Spatiotemporal Patterns of Irrigation Adoption in Alabama

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Introduction

Agricultural communities in Alabama are experiencing some of the nation's highest, and most rapidly increasing, rates of poverty and economic inequality. As agriculture plays a significant role in the statewide economy, one way to address this widespread disadvantage is with drastic increases in farm productivity. The transition from rain-fed to irrigation-fed (RFtoIF) agricultural practices has been shown to significantly increase crop productivity and farm profitability elsewhere in the United States. Despite this potential to encourage stability and resilience in rural economies, irrigated cropland accounts for only 5% of the state's total cropland as numerous barriers remain to irrigation adoption in Alabama. Despite ample annual rainfall, periodic seasonal droughts can create water restrictions, riparian rights laws prevent access to surface water for most farms, and the initial investment and maintenance costs for irrigation equipment vary widely throughout the state. To date, irrigation expansion policies and initiative have relied on cross-sectional and spatially coarse analyses, thus masking the factors influencing individual farmers decisions to adopt irrigation. A more holistic approach to improving irrigation policy and practice requires identifying challenges faced by individual farms and communities. This project presents a multi-level mixed effects survival analysis to identify the physiographic, socioecological, and economic factors that influence farmers' receptiveness to the RFtoIF transition. We use individual farms as the unit of analysis and integrate spatiotemporal cropland and climatological data with field-verified locations of center-pivot irrigation systems and farm-level data including surface water access and average well depth. The results identify the degree to which specific factors influence the timing and location of irrigation adoption and highlight the incentives needed to spur the RFtoIF transition in Alabama.

Study Area

Agriculture in Alabama is at the intersection of dual challenges of adapting to climate change and growing rural poverty and inequality. Increasing agricultural productivity through adoption of irrigation can address both challenges, yet efforts to expand irrigation in Alabama have had little success. In humid regions such as the Southeast, perceptions of water abundance among farmers and/or policy-makers can hinder irrigation expansion. Despite abundant annual rainfall, however, statewide precipitation is becoming more seasonal, with heavier rainfall in the winter and spring and increasing dry periods during the end of the growing season. Alabama is a riparian rights state, which limits water access to properties adjacent to waterways. From a management perspective, Alabama's state-developed water use monitoring program experiences consistently limited and inaccurate reporting from irrigation users. Furthermore, there is no centralized source for disseminating reliable information on potential irrigation strategies or the profitability of long-term investments in equipment and operating costs. This project is linking farm-level attributes to irrigation adoption decisions and exploring the how broader social influences impact patterns of irrigation in Alabama.

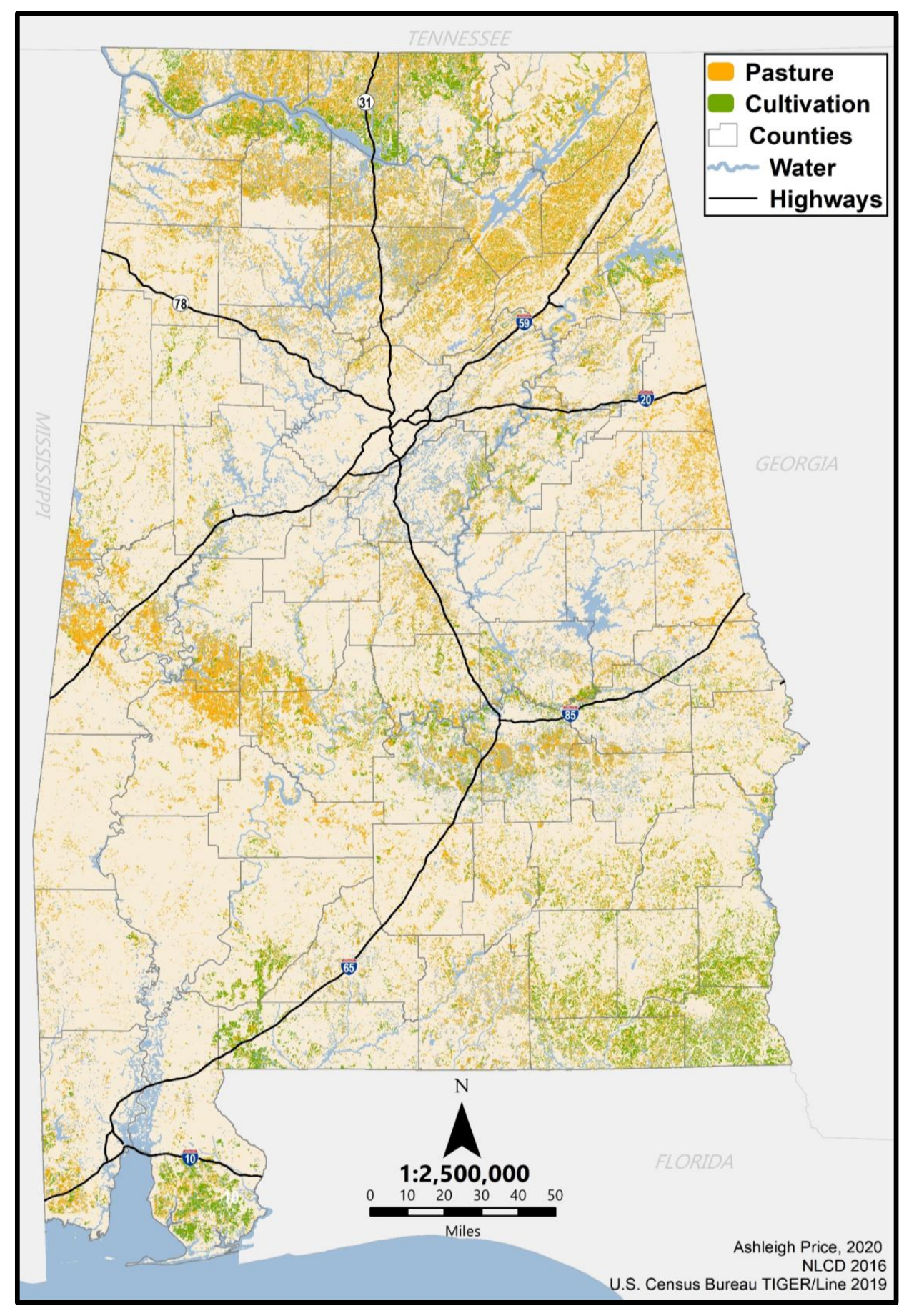

Figure 1: Cultivated Cropland in Alabama

Data

The dependent variable is the time to irrigation adoption, identified using the locations of 1,014 center pivot polygons installed 2006-2015. The unit of analysis is the individual farm, determined using 2020 Alabama real estate parcels from Landgrid and the 2013 NLCD classification for cultivated crops, resulting in 32,044 farms with irrigation potential. Access to information was operationalized as the distance from each farm to the nearest Alabama Farmers' Cooperative location. To incorporate social influence among farmers with access to similar resources, 'Social Neighborhoods' were generated around each of the coop locations using Thiessen polygons.

Table1 : Data Sources

Variable	Description	Units	Source
Dependent Variable			
Time to Irrigation	Center pivot irrigation locations 2006, 2009, 2011, 2013, & 2015.	Polygons	Office of Water Resources, UAH
Static Independent Variables			
Riparian Rights	Presence of perennial stream	Vector	Geological Society of Alabama
Surface Water Access	Presence of Lake/Pond	Polygons	Geological Society of Alabama
Soil suitability	Soil Suitability Class (1-4)	10m	USGS GSSURGO geodatabase
Groundwater Costs	Interpolated well depth	Depth (ft)	Geological Survey of Alabama
Information Access	Distance to Cooperative/Extension	Points	Alabama Farmers Cooperative, Alabama Extension
Dynamic Independent Variables			
Crop prices	Annual global commodity, normalized by market index	$/ bushel 30s	Index Mundy, Verburg (2011)
Precipitation	Variation from long-term average precipitation	Inches	PRISM
Social Influence	Irrigated Acres in Social Neighborhood	Thiessen Polygon	Alabama Farmers Cooperative, Alabama Extension

Survival Analysis

This study investigates the contextual and dynamics factors that have shaped spatiotemporal patterns of center pivot irrigation adoption throughout the state of Alabama. Data for the locations of center-pivot irrigation was available for 5 years from 2006-2015. Since the actual time to an irrigation an adoption is unobserved for much of the sample, methods such as linear regression would overestimate the duration of unaffected subjects. Survival analysis is a set of time-to-event models that can accommodate right-censored data to reveal the degree to which the effects of covariates influences the probability of an event. This project uses survival analysis to analyze the causal effects of farm-level and regional factors on the *timing* of irrigation adoption. Specifically, we test the following hypotheses:

- *Hypothesis*: Social influences, including the prevalence of nearby irrigated farms, is a stronger predictor of the timing and location of irrigation expansion in Alabama than biophysical factors.
- *Hypothesis*: Economic factors, including initial investment costs and commodity prices are a stronger influence on the timing and location of irrigation expansion in than biophysical factors.

Survival Function - Kaplan-Meier Estimation

Formula 1 shows the Kaplan-Meier estimation of the *Survival Function* where n_i is the number of farms *at risk* of irrigation adoption up until time t and d_i is the number of adoption decisions at time t. The plot of the Kaplan-Meier estimate is shown in Figure 2a, where survival probability is the likelihood that a farm will remain unirrigated through each time period. To understand the influence of water access on survival times, conditional Kaplan-Meier estimates were plotted for riparian rights and the presence of surface water (Figures 2b,c). As expected, the survival probabilities are higher for farms without access surface water or riparian rights.

$$\hat{S}(t) = \prod_{t_i<t} \frac{n_i - d_i}{n_i}$$

Formula 1: Kaplan-Meier Estimator

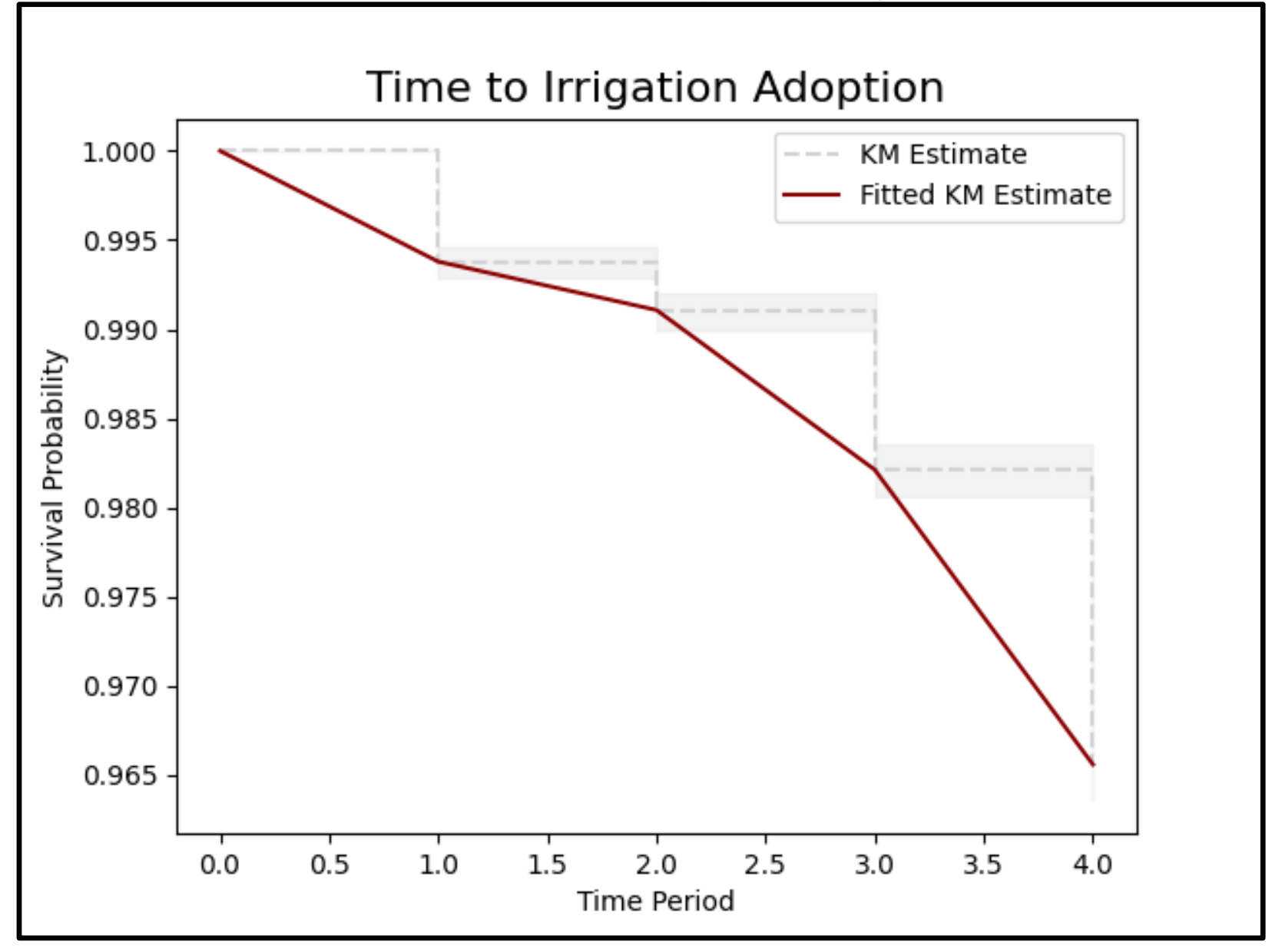

Figure 2a: Kaplan-Meier Estimate

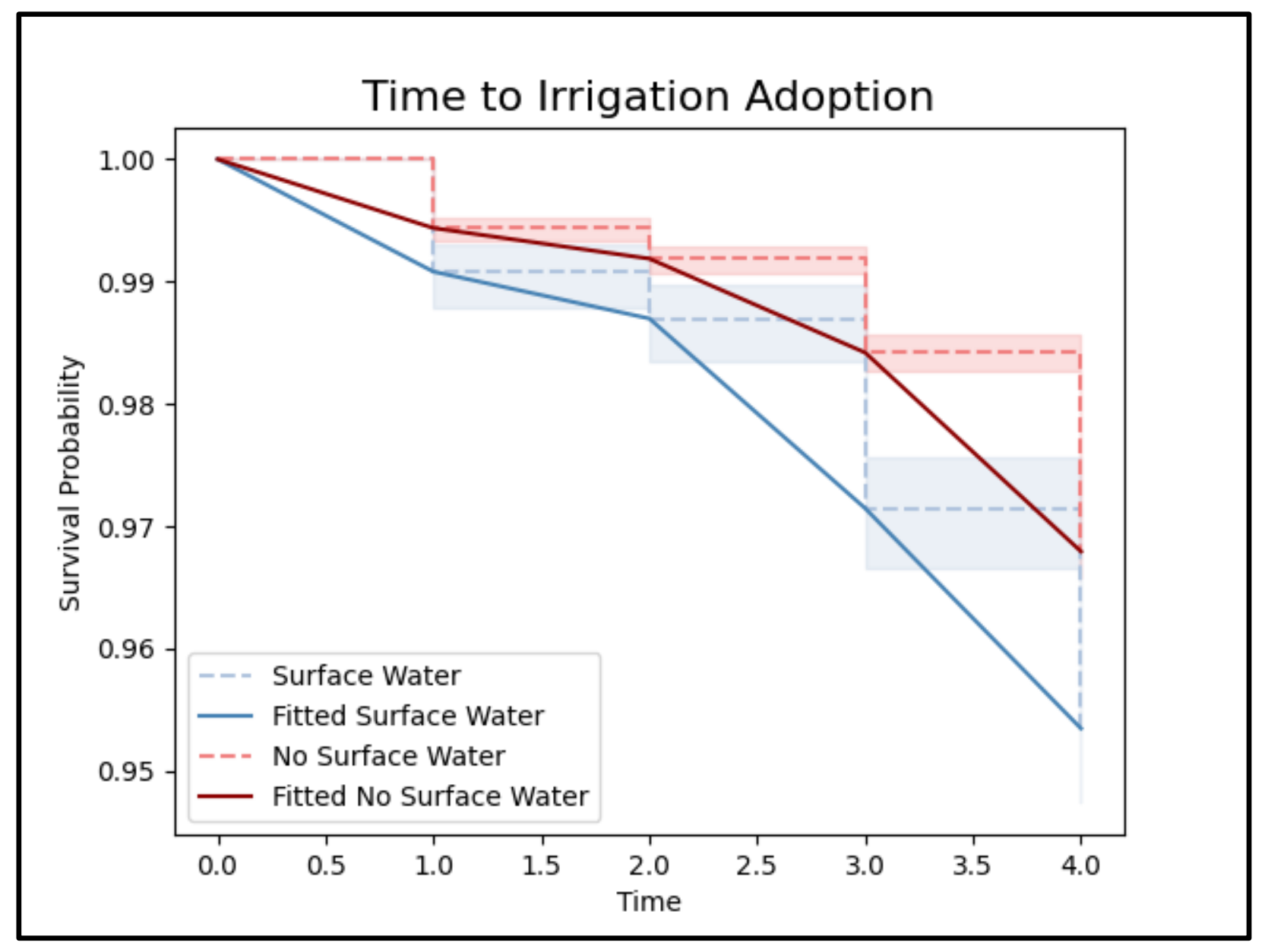

Figure 2b: Kaplan-Meier Estimate Surface Water

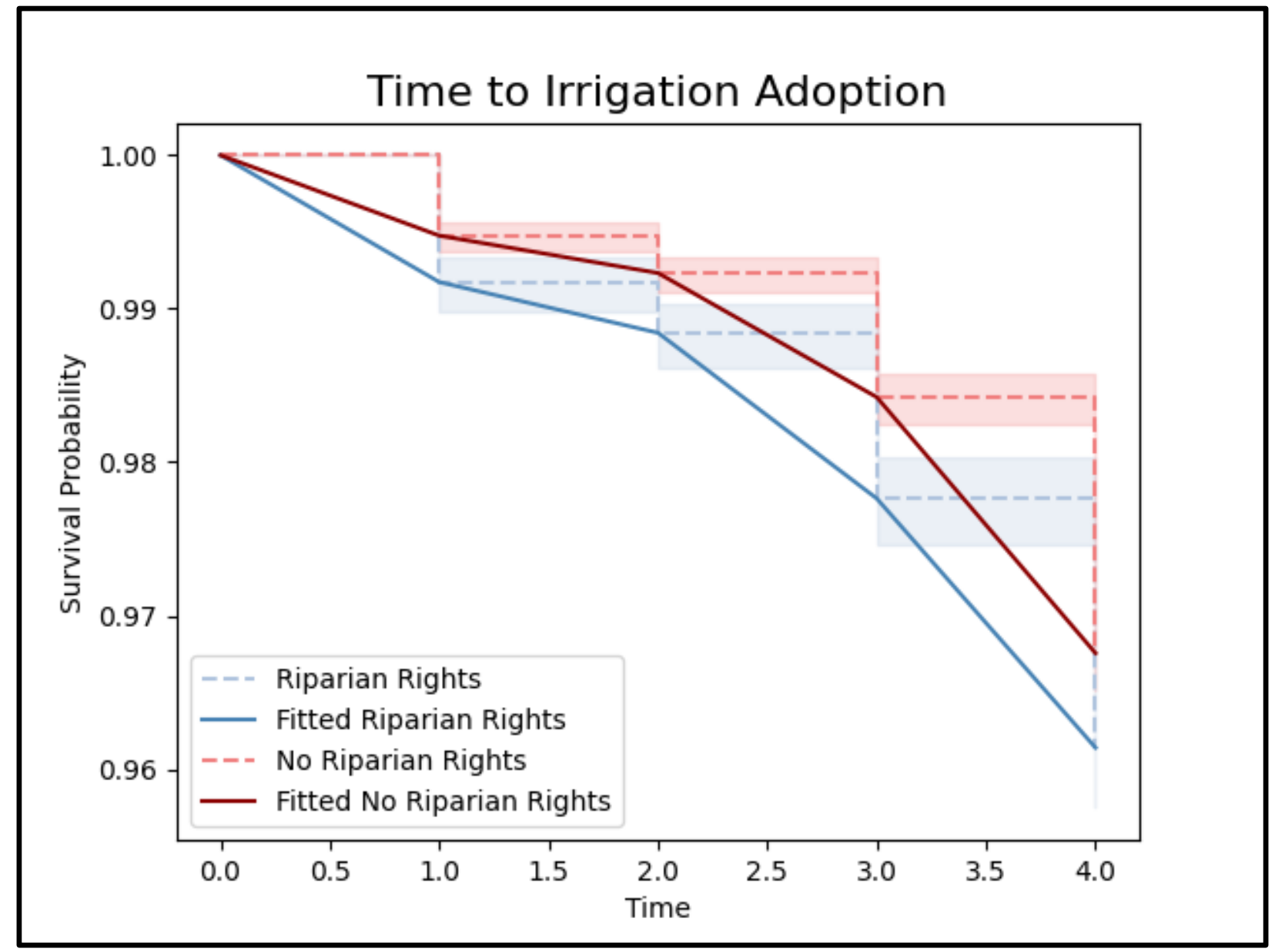

Figure 2c: Kaplan-Meier Estimate Riparian Rights

Hazard Function – Nelson-Aalen Estimator

Formula 2 shows the Nelson-Aalen estimation of the *Cumulative Hazard Function* where n_i is the number of farms *at risk* of irrigation at time t and d_i is the number of adoption decisions at time t. Figure 3 shows the relationships among functions used in survival analysis. The Nelson-Aalen estimation of the cumulative hazard rate is used to approximate the baseline hazard function, the survival function, and less directly, the cumulative distribution function.(Figure 3).

$$\hat{H}(t) = \sum_{t_i \le t} \frac{d_i}{n_i}$$

Formula 2: Nelson-Aalen Estimate

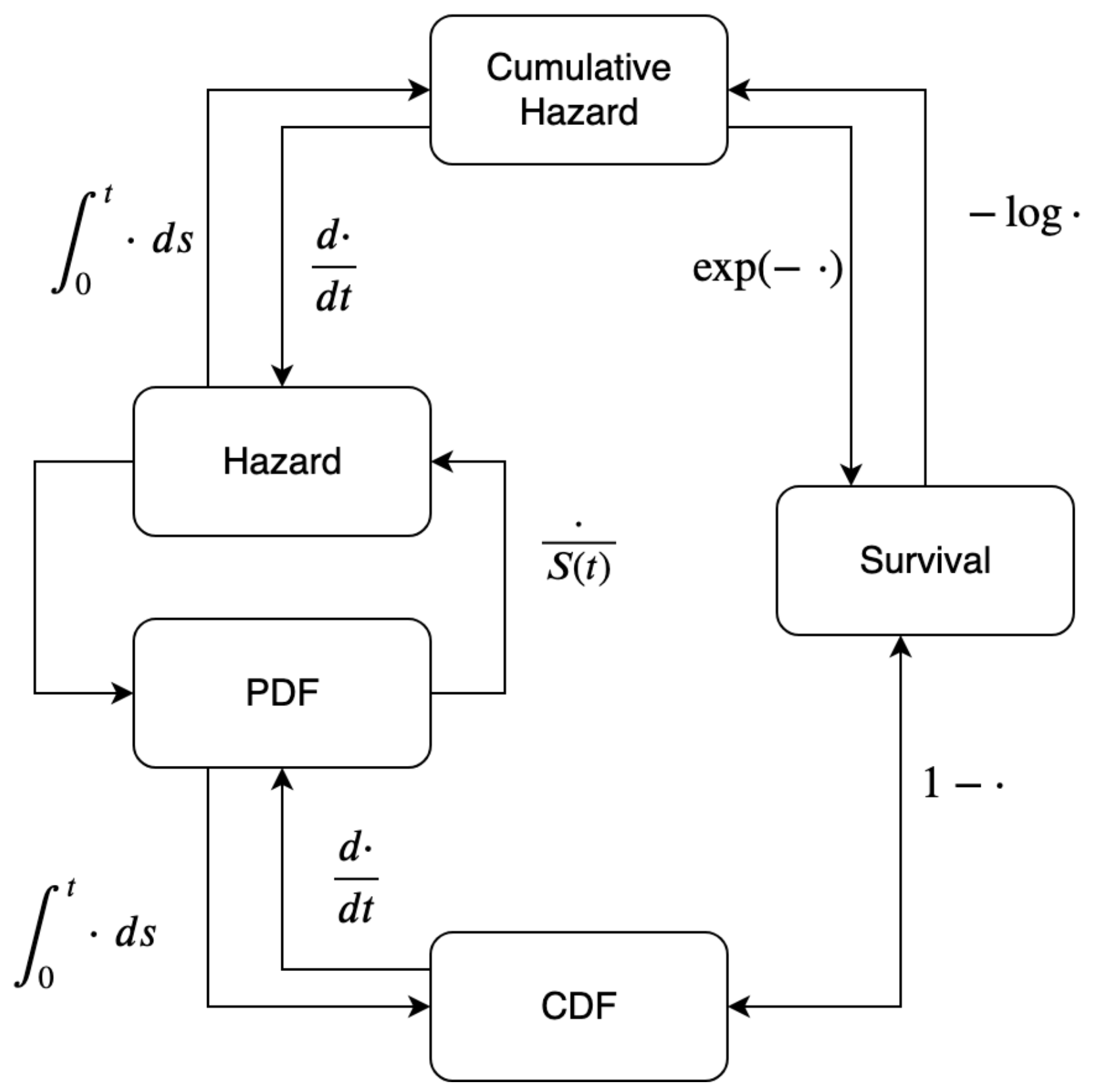

Figure 3: Functions used in Survival Analysis

(source: Lifelines)

Results & Discussion

Cox's Time Varying Proportional Hazard Model

Dynamic covariates were introduced into the survival analysis using the Cox's Time Varying Proportional Hazard Model (Formula 3) in the Lifelines Python module and was executed in ArcGIS Pro 2.7. Cox's Proportional Hazards models represent the hazard rate $h(t|x)$ as a function of time t. The baseline hazard $b_0(t)$ functions similar to an intercept in linear regression models and describes the cumulative risk at ime t. The log-hazard of subject i is a linear function of time-varying covariates x. The hazard ratio is represented by exp(β) and indicates the effect of a covariate on survival time.

$$h(t|x) = b_0(t)exp\left(\sum_{i=1}^{n} \beta(x_i(t) - \overline{x_i})\right)$$

Formula 3: Cox's Time Varying Proportional Hazard Model

Table 2: Time Varying Hazard Model Results

Cox Time-Varying Proportional Hazard Model				
Events (n = 1103) Farms (n = 32,044)				
Static				
	Coef	Exp(β)	z	p
Surface Water Access	0.0360	1.03	1.5565	0.1196
Soil suitability	0.0661	1.05	1.4939	0.1352
Well Depth	-0.0000	0.99	-0.0305	0.9757
Information Access	0.000	1.00	1.0116	0.3117
Dynamic				
Corn Prices	-0.0007	0.99	-0.1726	0.8629
Cotton Prices	-0.0014	0.99	-0.1681	0.8665
Precipitation	0.000	0.99	0.0008	0.994
Social Influence	0.000	1.00	0.1872	0.8515

The results of the time varying survival analysis are shown in table 2. The coef column gives the parameter estimates for each of the covariates, with the sign indicating the direction of influence to duration. As a known barrier to irrigation adoption, the Cox model was stratified into parcels with and without riparian rights. This analysis used well depth as a proxy for initial investment cost/access to groundwater. At the farm level, the likelihood of irrigation adoption decreases as well depth increases. Similarly, negative coefficients associated with annual corn and cotton prices indicate decreased risk of irrigation adoption in more profitable years. Several coefficients show no effect on duration. Precipitation was operationalized as annual variation from the long-term average during the growing season. Social influences, proxied as the number of irrigated acres in the Social Neighborhood and the distance to the nearest Alabama Farmers' Cooperative location, similarly had no effect on duration. The lack of statistically significant results is likely due to the small fraction of parcels experiencing events and the limited number of time periods in the analysis.

Future Research

Other forms of irrigation such as drip or micro-irrigation, that we did not consider, may be more feasible for smaller and/or disadvantaged farms. Similarly, due to the focus on center pivot irrigation, these results are most applicable to commodity crop producing farms and may not be fully transferable to all farm types likely to irrigate, such as peri-urban farms producing high value produce for direct sale (e.g., farmers' markets). Future research will include household-level, semi-structured interviews to improve the understanding of the social, economic, and demographic status of farmers throughout the region and will shed light on motivations for crop choices and irrigation practices. Moreover, the analysis shown here warrants further investigation into the possible ways to implement conceptual variables, particularly social influence. Social interactions may be better represented by a network structure, rather than a spatial neighborhood or proximity to the neighborhood center. An analysis that explicitly incorporates social connections - independent from spatial proximity - is planned in the future. Similarly, there is a potential interaction between dry season rainfall, commodity prices, and likelihood of irrigation adoption. Disentangling the intersections of these factors requires further analysis, and additional data collection through farmer interviews and surveys.

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