Tropentag 2025
September 10-12, 2025
Conference on International Research on Food Security, Natural Resources Management and Rural Development
Organised by the University of Bonn, Bonn, Germany

Resilient Land Use and Food Security in Afghanistan: A Mathematical-Econometric Framework for Sustainable Agriculture

Mojtaba Nikzad[a], Eva Gerharz[b]

a Hochschule Fulda (Fulda University of Applied Sciences), Dept. of Social and Cultural Sciences, Fulda, Germany, E-mail: mojtaba.nikzad@sk.hs-fulda.de[1]
b Hochschule Fulda (Fulda University of Applied Sciences), Dept. of Social and Cultural Sciences, Fulda, Germany

Abstract

In Afghanistan, where resource constraints, economic instability, and climate variability limit agricultural productivity, food security and sustainable land use continue to be major issues. In order to optimise land use and assess the effects of policy interventions on food security over the period 2000–2025, this study combines econometric modelling and mathematical programming. In order to ascertain the best distribution of land resources among important crops, a multi-objective non-linear programming (MONLP) model is created, taking into account limitations like labour supply, soil fertility, water availability, and economic profitability. Concurrently, the relationship between agricultural policies, market dynamics, and food security indicators over the previous 25 years is examined using an econometric panel data analysis (fixed and random effects models). Both primary and secondary data are used in the study. Structured farmer surveys in various agroecological zones of Afghanistan are used to collect primary data, which includes factors like farm size, crop yield, input costs, and climate adaptation strategies. FAO databases, World Bank indicators, national agricultural reports, and remote sensing data on land use changes are some of the sources of secondary data. Land-use configurations that optimise food production while reducing environmental degradation are identified by the MONLP model. The econometric analysis evaluates how important policy measures, such as trade regulations, irrigation infrastructure, extension services, and input subsidies, affect agricultural sustainability and food security. According to preliminary research, the best land allocation techniques can reduce soil degradation and water stress by 15–25 % and increase food security by 18–36 %. The econometric findings show that while poorly thought-out subsidy schemes may distort production incentives, targeted policies like better irrigation management and market access programmes greatly increase agricultural resilience. This study offers policymakers practical insights, highlighting the necessity of: (1) developing policies for climate-smart agriculture; (2) investing in effective water management systems; (3) strengthening rural credit and insurance programs; (4) promoting crop diversification to reduce risk; and (5) enhancing regional trade cooperation to stabilise food markets. This study provides a solid foundation for developing sustainable agricultural strategies in Afghanistan and other resource-constrained economies by integrating quantitative modelling with empirical policy evaluation.

Keywords: Afghanistan, agricultural sustainability, econometrics, food security, land use optimisation, mathematical programming, policy evaluation

[1] **Contact Address:** Mojtaba Nikzad, Hochschule Fulda (Fulda University of Applied Sciences), Dept. of Social and Cultural Sciences, Leipziger straße 123, 36037 Fulda, Germany, e-mail: mojtaba.nikzad@sk.hs-fulda.de

Introduction

Afghanistan's agricultural sector remains the backbone of rural livelihoods, food provision, and economic subsistence for nearly 70% of its population (Doudiyal, 2024). Yet, over the past two decades, structural constraints—including protracted conflict, institutional fragility, climate variability, and weak infrastructure—have significantly eroded agricultural productivity and sustainability. As a result, the country continues to grapple with widespread food insecurity, inefficient land use, and environmental degradation (Yar & Zazia, 2024; Safi et al., 2024).

Despite efforts by the government and international donors to stabilize the sector, challenges such as soil depletion, inefficient irrigation, lack of access to credit and markets, and vulnerability to global food price fluctuations persist. These challenges are compounded by rapidly changing climatic conditions, such as increased drought frequency and erratic precipitation, which further threaten the resilience of agricultural systems (Zahir et al., 2024). Food security and optimal land use are deeply interlinked in fragile contexts such as Afghanistan, where arable land is limited, resource management is inefficient, and policy interventions often lack coordination or evidence-based grounding (Davidson, 2025).

The absence of robust planning tools to guide land allocation and limited empirical evaluation of agricultural policies has hampered the formulation of coherent strategies to enhance productivity and food security. Furthermore, most previous studies on Afghan agriculture focus either on descriptive assessments or single policy domains, without integrating quantitative optimization models with empirical policy evaluation. This fragmented approach fails to address the complex trade-offs that policymakers must consider between environmental sustainability, economic profitability, and food self-sufficiency.

This study addresses these critical gaps by adopting a dual-method approach. First, it introduces a multi-objective non-linear programming (MONLP) model to determine optimal land allocation strategies for major crops, taking into account biophysical constraints (e.g., water availability, soil fertility), socio-economic conditions (e.g., labor availability, market prices), and environmental considerations. Second, the study employs panel econometric techniques—including fixed and random effects models—to evaluate the impact of agricultural policies on food security indicators over the period 2000–2025, using a rich dataset of both primary and secondary sources.

This integrated modelling approach offers a holistic framework to answer key policy questions: Which land-use configurations yield the greatest food security gains under environmental and economic constraints? Which agricultural policies have historically improved resilience, and which have introduced distortions or unintended consequences? How can resource allocation be optimized to ensure long-term sustainability in Afghanistan's vulnerable agroeconomic zones?

The significance of this study lies not only in its methodological contribution but also in its direct applicability to policy formulation. By aligning land-use decisions with empirical evidence on policy effectiveness, this research provides actionable insights for Afghan policymakers, international donors, and development practitioners working to rebuild Afghanistan's agricultural sector. Furthermore, the findings have broader implications for similarly resource-constrained and climate-vulnerable economies in the Global South, where the trade-offs between food security, economic growth, and sustainability are increasingly urgent. In doing so, this research responds to the growing call for climate-smart agriculture, adaptive land management, and data-driven policymaking. It moves beyond conventional descriptive studies by offering a quantitative and operationalizable strategy to enhance food security, reduce land degradation, and improve the efficiency of agricultural investments in a fragile and high-risk context. This dual-framework methodology—blending mathematical programming and econometric evaluation—provides a replicable template for other post-conflict or transitional economies facing similar policy dilemmas.

Materials and Methods

This study employs an integrated methodological approach combining multi-objective nonlinear programming (MONLP) and panel econometric analysis to optimize land allocation and assess the impact of agricultural policy interventions on food security in Afghanistan (period 2000–2025).

Mathematical Programming Model: The MONLP model (Miettinen, 1999) determines the optimal land allocation among major crops by maximizing a weighted combination of objectives, including food production, economic profitability, and environmental sustainability. The General formulation is:

$$\propto_i f_i(x) \sum_{i=1}^{n} = \max Z$$

Where $\boldsymbol{f_i(x)}$ represents objective functions such as crop yield, net returns, and environmental indicators (e.g., water stress index, input-output profitability ratio, and soil erosion rate), and $\propto_i$The weights assigned to each objective are based on policy priorities.

The model incorporates a comprehensive set of constraints reflecting the real-world resource and structural limitations of Afghanistan's agricultural sector. These include total cultivable land differentiated by agroecological zones and crop suitability; water resource availability including irrigation capacity and seasonal rainfall variability; labor availability during peak agricultural periods; capital access for financing machinery, inputs, and irrigation infrastructure; affordability and availability of key inputs such as fertilizers, improved seeds, fuel, and pesticides; soil fertility status and erosion sensitivity; access to improved technologies and mechanization; and market-related requirements, including local consumption thresholds and contract farming obligations. The model is solved using GAMS and MATLAB software environments.

Econometric Model: To empirically evaluate how agricultural policy and macroeconomic variables influence food security, a panel regression model (Baltagi, 2008) is estimated using both fixed effects and random effects approaches across Afghanistan's 34 provinces from 2000 to 2025. Independent variables include policy instruments such as irrigation infrastructure, extension services, and input subsidies, alongside macroeconomic and climatic indicators. Food security is proxied through caloric availability, crop diversity indices, and poverty-adjusted food access metrics. Model diagnostics—including the Hausman test, Breusch-Pagan Lagrange Multiplier, and Variance Inflation Factor (VIF)—were used to guide model specification and test for multicollinearity. Robust standard errors were applied to correct for heteroskedasticity and serial correlation, ensuring reliable statistical inference.

This study integrates annual time-series and spatial datasets from a diverse range of reputable sources, including: the Afghan Ministry of Agriculture, Irrigation and Livestock (MAIL); the National Statistics and Information Authority (NSIA); the Food and Agriculture Organization (FAO); the World Bank World Development Indicators (WDI); high-resolution remote sensing data (e.g., MODIS, CHIRPS); national agricultural surveys and reports; and custom-designed structured farmer surveys across major agroeconomic zones (Nikzad et al., 2022). These sources jointly provide the essential data required on crop yields, land use dynamics, input costs, climate variability, policy interventions, and socioeconomic indicators for both modeling and empirical analysis.

Results and Discussion

The integrated MONLP and panel econometric analysis offers compact yet comprehensive insight into land-use optimization and food security in Afghanistan (2000–2025). The MONLP model, constrained by land, water, labor, capital, input access, soil fertility, and technology, shows that shifting land toward drought-tolerant, high-value crops can improve food production efficiency by 20%, raise net income by 15–22%, and reduce environmental pressures like erosion and water stress by 15–25%. It captures trade-offs between short-term gains and long-term sustainability, emphasizing the role of local labor availability, capital for mechanization and irrigation, and region-specific soil and market conditions. The econometric model, using provincial panel data and variables such as irrigation, extension, subsidies, credit access, market integration, climate

anomalies, and price volatility, finds that targeted policies (notably irrigation and advisory services) significantly improve yields and dietary energy supply. While well-designed subsidies and rural credit access enhance productivity and resilience, poorly targeted ones create inefficiencies. Climate variability consistently undermines food security outcomes. Model diagnostics confirm robustness and correct specification.

Given space limitations, this summary cannot include detailed results, crop-level outputs, or regional policy simulations. Still, findings cover all methodological variables and confirm the benefit of combining optimization and empirical policy analysis. Together, they underscore the need for context-specific strategies balancing resource limits, economic viability, and environmental goals.

Conclusions and Outlook

Findings highlight those sustainable improvements in agricultural productivity and food availability depend on optimizing land use under real-world constraints and applying evidence-based policy interventions to enhance resilience against climatic and market shocks. While detailed outputs—such as crop-specific outcomes and provincial-level policy scenarios—are beyond this summary's scope, the integrated framework provides robust empirical evidence on resource allocation strategies and their effects on food security. Taken together, the results underscore the importance of precise policy targeting: aligning the allocation of land, labor, and inputs with agroecological conditions, and ensuring institutional investments in irrigation, rural finance, and agricultural services are context-specific and resilience-focused. This provides a solid quantitative foundation for designing sustainable, regionally adaptive agricultural strategies in Afghanistan's fragile and resource-constrained environment. From a policy perspective, five interlinked recommendations emerge: (1) scale up climate-smart agriculture tailored to specific agroecological zones; (2) expand investment in efficient, equitable irrigation and water management systems; (3) strengthen rural credit access and risk-sharing mechanisms for smallholders; (4) promote crop diversification to reduce vulnerability and stabilize rural incomes; and (5) foster regional trade coordination to improve food market stability. Overall, this research delivers a replicable, data-driven framework for guiding agricultural transformation and food security planning in similarly vulnerable economies facing complex environmental and institutional constraints.

References

1. Baltagi, B. H. (2008). Econometric analysis of panel data. *Rohn Wiley*.
2. Davidson, A. A., O'Connor, P. J., Leake, J., & Zeng, D. (2025). Striving for Food Security in a Fragile and Conflict-Affected Situation: The Unintended Consequences of Delivering Intended Outcomes in Afghanistan. *Available at SSRN 5226522*.
3. Doudiyal, M. B. (2024). The Capacity of Afghanistan's Economy, Agriculture Sector, and Essential Future Contrivances. In *The Failure of a Pseudo-Democratic State in Afghanistan: Misunderstandings and Challenges* (pp. 243-263). Cham: Springer Nature Switzerland.
4. Miettinen, K. (1999). *Nonlinear multiobjective optimization* (Vol. 12). Springer Science & Business Media
5. Nikzad, M., Hosseini, S. S., Salami, H., Chizari, A. H., and Ahady, A. (2022). Evaluation and Analysis of Comparative Advantages, Competitiveness, and the Effects of Supportive Policies on Selected Products of Afghanistan's Economic-Agricultural Zones. *Iranian Journal of Agricultural Economics and Development Research*, *53*(2), 301-323. doi: 10.22059/ijaedr.2021.315282.668985
6. Safi, L., Mujeeb, M., Sahak, K., Mushwani, H., & Hashmi, S. K. (2024). Climate change impacts and threats on basic livelihood resources, food security and social stability in Afghanistan. *GeoJournal*, *89*(2), 85.
7. Yar, F. G. M., & Zazia, J. G. (2024). Obstacles and Challenges of Rural Development in Afghanistan: Examining Problems and Solutions: A Review. *Formosa Journal of Multidisciplinary Research*, *3*(9), 3639-3656.
8. Zahir, A., Nasim, M., Jauhar, S., Naseri, E., Sarwary, A., Noor, A., ... & Hamdard, E. (2024). The Role of Livestock Resources in Sustainable Food Security and Livelihoods in Afghanistan. *Journal of Natural Science Review*, *2*(Special Issue), 495-516.