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Learning from Neighboring Communities: A Spatial Analysis of Improved Seed Adoption

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“Aprendiendo de Comunidades Vecinas: Análisis Espacial sobre la Adopción de Semillas Mejoradas”

Resumen

Esta investigación analiza cómo las interacciones espaciales entre comunidades vecinas influyen en las decisiones sobre la proporción de adopción de semillas mejoradas en zonas rurales de Malawi. Usando datos panel georreferenciados a nivel comunitario entre 2010 y 2019, se abordan dos preguntas: (1) cómo las interacciones espaciales influyen en la proporción de adopción de semillas mejoradas, incluyendo si determinantes financieros clave generan efectos de derrame; y (2) cómo los shocks de sequía afectan la magnitud y dirección de estos efectos entre pares. Para cuantificar estas interacciones se estima un Modelo de Rezago Espacial (SLM), cuyos resultados muestran que el comportamiento de las comunidades vecinas influye significativamente en las tasas locales de adopción. Niveles más altos de adopción en comunidades cercanas se asocian con mayor adopción local, confirmando la existencia de efectos entre pares. Además, se encuentra que el acceso a subsidios para semillas (cupones) no solo promueve la adopción dentro de la comunidad, sino que también genera efectos positivos en comunidades vecinas, lo que destaca el potencial de intervenciones focalizadas para lograr impactos regionales amplificados. Para abordar la segunda pregunta, se incorpora la variabilidad climática mediante el Índice Estandarizado de Precipitación y Evapotranspiración (SPEI), con el fin de analizar si los shocks de sequía modifican la dinámica de los efectos entre pares. Utilizando un enfoque de variables instrumentales, los resultados muestran que dichos shocks no alteran significativamente el grado de influencia entre comunidades, lo que sugiere que los efectos entre pares se mantienen relativamente estables incluso ante condiciones climáticas adversas.

Palabras Clave

Adopción de semillas mejoradas, econometría espacial, efectos entre pares, shocks de sequía, aprendizaje social, Modelo de Rezago Espacial (SLM), Malawi, difusión tecnológica, agricultura de pequeños productores, variables instrumentales.

“Learning from Neighboring Communities: A Spatial Analysis of Improved Seed Adoption”

Abstract

This study investigates how spatial interactions between neighboring communities influence decisions regarding the proportion of improved seed adoption in rural Malawi. Using georeferenced community panel data from 2010 to 2019, the study explores two key research questions: (1) how spatial interactions with neighboring communities influence the proportion of improved seed varieties adopted, including whether key financial determinants have spillover effects on adoption, and (2) how drought shocks affect the strength and direction of these peer effects. A Spatial Lag Model (SLM) is estimated to quantify this spatial interaction, where results show that neighboring communities’ behavior significantly influences local adoption rates. Higher adoption levels in neighboring areas are associated with significantly higher local adoption rates, confirming the presence of peer effects across communities. However, the influence of neighboring communities extends beyond their own adoption behavior alone. The analysis shows that access to seed subsidies (coupons) not only drive local adoption but also spill over to influence adoption patterns in nearby communities, underscoring the potential of targeted interventions to generate broader regional impact. To address the second question, the analysis incorporates climate variability using the Standardized Precipitation Evapotranspiration Index (SPEI), which allows for the examination of how drought shocks alter the dynamics of peer effects in the adoption process. Using an instrumental variables approach, the analysis finds that these shocks do not significantly alter the degree to which neighboring communities influence each other’s adoption behavior, suggesting that peer effects remain relatively stable even under adverse weather conditions.

Keywords

Improved seed adoption, spatial econometrics, peer effects, drought shocks, social learning, Spatial Lag Model (SLM), Malawi, technology diffusion, smallholder agriculture, instrumental variables.

Códigos JEL: C31, C33, C36, Q12, Q15, Q24, Q54.

1 Introduction

The adoption of new technologies has become crucial in tackling climate change, especially for those regions facing socioeconomic adversities. Sub-Saharan Africa (SSA) continues to face profound challenges as the most food-insecure region in the world, exacerbated by the limited adoption of advanced technological interventions (Arslan et al., 2016). Smallholder agriculture remains the primary driver of economic growth in most SSA countries, yet it is also the most vulnerable to the adverse effects of climate change (Barrios et al., 2008). Adopting improved seed varieties has been shown to increase agricultural productivity, accounting for about 50–90% of global crop yield increase (Kafle, 2010). The likelihood of SSA farmers adopting new improved seed varieties and becoming aware of new agricultural technology is still very limited. Indeed, information, or the lack thereof, is often found to be the most important factor limiting rural development among farmers and communities (Fang and Richards, 2018).

The decision to adopt improved seed varieties is heavily influenced by both farmers and community characteristics. According to research, factors such as access to seeds, extension services, labor availability, and the location of farm households play a crucial role in determining adoption rates (Martey et al., 2020). Additionally, characteristics like farm size and membership in farmer organizations have been found to positively impact the adoption of improved seed varieties. The latter characteristic enhances access to information and facilitates collective action, which strengthens the dissemination of agricultural technologies and encourages broader adoption of new practices (Kalinda et al., 2014). Furthermore, seed scaling programs implemented through community institutions have been shown to significantly increase adoption rates compared to non-collective approaches (Hossain et al., 2024), highlighting the importance of community structures in the adoption process.

The influence of neighboring farmers and communities plays a pivotal role in the adoption of improved seed varieties. Social learning, or learning by observing others, has been identified as a key mechanism that increases the likelihood of adoption (Fang and Richards, 2018; Läpple and Kelley, 2015; Singha, 2019; Zheng et al., 2021; Ward and Pede, 2015). Farmers tend to cluster around similar practices, where the decisions of neighboring farmers significantly impact their own choices regarding seed adoption. In addition, Fang and Richards (2018) showed that local networks act as important agents for information exchange, where farmers significantly weigh their immediate neighbors' opinions in their decision-making. They also go beyond immediate neighbors to exploit extended social networks for gathering information. This spatial dependency is critical, as interactions within these networks facilitate the diffusion of information, leading to higher adoption rates.

These social learning dynamics and interactions with neighboring communities are commonly referred to as peer effects. As defined by Bramoullé et al. (2020), peer effects occur when individuals are influenced by others across various dimensions and contexts, meaning

that the behavior, choices, or outcomes of peers affect one's own decision-making process. In the context of agricultural technology adoption, peer effects can emerge through mechanisms such as social learning, conformity to local norms, or social pressure, where farmers adapt their behavior based on what others in their community are doing. However, identifying causal peer effects poses a significant empirical challenge. The reflection problem, as outlined by Manski (1993), arises when it becomes difficult to determine whether individuals are truly influencing each other, reacting to a common external factor, or simply exhibiting similar behavior due to self-selection into the same environment. To address this challenge, the present study applies spatial econometric techniques, which allows for the control of unobserved spatial correlation and the isolation of the effect of neighboring communities on local adoption decisions. By explicitly modeling spatial interactions, this study intends to provide more credible evidence on peer effects and gain a deeper understanding of how these dynamics shape the diffusion of improved seed varieties.

The interaction effect of social learning offers valuable insights into how neighboring communities influence decisions regarding the quantity of improved seed varieties used. Based on the literature, a positive spatial dependence effect when a community follows the practices of its neighbors is anticipated; whereas a negative spatial dependence effect is expected when it diverges from them. Social learning is expected to operate through spatially embedded networks, where interactions are shaped not only by shared knowledge and behaviors but also by financial factors. In this context, financial spillover effects, such as access to credit and seed coupons in neighboring communities, can serve as important channels through which peer dynamics influence local adoption behavior.

Smallholder farming systems are accustomed to coping with many challenges, including climate variability (Nordhagen and Pascual, 2013). However, climate change may pose formidable novel challenges for which traditional livelihood strategies may not be fully suited (FAO, 2008). Some of the key adaptation strategies that have been studied in the literature include: switching toward crop varieties resistant to heat and drought, development and adoption of new cultivars, changing the farm portfolio of crops and livestock, integrating the use of forecasts into cropping decisions, uses on fertilizers and irrigation, increased storage of food/feed or reliance on imports, and many more (Nordhagen and Pascual, 2013). Under drought shocks, farmer's seed security becomes profoundly influenced. Seed security is often defined by the three parameters of availability (seed being available in space and time), access (physical and economic access), and utilization (seed quality meets user's needs and preferences) (Makate et al., 2023; Sperling et al., 2008; McGuire and Sperling, 2016). Seed purchasing and the quantity of what seed variety to use enables the farmer and farmer communities to respond to negative factors that result in chronic and temporary seed insecurity, like drought shocks. Some studies have found that drought shock exposure in prior seasons increases seed purchasing for both improved and local seeds in Malawi and Tanzania, while in Ethiopia, local seed purchases are favored to the

detriment of improved seeds (Makate et al., 2023). Others found that having experienced an adverse weather-related shock had a significantly positive impact on the likelihood of farmers purchasing local seeds (Nordhagen and Pascual, 2013). Following this line, a study in Kenya found that frequent past climatic shocks, as manifested by drought incidence, reduce the maize area share per farm allocated to hybrid seeds (Bozzola et al., 2018). Building on this literature, it is anticipated that a drought shock during the previous rainy season, when crops are grown, will increase the likelihood of farmers purchasing local seeds. However, there is a gap in understanding how such drought shocks might alter the influence of neighbors on farmers' decision regarding the quantity of seed varieties to use.

This study focuses on Malawi, a representative case within Sub-Saharan Africa where agriculture plays a central role in economic development and poverty alleviation. It aims to: (1) assess how spatial interactions with neighboring communities influence the proportion of improved seed varieties adopted, including whether key financial determinants have spillover effects on adoption, and (2) examine how drought shocks shape the dynamics of peer effects on adoption, using georeferenced panel data from 2010 to 2019.

The key contribution of this study lies in the explicit use of spatial econometric techniques to identify and quantify peer effects in the adoption of improved seed varieties, something that has not yet been explored in the context of Malawi. While previous studies have acknowledged the role of social networks and neighborhood effects in technology adoption, they have largely relied on non-spatial methods, such as regression models with interaction terms or qualitative case studies, e.g., Makate et al. (2023); Kalinda et al. (2014); Hossain et al. (2024). In contrast, this study uses a Spatial Lag Model (SLM) to formally capture spatial dependence and spillover effects in adoption behavior across georeferenced communities. A novel aspect of this study is its focus on community-level dynamics, rather than individual farmer decisions (Fang and Richards, 2018; Läpple and Kelley, 2015; Li et al., 2021; Zheng et al., 2021; Skevas et al., 2018), allowing for the exploration of how the behavior of neighboring communities influences collective adoption outcomes. Furthermore, this study is among the first to examine how climatic shocks, specifically droughts, interact with spatial effects, providing new insights into how environmental stress reshapes local decision-making processes through peer influence.

The study is organized as follows. Section 2 presents the methodological framework, including the construction of spatial weight matrices, testing for spatial dependence, and the estimation strategy using spatial econometric models. Section 3 provides background information on Malawi, highlighting its agricultural context and vulnerability to climate shocks, and describes the data source. Section 4 presents the descriptive statistics. Section 5 reports the main results of peer effects on improved seed adoption. Section 6 presents further results, examining whether drought shocks shape the dynamics of peer effects on adoption. Section 7 presents robustness checks to validate the main findings. Finally, Section 8 concludes with a

summary of the results and policy implications.

2 Methodology

This section presents the methodological framework used to analyze spatial dependence in the adoption of improved seed varieties across rural communities in Malawi. The analysis is based on spatial panel econometric techniques, which are well-suited to identify how adoption decisions in one community are influenced by those in neighboring areas over time. This study begins by presenting the spatial econometric model used to study how spatial interactions with neighboring communities influence the proportion of improved seed varieties adopted. Next, it constructs spatial weight matrices to formally capture geographic relationships between communities, and applies Moran's I test to assess the presence of spatial autocorrelation. Preliminary tests would be done to explore whether additional spatial components should be incorporated into the analysis of improved seed adoption, such as Lagrange Multiplier (LM) and Likelihood Ratio (LR) tests. The study estimates the spatial model using Maximum Likelihood, allowing it to formally quantify peer effects and capture spatial spillovers in the adoption process.

2.1 Empirical Framework - SLM Model

The decision of a community to adopt an improved seed variety is ultimately an investment decision, often made under uncertainty. In making this choice, the behavior of neighboring communities plays a crucial role: what others decide influences, directly or indirectly, a community's own willingness to adopt. These spatial interactions, whether through observation, shared information, or social influence, shape the adoption decision, introducing what is commonly referred to as a peer effect. Based on this idea, this study assumes that the decision to adopt an improved seed variety is part of a spatially dependent process. To formally account for this spatial dependence, it uses a Spatial Lag Model (SLM), which is specified as follows:

$$y_{it} = \rho \sum_{j=1, j \neq i}^n w_{ij} y_{jt} + x_{it} \beta + u_{it}, \quad (1)$$

where y_{it} is the proportion of improved seeds adopted by a community i in the period t ; $\sum_{j=1, j \neq i}^n w_{ij} y_{jt}$ represents the spatial lag of dependent variable, where the elements w_{ij} 's are different to zero if the communities j (from 1 to n , the number of cross-section units) and i are neighbors, and zero otherwise; ρ captures the spatial autoregressive coefficient. The x_{it} is a vector of order k with community's characteristics of i th in the period t , with its corresponding β coefficients. Finally, the u_{it} refers to the error term.

The key elements of equation (1) are the weights w_{ij} , which can be represented in the form of an $n \times n$ matrix \mathbf{W} , known as the spatial weighting matrix. The i th row of \mathbf{W} will have only the number nonzero elements $w_{i1}, w_{i2}, \dots, w_{in}$. If $\sum_{j=1}^n w_{ij} = 1$ for all i , the weighting

matrix is said to be *row-normalized*. Because a unit is not considered its own neighbor, $w_{ii} = 0$ for $i = 1, \dots, n$, that is, the main diagonal of \mathbf{W} is zero. Following the interpretation of Li et al. (2021), the peer effect is represented by the interaction term $\mathbf{W}\mathbf{y}$, which captures the endogenous spatial lag and reflects the average improved adoption behavior in neighboring communities. The coefficient ρ measures the strength of the spatial autocorrelation on improved seed adoption behavior.

The decision to use the SLM model is supported by previous studies such as Fang and Richards (2018), Singha (2019), and Wollni and Andersson (2014), which also examine peer effects and spatial interactions in agricultural technology adoption. These studies demonstrate the relevance of capturing spatially lagged dependent variables to model decision-making influenced by neighboring agents. Other research in the field has employed more general spatial econometric models, such as the Spatial Durbin Model (SDM) and the SARAR model, which incorporate additional spatial components like exogenous spatial lags or spatially correlated error terms (Zheng et al., 2021; Läpple and Kelley, 2015; Skevas et al., 2018; Ward and Pede, 2015). To determine whether such additional spatial effects are present in this study's context, a series of specification tests are conducted to assess whether these alternative models provide a better fit than the baseline SLM.

2.2 Spatial Weight Matrix & Spatial Dependence

In spatial econometrics, the assumption of independence across observations is highly restrictive, as the observed values y_i are often statistically correlated with those from neighboring locations, this phenomenon is known as spatial dependence (Ahumada et al., 2018). To estimate it, a starting point is to define an appropriate weights matrix, \mathbf{W} . According to Tobler (1970)'s First Law of Geography: “everything is related to everything else, but near things are more related than distant things,” the weighting matrix defines which units interact and the strength of those interactions among spatial observations.

Since the community's proportion of improved seed varieties used are more likely to be influenced by their nearby neighbor communities rather than the remote ones, the inverse distance between communities' locations is usually used as weights to measure the proximity between communities and neighboring communities (Elhorst, 2014; LeSage and Pace, 2009). To construct the distance-based weight matrix \mathbf{W}_d , following the studies of Zheng et al. (2021); Fang and Richards (2018); Li et al. (2021); Ward and Pede (2015), the spatial weight are created as:

$$w_{ij} = \begin{cases} 0 & \text{if } i = j \\ 1/d_{ij} & \text{if } d_{ij} \leq D \\ 0 & \text{if } d_{ij} > D, \end{cases}, \quad (2)$$

where d_{ij} is the arc-distance between the centroids of community i and the neighboring community j . D is the critical distance cut-off, it would be assumed that there is no spatial

relationship between communities that are beyond the distance D from each other, as indicated in equation (2). The critical distance cut-off D to be used would be 100 km.

Additionally, to test the robustness of our results to different definitions of neighborhood proximity, alternative versions of the matrix \mathbf{W}_d are constructed using buffer distances of 80 km and 120 km. These allow to evaluate how sensitive the model results are to the choice of spatial threshold, while maintaining the same inverse-distance structure.

To test whether there is spatial dependence on the proportion of improved seeds used, the Moran's I test would be employed for the panel dataset, which is averaged from all time periods:

$$I_t = \frac{n}{S_0} \cdot \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij}(y_{it} - \bar{y}_t)(y_{jt} - \bar{y}_t)}{\sum_{i=1}^n (y_{it} - \bar{y}_t)^2}, \text{ for } t = 2010, \dots, 2019, \quad (3)$$

where $\bar{y}_t = \frac{1}{n} \sum_{i=1}^n y_{it}$, y_{it} indicates the observed value in the i th communities in the period t , w_{ij} is the spatial weight defined previously, n refers to the total number of communities, and t to the number of periods. It is important that each community persists across each wave so that \mathbf{W} is constant over time and the panel is balanced (Elhorst, 2014).

3 Study Context & Data

This section provides essential background and data information for the analysis. It begins with an overview of the socioeconomic and agricultural context of Malawi, the country where the study is conducted. Understanding Malawi's rural structure and agricultural dependence is crucial for interpreting the patterns of technology adoption analyzed in this research. Following this contextual overview, the section presents the dataset used for the empirical analysis, the Malawi Integrated Household Panel Survey (IHPS). This georeferenced dataset includes detailed information on household, community, and agricultural characteristics, as well as data on the use of improved seed adoption.

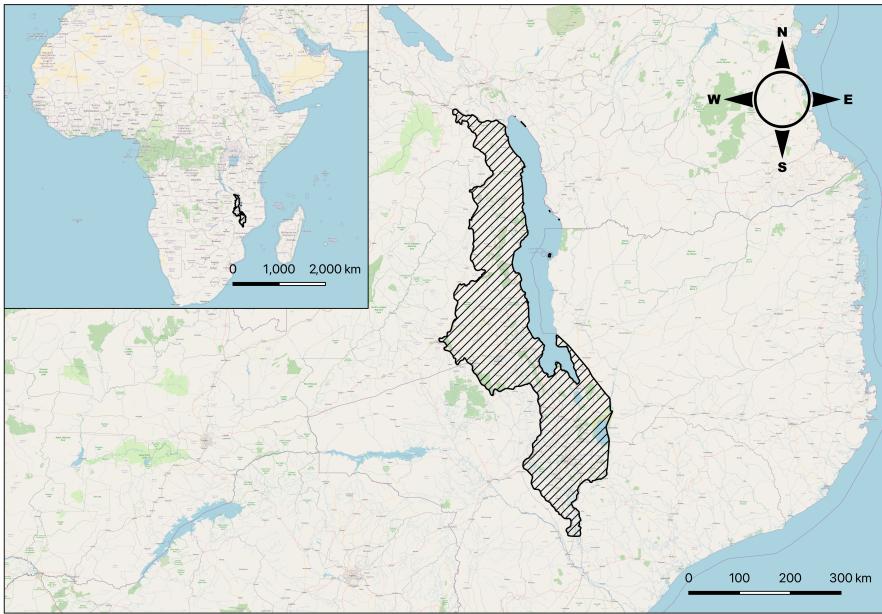
3.1 Study Context: Malawi

Malawi is a small, landlocked country in southern Africa, bordered by Tanzania, Mozambique, and Zambia, as shown in Figure 1. It has a population of 19 million and is divided into 28 districts across three regions: northern, central, and southern. The Great Rift Valley runs through the country from north to south, with Lake Malawi (also known as Lake Nyasa) forming more than three-quarters of its eastern boundary.

Malawi is one of the world's least developed countries, with 50.7% of the population living in poverty and 20.5% in extreme poverty (NSO, 2021). The economy is heavily reliant on agriculture, being responsible of more than 40% of the country's economic growth in recent

¹Own elaboration using QGIS.

Figure 1: Map of Malawi.¹



years. More than 75% of Malawian adults work in agriculture, primarily in small-scale, rainfed farming. The rural economy, which encompasses various income-generating activities in rural areas, represents a major share of both employment and national output. According to the Malawi 2018 census, 84% of the population resides in rural areas and depends largely on subsistence farming (Engel et al., 2022).

Ninety-four percent of poor households in Malawi are located in rural areas, where the poverty headcount ratio reaches 57%, almost three times higher than in urban centers (19%) (Gross et al., 2021). This disparity is driven by low agricultural productivity, which could be partially attributed to having an average farm size of only 0.7 ha, being significantly smaller than in other countries in the region (World Bank, 2022). Productivity among smallholder farmers is particularly low due to multiple constraints, including climate variability (floods and dry spells), limited adoption of improved agricultural technologies and practices, restricted access to quality inputs, and poor availability of credit and markets. These challenges hinder rural households from increasing yields and improving their economic conditions.

Malawi has two distinct seasons: a wet, warm season from October to April and a dry, cool season from May to September (CIAT and World Bank, 2018). Agricultural production is concentrated during the wet season, as 90% of farming is rain-fed and only 4% of the total cultivated area is irrigated (CIAT and World Bank, 2018). The seven major crops cultivated in the country are maize, groundnuts, pigeon peas, beans, soybeans, rice, and tobacco. Among smallholder farmers, 96% grow maize, while 30% cultivate groundnuts, 25% pigeon peas, 10% soybeans and rice, and 3% tobacco (National Statistical Office, 2020). Maize is the most widely produced crop, occupying 28% of total agricultural land, followed by groundnuts with 6% (CIAT and World Bank, 2018).

3.2 Malawi Integrated Household Panel Survey

This study uses the Malawi Integrated Household Panel Survey (IHPS). This is a nationally representative panel data of household, community, fishery and agriculture surveys implemented by the Government of Malawi through the National Statistical Office. The data was collected by World Bank's Living Standards Measurements Survey (LSMS) program. It is a georeferenced database, meaning that each enumeration area (EA)/community has its longitude and latitude coordinates. Given the increasing numbers of households to be tracked, as well as budget/resource constraints, starting in 2016, the IHPS target household sample was adjusted as the households that have been associated with 102 out of 204 baseline EAs. The IHPS collects data about health, education, labor, crop production, fertilizers, weather conditions, among others. The survey conducts interviews over a year, encompassing four waves occurring biennially.

From this study, the quantity of improved seed varieties used at the community level can be obtained for the 2010, 2013, 2016 and 2019 year waves from the agriculture questionnaire focused on the main rainy season. The focus is put exclusively on households that own at least one agricultural plot. Accordingly, the dataset includes 95 out of the 102 georeferenced enumeration areas (EAs) or communities, comprising 885 households per round. Additionally, it collects data on community characteristics and the information they have acquired regarding agricultural practices. From the panel dataset, those household members who migrated or lost track from the original household during the waves are erased.

Improved seeds are defined as hybrid seeds, which, compared to local seeds, have the potential to produce higher yields. Hybrid seeds are the result of controlled crossbreeding between two genetically distinct parent plants of the same species to produce offspring with enhanced agricultural traits. This process, known as hybridization, aims to combine desirable characteristics from both parent lines, such as higher yield potential, disease resistance, stress tolerance, and improved uniformity (Acquaah, 2009). Unlike open-pollinated or local/traditional seeds, hybrid seeds do not produce offspring with identical traits in subsequent generations, meaning farmers must purchase new seeds each planting season to maintain optimal performance (Fehr, 1991). From the Agriculture Section, improved seeds include: Maize Hybrid, Groundnut CG7, Groundnut Manipinta, Groundnut Mawanga, Groundnut JL24, Rice Faya, Rice Pussa, Rice TCG10, Rice IET4094 and Rice ITA ².

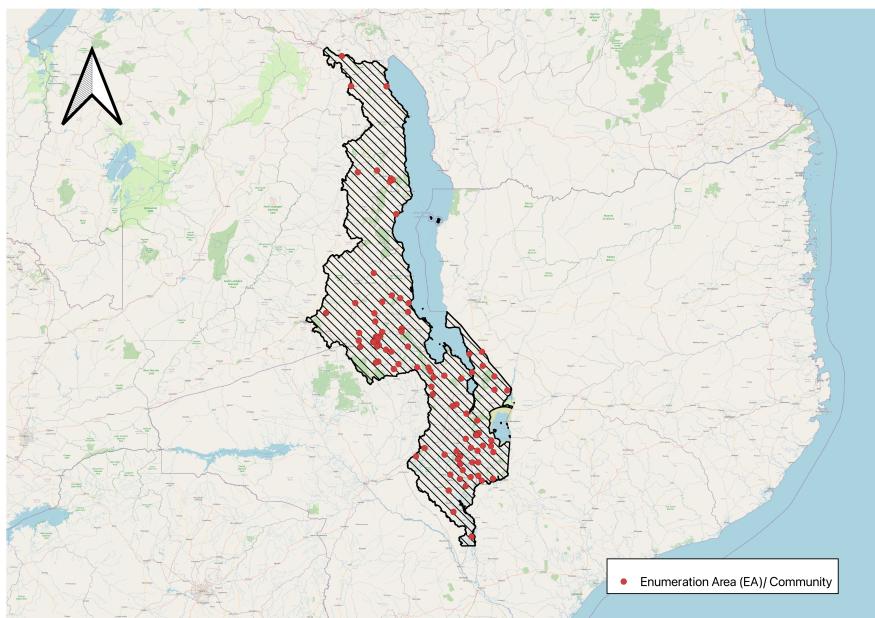
4 Descriptive Statistics

To provide an overview of the datasets used in this study, Figure 2 displays the geographic distribution of Enumeration Areas (EAs)/Communities in Malawi, while Table 1 presents key variables relevant to the analysis. The adoption variable measures the proportion of improved

²See: Malawi Integrated Household Panel Survey, Agriculture and Fishery Enumerator Manual (ANNEX 3)

seed varieties used within communities, showing that, on average, 34% of plots have adopted improved seeds in each community. This metric serves as a key continuous variable for assessing the adoption of improved seeds, capturing variations in uptake across different regions.

Figure 2: Map of Malawi with the Enumeration Areas (EAs)/ Communities.³



Household and agricultural characteristics, following the frameworks of Fang and Richards (2018) and Li et al. (2021), describe the socioeconomic context of the communities. On average, 25% of household heads are women, with a mean age of 44 years, and 20% are engaged in salaried employment. In terms of education, 54% of household heads have never received formal schooling, while only 11% have completed primary education. Regarding agricultural variables, the average household plot size is 16.14 acres. Access to subsidies and financial support remains limited, with only 4% of households receiving coupons to purchase improved seeds and 13% accessing credit for improved seed purchases. Additionally, 43% of households rely on leftover seeds from the previous season for planting, highlighting the constraints many farmers face in adopting improved seed varieties.

³Own elaboration using QGIS.

Table 1: Descriptive Statistics of Key Variables.

Variable	Description	Mean	SD
<i>Adoption Var.</i>			
Prop. imp.	Proportion of improved seed used	0.34	0.25
<i>Household Var.</i>			
Prop. female head	Proportion of female head in households	0.25	0.20
Mean age head	Mean age of household head	44.73	6.17
Prop. salaried head	Proportion of being salaried employed	0.20	0.25
Prop. head edu. 1	Proportion of head with no education	0.54	0.29
Prop. head edu. 2	Proportion of head with PSLC education	0.11	0.17
Prop. head edu. 3	Proportion of head with JCE education	0.09	0.16
Prop. head edu. 4	Proportion of head with MSCE education	0.07	0.15
Prop. head edu. 5	Proportion of head with non-university education	0.03	0.12
Prop. head edu. 6	Proportion of head with university degree education	0.01	0.08
Prop. head edu. 7	Proportion of head with post-grad degree education	0.01	0.05
<i>Agriculture Var.</i>			
Total plot size	Plot size in Community (acres)	16.14	11.87
Prop. coupon	Proportion of seeds bought with coupons	0.04	0.06
Prop. credit	Proportion of seeds bought with credit	0.13	0.16
Prop. left seeds	Proportion who used left over seeds from previous season	0.43	0.22

Note: Mean and standard deviation are rounded to 2 decimal places.

5 Results

This section presents the main findings on improved seed adoption in Malawi. Preliminary tests confirmed the presence of spatial dependence in the data, and based on diagnostic statistics including the LM and LR tests, the SLM model was selected as the most appropriate specification (detailed test results are provided in the Appendix - see *Testing for Additional Spatial Effects*). The analysis now turns to the estimation of this model to evaluate how neighboring communities influence improved seed adoption including whether key financial determinants have spillover effects on adoption.

To examine whether and how spatial interactions between neighboring communities influence the proportion of improved seeds adopted and whether key financial community characteristics generate spillover effects, the following equation is specified:

$$y_t = \rho \mathbf{W}_d y_t + \beta_1 cupon_t + \beta_2 credit_t + \mathbf{X}_t \boldsymbol{\delta} + \gamma_t \mathbf{1}_n + \boldsymbol{\alpha} + u_t, \quad (4)$$

where y_t is an n -dimensional vector representing the proportion of improved seeds adopted by

the communities in year t . The variable $cupon_t$ is the proportion of seeds bought with coupons and the variable $credit_t$ is the proportion of seeds bought with credit, both at year t . \mathbf{X}_t represents a matrix of the community's characteristics as control. Following the interpretation of Li et al. (2021), the peer effect is represented by the interaction term \mathbf{W}_{dy_t} , which captures the endogenous spatial lag and reflects the average improved adoption behavior in neighboring communities. The ρ is the spatial autoregression coefficient and measures the strength of the spatial autocorrelation on improved seed adoption behavior. γ_t denote time-period-specific effects, where 1_n is an $n \times 1$ vector of ones, included to control for all time-specific, unit-invariant factors whose omission could bias the estimates in a typical time-series analysis. The $n \times 1$ vector $\boldsymbol{\alpha} = (\alpha_1, \dots, \alpha_n)'$ contains the spatial-specific effects α_i , included to control for all spatial-specific, time-invariant factors whose omission could bias the estimates in a typical cross-sectional analysis. Finally, $u_t = (u_{1t}, \dots, u_{nt})'$ is a vector of i.i.d. disturbance terms, whose elements have zero mean and finite variance σ^2 . Based on the findings from the previous section, where the SLM model was identified as the most suitable model, it is estimated it under Maximum Likelihood estimation (ML).

To draw general conclusions, Table 2 presents results from the equation (4) under three distance-based spatial weight matrices alternatives (\mathbf{W}_{d80} , \mathbf{W}_{d100} , \mathbf{W}_{d120}).

Table 2: Regression Estimates: SLM model with \mathbf{W}_d .

	SLM (\mathbf{W}_{d80})	SLM (\mathbf{W}_{d100})	SLM (\mathbf{W}_{d120})
Main Variables	(1)	(2)	(3)
Prop. coupon	0.620*** (0.170)	0.624*** (0.171)	0.638*** (0.171)
Prop. credit	0.142* (0.080)	0.146* (0.080)	0.146* (0.080)
Spatial Parameter			
ρ	0.244*** (0.088)	0.205** (0.103)	0.182 (0.111)
Variance			
σ_e^2	0.030*** (0.002)	0.031*** (0.002)	0.031*** (0.002)
Fixed Effects	Yes	Yes	Yes
Observations	380	380	380
Log-Likelihood	124.10	122.40	121.78
AIC	-216.20	-212.80	-209.56

Note: This table presents ML estimates from the Spatial Lag Model (SLM) using distance-based spatial weights matrices: \mathbf{W}_{d80} , \mathbf{W}_{d100} , and \mathbf{W}_{d120} . All models include community-level control variables, which are omitted from the table for brevity (See Table 9 in Appendix). Robust standard errors in parentheses. Statistical significance: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Column (1) presents the estimated parameters of the SLM model using the inverse 80 km arc-distance spatial weight matrix (\mathbf{W}_{d80}). The results confirm the presence of positive spatial dependence, as indicated by a statistically significant spatial autoregressive parameter (ρ) (1% level), suggesting that higher adoption levels in neighboring communities are associated with higher local adoption of improved seeds. While the coefficients from the ML estimation do not directly reflect marginal effects, their signs and significance provide insight into the direction and relevance of each variable's association with adoption. For example, greater access to seed obtained through coupons and agricultural credit is positively associated with adoption: higher shares of seed purchased with coupons and credit are linked to increased adoption rates, highlighting the importance of financial accessibility. Column (2) reports results for the SLM model estimated with a 100 km distance matrix (\mathbf{W}_{d100}). Again, positive spatial dependence is evident at a 5% level, reinforcing the conclusion that improved seed adoption in one area is positively associated with adoption in nearby areas. These findings collectively underscore the role of spatial processes and local conditions in shaping adoption behavior, even though the precise magnitudes of effects are better captured in the direct, indirect, and total impact decomposition.

Column (3) presents the estimated parameters of the SLM model under the inverse 120 km arc-distance spatial weight matrix (\mathbf{W}_{d120}). Here, even-though that the estimation results has a positive spatial dependence is not statistically significant. One of the possible explanation for this result is that there might be a dilution of spatial influence over distance. As distance band increases, the additional neighbors are less likely to influence a community's seed adoption behavior. This dilutes the strength of the spatial autocorrelation, making ρ harder to estimate precisely (larger robust standard error) and thus statistically insignificant. In addition, when you increase the distance to 120 km, you're potentially connecting units that are not meaningfully related in practice, making the spatial dependence to become weaker.

When analyzing the adoption of improved seeds across communities, spatial interactions play a crucial role in shaping outcomes. The SLM model accounts for these dependencies by incorporating a spatially lagged dependent variable, allowing it to distinguish between the direct impact of explanatory factors within a given community and the indirect spillover effects originating from neighboring communities. To better capture and interpret these effects, the estimated coefficients are decomposed into direct, indirect, and total effects. This decomposition allows to test the hypothesis of whether spatial spillovers exist, as suggested by Elhorst (2014). In this context, indirect effects measure how changes in an explanatory variable in one community influence adoption behavior in nearby communities through spatial linkages. If significant, they provide strong evidence of peer influence or regional diffusion mechanisms. The total effects, meanwhile, reflect the overall impact of each variable, combining both local and neighboring influences.

In this study, the analysis of spillovers focuses specifically on financial variables—namely, access to agricultural credit and input subsidies (coupons)—as potential mechanisms through which adoption behavior may diffuse spatially across communities. Table 3 presents the direct, indirect and total effects of the SLM model with \mathbf{W}_{d80} that capture both local influences and broader regional spillovers, providing a more comprehensive view of how different financial factors drive improved seed adoption. As shown in the indirect effect column, the only variable with a significant and positive indirect effect is the proportion of improved seeds obtained through coupons. A 10 percent point increase in the proportion of seeds obtained via coupons in one community leads to an average increase of 2.05 percentage points in improved seed adoption in neighboring communities, statistically significant at a 10% level. There is not enough evidence to suggest that the proportion of improved seeds obtained through credit have regional indirect spillover effects. This results indicate that farmer coupon-based interventions generate positive spillover effects. Seed subsidies do not only benefit the direct recipients—they also increase adoption in neighboring communities, likely through informal seed sharing, observable yield improvements, or word-of-mouth awareness of the program. This highlights the importance of designing interventions with the potential for regional diffusion, not just localized impact. Notably, these indirect effects are statistically significant under the 80 km spatial weight matrix (\mathbf{W}_{d80}), while models with broader distance thresholds, 100 km and 120 km, do not show statistically significant spillovers, suggesting that spatial influence might weaken as distance increases ⁴.

Table 3: Direct, Indirect, and Total Effects of SLM Model with \mathbf{W}_{d80}

Variable	Direct	Indirect	Total
Prop. coupon	0.639*** (0.1800)	0.205* (0.1116)	0.844*** (0.2570)
Prop. credit	0.143 (0.0807)	0.045 (0.0334)	0.189 (0.1083)

Note: Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

6 Drought Shocks over Improved Seed Adoption

Higher levels of improved seed adoption in neighboring communities are found to be associated with higher local adoption rates, indicating that spatial interactions play a significant role in shaping adoption decisions. However, an important question remains: how are these peer effects dynamics influenced by external shocks, such as climate-related events? In this section, how drought shocks modify the strength and dynamics of peer effects are examined, providing insights into how environmental stress may alter the diffusion of improved seed technologies across communities.

⁴See Tables 11 and 12 at the Appendix Section.

The dataset used to construct the drought shock index is first introduced, enabling the capture of climate variability across communities. Next, the descriptive statistics related to drought exposure and seed adoption are presented. Finally, the empirical model used is outlined to assess the impact of drought shocks on the proportion of improved seeds adopted, and to examine whether these shocks influence the strength of spatial interactions, that is, how neighboring communities affect each other's adoption behavior under climate stress.

6.1 Weather Data & Drought Index

To address for drought shocks we utilized the Climatic Research Unit (CRU) SPEI database⁵. This base is a global scale high-resolution drought index developed from a combination of precipitation and potential evapotranspiration datasets for the Hydro-JULES project (Solomon Gebrechorkos, 2023). The drought index is developed using the Standardized Precipitation Evapotranspiration Index (SPEI). SPEI classifies drought based on precipitation data for 3-, 6-, 12-, 24-, and 48-month timescales. However, what sets SPEI apart from other drought indices is its consideration of reference evapotranspiration, which represents the amount of water that would evaporate under reference conditions. SPEI considers climatic factors such as temperature, humidity, solar radiation, and wind, providing a more comprehensive measure of the available water (climatic water balance). By incorporating climatic factors, SPEI offers insights into the combined effects of precipitation and evapotranspiration on drought severity in different locations and time periods (Beguería et al., 2014).

This high-resolution global scale drought index is available from 1981-2022 at a monthly and 5km spatial resolution (0.05 degree). The SPEI index is available from 1-48 months timescales. Selecting a specific timescale depends on assessing drought impacts on different water resources. For example, meteorological drought requires a 1- or 2-month SPEI, while agricultural drought analysis utilizes SPEI ranging from 1 to 6 months. For hydrological drought investigations and applications, longer timescales, such as six months up to 24 months or more, are typically employed (McKee et al., 1993; Svoboda et al., 2012; Santiago Beguería, 2023).

As it was previously mentioned, in Malawi, there are two distinct seasons: a dry season from May to September and a wet season from October to May where the main crops are produced. Malawi's seven primary crops -maize, groundnuts, pigeon peas, beans, soybeans, rice, and tobacco—share similar agricultural calendars, with overlapping periods for planting, flowering, and harvesting. These crops are generally planted with the onset of the rainy season, typically between October and December, and begin flowering around three months later. The first three months after planting are particularly critical, as they represent the phase of highest water demand for the crops. Adequate and timely rainfall during this stage is essential, contributing to approximately 70% of the final yield ⁶. In contrast, drought conditions during this period

⁵SPEI Dataset: <https://catalogue.ceda.ac.uk/uuid/ac43da11867243a1bb414e1637802dec/>

⁶As stated by two agronomic engineers during an interview.

significantly increase the likelihood of yield losses and crop failure. Given the importance of this window, the study uses a 3-month Standardized Precipitation Evapotranspiration Index (SPEI) calculated for each grid cell, capturing drought variability during the crucial December to February period of the rainy season.

6.2 Descriptive Statistics - Drought Shock

Spatial interactions under drought shocks can shape the weight your neighbor has on your decision making across communities. Spatial interactions under drought shocks can influence how much a neighbor's decision impacts your own across communities. As discussed in Section 2, agriculture plays a central role in Malawi's economy, and climate shocks like drought can affect decision-making, including the choice between improved or local seeds, while also shaping the influence of neighboring farmers' choices have on the farmer.

Figure 3 presents the 3-month SPEI drought shocks in Malawi during the key planting period of the previous long rain season for each survey round. The year before the surveys were conducted, some areas experienced severe drought shocks during the key planting period, potentially influencing farmers' seed adoption decisions in the following season. Map (a) shows that many communities in the central region faced severe drought, likely leading to lower yields due to insufficient rainfall. In contrast, map (b) indicates that communities in the southern region received abundant rainfall, which may have resulted in higher yields, while those in the northern region experienced relatively low rainfall.

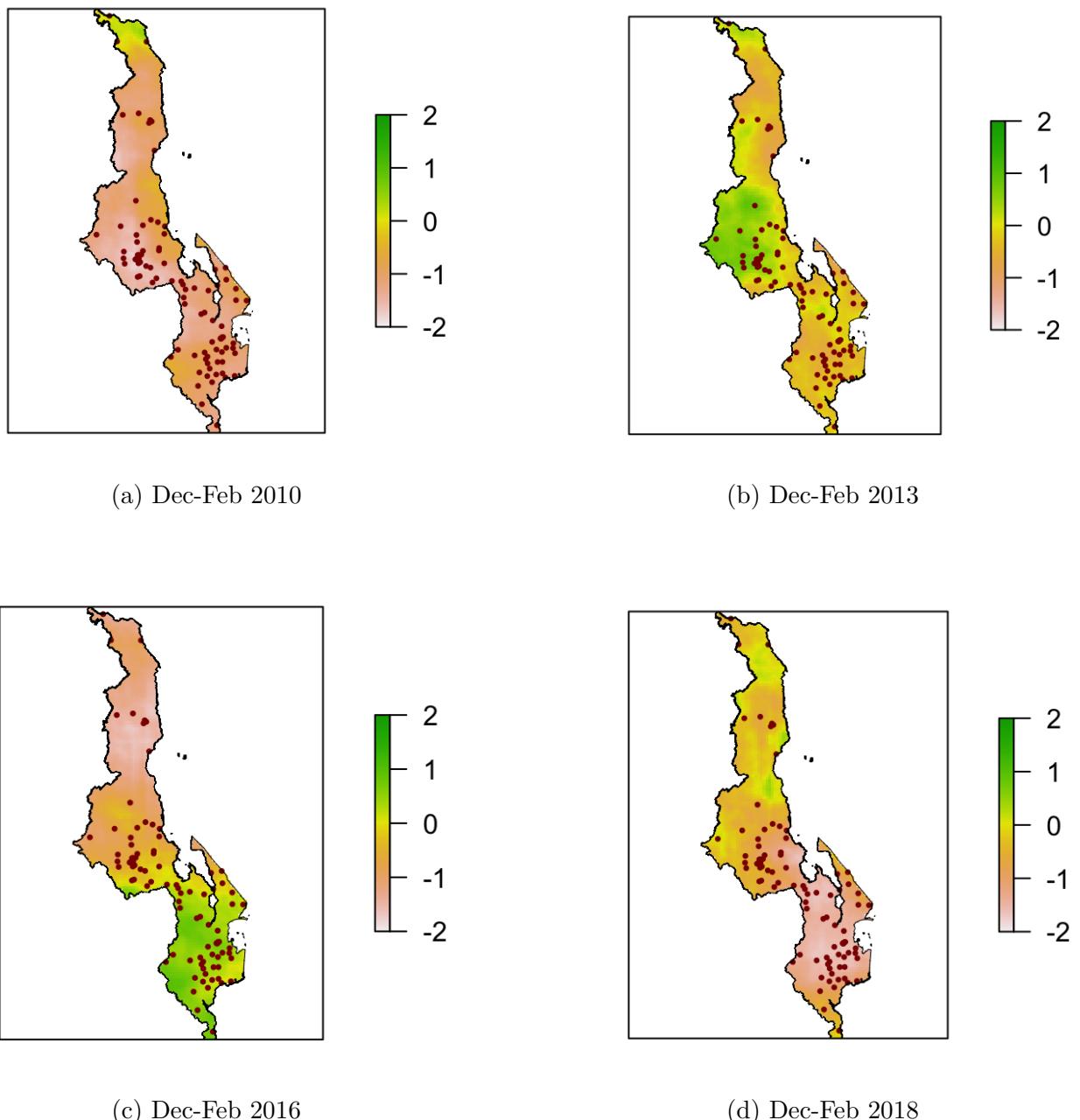
Table 4 shows the number of communities that experienced a drought shock during the previous year's planting season. In 2009, 22 communities faced a severe drought shock. In 2012, no community experienced a drought shock. In 2015, only one community faced a severe drought shock. Finally in 2018, 22 communities experienced a severe drought shock. In addition to this, Table 12 (in the Appendix Section) examines whether communities' pre-treatment characteristics are balanced across those who are never exposed to a drought shock in the previous year's planting season of each round (control) and those who are eventually exposed (eventually treated). For 12 out of 14 characteristics available there are no statistical significant differences across those never exposed and those eventually exposed to a drought shock.

Table 4: Communities under a 3-month SPEI Drought Shock

Drought Shock	2009	2012	2015	2018	Total
No Shock	73	95	94	73	335
Severe Shock	22	0	1	22	45

⁷Own elaboration using R-Studio.

Figure 3: 3-month SPEI Drought Shock in Malawi.⁷



6.3 Instrumental Variables - Peer Effect under Drought Shock

To examine how drought shocks have a direct effect over the proportion of improved seeds adopted and how that drought shock might affect how the spatial interactions between neighboring communities influence the adoption, formally the following model is estimated:

$$y_t = \rho_1 \mathbf{W}_d y_t + \rho_2 (DroughtShock * \mathbf{W}_d y_t) + \mathbf{X}_t \boldsymbol{\delta} + \gamma_t \mathbf{1}_n + \boldsymbol{\alpha} + u_t, \quad (5)$$

where y_t is an n -dimensional vector representing the proportion of improved seeds adopted by the communities in year t . \mathbf{X}_t represents a matrix of the community's characteristics as control. Following the interpretation of Li et al. (2021), the peer effect is represented by the interaction term $\mathbf{W}_d y_t$, which captures the endogenous spatial lag and reflects the average improved adoption behavior in neighboring communities. The ρ_1 is the spatial autoregression coefficient and measures the strength of the spatial autocorrelation on improved seed adoption behavior. $DroughtShock$ is an n -dimensional binary vector that takes the value of 1 if the community in the previous long rainy season experienced severe drought shock. Otherwise, it takes the value of zero. In addition, $(DroughtShock * \mathbf{W}_d y_t)$ is an interaction effect capturing how the drought shock modifies the average improved adoption behavior in neighboring communities. The ρ_2 is also a spatial autoregression coefficient but measures the strength of the spatial autocorrelation on improved seed adoption behavior under drought shocks. γ_t denote time-period-specific effects, where $\mathbf{1}_n$ is an $n \times 1$ vector of ones, included to control for all time-specific, unit-invariant factors whose omission could bias the estimates in a typical time-series analysis. The $n \times 1$ vector $\boldsymbol{\alpha} = (\alpha_1, \dots, \alpha_n)'$ contains the spatial-specific effects α_i , included to control for all spatial-specific, time-invariant factors whose omission could bias the estimates in a typical cross-sectional analysis. Finally, $u_t = (u_{1t}, \dots, u_{nt})'$ is a vector of i.i.d. disturbance terms, whose elements have zero mean and finite variance σ^2 .

Equation (5) cannot be estimated with the usual methods as there exists an endogenous variable, $W y$, that is correlated with the error term. Following the IV model presented by Herrera Gómez (2015), the alternative is to find an instrument H that is relevant on explaining $W y$ and satisfies the exclusion restriction. That is, the instrument H has to satisfy:

$$\text{plim} \left(\frac{1}{n} \right) H' W y = M_H W y, \quad (6)$$

$$\text{plim} \left(\frac{1}{n} \right) H' u = 0, \quad (7)$$

being $M_H W y$ a non-singular finite matrix.

As Herrera Gómez (2015) mention, the $E(W y)$ is linearly related to $WX, W^2X, W^3X, \dots, W^qX$, which serve as valid instruments for the endogenous variable $W y$. Monte Carlo simulations suggest that using instruments up to the second order ($q = 2$) yields good performance. Therefore, in this study, these two sets of spatial lags of the exogenous variables (WX and W^2X) are

used as instruments. Including higher-order terms increases the risk of multicollinearity with the regressors. Applying this idea, the estimator of instrumental variables for $W\mathbf{y}$ is obtained:

$$\hat{\rho} = (\hat{Z}'Z)^{-1}\hat{Z}'y, \quad (8)$$

where $\hat{Z} = P_H \widehat{W\mathbf{y}} = [X, \widehat{W\mathbf{y}}]$, $\widehat{W\mathbf{y}} = P_H W\mathbf{y}$ and $P_H = H(H'H)^{-1}H'$. Instrumental Variable (IV) estimations are carried out through the Two-Stage Least Squares (2SLS) method.

Table 5: 2SLS Regression Estimates – Drought Shock Interaction Effect

Variable	(1)	(2)	(3)
WY_1	0.552*** (0.179)	0.732*** (0.191)	0.793*** (0.204)
WY_2	0.106 (0.315)	-0.231 (0.374)	-0.083 (0.328)
Fixed Effects	Yes	Yes	Yes
Observations	380	380	380

Note: Clustered standard errors are reported in parentheses. WY_1 and WY_2 are instrumented using first- and second-order spatial lags of X characteristics, based on three different spatial weight matrices. Column (1) uses W_{80} , Column (2) uses W_{100} , and Column (3) uses W_{120} . All models include community-level control variables, which are omitted from the table for brevity (See Table 16 in Appendix). Statistical significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5 presents the estimated 2SLS results under the distance-based spatial weight matrices (\mathbf{W}_{d80} , \mathbf{W}_{d100} , \mathbf{W}_{d120}). Column (1) presents the estimated parameters using the \mathbf{W}_{d80} spatial weight matrix. The results indicate that there is no enough evidence to suggest that experiencing a drought shock in the previous crop season significantly affects the proportion of improved seed adoption. This pattern is consistent in Column (2) and (3), which estimates the SLM model using the \mathbf{W}_{d100} and \mathbf{W}_{d120} spatial weight matrix respectively. Building on these results, we do not find enough evidence to say that experiencing a severe drought shock in the previous crop season significantly strengthens the influence of neighboring communities on the proportion of improved seed adoption.

7 Robustness Check

To further validate the robustness of our findings, additional spatial weight matrices with varying specifications are incorporated. In the main analysis, different distance-based cutoffs were tested, specifically 80 km and 120 km using inverse arc-distance matrices (\mathbf{W}_{d80} and \mathbf{W}_{d120}). These variations served to verify that the results were not sensitive to the specific threshold used to define spatial proximity. In addition to these, and to further validate the robustness of our findings, an additional spatial weight matrix is constructed to emphasize the influence of

immediate neighbors. Following the study of Fang and Richards (2018), a k -nearest neighbor weight matrix (\mathbf{W}_k) is constructed, where the k closest observations or communities are considered to exert spatial influence. Based on the average number of neighbors under the 80km inverse arc distance matrix used in the study, a $k = 8$ would be used,

$$\mathbf{W}_k = w_{ij} = \begin{cases} 1 & \text{if } d_{ij} \leq d_{ij}^k \\ 0 & \text{if } d_{ij} > d_{ij}^k \end{cases}, \quad (9)$$

where d_{ij} is the distance between observations i and j . d_{ij}^k represents the distance to the k -th nearest neighbor of i , where $k = 8$ in this case. So, if j is within the k -th nearest neighbors of i (i.e., $d_{ij} \leq d_{ij}^k$, then $w_{ij} = 1$. Otherwise, if $d_{ij} > d_{ij}^k$, then $w_{ij} = 0$.

Following the methodology framework outlined, it is found that the SLM model is the most competent specification for capturing spatial dynamics in improved seed adoption for this weight matrix \mathbf{W}_k (See Table 13, 14 and 15 at the Appendix Section for Moran's I, LM and LR tests respectively). We then estimate Equation (4) using the SLM model.

Table 17 (see Appendix) presents the results from regressing equation (4) and Table 18 (see Appendix) presents the direct, indirect and total effects under the k -nearest neighbor weight matrix (\mathbf{W}_k). The findings remain consistent with the study main results: higher adoption levels of improved seeds in neighboring communities are associated with higher local adoption. Moreover, both localized peer effects and broader regional spillovers persist under this alternative specification. Specifically, the proportion of seeds obtained through coupons continue to generate positive spillover effects on adoption behavior.

8 Conclusion

This study investigated how spatial interactions among neighboring communities influence the adoption of improved seed varieties in rural Malawi. Using georeferenced panel data from the Malawi Integrated Household Panel Survey (IHPS) between 2010 and 2019, the research examined two central questions: (1) whether the adoption behavior in one community is affected by that of its neighbors including whether key financial determinants have spillover effects on adoption, and (2) whether drought shocks influence the strength and nature of these peer effects. The empirical strategy centered around spatial econometric techniques, particularly the SLM model, to capture spatial dependence in the adoption process and provide robust evidence of peer effects in a rural, agriculture-dependent context, where technology adoptions are becoming more relevant.

The study results reveal strong and consistent evidence of peer effects: communities tend to adopt improved seed varieties in alignment with the behavior of neighboring communities. This spatial dependence is particularly significant under proximity-based weight matrices,

where neighboring influence is strongest at shorter distances (e.g., 80 km). The SLM estimation shows that improved seed adoption is influenced not only by local factors but also by external financial characteristics from surrounding communities, transmitted through spatial interactions. Notably, a positive and statistically significant spillover effects from seed subsidies (coupons) is found, highlighting the regional impact of localized financial interventions.

Also, this study explored how exposure to drought shocks affects these peer dynamics. Using the 3-month Standardized Precipitation Evapotranspiration Index (SPEI) to capture severe climate shocks during critical crop stages, this study examines whether such shocks amplify or attenuate the influence of neighboring communities on the adoption of improved seed varieties. Contrary to the study expectations, the instrumental variables analysis showed no statistically significant interaction between drought exposure and spatial spillovers. That is, although drought shocks are a major constraint to agricultural productivity, they do not appear to significantly alter how much neighboring communities influence one another in terms of seed adoption decisions. This suggests that peer effects between communities are relatively stable across adverse weather conditions, or that other mechanisms (e.g., credit access, availability of local varieties) may mediate the drought response more strongly than spatial learning.

This work contributes to the growing literature on agricultural technology adoption by explicitly modeling spatial dependence at the community level, something that has received limited attention, particularly in the context of Malawi. The use of spatial panel econometrics allows it to move beyond traditional linear models and address the reflection problem by controlling for unobserved spatial correlation. Still, there are areas for further research. One key limitation of this study is the use of community-level rather than individual-level data, which may obscure heterogeneity in adoption behavior. Future research could benefit from integrating household-level or individual-level data to better identify causal peer effects, especially in the context of climate shocks. This more granular approach may help uncover whether and how drought exposure shapes peer dynamics at a finer scale than community averages allow. Additionally, exploring how other shocks, such as flooding, pests, or fires, interact with peer dynamics could offer a more comprehensive understanding of resilience in agricultural systems.

Ultimately, this study underscores the importance of designing agricultural policies and extension programs that recognize and leverage spatial spillovers. Interventions that target influential communities or build on local peer networks could have amplified regional effects, enhancing the efficiency and reach of policy efforts aimed at boosting the adoption of climate-resilient technologies in vulnerable rural settings.

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A Appendix

A.1 Testing for Additional Spatial Effects

This section begins by defining the baseline specification: the Spatial Lag Model (SLM). This model assumes that the adoption of improved seeds in a given community is directly influenced by the adoption behavior of neighboring communities. Formally, the SLM includes a spatially lagged dependent variable, represented by ρWy , where W is the spatial weight matrix and ρ is the spatial autoregressive parameter.

To evaluate whether additional spatial effects, such as spatial error dependence (λ) or exogenous spatial lags (θ), should be incorporated, the specific-to-general (STGE) framework is followed, as described in Section 3.3. This strategy begins with a simpler model and progressively tests more complex, nested alternatives. The full set of spatial models is estimated using \mathbf{W}_d (inverse arc-distance of 100 km).

To detect spatial dependence in the baseline (non-spatial) model, Moran's I statistic is first computed, as shown in Table 6. The statistic is significant at the 1% level, indicating the presence of spatial autocorrelation in the proportion of improved seed used. The result holds both with and without fixed effects.

Following, Lagrange Multiplier (LM) tests to determine the nature of this spatial dependence are conducted. The LM tests, also presented in Table 6, provide strong evidence of spatial lag dependence ($\rho \neq 0$) at the 1% level. However, there is no sufficient evidence of spatial error dependence ($\lambda = 0$), particularly in the fixed effects specification. Based on these findings, the SLM appears to be the most appropriate model at this stage.

To explore whether exogenous spatial lags should also be considered, the SLX model is tested, which imposes $\rho = 0$ and $\lambda = 0$. Results from Moran's I and LM tests for this model (Table 7) also suggest significant spatial dependence. The LM tests indicate the presence of exogenous spatial lag dependence ($\theta \neq 0$), suggesting that the Spatial Durbin Model (SDM) may also be a viable alternative.

Finally, to determine whether the more general models (SARAR or SDM) offer a better fit than the SLM, the Likelihood Ratio (LR) tests are conducted (Table 8). In both comparisons, SLM vs SARAR and SLM vs SDM, no strong evidence that including λ or θ significantly improves the model fit is found. Thus, it is concluded that the SLM is the most competent specification for capturing spatial dynamics in improved seed adoption.

A.2 Additional Tables

Table 6: Moran's I and LM Tests from No-Spatial Model with W_d .

Test	OLS			OLS w/ FE		
	Statistic	df	p-value	Statistic	df	p-value
Spatial error:						
Moran's I	3.784	1	0.000 ***	3.802	1	0.000 ***
Lagrange multiplier	12.567	1	0.000 ***	12.799	1	0.000 ***
Robust Lagrange multiplier	1.410	1	0.235	1.063	1	0.302
Spatial lag:						
Lagrange multiplier	17.258	1	0.000 ***	17.428	1	0.000 ***
Robust Lagrange multiplier	6.100	1	0.014 **	5.692	1	0.017 **

Note: Results obtained from an OLS regression. Statistical significance levels: * p<0.1, ** p<0.05, *** p<0.01.

Table 7: Moran's I and LM Tests from SLX Model with W_d .

Test	Statistic	df	p-value
Spatial error:			
Moran's I	1.969	1	0.049 *
Lagrange multiplier	0.668	1	0.414
Robust Lagrange multiplier	2.352	1	0.125
Spatial lag:			
Lagrange multiplier	1.466	1	0.226
Robust Lagrange multiplier	3.151	1	0.076 *

Note: Results obtained from an ML regression. Statistical significance levels: * p<0.1, ** p<0.05, *** p<0.01.

Table 8: Likelihood-Ratio (LR) Tests with W_d .

Test Comparison	LR Chi2	p-value
SLM vs. SARAR	0.38	0.54
SLM vs. SDM	12.31	0.42

Table 9: Regression Estimates: SLM model with \mathbf{W}_d .

	SLM (\mathbf{W}_{d80})	SLM (\mathbf{W}_{d100})	SLM (\mathbf{W}_{d120})
Main Variables	(1)	(2)	(3)
Prop. female head	-0.084 (0.080)	-0.073 (0.081)	-0.076 (0.081)
Mean age head	0.001 (0.003)	0.000 (0.003)	0.000 (0.003)
Prop. salaried head	0.013 (0.074)	0.016 (0.075)	0.016 (0.075)
Prop. head edu. 1	0.182** (0.078)	0.185** (0.079)	0.184** (0.079)
Prop. head edu. 2	0.232** (0.100)	0.241** (0.100)	0.237** (0.101)
Prop. head edu. 3	0.056 (0.109)	0.063 (0.110)	0.055 (0.110)
Prop. head edu. 4	0.037 (0.139)	0.041 (0.140)	0.033 (0.140)
Prop. head edu. 5	0.132 (0.156)	0.114 (0.157)	0.101 (0.157)
Prop. head edu. 6	0.597*** (0.193)	0.584*** (0.195)	0.568*** (0.195)
Prop. head edu. 7	0.036 (0.279)	0.007 (0.280)	-0.007 (0.280)
Total plot size	0.002 (0.002)	0.002 (0.002)	0.002 (0.002)
Prop. coupon	0.620*** (0.170)	0.624*** (0.171)	0.638*** (0.171)
Prop. credit	0.142* (0.080)	0.146* (0.080)	0.146* (0.080)
Prop. left seeds	0.091 (0.082)	0.086 (0.082)	0.085 (0.082)
Spatial Effects			
ρ	0.244*** (0.088)	0.205** (0.103)	0.182 (0.111)
Variance			
σ_e^2	0.030*** (0.002)	0.031*** (0.002)	0.031*** (0.002)
Fixed Effects	Yes	Yes	Yes
Observations	380	380	380
Log-Likelihood	124.10	122.40	121.78
AIC	-216.20	-212.80	-209.56

Note: This table presents ML estimates from the Spatial Lag Model (SLM) using distance-based spatial weights matrices: \mathbf{W}_{d80} , \mathbf{W}_{d100} , and \mathbf{W}_{d120} . Robust standard errors in parentheses.

Statistical significance: * p<0.1, ** p<0.05, *** p<0.01.

Table 10: Direct, Indirect, and Total Effects of SLM Model with \mathbf{W}_{d100}

Variable	Direct	Indirect	Total
Prop. female head	-0.074 (0.083)	-0.020 (0.028)	-0.094 (0.106)
Mean age head	0.0004 (0.0028)	0.0001 (0.0008)	0.0006 (0.0036)
Prop. salaried head	0.025 (0.072)	0.007 (0.022)	0.032 (0.091)
Prop. head edu. 1	0.183** (0.076)	0.048 (0.038)	0.231** (0.103)
Prop. head edu. 2	0.237** (0.096)	0.062 (0.047)	0.299** (0.128)
Prop. head edu. 3	0.059 (0.104)	0.015 (0.033)	0.074 (0.132)
Prop. head edu. 4	0.039 (0.139)	0.012 (0.046)	0.051 (0.180)
Prop. head edu. 5	0.106 (0.148)	0.030 (0.048)	0.135 (0.189)
Prop. head edu. 6	0.591*** (0.189)	0.158 (0.113)	0.749*** (0.264)
Prop. head edu. 7	0.004 (0.278)	0.003 (0.085)	0.008 (0.353)
Total plot size	0.0017 (0.0022)	0.0004 (0.0007)	0.0021 (0.0029)
Prop. coupon	0.650*** (0.181)	0.172 (0.117)	0.821*** (0.255)
Prop. credit	0.142* (0.081)	0.036 (0.031)	0.178* (0.104)
Prop. left seeds	0.089 (0.081)	0.024 (0.027)	0.113 (0.103)

Note: Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 11: Direct, Indirect, and Total Effects of SLM Model with \mathbf{W}_{d120}

Variable	Direct	Indirect	Total
Prop. female head	-0.074 (0.083)	-0.018 (0.026)	-0.092 (0.104)
Mean age head	0.0003 (0.0028)	0.0001 (0.0008)	0.0004 (0.0035)
Prop. salaried head	0.024 (0.072)	0.006 (0.020)	0.030 (0.089)
Prop. head edu. 1	0.183** (0.076)	0.043 (0.038)	0.226** (0.101)
Prop. head edu. 2	0.235** (0.096)	0.054 (0.047)	0.289** (0.125)
Prop. head edu. 3	0.055 (0.104)	0.012 (0.031)	0.066 (0.129)
Prop. head edu. 4	0.031 (0.139)	0.009 (0.042)	0.039 (0.175)
Prop. head edu. 5	0.096 (0.148)	0.024 (0.044)	0.119 (0.183)
Prop. head edu. 6	0.579*** (0.189)	0.137 (0.113)	0.716*** (0.259)
Prop. head edu. 7	-0.005 (0.278)	0.0005 (0.079)	-0.005 (0.345)
Total plot size	0.0017 (0.0022)	0.0004 (0.0007)	0.0021 (0.0028)
Prop. coupon	0.655*** (0.181)	0.154 (0.121)	0.809*** (0.255)
Prop. credit	0.146* (0.081)	0.033 (0.031)	0.179* (0.103)
Prop. left seeds	0.089 (0.081)	0.021 (0.026)	0.111 (0.101)

Note: Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

Table 12: Pre-Treatment Characteristics.

Variable	Control	Eventually Treated	Difference
Prop. female head	0.24 (0.21)	0.19 (0.18)	0.05 [0.04]
Mean age head	42.79 (5.92)	42.58 (6.71)	0.22 [1.30]
Prop. salaried head	0.18 (0.23)	0.32 (0.33)	-0.13** [0.06]
Prop. head edu. 1	0.55 (0.22)	0.46 (0.33)	0.09 [0.06]
Prop. head edu. 2	0.09 (0.15)	0.15 (0.24)	-0.05 [0.04]
Prop. head edu. 3	0.09 (0.17)	0.12 (0.24)	-0.03 [0.04]
Prop. head edu. 4	0.05 (0.11)	0.10 (0.21)	-0.05 [0.03]
Prop. head edu. 5	0.00 (0.00)	0.03 (0.13)	-0.03* [0.02]
Prop. head edu. 6	0.00 (0.00)	0.01 (0.07)	-0.01 [0.01]
Prop. head edu. 7	0.00 (0.00)	0.01 (0.04)	-0.01 [0.01]
Total plot size	18.83 (11.30)	14.88 (12.34)	3.95 [2.43]
Prop. coupon	0.06 (0.05)	0.06 (0.06)	-0.00 [0.01]
Prop. credit	0.14 (0.14)	0.19 (0.23)	-0.05 [0.04]
Prop. left seeds	0.48 (0.21)	0.42 (0.26)	0.06 [0.05]

Note: Standard deviations are in parentheses. Standard errors are in brackets. Statistical significance levels: * p<0.1, ** p<0.05, *** p<0.01.

Table 13: Moran's I and LM Tests from No-Spatial Model with W_k .

OLS w/ FE			
Test	Statistic	df	p-value
Spatial error:			
Moran's I	3.65	1	0.000 ***
Lagrange multiplier	11.68	1	0.001 ***
Robust Lagrange multiplier	2.24	1	0.134
Spatial lag:			
Lagrange multiplier	18.35	1	0.000 ***
Robust Lagrange multiplier	8.91	1	0.003 ***

Note: Results obtained from an OLS regression. Statistical significance levels: * p<0.1, ** p<0.05, *** p<0.01.

Table 14: Moran's I and LM Tests from SLX Model with W_k .

Test	Statistic	df	p-value
Spatial error:			
Moran's I	3.01	1	0.003 ***
Lagrange multiplier	3.01	1	0.083
Robust Lagrange multiplier	2.623	1	0.101
Spatial lag:			
Lagrange multiplier	4.67	1	0.031 **
Robust Lagrange multiplier	4.43	1	0.035 **

Note: Results obtained from an ML regression. Statistical significance levels: * p<0.1, ** p<0.05, *** p<0.01.

Table 15: Likelihood-Ratio (LR) Tests with W_k .

Test Comparison	LR Chi2	p-value
SLM vs. SARAR	0.37	0.57
SLM vs. SDM	15.59	0.34

Table 16: 2SLS Regression Estimates – Drought Shock Interaction Effect

Variable	(1)	(2)	(3)
WY_1	0.552*** (0.179)	0.732*** (0.191)	0.793*** (0.204)
WY_2	0.106 (0.315)	-0.231 (0.374)	-0.083 (0.328)
Prop. female head	-0.094 (0.081)	-0.085 (0.079)	-0.068 (0.078)
Mean age head	0.004 (0.003)	0.004 (0.003)	0.004 (0.003)
Prop. salaried head	0.167** (0.085)	0.183** (0.084)	0.186** (0.087)
Prop. head edu. 1	0.081 (0.093)	0.071 (0.100)	0.075 (0.098)
Prop. head edu. 2	0.190* (0.100)	0.195* (0.104)	0.187* (0.101)
Prop. head edu. 3	-0.013 (0.143)	-0.020 (0.130)	-0.019 (0.132)
Prop. head edu. 4	0.097 (0.149)	0.088 (0.145)	0.089 (0.147)
Prop. head edu. 5	0.260* (0.143)	0.204 (0.148)	0.210 (0.146)
Prop. head edu. 6	0.606*** (0.186)	0.607*** (0.174)	0.606*** (0.181)
Prop. head edu. 7	0.040 (0.146)	0.062 (0.141)	0.047 (0.146)
Total plot size	0.000 (0.002)	0.000 (0.002)	0.000 (0.001)
Prop. coupon	0.694*** (0.149)	0.642*** (0.158)	0.684*** (0.152)
Prop. credit	0.165* (0.097)	0.149 (0.095)	0.164* (0.093)
Prop. left seeds	0.071 (0.090)	0.024 (0.086)	0.043 (0.087)
Constant	-0.263* (0.140)	-0.269** (0.136)	-0.313** (0.138)
Fixed Effects	Yes	Yes	Yes
Observations	380	380	380

Note: Clustered standard errors are reported in parentheses. WY_1 and WY_2 are instrumented using first- and second-order spatial lags of X characteristics, based on three different spatial weight matrices. Column (1) uses W_{80} , Column (2) uses W_{100} , and Column (3) uses W_{120} . Statistical significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 17: Regression Estimates: SLM model with \mathbf{W}_k .

SLM (\mathbf{W}_k)	
Main Variables	(1)
Prop. female head	-0.080 (0.080)
Mean age head	0.001 (0.003)
Prop. salaried head	0.007 (0.074)
Prop. head edu. 1	0.182** (0.078)
Prop. head edu. 2	0.251** (0.099)
Prop. head edu. 3	0.070 (0.109)
Prop. head edu. 4	0.043 (0.139)
Prop. head edu. 5	0.131 (0.155)
Prop. head edu. 6	0.581*** (0.191)
Prop. head edu. 7	0.038 (0.278)
Total plot size	0.002 (0.002)
Prop. coupon	0.611*** (0.169)
Prop. credit	0.146* (0.079)
Prop. left seeds	0.083 (0.082)
Spatial Effects	
ρ	0.302*** (0.092)
Variance	
σ_e^2	0.030*** (0.002)
Fixed Effects	Yes
Observations	380
Log-Likelihood	114.54

Note: Robust standard errors in parentheses. Statistical significance: * p<0.1, ** p<0.05, *** p<0.01.

Table 18: Direct, Indirect, and Total Effects of SLM Model with \mathbf{W}_k

Variable	Direct	Indirect	Total
Prop. coupon	0.631*** (0.1797)	0.271* (0.1397)	0.902*** (0.2822)
Prop. credit	0.147* (0.0806)	0.063 (0.0445)	0.210* (0.1187)

Note: Robust standard errors in parentheses. * p<0.1, ** p<0.05, *** p<0.01.