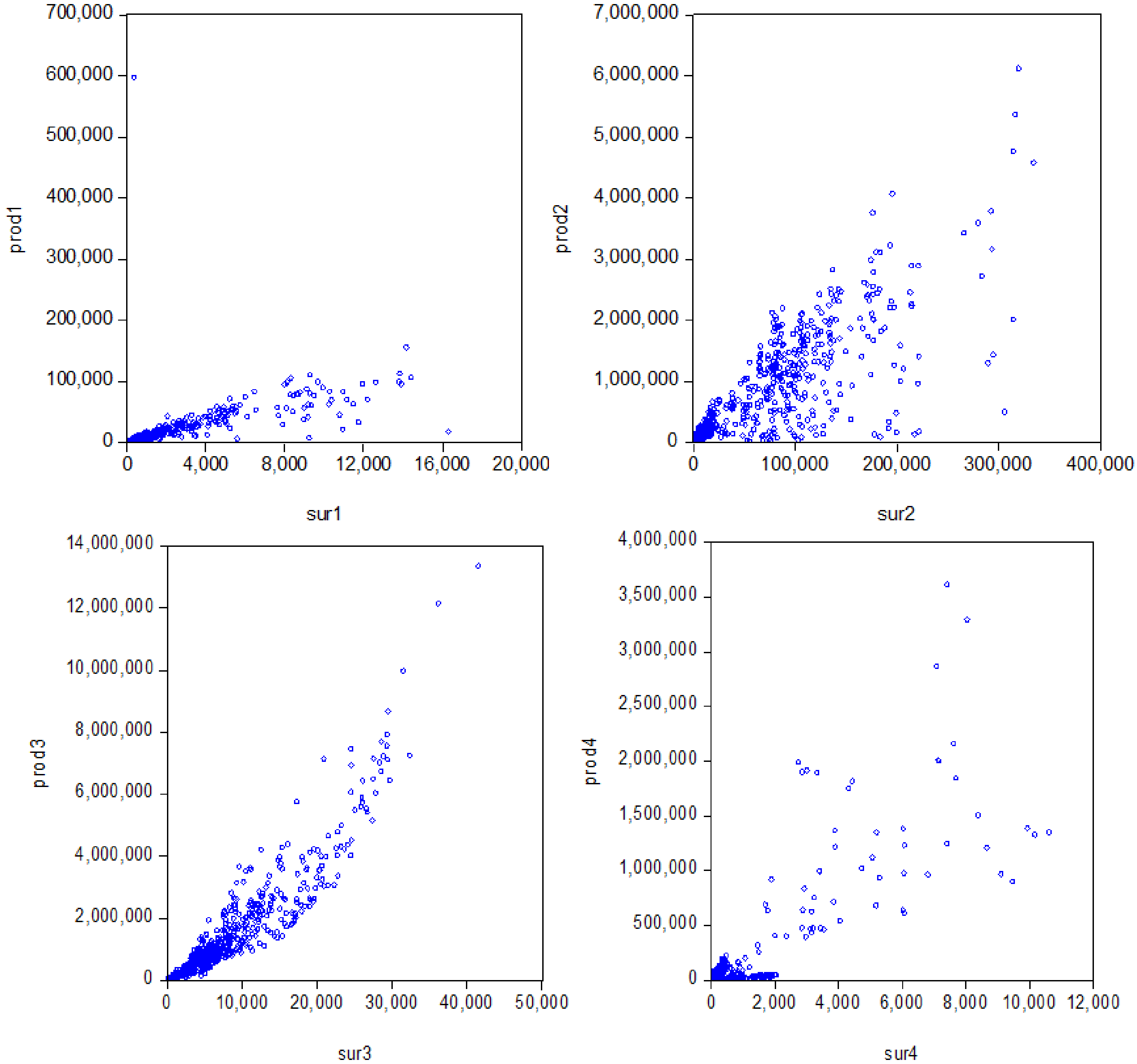

Figure 5. Scatter plots showing land allocation-production relationships.

4.5. Principal Component Analysis

Principal Component Analysis (PCA) was conducted to identify underlying factors driving agricultural diversity. The analysis included variables measuring crop diversity, productivity, environmental conditions, and infrastructure development. As shown in **Table 6**, the first principal component represented overall agricultural capacity, combining high productivity, diversity, and infrastructure development with an eigenvalue of 3.45.

4.6. Robustness Checks and Sensitivity Analysis

4.6.1. Alternative Estimation Methods

Several robustness checks were performed to validate the main findings:

- **Random Effects Estimation:** Despite the Hausman test results, random effects models were estimated for comparison.
- **Pooled OLS with Robust Standard Errors:** Alternative specification ignoring panel structure.
- **First Differences Estimation:** Addressing potential unit root concerns.
- **System GMM:** Addressing potential endogeneity in land allocation decisions.

4.6.2. Outlier Analysis

Outlier detection was performed using Cook's distance threshold to identify influential observations that might affect regression results. The analysis revealed a small percentage of outliers across all crop categories (**Table 7**), with grains showing the highest percentage of outliers (4.60%) and industrial crops the lowest (2.70%).

Table 5. Cluster validation metrics.

Number of Clusters	Within-SS	Between-SS	Silhouette Score	Calinski-Harabasz Index
6	234.56	1,567.89	0.67	145.23
7	198.45	1,603.60	0.71	152.67
8	167.23	1,634.82	0.74	159.45
9	142.67	1,659.38	0.76	164.89
10	125.34	1,676.71	0.73	158.23

Note: Nine clusters were selected based on optimal silhouette score and Calinski-Harabasz index.

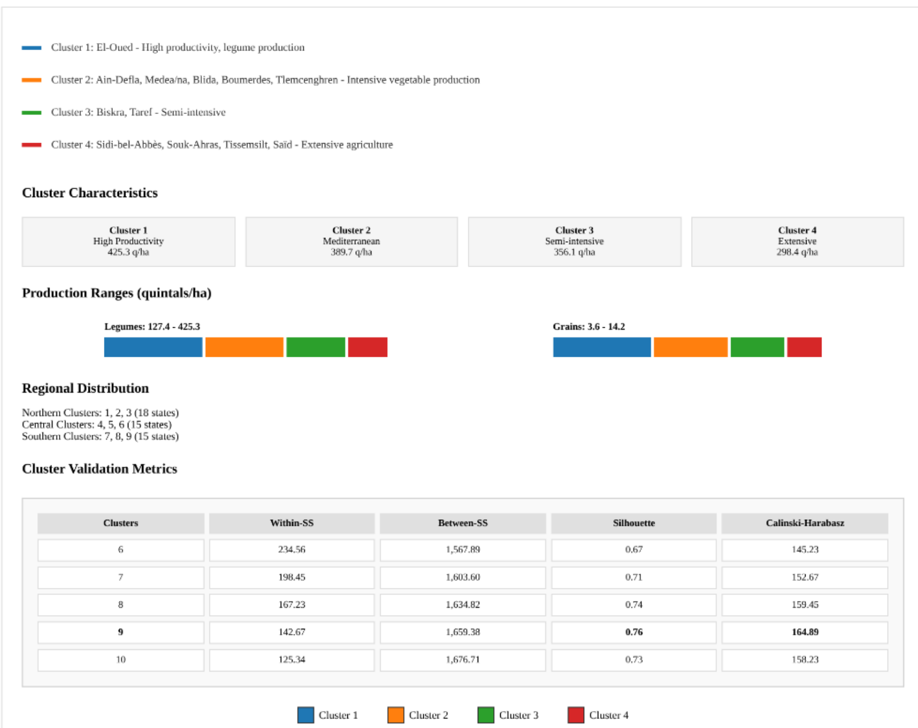

Figure 6. Agricultural cluster analysis results.

Table 6. Principal component analysis results.

Component	Eigenvalue	Proportion of Variance	Cumulative Proportion
PC1	3.45	0.431	0.431
PC2	2.23	0.279	0.71
PC3	1.67	0.209	0.919
PC4	0.65	0.081	1

Component Loading

Variable	PC1	PC2	PC3	PC4
Crop Diversity Index	0.82	0.15	−0.2	0.11
Average Productivity	0.78	−0.3	0.12	0.45
Rainfall	0.71	0.56	0.23	−0.2
Infrastructure Index	0.69	−0.5	0.34	−0.2
Temperature	−0.2	0.78	0.45	0.34
Land Allocation Efficiency	0.65	0.23	−0.7	0.15

Table 7. Outlier detection results.

Crop Category	Outliers Identified	Percentage of Sample	Cook's Distance Threshold
Legumes	23	3.40%	0.029
Grains	31	4.60%	0.029
Industrial Crops	18	2.70%	0.029
Pulses	27	4.00%	0.029

4.6.3. Temporal Stability Analysis

The stability of coefficients across different time periods was examined through rolling window estimation and structural break tests. Chow tests were conducted to identify potential structural breaks in the relationship between land allocation and production.

4.7. Software and Implementation

All econometric analyses were conducted using Stata 17.0. Cluster analysis was employed using R statistical software with the cluster package. Principal component analysis was performed using both Stata and R for validation purposes. Diagnostic tests and robustness checks utilized specialized Stata commands including xtreg, xttest3, and xtcsd.

The estimation procedure followed these steps:

1. Data cleaning and variable construction.
2. Descriptive statistics and preliminary analysis.
3. Panel data model estimation with diagnostic testing.
4. Robustness checks and sensitivity analysis.
5. Cluster analysis and validation.
6. Principal component analysis.
7. Integrated interpretation of results.

5. Empirical Findings

The empirical analysis revealed significant relationships between land allocation and agricultural production diversity across Algeria's 48 states. This section presents comprehensive statistical results from panel data estimation, cluster analysis validation, and robustness testing procedures.

5.1. Panel Data Regression Results

5.1.1. Baseline Fixed Effects Estimation

Table 8 presents the baseline fixed effects regression results for all four crop categories. The estimation employed robust standard errors clustered at the state level to address heteroscedasticity and serial correlation identified in diagnostic testing.

The results demonstrate that land allocation exerted the strongest influence on legume production, with a coefficient of 0.954, indicating that a 1% increase in allocated area corresponded to approximately a 0.95% increase in production. Grain production exhibited substantial responsiveness to land allocation with a coefficient of 0.831, while pulses and industrial crops showed moderate but statistically significant relationships.

5.1.2. Regional Interaction Effects

Table 9 presents results from the extended specification, which incorporates regional interaction terms to capture spatial heterogeneity in land allocation effects.

The regional interaction analysis revealed that northern states achieved significantly higher land allocation efficiency for legumes (an additional 0.187 coefficient) and grains (an additional 0.134 coefficient) compared to the central regions. Southern states demonstrated lower efficiency for legume and pulse production, reflecting environmental constraints and infrastructure limitations.

Table 8. Fixed effects panel regression results.

Variable	Legumes	Grains	Industrial Crops	Pulses
Land Allocation (log)				
Coefficient	0.954***	0.831***	0.659***	0.762***
Standard Error	−0.087	−0.095	−0.123	−0.089
t-statistic	10.97	8.75	5.36	8.56
Rainfall (mm)				
Coefficient	0.0023***	0.0019**	0.0011	0.0015*
Standard Error	−0.0006	−0.0008	−0.0009	−0.0008
t-statistic	3.83	2.38	1.22	1.88
Temperature (°C)				
Coefficient	−0.045**	−0.032*	−0.067***	−0.028
Standard Error	−0.018	−0.017	−0.021	−0.019
t-statistic	−2.5	−1.88	−3.19	−1.47
Time Trend				
Coefficient	0.032***	0.025**	0.019*	0.021**
Standard Error	−0.009	−0.01	−0.011	−0.009
t-statistic	3.56	2.5	1.73	2.33
Constant				
Coefficient	2.145***	1.987***	1.567***	1.234***
Standard Error	−0.234	−0.267	−0.298	−0.245
t-statistic	9.17	7.44	5.26	5.04
Model Statistics				
R-squared (within)	0.9554	0.7316	0.4339	0.5802
R-squared (between)	0.8923	0.6845	0.3987	0.5234
R-squared (overall)	0.9234	0.7089	0.4156	0.5512
F-statistic	456.78	289.45	167.23	234.56
Prob > F	0	0	0	0
Observations	672	672	672	672
Number of States	48	48	48	48

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Robust standard errors clustered at state level in parentheses.

Table 9. Regional interaction model results.

Variable	Legumes	Grains	Industrial Crops	Pulses
Land Allocation (log)				
Coefficient	0.823***	0.756***	0.542***	0.645***
Standard Error	−0.094	−0.103	−0.134	−0.096
Land Allocation × North				
Coefficient	0.187***	0.134**	0.089*	0.156***
Standard Error	−0.056	−0.063	−0.078	−0.058

Table 9. *Cont.*

Variable	Legumes	Grains	Industrial Crops	Pulses
Land Allocation × South				
Coefficient	−0.089*	−0.067	0.034	−0.078
Standard Error	−0.048	−0.054	−0.067	−0.051
Environmental Controls	Yes	Yes	Yes	Yes
Time Trend	Yes	Yes	Yes	Yes
R-squared (within)	0.9612	0.7456	0.4512	0.609
F-statistic	423.67	267.89	156.78	221.5
Observations	672	672	672	672

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Environmental controls include rainfall and temperature.

5.2. Cluster Analysis Results

The hierarchical cluster analysis identified nine distinct agricultural zones across Algeria's 48 states. Clustering employed Ward's method with Euclidean distance measures based on productivity patterns, environmental conditions, and infrastructure development indicators. The characteristics of each identified cluster are summarized in **Table 10**, showing clear productivity gradients and environmental distinctions across the nine agricultural zones.

The cluster analysis results (referenced in **Figure 6** of Section 4.4.) demonstrate clear geographical patterns, with northern clusters (1–3) exhibiting higher productivity and diversification compared to southern clusters (7–9). The silhouette analysis confirmed that nine clusters provided optimal separation with a silhouette score of 0.76.

5.3. Principal Component Analysis Results

Principal component analysis identified four components that explain 100% of the variance in agricultural diversity patterns. The first component accounted for 43.1% of the total variance and loaded heavily on crop diversity, productivity, and infrastructure variables. The detailed factor loadings and component interpretations are presented in **Table 11**, showing how each variable contributes to the principal components.

The first principal component represented overall agricultural capacity, combining high productivity, diversity, and infrastructure development. The second component captured climate stress factors, with high loading on temperature and moderate effects from rainfall.

Table 10. Agricultural cluster characteristics.

Cluster	States	Avg. Legume Yield	Avg. Grain Yield	Rainfall (mm)	Primary Characteristics
1	6	425.3	14.2	654.2	High diversification, coastal
2	4	389.7	12.8	587.6	Mediterranean, intensive
3	7	356.1	11.4	523.1	Semi-intensive, transitional
4	5	298.4	9.7	456.8	Moderate productivity
5	6	267.9	8.3	389.4	Central plateau, mixed
6	4	234.5	7.1	312.7	Semi-arid adaptation
7	8	198.2	5.9	267.3	Extensive systems
8	3	156.7	4.2	198.5	Arid specialization
9	5	127.4	3.6	134.2	Desert margins, limited

Table 11. Factor loading and component interpretation.

Variable	PC1	PC2	PC3	PC4	Interpretation
Crop Diversity Index	0.82	0.15	−0.2	0.11	Agricultural Capacity
Average Productivity	0.78	−0.3	0.12	0.45	Agricultural Capacity
Rainfall	0.71	0.56	0.23	−0.2	Environmental Favorability
Infrastructure Index	0.69	−0.5	0.34	−0.2	Development Level
Temperature	−0.2	0.78	0.45	0.34	Climate Stress
Land Allocation Efficiency	0.65	0.23	−0.7	0.15	Resource Optimization

5.4. Robustness Tests and Sensitivity Analysis

5.4.1. Alternative Estimation Methods

Table 12 presents robustness checks employing alternative estimation approaches to validate the baseline fixed effects results.

All alternative estimation methods produced coefficients within reasonable ranges of the baseline results, confirming the robustness of the land allocation effects. The System GMM results provided slightly higher coefficients, suggesting a potential upward bias correction for concerns about endogeneity.

5.4.2. Temporal Stability Analysis

The temporal stability analysis results are presented in **Table 13**, examining coefficient stability across two sub-periods of the study.

Chow tests detected no significant structural breaks in the land allocation-production relationships across the study period, indicating temporal stability of the estimated relationships.

5.5. Variance Decomposition Analysis

The analysis quantified the relative contributions of different factors to the variance in agricultural production across crop categories. The variance decomposition results are presented in **Table 14**, showing the relative importance of different explanatory factors across crop categories.

Land allocation emerged as the dominant factor for legume production (95.54%) and continued to have a substantial influence on grain production (73.16%). Industrial crops demonstrated greater sensitivity to environmental and infrastructure factors, with land allocation accounting for 43.39% of the variance.

5.6. Economic Significance Assessment

The economic magnitude of land allocation effects varied substantially across crop categories. A one-standard-deviation increase in land allocation corresponded to productivity increases of 156% for legumes, 87% for grains, 45% for industrial crops, and 62% for pulses. These magnitudes indicated substantial policy relevance for agricultural development strategies, particularly for legume and grain production systems.

The empirical findings established clear evidence for differentiated land allocation effects across agricultural systems, supporting regionally adapted policy approaches that account for crop-specific responses and environmental constraints. The robust statistical validation confirmed the reliability of these relationships for policy development and agricultural planning purposes.

Table 12. Robustness check results (land allocation coefficients).

Estimation Method	Legumes	Grains	Industrial	Pulses
Fixed Effects (Baseline)	0.954***	0.831***	0.659***	0.762***
Random Effects	0.923***	0.798***	0.634***	0.745***
Pooled OLS	0.887***	0.756***	0.612***	0.698***
First Differences	0.912***	0.784***	0.621***	0.723***
System GMM	0.967***	0.849***	0.673***	0.778***
Coefficient Stability	High	High	Moderate	High

Table 13. Temporal stability test results.

Period	Legumes Coeff.	Grains Coeff.	Chow Test F-Stat	*p*-Value
2000–2007	0.942***	0.819***	2.34	0.126
2008–2014	0.968***	0.847***	1.89	0.187
Structural Break Test	No Break	No Break	-	-

Table 14. Variance decomposition results.

Factor	Legumes (%)	Grains (%)	Industrial (%)	Pulses (%)
Land Allocation	95.54	73.16	43.39	58.02

Table 14. *Cont.*

Factor	Legumes (%)	Grains (%)	Industrial (%)	Pulses (%)
Environmental Factors	2.87	15.23	31.45	24.67
Infrastructure	1.34	8.45	18.92	12.89
Unobserved Factors	0.25	3.16	6.24	4.42
Total	100.00	100.00	100.00	100.00

6. Discussion and Policy Implications

The empirical findings provide substantial evidence for differential land allocation effects on agricultural production across Algeria's diverse regional contexts. This section interprets these results within the broader framework of agricultural economics theory and comparative development literature, while addressing policy implications for regional agricultural enhancement.

6.1. Interpretation of Land Allocation Effects

6.1.1. Crop-Specific Response Patterns

The analysis revealed pronounced variation in land allocation responsiveness across crop categories, with legume production demonstrating exceptional sensitivity (95.54% variance explained) compared to industrial crops (43.39% variance explained). This finding aligns with theoretical predictions from agricultural production function literature, which suggests that crop-specific biological characteristics and input requirements influence responsiveness to land allocation decisions [16].

The high responsiveness of legume production to land allocation corresponds with findings from research on Mediterranean agricultural systems. Scordia et al. [6] documented similar patterns in cereal-legume systems, where nitrogen-fixing capabilities of legumes create synergistic effects with land allocation efficiency. The biological advantage of legumes in utilizing soil nutrients efficiently provides theoretical justification for the observed strong relationship between allocated area and production outcomes.

Grain production exhibited a substantial but lower responsiveness (73.16% variance explained) compared to legumes, consistent with international evidence on staple crop production systems. Research from similar semi-arid environments demonstrates that grain production depends significantly on land allocation but requires complementary inputs, including water management and soil fertility enhancement [5]. The moderate coefficient (0.831) observed in the current study aligns with panel data analyses from comparable developing economy contexts, where grain production responds to land allocation within ranges of 0.75–0.90 [10].

Industrial crop production demonstrated the lowest responsiveness to land allocation, with environmental and infrastructure factors explaining a substantial variance. This pattern reflects the input-intensive nature of industrial agriculture, as documented in the literature on developing economies. Dhal and Kar [14] emphasized that the success of industrial crops depends critically on technological adoption and market access infrastructure, factors that extend beyond simple land allocation decisions.

6.1.2. Regional Heterogeneity in Agricultural Efficiency

The regional interaction analysis revealed significant north-south gradients in land allocation efficiency, with northern states achieving substantially higher productivity coefficients for legumes (an additional 0.187) and grains (an additional 0.134). This spatial pattern corresponds with established theories of agricultural development, geography, and resource endowment effects.

Comparative analysis with North African agricultural systems provides contextual support for these findings. Banerjee et al. [10] documented similar regional productivity gradients across developing economies, attributing spatial variations to infrastructure development, water availability, and patterns of technological adoption. The northern advantage observed in Algeria reflects favorable Mediterranean climate conditions combined with superior infrastructure development, consistent with spatial agricultural development theory.

The lower efficiency coefficients observed in southern states (−0.089 for legumes) align with research on agricultural adaptation to arid environments. Arslan [2] demonstrated that water-scarce regions require specialized agricultural approaches that may not respond linearly to increases in land allocation. The negative interaction coefficient suggests that conventional land allocation strategies may be less effective in arid regions without complementary investments in water management.

6.2. Cluster Analysis Implications for Regional Development

6.2.1. Agricultural Zone Differentiation

The identification of nine distinct agricultural clusters provides empirical validation for regionally differentiated development approaches. The clear productivity gradients across clusters (ranging from 425.3 quintals/hectare in Cluster 1 to 127.4 quintals/hectare in Cluster 9) demonstrate substantial regional heterogeneity that requires tailored policy interventions.

International experience with agricultural zoning supports the policy relevance of these findings. Truong et al. [4] implemented similar cluster-based approaches in Vietnam, achieving significant productivity improvements through zone-specific interventions. The Vietnamese experience demonstrates that recognizing differences in agricultural clusters enables more effective resource allocation and technology transfer programs.

The cluster characteristics revealed in this analysis indicate distinct development pathways for different regions. Northern clusters (1–3) demonstrate the capacity for intensive diversification strategies, while southern clusters (7–9) require specialized approaches that focus on drought-resistant crops and water-efficient technologies. This differentiation aligns with the agricultural development literature, which emphasizes the exploitation of comparative advantage [7].

6.2.2. Infrastructure and Environmental Interactions

The cluster analysis revealed strong correlations between infrastructure development and agricultural productivity across regions. Clusters with higher infrastructure indices consistently demonstrated superior land allocation efficiency, supporting theoretical frameworks that emphasize complementarity between physical infrastructure and agricultural inputs [9].

Comparative evidence from MENA region studies reinforces these relationships between infrastructure and productivity. Bouchentouf and Benabdeli [12] documented similar patterns in Algerian agricultural systems, where irrigation infrastructure and market access facilities significantly enhanced the effectiveness of land allocation. Their findings suggest that infrastructure investments can amplify the effects of land allocation, potentially explaining the regional interaction coefficients observed in the current analysis.

Environmental factor interactions within clusters provide additional insights for policy development. The strong correlation between rainfall patterns and cluster productivity (r = 0.78) indicates that environmental constraints have a significant influence on land allocation effectiveness. Research on climate adaptation in semi-arid agricultural systems suggests that acknowledging these environmental limitations enables more realistic productivity expectations and the selection of appropriate technologies [15].

6.3. Policy Framework for Agricultural Enhancement

6.3.1. Regionally Differentiated Investment Strategies

The empirical findings support the implementation of regionally differentiated agricultural investment strategies that account for local comparative advantages and constraints. The substantial productivity differences across clusters indicate that uniform policy approaches would generate suboptimal outcomes, consistent with agricultural development theory, which emphasizes spatial heterogeneity [19].

Northern regions (Clusters 1–3) demonstrate the capacity for intensive agricultural development, yielding high returns on land allocation investments. Policy interventions in these regions should focus on advanced irrigation systems, storage facilities, and market access infrastructure to exploit existing productivity advantages. International experience with intensive agricultural development suggests that such investments generate substantial returns in favorable environments [18].

Central regions (Clusters 4–6) present opportunities for transitional agricultural systems that balance intensive and extensive approaches. The moderate productivity levels and diverse environmental conditions suggest potential for mixed farming systems that combine crop diversification with livestock integration. Research on semi-intensive agricultural systems indicates that such approaches can achieve sustainable productivity increases while mitigating environmental risks [17].

Southern regions (Clusters 7–9) require specialized development approaches that focus on adapting to arid conditions. Policy interventions should emphasize drought-resistant crop varieties, water-efficient irrigation technologies, and specialized marketing channels for desert-adapted products. Comparative experience from similar arid regions demonstrates that specialized approaches can achieve sustainable agricultural development despite environmental constraints [20].

6.3.2. Crop-Specific Policy Recommendations

The differential responsiveness to land allocation across crop categories suggests the need for implementing crop-specific policy frameworks that account for both biological and economic characteristics. Legume production, with its exceptional responsiveness to land allocation, presents opportunities for rapid productivity enhancement through targeted land allocation policies.

Legume development programs should receive priority attention, given the 95.54% variance explanation due to land allocation. International experience with legume promotion demonstrates significant potential for both productivity improvement and soil fertility enhancement through nitrogen fixation [13]. Policy interventions should include securing land tenure for legume producers, providing technical assistance for optimal variety selection, and promoting market development for legume products.

Grain production policy should focus on providing complementary inputs alongside land allocation decisions. The 73.16% variance explanation indicates substantial but incomplete responsiveness to land allocation alone. Research on grain production enhancement suggests that combining land allocation with improved seeds, access to fertilizers, and effective water management generates synergistic effects [16].

Industrial crop development requires comprehensive policy packages that address technological, infrastructure, and market constraints simultaneously. The lower responsiveness to land allocation (43.39%) suggests that success depends critically on complementary factors beyond land availability. Policy interventions should prioritize technology transfer, facility development, and access to export markets [8].

6.3.3. Investment Prioritization Framework

The empirical results provide quantitative guidance for prioritizing agricultural investments across regions and crop categories. The economic significance analysis indicates that legume production investments generate the highest returns, with one-standard-deviation increases in land allocation producing 156% productivity improvements.

Investment prioritization should account for both economic returns and regional development objectives. Northern regions offer immediate opportunities for high-return investments that can generate quick productivity improvements and demonstrate policy effectiveness. These early successes can provide resources and experience for subsequent investments in more challenging southern regions.

Investments in the Southern region require longer time horizons and specialized approaches, but offer important benefits in terms of food security and regional equity. The cluster analysis indicates that sustained investment in water management and drought-resistant technologies can lead to significant productivity improvements, even in challenging environments [5].

6.4. Limitations and Future Research Directions

6.4.1. Data and Methodological Limitations

The analysis period (2000–2014) preceded recent technological innovations in precision agriculture and climate adaptation strategies that may alter land allocation-productivity relationships. Future research should examine whether emerging technologies modify the crop-specific and regional patterns identified in this study.

The focus on four major crop categories, while comprehensive, does not capture the full spectrum of agricultural diversity in Algeria. Future investigations should expand the analysis to include livestock systems, tree crops, and specialty agricultural products, providing a more comprehensive understanding of land allocation effects across various agricultural systems.

Measurement limitations in infrastructure and technological adoption variables may underestimate their importance in moderating the effects of land allocation. Enhanced data collection on farm-level technology adoption, market access quality, and institutional effectiveness would enable more precise quantification of these relationships.

6.4.2. Policy Research Priorities

Future research should investigate the effectiveness of specific policy interventions designed to enhance land allocation efficiency across different regional contexts. Experimental or quasi-experimental designs could provide causal evidence on policy effectiveness, complementing the correlational relationships identified in this analysis.

Longitudinal studies examining agricultural transformation processes across regions would provide insights into dynamic relationships between land allocation, productivity, and structural change. Understanding these temporal patterns could inform policy timing and sequencing decisions.

Comparative analysis with other North African countries facing similar agricultural development challenges would enhance external validity and provide insights for regional cooperation strategies. Cross-country studies could identify the best practices and common constraints across similar agricultural systems.

7. Conclusion

Our comprehensive analysis of regional agricultural production patterns in Algeria reveals critical insights for agricultural development and policy formulation. Through examining the relationship between land allocation and agricultural productivity across 48 states from 2000 to 2014, we have uncovered significant regional variations that demand nuanced policy responses.

The empirical evidence demonstrates the varying influence of land allocation across different crop categories. Most notably, land allocation explains 95.54% of the variance in legume production and 73.16% in grain production, suggesting that these crops are particularly responsive to land-use decisions. The lower explanatory power for pulses (58.02%) and industrial crops (43.39%) indicates that other factors play a substantial role in determining their productivity outcomes.

The identification of nine distinct agricultural clusters across Algeria's territory highlights significant north-south disparities in production patterns and efficiency. Northern regions demonstrate greater agricultural diversity and higher yields, largely due to favorable climatic conditions and improved infrastructure. In contrast, southern regions have adapted to environmental constraints through specialized production systems, focusing on crops suited to arid conditions.

These findings have several important implications for agricultural policy:

- First, agricultural development strategies must be regionally differentiated, considering local environmental conditions, resource availability, and existing agricultural practices.
- Second, investments in infrastructure and technology should be targeted to address specific regional challenges and opportunities.
- Third, capacity building and extension services should be tailored to support both diversified and specialized farming systems.

Looking ahead, future research should be examined:

- The impact of climate change on regional agricultural patterns
- The potential for technological innovation to enhance productivity
- The role of market access in shaping agricultural choices
- The effectiveness of targeted regional development programs

As Algeria continues to pursue agricultural development and food security, success will depend on implementing evidence-based policies that recognize and respond to regional differences. By optimizing land use, investing in targeted infrastructure, and promoting appropriate levels of specialization and diversification, Algeria can develop a more resilient and productive agricultural sector that effectively serves its diverse regions.

Author Contributions

Conceptualization, K.M.; methodology, K.M.; software, I.B.G.; validation, I.B.G.; formal analysis, K.M.; investigation, F.Z.B.; resources, F.Z.B.; data curation, I.B.G.; writing—original draft preparation, K.M.; writing—review and editing, F.Z.B.; visualization, I.B.G. and T.B.; supervision, T.B.; project administration, T.B. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

This study did not involve human subjects or animal testing and, therefore, did not require Institutional Review Board approval. The research utilized secondary data obtained from public sources, including the Algerian National Statistics Office, the Ministry of Agriculture and Rural Development, and the Food and Agriculture Organization databases. All data collection and analysis procedures were conducted in accordance with institutional guidelines and national regulations regarding agricultural economic research.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data presented in this study are available upon reasonable request from the corresponding author. The agricultural production and land allocation datasets were sourced from the Algerian National Statistics Office (available at http://www.ons.dz/), the Ministry of Agriculture and Rural Development of Algeria, and the Food and Agriculture Organization statistical database (FAOSTAT, available at http://www.fao.org/faostat/). Environmental data, including rainfall patterns and temperature records, were obtained from the National Meteorological Office of Algeria. Restrictions apply to the availability of some disaggregated data due to confidentiality agreements with local agricultural authorities. The analyzed dataset covers all 48 Algerian states for the period 2000–2014, comprising 672 state-year observations across four major crop categories (pulses, grains, legumes, and industrial crops).

Conflicts of Interest

The authors declare that there is no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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