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Classifying Interdependencies in the Food and Agriculture Critical Infrastructure Sector

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Classifying Interdependencies in the Food and Agriculture Critical Infrastructure Sector

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by

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Abstract

This work classifies examples of infrastructure interdependencies found in the food and agriculture critical infrastructure sector. Interdependencies are identified through an examination of rice and poultry agriculture throughout the state of Arkansas. The subtleties of interdependence examples in the food and agriculture sector are inadequately captured by the well-studied interdependence classification taxonomies. Through 39 interviews, we develop an understanding of the subtle temporal, geographic, and productivity scales of interdependence in over 100 examples and present five new, distinct classifications of interdependence: (1) dynamic physical, (2) dynamic geographic, (3) deadline, (4) delay, and (5) human, economic, and natural resource interdependencies. An analysis of these interdependencies and their intricacies provides the opportunity to generalize these ideas across other critical infrastructure sectors and model infrastructure restoration and resilience with greater concern for seasonality, resource scarcity, and punctuality.

Acknowledgements

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Preface

This thesis represents the the culmination of my original work in the context of funded research projects coordinated by Sarah Nurre Pinkley, Kelly M. Sullivan, and Benjamin R. K. Runkle (“Research team”). This section serves to delineate original contributions from the contributions of the research team. Throughout these projects, I was responsible for scheduling interviews, performing each interview with at least one member of the research team, summarizing interview discussions, identifying examples of interdependence, classifying observed examples, and the original writing of this document in conjunction with the creation of visualizations contained within.

Contents

Chapter 1

Introduction

Simulation and modeling of critical infrastructure systems (CIS) build upon an understanding of infrastructure interdependence. The study of critical infrastructure systems systematically characterizes an infrastructure's operational requirements, capabilities, and environmental factors as interdependencies. From this characterization, critical infrastructure systems are modeled and disruption scenarios are simulated to further study infrastructure restoration, resilience, and reliability. The transportation, energy, telecommunications, and water and wastewater (water) *lifeline* infrastructure systems described in Lee et al. [1] are studied throughout CIS literature (see Amin [2], Bao-Hua et al. [3], Reed et al. [4], Islam and Moselhi [5], Portante et al. [6]). However, this work aims to develop understanding of the food and agriculture sector via study of rice and poultry production in the state of Arkansas. This study is a means to classify operational interdependencies in the food and agriculture sector and introduce five new, distinct classifications of interdependence.

Societal reliance on critical infrastructure systems may be most evident in the aftermath of an extreme event (e.g., terrorist attack, weather phenomena). The extreme event responsible for exposing critical infrastructure system vulnerabilities and establishing CIS protection programs was the 1995 terrorist bombing of the Alfred P. Murrah Federal Building in Oklahoma City, Oklahoma. In the months following the bombing, President Bill Clinton established the President's Commission on Critical Infrastructure Protection (the Commission) to identify infrastructure systems vital to national security, determine infrastructure vulnerabilities, and propose infrastructure protection strategies. The Commission's *Report* was published in 1997, formally defining critical infrastructure as a "network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services . . . so vital that their incapacity or destruction would have a debilitating impact on our defense and national security" [7].

Similar to the Commission's *Report*, opportunities to study CIS and infrastructure interdependencies materialize in the aftermath of extreme events. Observable infrastructure interdependencies and CIS disruption propagation patterns have been studied following extreme event occurrences. Earthquake engineers mapped and analyzed damage propagation patterns throughout lifeline infrastructures following the 1995 Kobe earthquake [8]. In turn, the Kobe earthquake study facilitated the formalization of infrastructure failure interdependencies (IFIs) in the work [9]. Additionally, the study of New Jersey, New York City, and Long Island's recovery after Hurricane Sandy made landfall in 2012 prompted the formalization of infrastructure restoration interdependencies [10]. Moreover, mathematical infrastructure restoration models were developed in an extreme event response framework [1, 11]. Alternatively, some CIS studies examine infrastructure interdependencies in the absence of disruptions and extreme events (see Haimes [12], Laugé et al. [13]). The focus of this study is an examination of Arkansas's food and agriculture sector at large.

Contextualizing Arkansas's rice and poultry productions as a critical infrastructure system and classifying operational interdependencies is the basis for modeling and simulation in the food and agriculture sector. The food and agriculture sector was not recognized to be vital for domestic well-being or national security until 2013 when President Barack Obama directed the United States Department of Homeland Security (DHS) to oversee the protection and strengthening of 16 infrastructure sectors critical to national security [14]. Food and agriculture was designated as critical and defined to be "composed of complex production, processing, and delivery systems and has the capacity to feed people and animals both within and beyond the boundaries of the United States" [15].

Indeed, the food and agriculture critical infrastructure is a complex system whose protection is paramount to national security. The food and agriculture critical infrastructure sector is a diverse composition of animal production, crop production, food and beverage manufacturing, food product warehousing, grocery stores, and restaurants. The operational diversity among components of the food and agriculture sector is responsible for producing nutrients for biological subsistence. Operational diversity underpinned by ubiquitous dependence on the sector promotes multidisciplinary interest in the food and agriculture sector - e.g, food science, agronomy, animal science, plant science, operations research, biological and agricultural engineering, agricultural economics, and agricultural science. Interdependencies existing among the food and agriculture, water, and energy infrastructure sectors have been examined through studies of the food-energy-water nexus and critical infrastructure systems [16, 17].

This study of the food and agriculture sector in Arkansas primarily focuses on classifying operational interdependencies that exist among the 16 DHS critical infrastructure sectors and Arkansas's food and agriculture infrastructures. Arkansas is well-suited for this study; approximately one-third of the state's land, 13,600,000 acres, is used for agricultural production. In 2012, Arkansas produced more rice than other state and produced the third most cotton, broiler chickens, and turkeys [18]. Moreover, 2012 sales of commodity grain in Arkansas reached \$4.2 billion, while poultry and cotton sales exceeded \$4 billion and \$445 million, respectively [18]. Maintaining high crop and animal production levels requires a robust supply chain of power plants, chemical manufacturing plants, water supplies and distribution, transportation networks, and agricultural production facilities.

The prevalence of food and agriculture operations throughout the state form a rich environment to study operational interdependencies. Furthermore, diversity of the state's agricultural operations present interdependency characteristics ranging from generic resource requirements between distinct infrastructure sectors to time-sensitive resource requirements between components of the same infrastructure. The rice production lifecycle analysis presented in Pagani et al. [19] investigates energy and input requirements necessary to grow rice Missouri's Mississippi river delta region which is visualized in Figure 1.1. Similarly, the poultry lifecycle analysis in Pelletier [20] examined direct inputs and emissions associated with producing one live-weight ton of broiler poultry which is visualized in Figure 1.2.

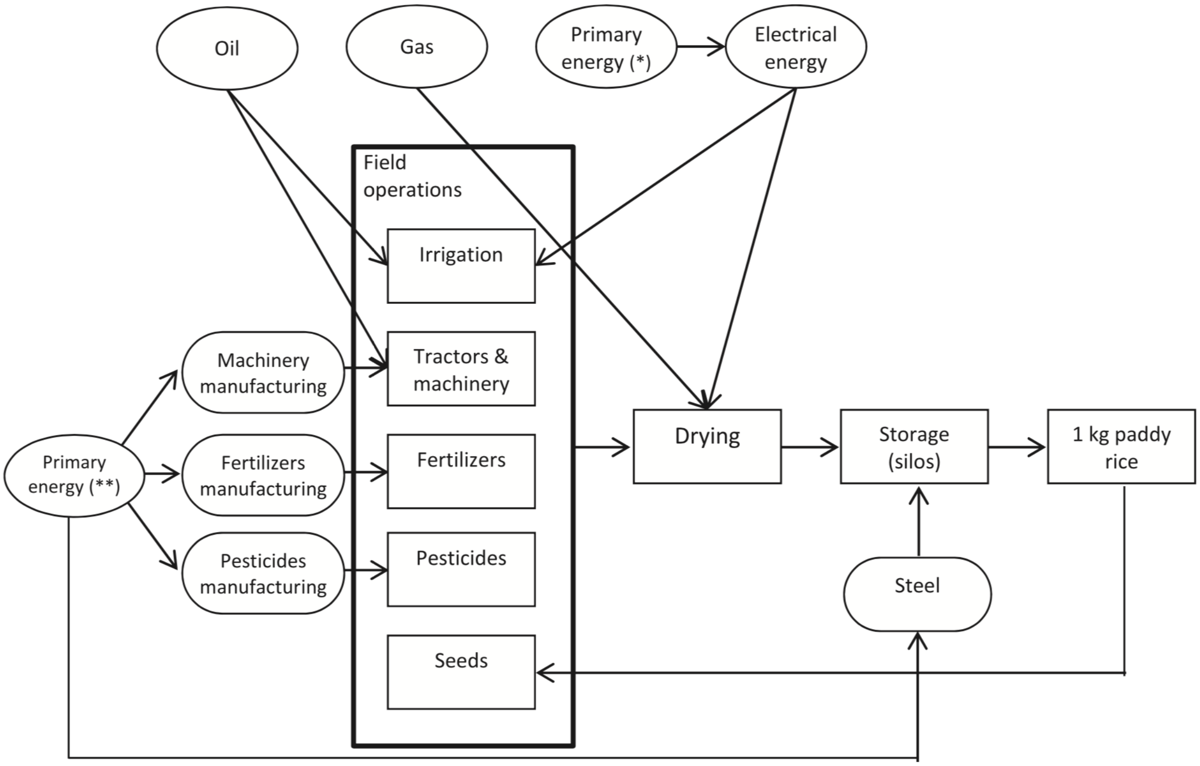

Figure 1.1: Flowchart of energy inputs from the rice lifecycle assessment of Pagani et al. [19] which illustrates primary resource requirements of the rice production infrastructure. Primary energy inputs denoted with (*) indicate the authors' directly determined the mix of fossil fuels and renewable resources used in power generation whereas primary energy inputs denoted with (**) indicate the authors determined the source of power generation based on regional operations.

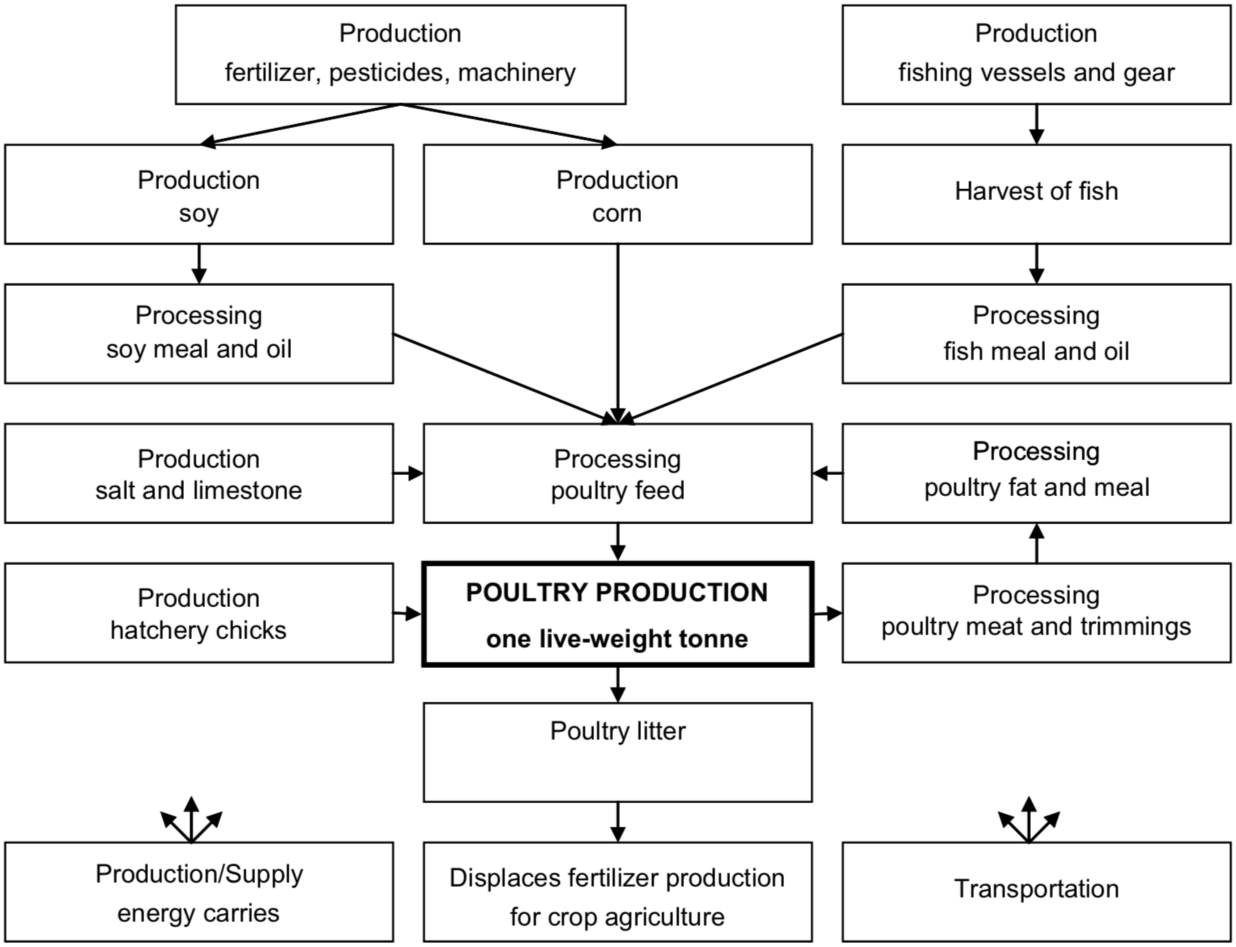

Figure 1.2: The lifecycle analysis visualized in Pelletier [20] represents direct energy inputs necessary to feed and grow one ton of live-weight broiler chickens as single arrows from resource to production process, and emissions are represented using three arrows originating from a production process.

This study classified approximately 115 observed infrastructure interdependencies; 65 interdependencies were adequately characterized by the existing taxonomy and 50 interdependencies were classified using a new, expanded taxonomy we propose. The expanded taxonomy consists of five new, distinct interdependence classifications to account for variations in resource requirements, temporal scales, geographic scales, and productivity scales. Classified interdependencies span 13 critical infrastructure sectors. The food and agriculture sector appears most frequently in 107 classified interdependencies. The transportation and water sectors appear second and third most frequently, in 26 and 18 classified examples, respectively.

This work's contributions are as follows. First, we contribute a qualitative examination of empirical evidence to classify interdependencies observed in Arkansas's food and agriculture infrastructures in accordance with the existing taxonomy. Next, we expand the existing taxonomy with five new, distinct interdependence classes adequately characterizing the remaining interdependence examples. Finally, we discuss and analyze the defining characteristics for each class of the expanded taxonomy.

This work proceeds as follows. Chapter 2 presents a review of literature relevant to critical infrastructure systems and the food and agriculture sector. Chapter 3 describes the methods used to examine the food and agriculture sector and classify interdependence examples. Chapter 4 introduces our classification scheme, Chapter 5 classifies interdependence examples using the existing taxonomy, and the formalization and classification of examples using the expanded taxonomy follows in Chapter 6. An analysis of the characteristics of the examples is presented in Chapter 7, and Chapter 8 explores future directions of this work and its implications.

Chapter 2

Review of Critical Infrastructure Systems and Interdependence Literature

It is necessary to formalize the terminology used throughout this work before surveying relevant literature. This work generalizes the formal definition of infrastructure given in Chapter 1. Infrastructure broadly refers to a collection of systems responsible for the production of an output or completion of a task. An infrastructure sector (sector) references the population of infrastructures engaged in the production and distribution of goods and services to society. This distinction between infrastructure and infrastructure sector allows us to compare classified interdependencies in Chapters 5 and 6 at the infrastructure and infrastructure sector levels. An interdependence is the relationship among infrastructures with correlated operational states.

Works motivating the study of critical infrastructure systems and specifically infrastructure interdependencies underscore the complexity of infrastructure interactions and the integral roles of infrastructures in society. The analysis of Amin [2] on the operational capabilities of the energy, telecommunications, and transportation infrastructures quantifies societal dependence on these infrastructure sectors. The work of Little [21] highlights the interconnected nature of infrastructure systems necessitating infrastructures be studied as complex adaptive systems (CAS). The infrastructure interdependency assessment process presented in Brown et al. [22] aims to mitigate risks of disruption arising the complex, interconnected nature of infrastructure systems. These works highlight the necessity of identifying infrastructure interdependencies to protect critical infrastructures.

Multiple operational interdependence taxonomies have been defined and proposed to address specific characteristics not adequately captured in the previous formalizations. The works of Zimmerman [23] and Rinaldi et al. [24] developed general classifications of operational interdependencies. An interdependence classification taxonomy was proposed in Wallace et al. [25] to formalize shared and exclusive-or interdependencies not adequately characterized by previous classes. Mathematical formalization was developed for defining operational interdependencies in Dudenhoeffer et al. [26] with consideration of interdependence induced by policy and regulation. The framework of Zhang and Peeta [27] formalized budgetary and economic interdependencies applied to economic input/output models. The concept of operational interdependence is well-studied, and this work refers to the collection of classes proposed in Zimmerman [23], Rinaldi et al. [24], Wallace et al. [25], Dudenhoeffer et al. [26], Zhang and Peeta [27] as the "well-studied interdependencies." Additionally, the taxonomies presented to characterize infrastructure failure interdependencies and restoration interdependencies in Chang et al. [9] and Sharkey et al. [10] respectively, are also considered integral to the well-studied interdependencies. For reference, a tabular presentation of each taxonomy of the well-studied interdependencies with formal descriptions for each associated interdependence class may be found in Appendix A. The formalization of interdependencies and infrastructure interactions in these two studies have facilitated the further study and comprehension of infrastructure interdependence. We consider our formalizations to be most similar to operational interdependencies with specific application to food and agriculture infrastructures. Our work focuses on developing interdependence classes that capture prevalent complicating factors or confounding attributes whose true nature is inadequately captured by existing interdependence classes. We also throughly investigate instances of resource consumption varying over time, productivity varying over time, along with the spatial and temporal characteristics affecting an infrastructure's operability. The work of Sharkey et al. [10] formalizes the concept of time-sensitive options, a restoration interdependence characterizing the difficulty of completing a restoration task increasing at a certain unknown time during the restoration process because restoration of an independent infrastructure has not been completed. The Pederson et al. [28], Xiao et al. [29], Ouyang [30] and Saidi et al. [31] literature reviews further discuss the well-studied interdependencies. The widely-cited analysis of Ouyang [30] compared the operational interdependence taxonomies of the well-studied interdependencies to determine which taxonomy most effectively and efficiently classified ten arbitrary examples of interdependence. The widely understood Rinaldi et al. [24] taxonomy was the only taxonomy that appropriately classified all ten examples of interdependence, and is well suited for classifying general examples of interdependence compared to other taxonomies. Therefore, this work refers to the interdependence classifications and classification framework of Rinaldi et al. [24] as the "existing taxonomy" used in Chapter 5.

Operational interdependence refers to relationships among infrastructures such that the operational state of an infrastructure depends on an independent infrastructure's productivity. These interdependencies are subject to cascading failures propagating from a single disruption throughout a complex network of interdependent infrastructures [9, 24, 32]. In general, interdependencies are identified through empirical examinations of infrastructures and examining disruption propagation patterns following extreme events. Interdependencies are identified and discussed in CIS studies aiming to build conceptual understanding of interdependencies and parameterize infrastructure models and simulations.

Each of the works composing the well-studied interdependencies created further conceptual understanding of operational interdependencies. The operational interdependencies identified in New York City presented in Wallace et al. [25] identified mechanisms inducing operational interdependence not yet formalized. The study of infrastructure interdependence has evolved beyond operational interdependencies. The concept of IFIs presented in Chang et al. [9] was formulated through the study of infrastructure disruption patterns observed after the 1995 Kobe earthquake. Pragmatic examples of IFIs were studied in the aftermath of power blackouts, hurricanes, and ice storms were documented in McDaniels et al. [32], Chang et al. [33], McDaniels et al. [34], and McDaniels et al. [35] and then aggregated into an IFI database presented in Chang et al. [36] to inform risk mitigation strategies. Similarly, Sharkey et al. [10] presented the concept of infrastructure restoration interdependencies formulated from observation of restoration activities in the wake of Hurricane Sandy.

Applications of empirical interdependence classification are the development of quantitative measures of interdependence, empirical risk analyses, and parameterization of infrastructure interdependence and restoration models. The works of Zimmerman [23, 37], and Zimmerman et al. [38] analyze cross-sector interdependencies, the effects of cascading failures on infrastructure sectors, and infrastructure sector resilience, respectively using quantitative interdependence and resilience metrics. Further quantification of infrastructure resilience metrics (e.g., robustness, rapidity, performance loss) are presented in Nan and Sansavini [39]. The work of Chang and Shinozuka [40] quantifies water distribution infrastructure resilience to disruptions caused by earthquakes. Quantitative metrics of operational interdependencies in Kajitani and Sagai [41] are derived from structural engineering data, system operations plans, and economic data. Statistical significance tests are performed in Mendonça and Wallace [42] and Dueñas-Osorio and Kwasinski [43] to determine significant cross-sector interactions following the 2001 World Trade Center terrorist attacks and 2010 Chilean earthquake. Operational interdependencies were quantified to perform a CIS risk assessment in Kjølle et al. [44] by computing failure probabilities used to predict disruption frequency and severity in a Norwegian energy infrastructure. Operational interdependencies presented in Espada et al. [45] are inform network flow parameters in a GIS network model established to assess flood vulnerabilities.

Infrastructure interdependencies are identified to develop infrastructure modeling and simulation techniques throughout critical infrastructure sectors. The modeling literature extensively focuses on the lifeline infrastructure sectors. The work of Zimmerman et al. [17] explores interdependencies among the food and agriculture, water, and energy infrastructure sectors with special attention paid to organic farming. Similarly, Scott et al. [46] and D'Odorico et al. [16] expound on the interdisciplinary food-water-energy nexus field of study. This work aims to comprehensively characterize the interdependencies found in the food and agriculture infrastructure sector and present interdependence classes applicable to sectors beyond food and agriculture.

Chapter 3

Methods for Classifying Interdependencies

The aim of this study is to document observed examples of interdependencies found in Arkansas's food and agriculture critical infrastructure sector. The documented interdependency examples are presented in a classification framework expanding the prevalent classifications of Rinaldi et al. [24]. The newly defined, distinct classifications are used to capture frequently appearing subtleties among the observed examples. Interdependencies in the food and agriculture sector are subject to complicating factors discussed in Rinaldi [47] like varying time scales, geographic scales, and productivity. Clear exposition and general application of these complications further motivates our study of the food and agriculture sector interdependencies.

Studying Arkansas's food and agriculture sector is facilitated by the sector's productivity and geographic footprint. In 2014, the food and agriculture sector's total economic contribution to state GDP exceeded 20 billion USD, more than 17% of Arkansas GDP, from producers spanning the poultry operations in northwestern Arkansas to row crop farming on the state's eastern side [48]. The food and agriculture sector's combined economic and geographic presence encourages public and commercial enterprises to thoroughly understand the sector's operations. This work relies on the knowledge and experience of food and agricultural operators and stakeholders in interdependent infrastructure sectors.

Examples of infrastructure interdependencies were collected, most significantly, through a series of interviews with stakeholders in the food and agriculture sector throughout Arkansas. Interviews were conducted with 39 individuals representing food and agriculture operations, public utilities, emergency services, financial institutions, and higher education. Of the 39 individuals, 12 are academic experts in food science, poultry science, agriculture, engineering, or agricultural economics. The remaining 27 interviewees operated or managed food and agriculture production, food milling and processing plants, public enterprises, financial institutions, government organizations, and agriculturally focused policy initiatives. We recognize there is a discrepancy in responses from poultry professionals in comparison to experts in rice production interviewed throughout the study. The amount of time we spent interviewing respondents that are knowledgeable about rice production is substantially longer than those in the poultry field, which introduces bias into our study. Throughout the planning and interviewing stages, we attempted to interview professionals in both fields earnestly. Recognizing bias resulting from studying interdependencies existing in the rice production infrastructures more deeply than poultry allowed us to understand that bias may also arise from our study of infrastructure interdependencies considering food and agriculture stakeholders to be the dependent infrastructure in many scenarios. Our respondents were exceptionally knowledgeable in their chosen fields, but a thorough understanding of how other critical infrastructure systems respond if food and agriculture is interrupted was elusive.

Generally, each interview was attended by at least two members of the research team and lasted appropriately one hour. The research team's preference was to conduct physical interviews when possible, if not, teleconferencing was used. The research team traveled to conduct interviews in Jonesboro at the *Arkansas Soil & Water Education Conference & Expo* on January 31, 2018, and then further traveled to Little Rock and the Arkansas delta region to interview commercial grain mill operators, commercial rice farmers, public servants, and policy advocates. Interviews were also conducted in northwest Arkansas with academics and utility providers. Each interview followed similar formats and guidelines to effectively identify infrastructure sector interdependencies and discuss specific examples of infrastructure interdependencies.

Three broad topics were addressed by each interviewee: the nature of their relationship with the food and agriculture sector, perceptions of how the food and agriculture sector depends on other DHS critical infrastructure sectors, and the risks or vulnerabilities affecting food and agriculture. All interviews began with an interviewee's personal introduction and explanation of their professional responsibilities and expertise. The research team then introduced this research and the study of critical infrastructure systems in the context of our interviewee's profession. Discussions identifying infrastructure sector dependencies were aided with a reference document enumerating and briefly discussing each of the critical infrastructure sectors. Sectors thought to be interdependent were further discussed to understand specific examples of interdependency that the interviewees had observed. The research team continued the discussion through questions designed to expose the nature of how specific infrastructure components interact along in as much detail as possible. Clarifications of specific examples developed an understanding of how these interactions and dependencies changed over time, varied with operational tasks within the food and agriculture sector, and exposed ancillary factors affecting the interdependence.

Furthermore, examples of interdependencies have been identified in news publications and Arkansas agricultural publications. Interview participants widely acknowledged food and agriculture production to be vulnerable to weather events. Specifically, the effects of Hurricane Harvey making landfall in late August of 2017, during the peak of the rice harvest, were well documented by news outlets and agricultural publications in Arkansas, Louisiana, and Texas. Our study includes a further investigation of Hurricane Harvey's effects on the food and agriculture sector in the tri-state region. Specific, fully characterized examples of interdependencies existing in the food and agriculture sector from the interviews and periodicals were then aggregated for further analysis and classification.

Initially, interdependencies were classified to be physical, cyber, geographic, or logical in accordance with the existing taxonomy. Analysis of the interdependency classification presented several distinct factors complicating multiple examples, each affecting the examples in a distinct, generic fashion. The complicating factors frequently observed in this study of the food and agriculture sector were identified in order to formally define new, distinct interdependence classifications. Formalizing these frequently occurring factors necessitates the proposal of five new classes of infrastructure interdependence which adequately capture subtle characteristics the existing taxonomy is unable to do. Subsequently, the examples were reclassified using a combination of the existing taxonomy and the newly-defined classifications referred to as the expanded taxonomy. To validate the classifications, the research team unanimously agrees the exposition of the example accurately characterizes the true nature of the interdependence and then the example is also appropriately classified. We then further standardized our observations using an industry classification taxonomy, North American Industry Classification System (NAICS) developed by United States Department of the Census. Through this standardization and aggregation, we are able to interpret our findings and provide accurate, concrete accounts of the interactions we observed across specific infrastructure components.

Chapter 4

Classification of Interdependencies in the Food and Agriculture Infrastructure Sector

The focus of this study is to classify infrastructure interdependencies observed throughout the food and agriculture sector. Interdependence classes of the existing taxonomy and expanded taxonomy are defined and explicated in Chapter 5 and Chapter 6, respectively. The expanded taxonomy interdependence classes are dynamic physical, dynamic geographic, deadline, delay, and human, economic, and natural resource. Expanded taxonomy interdependence classes are motivated by characteristics of infrastructure interdependencies observed in the food and agriculture sector exhibiting subtleties not adequately captured by the existing taxonomy. Further development of these concepts are found throughout Chapter 5 and Chapter 6. This work aims to observe and formalize operational interdependencies existing in the food and agriculture sector; more specifically, what factors characterize and confound the nature in which two infrastructures rely on one another to remain operational and productive day-to-day. We consider four of the five new, distinct interdependence classes presented in this work to satisfy the definition of operational interdependence. However, during the course of this work , we regularly observed a change in behavior among infrastructures in the aftermath of some type of disruption. More specifically, we observed instances in which a dependent infrastructure experienced a time lag before being impacted by an independent infrastructure's disruption, and we observed events requiring collaboration among neighbors in order to mitigate the impact of a disruption. These interactions characterized by the geographic, dynamic geographic, and delay interdependence classes more accurately characterize infrastructure tasks and operations that are undertaken in order to restore productivity after a disruption, hence we consider them to be restoration interdependencies.

This study of the food and agriculture sector identified and classified approximately 115 examples of infrastructure interdependence. Of the 115 classified examples, five examples outside of the food and agriculture sector were identified. The existing taxonomy appropriately classified 65 interdependencies, and the remaining 50 interdependencies were classified by the expanded taxonomy. This study found the food and agriculture sector to be interdependent with 13 of the 16 critical infrastructure sectors designated by DHS. Discussion and analysis of interdependence classifications in this study is provided in Chapter 7. Table 4.1 presents the notation used to formalize interdependence classes in this paper.

Table 4.1: The following symbols are used in this paper:

Notation	Definition and description
A, B, A_i	Infrastructure sectors are represented as A and B in a two-way interaction, where a collection of n geographically interdependent infrastructure sectors is represented A_i for $i = 1, \ldots, n$ for $n \geq 2$;
(A, B)	An interdependence between two infrastructure sectors such that infrastructure sectors A, in some way, depends on B;
$\underline{\text{infrastructure}}^{A,B,A_i}$	The description of each observed infrastructure interdependence denotes an infrastructure in infrastructure sectors A, B, A_i as $\underline{\text{independent infrastructure}}^{A}$, $\underline{\text{dependent infrastructure}}^{B}$, and $\underline{\text{geographically interdependent infrastructure}}^{A_i}$;
S	The set S is composed of distinct infrastructure sectors, A_i, when there exists an interdependence with another infrastructure sector, A_j, for $i, j \in \mathbb{N}$, i.e., $S = \{A_i : \exists (A_i, A_j) \text{ for } i = 1, \ldots, n,\ j = 1, \ldots, n, \text{ and } i \neq j\}$;
$\bar{t}$	The time at which an arbitrary deadline occurs is denoted $\bar{t}$; and
δt	An arbitrary interval of time is denoted δt.

Chapter 5

Interdependence Classifications in the Existing Taxonomy

Interdependence classifications begin with the physical, cyber, geographic, and logical classes of the existing taxonomy. Generally, the interdependence classes of the existing are simply defined and adequately capture broad dependence relationships among critical infrastructure sectors. This study considers physical, cyber, and logical interdependence classifications to appropriately characterize distinct, static dependence relationships among infrastructure sectors over time. Similarly, geographic interdependencies exhibit infrastructure consistency characteristics that are affected by some localized event.

5.1 Physical Interdependencies

Definition: The operational state of infrastructure A depends on a material output of infrastructure B [24].

Observed frequency: 37.

Examples (A, B):

- (Food and agriculture, Food and agriculture). Animal food manufacturing^{A} feed formulations depend on cereal grains produced by the crop production^{B} infrastructure.
- (Food and agriculture, Chemical). Crop production^{A} depends on fertilizer, herbicides, pesticides, and other agricultural chemicals produced by the agricultural chemical manufacturing^{B} infrastructure.
- (Food and agriculture, Critical manufacturing). Animal production^{A} and crop production^{A} depend on industrial equipment and farm machinery produced by the agricultural implement manufacturing^{B} infrastructure.

Discussion: The physical infrastructure interdependence classification characterizes an infrastructure's dependence on the productivity of another infrastructure sector. Examples of physical interdependencies may be generalized across similar entities within an infrastructure. For instance, feed formulations may vary across dairy cattle, beef cattle, swine, and poultry production operations based on nutritional requirements for a specific infrastructure's livestock or if the infrastructure's material outputs are organic or conventional, but invariably commercial animal production infrastructures require large volumes of cereal grains (e.g. soybeans, corn, wheat) to feed their livestock. Similarly, plant production operations vary in size, output volume, and crop output, but the operational activities among plant producers are similar, so there exists a uniform, collective dependence on agricultural chemicals (e.g., fertilizers and herbicides) produced in the chemical infrastructure sector and tractors, combines, and other farm equipment produced within the critical manufacturing infrastructure sector. The general, collective nature of physical interdependencies captures vital input requirements of the food and agriculture sector at an aggregate level. Thus, the dependent infrastructures exhibit a consistent demand over time. In summary, the defining characteristics of the physical interdependence classification are generic operational dependence on widely accessible outputs from independent infrastructures and, in the aggregate, variability in the nature and timing of operational activities across an infrastructure sector creates consistent dependence on material outputs from independent infrastructures over time.

A comprehensive list of all physical interdependencies classified in this study is presented in Appendix B.

5.2 Cyber Interdependencies

Definition: The operational state of infrastructure A is dependent on a material output of infrastructure B that is transmitted directly or indirectly through the information technology or communications critical infrastructure sectors [24].

Observed frequency: 20.

Examples (A, B):

- (Dams, Information technology). Water supply and irrigation systems$^{\mathrm{A}}$ floodwater impoundment and diversion activities are planned using real-time environmental data in the Damwatch web-application that depends on the data processing, hosting, and related services[B] infrastructure.

- (Food and agriculture, Communications). Farm management services[A] that remotely monitor and operate farm equipment such as grain bins depend on the wireless telecommunications carriers[B] infrastructure to transmit digital communications in rural areas.
- (Food and agriculture, Information technology). Agricultural research and development[A] depends on physical and cybersecurity measures in the security systems services[B] and data processing, hosting, and related services[B] infrastructures to protect proprietary technology and intellectual property from unauthorized access as a matter of corporate security and national security.

Discussion: The cyber interdependence classification is a special case of physical interdependencies. Indeed, the operational state of dependent infrastructures in the observed examples of cyber interdependence are dependent on material output and productivity of infrastructures operating within the information technology or communications critical infrastructure sectors. Modernization of entities within the food and agriculture sector has created operational dependencies on communications and information technology infrastructures in order to monitor automated business processes such as billing, production, and material management. Furthermore, reliance on automation and information technology in the food and agriculture sector increases the complexity of operational activities by allowing for farm management services to remotely monitor and control grain drying facilities or necessitating managed services providers implement additional cybersecurity measures in order to prevent corporate espionage and deter attempted of agri-terrorism. As in the case of physical interdependencies, we consistently observed food and agriculture infrastructures exhibiting dependence on generic outputs of the independent cyber infrastructures. Similarly, the defining characteristics of the cyber interdependence classification are generic operational dependence on widely accessible outputs from independent infrastructures and, in the aggregate, variability in the nature and timing of operational activities across an infrastructure sector creates consistent dependence on material outputs from independent infrastructures over time.

A comprehensive list of all cyber interdependencies classified in this study is presented in Appendix C.

5.3 Geographic Interdependencies

Definition: A "local environmental event can create state changes in all [infrastructures in a collection]" ($A_1, \ldots, A_n$) [24].

Observed frequency: 8.

Examples ($A_1, \ldots, A_n$):

- (Food and agriculture^{A_1}, Water^{A_2}). Food manufacturing^{A_1} facilities consume large amounts of potable water and require high volumes of wastewater collection and hence tend to be geographically clustered in regions where distribution networks and wastewater treatment facilities in the municipal water and sewage systems^{A_2} infrastructures are well established.

- (Food and agriculture$^{A_1, A_2, A_3}$, Transportation^{A_4}). Grain farming^{A_1}, grain milling^{A_2}, and grain elevators and storage^{A_3}, and the road transportation^{A_4} infrastructures used in crop production are typically within a 25 mile radius.

Discussion: Observed examples of geographic interdependencies exhibit characteristics formalized in the well-studied interdependencies. The first example of geographically interdependent infrastructures presented in our study are food processing facilities and municipal water and wastewater utilities. We have identified examples of geographic interdependence between food processing facilities and municipal water and sewer systems induced by capacities of the existing water distribution and wastewater collection networks. In smaller, rural communities food processing facilities were strategically located to avoid insufficient wastewater processing capacity which, in turn, may limit production capacity and prevent expanding operations in the region. Similarly, poultry processing facilities clustered in more populated areas are located in close spatial proximity because of high accessibility to the municipal water and sewer infrastructures. The second example of geographic interdependence in our study is based on the nature of operations for rice production in the Arkansas delta region. Rice production processes are typically localized such that rice growing, harvesting, milling, and processing all occur within a local area. This clustering of infrastructures responsible for productivity in multiple steps of the broader row crop production infrastructure creates opportunity for both production efficiencies and cascading disruptions that require neighboring facilities to increase production levels and transportation infrastructures to haul grain farther.

The rice production infrastructure's shifting preference for local grain drying and storage showcases the importance of differentiating between resource requirements as physical interdependencies and geographic interdependencies induced by co-location and spatial proximity. As the rice production infrastructures become more reliant on on-farm grain drying and storage systems, the sector's dependence on tractor trailers in order to haul wet, freshly-harvested grain to commercial rice mills that, generally, are located farther from rice harvesting activities than an on-farm drying and storage bin. This reduction in delivery distance implies an increase in operational efficiency during the transition from rice harvesting operations to grain processing activities, but there is simultaneously a geographic interdependence induced between the infrastructures when the physical facilities and operational activities occupy the same space. The rice production and grain processing infrastructures have both become susceptible to localized events, which may disrupt and damage the land, equipment, growing rice, and harvest rice simultaneously.

These examples of geographic interdependence are specific to our study but, as with the other classes of the existing taxonomy, geographic interdependencies characterize generic mechanisms that correlate operational states within a collection of infrastructures that is consistent across specific entities or infrastructures that perform similar operational activities within the larger critical infrastructure sector. A comprehensive list of all geographic interdependencies classified in this study is presented in Appendix D.

5.4 Logical Interdependencies

Definition: The operational state of A is dependent on B by some “mechanism that is not a physical, cyber, or geographic connection” [24].

Observed frequency: 5.

Examples (A, B):

- (Water, Food and agriculture). Water supply and irrigation system$^{\mathrm{A}}$ infrastructures in Arkansas depend on crop production$^{\mathrm{B}}$ to self-report groundwater usage to conservation districts monitoring groundwater use and forecasting groundwater availability for future growing seasons.

- (Food and agriculture, Financial services). Animal production$^{\mathrm{A}}$ and crop production$^{\mathrm{A}}$ depend on agriculturally-focused credit services$^{\mathrm{B}}$, the Farm Credit System, created, operated, and regulated by the federal government.

Discussion: The final interdependence class of the existing taxonomy is defined to comprehensively classify infrastructure interdependencies that exist beyond the interdependencies induced by operational input requirements or geospatial proximity. In this study, we classify observations as logical interdependencies in the cases such that neither input requirements nor spatial proximity is the primary mechanisms driving correlated state changes between infrastructures. Moreover, we classify observations as logical interdependencies if we are able to infer an interdependence is systematically observable in a more general context. In our first example of logical interdependence, a majority of crop production infrastructures throughout the state of Arkansas draw vast amounts of groundwater for irrigation, and the Arkansas Natural Resources Commission (ANRC) requires users to self-report usage data annually. Groundwater usage data is recorded and analyzed by ANRC in order to estimate groundwater levels, identify regions of critically low groundwater levels, and formulate the Arkansas Water Plan. In this example, our knowledge of the groundwater supply is informed by producers operating within the crop production infrastructure, and the producers operating within the crop production infrastructure influence groundwater availability and usage policy through continued irrigation. Moreover, instances of asymmetric information have influenced the actions of ANRC when users intentionally under-report or over-report usage in fear of municipal usage fees or groundwater rationing, respectively, as groundwater levels continue to fall. Despite the complexity, we have observed consistent activity from the mutually interdependent infrastructures over time and across the greater crop production infrastructures operating in the state of Arkansas. Summarily, the logical interdependence classification captures intricate correlations between the operability of infrastructures which are consistently observed over time and systematically occurring throughout the general critical infrastructure sector.

We must also distinguish the decision to classify these examples as logical interdependencies rather than human, economic, and natural resources interdependencies defined in Chapter 6. The first example of logical interdependence identifies the mechanism in which water supply and irrigation infrastructures depends on crop production infrastructures. This example is only classified under the logical interdependence because there is a regulatory mechanism coupling and confounding the relationship between independent and dependent infrastructures. Public entities mandate row crop farmers estimate and self-report groundwater usage around the aquifer, and then calculate groundwater metrics like water consumption projections, approximate water levels, and net change in the groundwater supply. Row crop farmers tend to be skeptical of the motivations for reporting groundwater consumption, hence clouding the validity of reported consumption. Clearly this example of interdependence is more complex, and we are unable to capture the true nature of the interaction between these infrastructures simply, hence the catch-all classification.

Similarly, agricultural infrastructures rely on financial services infrastructures coupled through a public enterprise under federal oversight and administration. Congress created the Farm Credit System in 1916 in order to finance agricultural production throughout the country, and operations of the Farm Credit System are influenced through public policy. Moreover, the establishment of a system that funds private enterprises by the federal government confounds the mechanisms in which animal production and crop production infrastructures receive the credit necessary to operate. The true nature of interdependence in the examples of logical interdependence is influenced by factors not solely determined to result from changing human, economic, and natural resource factors. Hence, the second complex example that involves human resources, economic resources, or natural resources that does not fit the definition of the new interdependence.

A comprehensive list of logical interdependencies classified in this study is presented in Appendix E.

Chapter 6

Interdependence Classifications in the Expanded Taxonomy

We examined the true nature of interactions captured by the physical, cyber, geographic, and logical interdependence classes of the existing taxonomy. Generally, existing taxonomy classifications characterize a given infrastructure's operational behavior in relation to an independent infrastructure's ability to produce and distribute resources necessary for production in the dependent infrastructure. We now aim to examine infrastructure interdependencies, input requirements, disruption effects, and the temporal and geographic scales of operational activities in a granular fashion through the classifications of our expanded taxonomy. In this section, we present and discuss the dynamic physical, dynamic geographic, deadline, and delay interdependencies along with our classification of human, economic, and natural resource interdependencies.

6.1 Dynamic Physical Interdependencies

The dynamic physical infrastructure interdependence classification enhances the resolution of physical interdependencies by accommodating resource requirements for time-varying operational activities in the dependent infrastructure. Enhancing the resolution of a physical interdependence necessitates we examine an infrastructure's production cycle more closely in order to identify sources of variation in between the independent and dependent infrastructures. We observed production and operational tasks that vary over time, due to seasonal demand fluctuations or environmentally constrained productivity among other reasons, exhibited analogous varying resource requirements. This examination of production cycles and time varying resource requirements provided key insights for our high-resolution analysis to more adequately capture the true nature of this behavior. Examining the operational infrastructure components, associated physical resource requirements, and schedule in which these processes occur underpins accurately assessing of timely component-level susceptibility to cascading failures and measuring disruption-driven performance degradation.

Definition: The time-varying operational activities of infrastructure sector A depend on different amounts of material outputs of infrastructure sector B over time.

Observed frequency: 14.

Examples (A, B):

- (Food and agriculture, Transportation). Broiler chicken production$^{\mathrm{A}}$ flock production cycles last approximately 10 weeks where the cycle begins with the placement of live chicks to begin a seven week grow-out period that ends when the mature birds are processed. Cleaning and sanitation tasks are completed in the final three weeks of the cycle while the house is empty, hence broiler chicken production depends on truck transportation$^{\mathrm{B}}$ to deliver poultry feed from the feedmill to poultry farms only during the seven week grow-out period when the house is occupied.

- (Food and agriculture, Water). Rice farming$^{\mathrm{A}}$ depends on water supply and irrigation systems$^{\mathrm{B}}$ to deliver groundwater for irrigating crops from May through September.

- (Transportation, Food and agriculture). Truck transportation$^{\mathrm{A}}$ depends on grain milling$^{\mathrm{B}}$ efficiency in September - November to efficiently unload grain deliveries preventing long queues that disrupt truck flow from grain mills to farms.

Discussion: In the first observed example of dynamic physical interdependence, we recognize that, generally, a tractor-trailer filled with age appropriate feed is filled at the feedmill and then dispatched to deliver the feed to a poultry flock that is being grown in multiple houses across many farms operated by contract-growers. Moreover, the standardized grow-out cycle includes several weeks where no livestock production activity occurs, when dependence on truck transportation of feed vanishes, in order to prepare for the arrival of the next flock. Disruptions in feed delivery typically do not fully disrupt production output, rather there is a reduction in the yield of the flock caused by a lack of feed during the disruption period.

The second example characterizes a rice farm's dependence on water and irrigation resources used specifically for the production period occurring annually from May to September. During periods when no crops are grown there is essentially no dependence on water infrastructures as no activities occurring in the rice growing infrastructures require irrigation. A disruption of water supply and irrigation systems during the growing period is unlikely to fully disrupt production, but reduces harvest yield as the crops were unable to grow during the disruption period. The disruption of water during harvest illustrates the effects of continuously occurring disruptions observed frequently in our study of the food and agriculture sector. Similarly, grain milling productivity spikes as rice is harvested and milled annually from September through November. Rice farms using the same rice mill typically have homogeneous production cycles caused by localized weather patterns; homogeneous production cycles, in turn, require grain milling facilities to accept high volumes of freshly harvested rice in a brief period. The influx of rice deliveries creates long queues of trucks waiting to be processed at production facilities which increases the lead time between deliveries. This increase in lead times at the production facility then stops harvesting operations if on-farm temporary storage reaches capacity. Harvesting operations may resume only if trucking infrastructures increase productivity by supplying more trucks to unload temporary storage containers that must wait in long queues or if rice milling facilities increase the rate deliveries are processed, unloaded, and released from the queue. More importantly, this disruption in the trucking infrastructure at harvest time is detrimental to total rice production.

A comprehensive list of dynamic physical interdependencies classified in this study is presented in Appendix F.

6.2 Dynamic Geographic Interdependencies

The dynamic geographic infrastructure interdependence classification extends and enhances a geographic interdependence by characterizing operational changes in a collection of infrastructures spontaneously and unexpected caused by a local event over a period of time. It is important to distinguish our dynamic geographic classification from the geographic class of the existing taxonomy. We consider the existing taxonomy to account for a static collection of infrastructures that are simultaneously disrupted, but our dynamic geographic classification is distinct through a recognition of interdependent infrastructures productivity levels shifting such that production and output exist in the affected infrastructures when other infrastructures, not necessarily subject to disruption by traditional geographic interdependence, become necessary to sustain output. This shift in productivity is recognized when there is a change in geographic footprint of operational activities is triggered by another disrupted infrastructure. The shifts in productivity result from a flow of output from one region unaffected by the triggering event to support production in the affected region. The change of infrastructure operations and output in the unaffected region that result from a disruption are the infrastructures which are classified by the dynamic geographic interdependence. This dynamic geographic interdependence further presents correlated activities during restoration activities in the event an infrastructure is disrupted by an extreme event. Thus, the dynamic geographic may also be classified as a new type of restoration interdependence.

Definition: The geographic or spatial scales in which a local event can create state changes in all infrastructures in a collection ($A_1, \ldots, A_n$) are altered by some process, event, or circumstance.

Observed frequency: 9.

Examples ($A_1, \ldots, A_n$):

- (Food and agriculture$^{A_1, A_2, A_3}$, Transportation^{A_4}). The geographic scale of crop production^{A_1}, grain milling^{A_2}, grain elevators and storage^{A_3}, and truck transportation^{A_4} infrastructures interdependence shrinks as on-farm grain drying storage systems become more prevalent.

- (Food and agriculture$^{A_1, A_2}$, Transportation^{A_3}). The geographic scale of animal production^{A_1}, animal food manufacturing^{A_2}, and truck transportation^{A_3} infrastructure interdependence increases when a feedmill is unable to manufacture feed creating dependence on neighboring feedmills for the production and transportation of feed

Discussion: The first example of dynamic geographic interdependence classifies infrastructures whose operations are determined by the usual grain production cycle but are shifting over time to accommodate changes in operational tasks during harvest which result from local farmers adopting on-farm grain drying systems as a substitute for immediately shipping freshly harvested grain to commercial mills during the harvest. The adoption of on-farm grain drying systems has added a number of operational activities in the crop production infrastructures and reduced the volume of operational activities in the grain milling and truck transportation infrastructures specifically when crops are harvested. The distances in which crop delivery trucks travel from the field to the dryer and elevator is reduced to the distance from the field to the on-farm systems. Similarly, commercial grain elevators observe reductions in the amount of wet rice that must be unloaded, processed, and dried as more farmers utilize local drying and storage solutions. These reductions of production volume correspond to the crop production infrastructures assuming the burden of drying grain locally. This reduction in operational activities is specific to grain drying infrastructures, but the total amount of work done by the truck transportation becomes more evenly distributed throughout the year since most farmers sell dried, unprocessed rice to commercial grain elevators that mill, package, and resell the inventory. However, there is a tradeoff between increased production efficiency resulting from co-locating the equipment and processes performed in the grain drying and storage stages of supply chain to the same space where row crops are grown and harvested. This co-location increases the susceptibility of both row crop production and grain milling operations to be affected by the same localized event that would have previously only disrupted the row crop production operations during the growing season.

The second example presented in our study occurs in the event a livestock feedmill, or more generally another production facility, becomes inoperable for some period of time. When production facilities in the food and agricultural sector are unable to operate as planned when biological processes occurring in livestock production, crop production, and food processing operations require productivity in interdependent infrastructure components then an increase in the volume of operational activities in those interdependent infrastructures is observed. In this case, neighboring feedmills are contracted to produce feed for livestock impacted by the disrupted feedmill. Delivery from this alternate location during the period of disruption increases the amount of production required from the truck transportation infrastructure. Moreover, the neighboring feedmill may have to increase total productivity in order to produce the volume of feed required for planned operations in addition to the feed production burden they are contracted to satisfy until operability of the affected infrastructures is restored.

A comprehensive list of dynamic geographic interdependencies classified in this study is presented in Appendix G.

6.3 Deadline Interdependencies

The deadline infrastructure interdependence classification also enhances the resolution of physical interdependencies by characterizing infrastructure components or tasks that require the operations of an independent infrastructure be completed by a specific deadline. Like the dynamic physical classification, deadline interdependence extends and enhances the physical interdependence class to accommodate a temporal factor observed frequently in our study of the food and agriculture sector. The deadline interdependence resembles the time-sensitive options restoration interdependence presented in Sharkey et al. [10] that characterizes the existence of a restoration task in the dependent infrastructure when restoration of an independent infrastructure is not completed by an unknown deadline. Comparatively, the deadline interdependence formalizes a resource requirement (in the form of a good or service) that must be satisfied by a known deadline. Furthermore, our study aimed to identify examples of deadline interdependence are observed during day-to-day operating tasks in the food and agriculture sector rather than during restoration tasks following a disruption. Productivity in the food and agriculture sector requires punctual operations and task completion in order to satisfy biological processes inherent in the production of plants, animals, and processed food products. For the purposes of this work, we consider a deadline $\bar{t}$ to be the point in time when some task or output required by the dependent infrastructure must be received such that the operational activities and production outputs are in-line with plans and expectations. The dependent infrastructure relies on punctual productivity in the independent infrastructure to prevent disruptions affecting output volumes and scheduled operations.

Definition: The operational state of infrastructure A depends on resources provided by infrastructure B by a deadline $\bar{t}$.

Observed frequency: 12.

Examples (A, B, $\bar{t}$):

- (Food and agriculture, Transportation, 10 hours). Poultry production$^{\mathrm{A}}$ and animal slaughtering and processing$^{\mathrm{A}}$ depends on truck transportation$^{\mathrm{B}}$ of live birds from poultry farms to processing plants as the birds lose mass during transit and perish if not processed within 10 hours.

- (Food and agriculture, Energy, 24 hours). Rice farming$^{\mathrm{A}}$ depends on electric power generation$^{\mathrm{B}}$ and natural gas distribution$^{\mathrm{B}}$ to power irrigation pumps so that no rice fields are not flooded or irrigated for longer than 24 hours.

- (Food and agriculture, Food and agriculture, June 30). Rice farming$^{\mathrm{A}}$ depends on crop production$^{\mathrm{B}}$ infrastructure to cultivate and distribute rice seeds to be planted by June 30.

Discussion: Output yield (in pounds produced) of the animal slaughtering and processing infrastructure is subject to fluctuations in the yield (in live weight) of each poultry flock grown in the poultry production infrastructure. The truck transportation infrastructure is responsible for bridging the gap between separate food and agriculture infrastructures by delivering poultry flocks from farms to slaughtering and processing facilities when the live birds reach market weight. The transition time for poultry beginning at pick-up and ending with delivery to processing facilities must not exceed 10 hours. Live birds actively lose mass during transport from the grow-out farms to the processing facility causing the livelihood of the poultry flock to rapidly deteriorate approximately 10 hours after the birds leave the grow-out facilities. Rapid deterioration of the flock disrupts total yield in the outputs of both the animal slaughtering and processing and poultry production while birds expire in transit and surviving birds lose substantial amounts of mass due to dehydration. Moreover, if this deadline is unmet by the truck transportation infrastructure then yield loss may disrupt planned operations and procedures in the food and agriculture sector so they may be altered to increase welfare standards in order to mitigate yield losses and societal backlash spurred by instances of animal cruelty causing excessive losses of live animals.

The second and third examples of deadline interdependencies characterize requirement deadlines observed in the rice farming infrastructure. Typically, irrigation pumps rely on the power and natural gas infrastructures in the energy sector to operate normally. A disruption in the infrastructure responsible for powering the pumps, in turn, triggers a 24 hour restoration deadline; rice crop vitality is correlated with soil moisture. The time until the deadline $\bar{t}$ is a function of the production tasks, extent of the disruption, and available contingencies. In this instance, backup generators powered by diesel fuel or natural gas would appreciably mitigate the impact of a disruption, but such contingencies are not frequently used by row crop farmers. Typically, irrigated rice fields are able to retain moisture and sustain plant growth for 24 hours before crops begin to wither, lose mass, and ultimately die in the summer heat. Rice harvest yield losses in the event this deadline is not met vary in relation to the the amount of crop land that is unable to be irrigated and with the length of the disruption. It is unlikely that disruptions in either the natural gas or power infrastructures occur on temporal and geographic scales large enough to bring a rice farm's output to zero, much less disrupt rice output of the entire rice farming infrastructure in a binary sense. The third example, however, has potential to reduce total output of domestic hybrid rice farming yields to zero. At the time of this writing, approximately half of rice farmers in Arkansas grow hybrid rice as opposed to conventional rice while there is only a single producer of hybrid rice seeds. Optimal planting dates vary throughout geographic regions, but the results of our study indicate rice farming infrastructures consider June 30 to be the latest possible planting date so that the growth and harvest processes occur in the usual fashion. Consequently, a disruption that prevents rice producers from meeting this planting deadline could escalate so severely that restoration becomes significantly more difficult or even impossible as the local environment is less suitable to facilitate the initial stages of rice production that should have occurred prior to the planting deadline. Restoring productivity in the wake of an escalating failure may not be possible until environmental conditions are appropriate for growing rice, hence there would be a full, binary production loss in the affected infrastructure components. The June 30 planting deadline generally applied to any rice farming operation, but we noted documented instances of a disruption in the production of hybrid rice seeds creating shortage concerns and complicating rice farming infrastructure operations as farmers considered altering crop rotations and other contingencies. During this event, the independent infrastructure was able to produce enough seed so that hybrid rice yield losses were marginal.

A comprehensive list of deadline interdependencies classified in this study is presented in Appendix H.

6.4 Delay Interdependencies

The delay infrastructure interdependence classification also enhances the resolution of physical interdependencies by characterizing the ability of some infrastructure processes to continue functioning for some period of time δt in the event an that infrastructure that produces a material input is disrupted. Similar to the dynamic physical classification, delay interdependence extends and enhances the physical interdependence class to accommodate a temporal factor observed frequently in our study of the food and agriculture sector. Some production processes in food and agriculture infrastructures are able to withstand temporary disruptions in independent infrastructures through raw material stockpiles that create a buffer between the time of a disruption onset in the independent infrastructure and the dependent infrastructure [49]. In addition to this buffering characteristic, we also observed instances such that a δt exists when circumstances prevent instantaneous detection of disruptions in the independent infrastructure's operating procedures.

Definition: The operational state of infrastructure A is dependent on a material output of infrastructure B and, from the onset of a disruption in B, A is unaffected for a period of time δt.

Observed frequency: 7.

Examples (A, B, δt):

- (Food and agriculture, Transportation, 24 hours). Poultry production^{A} growth processes experience a delayed onset disruption when the buffering stock of animal feed is depleted approximately 24 hours after a disruption in the truck transportation^{B} infrastructures responsible for delivering feed to poultry houses which causes the grow-out period to be extended while the birds reach market weight.
- (Food and agriculture, Energy, 24 hours). Poultry production^{A} growth processes experiences a delayed onset disruption when the buffering stock of diesel fuel powering a backup generator is depleted approximately 24 hours after a disruption in the electric power generation^{B} infrastructure which causes the grow-out period to be extended while the birds reach market weight.
- (Water, Food and agriculture, years). Water supply and irrigation systems^{A} experiences a delayed onset disruption of distribution when pollution is detected in the water supply, up to several years after polluting begins, after disruption in the animal production^{B}, crop production^{B}, and food manufacturing^{B} infrastructures allows pollutants to reach a water supply causing the water infrastructures to perform sanitation and restoration processes before distribution may be resumed.

Discussion: The first and second examples of delay interdependencies exhibit the dependent infrastructure's ability to continue operating following a disruption in an independent infrastructure that produces a material production input through an inventory buffer. Occasionally, contingencies that mitigate temporary disruptions in lifeline infrastructure systems are found in commercial production processes. A standard procedure for commercial poultry producers is to require contract growers to construct and use on-site storage tanks for water, poultry feed, and diesel fuel so livestock are able to withstand short periods of disruption without substantial yield losses on the affected grow-out farms. The feed and diesel fuel stored on-site compose buffers that mitigate reductions in production when the truck transportation and energy infrastructures are unable to deliver their respective inputs to the poultry farms. Generally, the contingency plans are implemented to create buffering stocks so that each farm may withstand disruptions lasting up to 24 hours. Furthermore, these contingencies are enacted with an assumption that disruptions are so widespread or severe that restoration processes will require more than 24 hours. When buffering stocks are depleted then, in these instances, the poultry production infrastructure is disrupted in the same manner as dynamic physical interdependencies. Instances of delay interdependencies with a buffering stock attribute are also observed in the food processing infrastructure. In contrast to the poultry production and crop production infrastructures, the food processing infrastructure operates more similarly to traditional manufacturing where production will cease if essential raw materials are unavailable and the buffering stock has been depleted. For instance, food processing facilities must meet sanitation and hygiene standards that require the use of cleaning chemicals, but if cleaning chemicals or substitutes are unavailable, then productivity and output cease at the facility affected by the disruption at time δt.

The third example of delay interdependence is an instance where the water infrastructure is unable to detect an ongoing disruption of environmental and waste management production processes that suppress environmental contamination. In the event industrial waste created by production processes in food and agriculture infrastructures continually contaminate a municipal water supply or groundwater sources, then the water supply infrastructure would operate normally until there exist detectable levels of contamination built up over a considerable δt. Once the contamination is detected, then water supply infrastructure must take appropriate countermeasures outside the scope of day-to-day operations in order to ensure their output meets health and safety standards. The delayed onset disruption in the example manifests exactly when pollutant concentration levels exceed the tolerances set by the water distribution infrastructure.

A comprehensive list of delay interdependencies classified in this study is presented in Appendix I.

6.5 Human, Economic, and Natural Resource Interdependencies

The human, economic, and natural resource interdependence classification is an extension and enhancement of the existing taxonomy's logical interdependence class. Because infrastructures operate as complex adaptive systems, operability is affected and influenced by societal factors in the operating environment. Human resources in an infrastructure's operating environment are composed of changes in production or operations influenced by the shifts in cultural and geographic factors affecting human operators and stake-holders of the infrastructure's production; human resources are examined through census-like demographics. Economic resources depict changes in the infrastructure's operational behavior in response to variations in credit availability, consumer preference, and the overall macroeconomic climate. Consumption of scarce natural resources used for production in the lifeline infrastructure sectors is altering the infrastructure operating environment which, in turn, necessitates interdependent infrastructures adapt production processes to become more efficient and robust to limited resource availability or allocation. This classification aims to evaluate modifications in an infrastructure's operational tasks that are correlated to changing human resources, economic resources, or natural resources within the infrastructure's operating environment.

Definition: The operational state of infrastructure A is affected by changes in human, economic, or natural resources provided by infrastructure B.

Observed frequency: 7.

Examples (A, B):

- (Food and agriculture, Energy). Grain crop production$^{\mathrm{A}}$ planting decisions are affected by petroleum merchants$^{\mathrm{B}}$ in OPEC due to a positive correlation of grain prices and commodity oil prices.
- (Food and agriculture, Chemical). Crop production$^{\mathrm{A}}$ depends on fertilizer, herbicides, pesticides, and other agricultural chemicals produced by the agricultural chemical manufacturing$^{\mathrm{B}}$ infrastructure which affects the natural environment and resources available in water and soil.
- (Food and agriculture, Water). A majority of irrigation for row crop production$^{\mathrm{A}}$ draws large amounts of water from groundwater aquifers and surface water reservoirs$^{\mathrm{B}}$.

Discussion: Typically, a single producer in the crop production infrastructure segments production among several crop varieties in order to maximize returns when the crops are harvested and improve soil quality based on the characteristics of biological processes for each crop in the rotation. A producer's desire to maximize crop returns may lead to strategic modifications of crop rotation and planting strategies based on speculation of oil prices, actions taken by OPEC, and considering the strategies used by other crop producers to estimate total crop yields across the infrastructure sector. Operations in the crop production infrastructure are reliant on production and operations in the petroleum merchant infrastructure when crop producers develop and implement production processes based on petroleum production and distribution decisions made by the petroleum merchants. While the effects of a disruption in the petroleum merchant infrastructure are variable and difficult to assess, identifying that producers alter operations and production decisions in response to productivity in the petroleum merchants infrastructure enhances a comprehensive understanding the infrastructure environment and solidifies the need for inter-disciplinary studies of critical infrastructure systems and the food and agriculture critical infrastructure sector.

In the second and third examples, production in the food and agriculture sector is affected by shifts in economic resources in the context of resource availability as a function of operations in the agricultural chemical manufacturing infrastructure sector and the water infrastructure, respectively. Productivity in the crop production infrastructure, along with its output, depend on availability of resource requirements coming from infrastructures that are also influenced by human, economic, and natural resource components of the independent infrastructure's operating environment. Furthermore, both examples depict production factors in an independent infrastructure influencing production decisions in the food and agriculture sector where each infrastructures' operational behaviors are correlated and altered productivity in the dependent infrastructure, composed of the operational activities, production processes, and output, is attributable to the availability of a production resource requirement. However, the interdependence classes defined in this study do not adequately capture the true nature of the relationship between the infrastructures.

It is important to note that the low frequency of interdependencies found in this classification indicates these examples rarely occur and the mechanisms in which human, socioeconomic, and environmental factors affect access to scarce resources is not widely considered. This classification provides the foundation to categorize the effects of changes in labor, population, demographics, socioeconomics, and natural environments which, in the near-term, seemingly have little consequence but influences change in infrastructure productivity and viability over the long run. This interdependence is contextualized through macro-scale shifts rather than the more granular classifications in our study that concretely describe infrastructure interdependence for specific infrastructure components, specific resource requirements, and specific types of disruptions.

A comprehensive list of human, economic, and natural resource interdependencies classified in this study is presented in Appendix J.

Chapter 7

Analysis of Interdependencies Observed in the Food and Agriculture Critical Infrastructure Sector

In total, we classified 116 examples of operational interdependencies during the course of this study. The existing taxonomy adequately classified 68 examples of operational interdependencies, and the remaining 48 examples, approximately 41 percent of all identified examples, were aggregated to formalize each of the interdependence classifications in the expanded taxonomy. As the study progressed, we continued to observe variations in operational tasks and resource requirements due to biological processes in plants and animals and the inconsistent nature of output when row crop producers routinely sell one year's productivity as the crops are harvested. Similarly, livestock have unpredictable, time varying changes in operational tasks. Infrastructures beyond food and agriculture also experience production dynamics and are subject to similar concerns presented in this work. The heatmap in Figure 7.1 is a visual representation of the frequency in which we identified examples of interdependency between the food and agriculture sector and and other critical infrastructure sectors where interactions occurring most frequently are shaded dark blue. Naively, we may inspect the figure and conclude that physical resource requirements between the food and agriculture sector and water, transportation, information technology, and energy infrastructures are most vital for stakeholders in the food and agriculture sector because those interactions were documented more frequently than others. However, the subtleties investigated in this study provided insight into necessities and considerations beyond resource requirements. Upon further inspection, we may observe elevated levels of interdependence within the food and agriculture sector, nontrivial restoration interdependencies induced by spatial proximity, and significant interactions between food and agriculture infrastructures and infrastructures providing resources more abstractly than traditional material input requirements for production. The analysis presented in this chapter further explicates these interdependence observations with concrete examples from our empirical study of the rice and poultry industries in Arkansas. This chapter presents a cross section of our analysis in order to compare and contrast the rice and poultry production infrastructures, and then generalize our findings to the highly fragmented and diverse food and agriculture infrastructure sector as we work towards recognizing dynamic interdependence among all critical infrastructure sectors. We then present the factors complicating our understanding of these interdependencies: dynamic temporal scales, spatial clustering of production that induces cooperation among producers, and prevalent nonbinary responses in production and operability in the wake of a disruption.

7.1 Food and Agriculture Sector Fragmentation

The food and agriculture critical infrastructure sector is unique among the critical infrastructures. The mix of goods grown, produced, and distributed by the food and agriculture sector is exceptionally diverse; the sector is responsible for growing and processing cereal grains, beverage manufacturing, producing further processed food items, restaurant dining, and even growing timber used by homebuilders and paper mills. Despite the breadth of operational tasks occurring within the sector, our work focused mainly on the large, commercial rice and poultry production infrastructures in Arkansas. The nature of food and agriculture production is unique due to variations in operational tasks depending on seasonality or the current stage of production. Furthermore, we observed agricultural producers create large production footprints through contract livestock growing, networks of production facilities built to accommodate a simultaneous annual influx of freshly harvested crops, and true mutual dependence between food and agriculture infrastructures.

We were able to interview 39 professional and academic experts during the course of our study, and each of the participants provided expert insight into the nature of food and agriculture productivity throughout the state. Out of the 39 participants, approximately five possessed exceptional knowledge of the poultry production infrastructure and approximately 14 possessed exceptional knowledge of the rice production and processing infrastructures. We

Figure 7.1: This heatmap shows the frequency in which each interdependence was observed throughout our study of the food and agriculture industry where depth of blue shading indicates higher observation frequencies.

recognize this disparity among our two study subjects; throughout the course of our study we were continuously able to connect with stakeholders in the rice production infrastructure but, through no lack of effort or attempts, meeting with poultry producers occurred less frequently than rice. We recognize this imbalance may introduce rice production infrastructure bias in the analysis. Despite the interview subject imbalance, we classified 47 and 37 distinct instances of infrastructure interdependence in the rice production and poultry production infrastructures, respectively. Furthermore, we were able to classify examples of interdependence extending beyond conventional rice production and poultry production in the food and agriculture sector. Our analysis of the empirical data showed that approximately 40% of our classified examples of interdependence in this study identified interdependencies between a component of the food and agriculture sector outside of the poultry production and rice production infrastructures. We observed examples of interdependence that, using the Department of the Census NAICS taxonomy, we identified to be significant components of capital planning, food processing and production, agricultural research and development, food storage, soil cultivation, agricultural transportation, and commercial farm management services for absentee land owners.

In total, the food and agriculture sector contextualizes the study of critical infrastructure systems and infrastructure interdependence so that both broad implications and intricate details are examined. For instance, by observed frequency, the three infrastructure components outside of the food and agriculture sector observed to be dependent of other infrastructures most frequently were water supply and irrigation components within the dams and water infrastructure sectors in addition to the truck transportation component of the transportation sector. More interestingly, the infrastructure components found to be an independent infrastructure most frequently were electric power generation and crop production infrastructures. Row crops are required ubiquitously throughout critical infrastructure sectors, but subtle infrastructure correlations exist between chemical manufacturers, utility companies, other food and agriculture infrastructures, and financial service infrastructures. These subtle correlations are more difficult to detect and appropriately classify, hence these interactions were identified less frequently than obvious resource requirements. We can refine this concept and develop further support for studying less obvious, more abstract examples of interdependence in the row crop infrastructure. The geographic area supporting most row crop farmland in Arkansas is experiencing a groundwater crisis as the aquifer is reaching critically low levels while farmers continue drawing unsustainably to grow crops. Impending scarcity and depletion of a natural resource like groundwater has spurred investment in surface water impoundments, sustainable farming practices and education, and more abstractly, conservation. Moreover, row crop farmers throughout Arkansas rely on the finite, concentrated groundwater supply in the aquifer to irrigate their fields; this concentrated, aggregate resource reliance affects the scale of geographic interdependencies as more infrastructures become reliant on alternative irrigation technologies or municipal utilities to provide that water.

7.2 Generalizing Dynamic Interdependencies Beyond Food and Agriculture

Certainly there are unique attributes to production in the food and agriculture infrastructure sector. However, using the interdependence concepts informed by this study, we were able to classify 30 examples of temporal phenomena, effects of geographic clustering, seasonality, and exogenous factors influencing infrastructure interactions in nine critical infrastructure sectors including financial services, information technology, healthcare, transportation, and energy. Despite the differences in operating characteristics and resource requirements of each infrastructure sector, the factors studied in the food and agriculture infrastructure sector also affect operations and restoration in dissimilar infrastructure sectors.

The empirical evidence we collected and analyzed to formalize the interdependence classifications that account for nontrivial complications observed specifically in the food and agriculture sector provided a firm foundation for this investigation. Similarly, the empirical evidence gathered and used to formalize the various taxonomies of the well-studied interdependencies. Each taxonomy of the well-studied interdependencies depicts and characterizes some unique factor not yet considered in the critical infrastructure systems literature. Just as the taxonomies of the well-studied interdependencies have been successfully applied and expanded beyond their initial scope; we have classified examples of dynamic interdependencies that are not associated with food and agriculture production. This study of interdependencies in the food and agriculture sector reinforces the importance utilizing empirical data as a stepping stone to develop more sophisticated methods in order to solve more general problems of time-varying interdependencies and variable resource consumption which we observed specifically in the food and agriculture infrastructure sector.

7.3 Temporal Analysis

Operations in the food and agriculture infrastructure sector are complex due to the field's fragmented nature; many different entities with dissimilar operations operate simply because we have biological requirements that necessitate a productive food and agriculture infrastructure. Time varying operations in the food and agriculture sector tend to be either seasonal or triggered by a precursing operational activity within a production process. Furthermore, variation in operational activities and resource requirements affect production levels at the infrastructure component level such that disruptions do not affect productivity or yield in a binary manner.

Seasonality in operational activities is observed more easily throughout the rice production infrastructures and, more generally, crop production infrastructures that consist of biological processes. The biological processes occurring during crop production cycles are dependent on natural resources and the surrounding environment. Generally, crop production has similar timetables for capital acquisition, field preparation, planting, growing, harvesting, and processing. The seasonal nature of these processes and resource requirements allows for the development of timetables that characterize and quantify resource requirements during the production cycle along with their effects on total yield (production) occurring at harvest. The changes in infrastructure operations throughout the year also influences the infrastructure's susceptibility to disruption, and the severity of disruptions based on production seasonality.

Conversely, there are operating activities occurring in the food and agriculture sector that are triggered by preceding events in the production cycle. Triggered operational activities are more prevalent in the livestock production infrastructures. Livestock production cycles are time sensitive in the sense that timeliness and punctuality is necessary to sustain biological processes for each animal in production, hence there must be stocks of food and water in place at the production facilities, transportation must occur within a short time window, and the conclusion of process necessitates the process in the production cycle begin immediately, else yield falls and overall productivity declines.

7.4 Geographic Analysis

There are interesting geographic characteristics in food and agriculture infrastructure operations. Food and agriculture operations tend to be clustered in close proximity due to environmental suitability, transportation timescales, and resource availability. Clustered operations may exhibit an enhanced susceptibility to disruptive events, especially when we consider the time-varying characteristics also observed in food and agriculture operations. Examining spatial relationships among interdependent infrastructures and interdependent components of the food and agriculture infrastructure supplements the temporal analysis performed above.

Environmental factors significantly affect the productivity and operability of food and agriculture infrastructures, and hence, productive components tend to cluster where the local environment supports production. For instance, the Mississippi river delta spanning the eastern side of Arkansas is mostly agricultural land used to grow rice, cotton, and soybeans. On the western side of the state, poultry production is the predominant form of agriculture. The delta region's environmental conditions are favorable for growing rice and other cereal grains, and cereal grain production then generally relies on the grain processing infrastructures to dry, mill, store, and sell harvested grain. The livestock production infrastructure requires significant amounts of grain to be used as the primary ingredient in feed. From this simple chain of resource requirements and infrastructure interdependencies found in the rice and poultry infrastructure sectors, the region most suitable for agricultural production must also accommodate the production facilties and infrastructures completing the agricultural supply chain. The clustering of agricultural infrastructures which rely on one another to complete production processes in the agricultural supply chain illustrates an agricultural intradependence such that distinct infrastructures operating in the same infrastructure layer have correlated states of operation. Our study identified readily apparent examples of intradependence in the food and agriculture infrastructure sector. Localizing grain drying and storage systems in the rice production infrastructure demonstrates tightly coupled infrastructure components exist in the agricultural supply chain, especially where environmental factors are ideal for crop production. As discussed in Chapter 6, spatial clustering of these infrastructures likely increases infrastructure production efficiency, but at the expense of increasing the entire supply chain's susceptibility to local extreme events.

Similarly, the clustering of agricultural infrastructures makes interdependent infrastructures more vulnerable to failures and disruptions that are locally devastating. Consider the interdependent relationship between the row crop production infrastructure and the financial institution financing crop production. Typically, the banks providing financing for crop production are members of the Farm Credit System that lend strictly for agricultural production financing, agricultural equipment purchase/lease, or to purchase a home in a rural area. The member banks of the Farm Credit System also typically operate small branches in rural communities to serve customers locally. Based on the operational interdependencies and temporal analysis given throughout this study, we can assume the financial institutions operating in close proximity to the crop production infrastructures are geographically interdependent. If an extreme event were to disrupt the local area and devastate crop production operations, then banking operability is disrupted because the locally concentrated row crop producers each suffered significant losses and are unable to repay the operating line of credit. Furthermore, the financial institution is not going to recoup any of the losses from this year's disaster until next year when row crop production reaches a point of productivity when the environmental conditions allow it. So, the aspects of spatial clustering in the food and agricultural sector are on a continuum. There are positive aspects of spatial clustering that allow for dynamic restoration from neighboring areas to sharing vulnerabilities to disruption and extreme events through operational relationships. Correlated states of operation of infrastructures in geographically interdependent infrastructures may compound disruption susceptibility at the component (or individual infrastructure level) and reduce overall resilience of an infrastructure sector depending on how other factors are affecting the infrastructure system.

7.5 Nonbinary Response to Disruption

The unique characteristics of food and agriculture production we have presented culminate in an infrastructure system that, in general, does not respond to a disruption in resource requirements in a binary manner. Production in the food and agriculture sector is unique. For instance, the growing season for rice shifts marginally across the state of Arkansas where the optimal dates to plant rice seed vary by 10 days across the southern, central, and northern regions of the state [50]. Furthermore rice fields account for a significant portion of Arkansas's 14 million acres dedicated to agricultural production. We infer that the operational process of growing rice across the region does not vary significantly from producer to producer, and the abundance of producers spread across large amounts of land reinforces the ability of the rice crop, and more generally row crops, to survive disruptions in some input to a growing process and simply yield less at harvest than if the disruption had not occurred rather than suffer catastrophic loss in the case of a binary disruption. Similarly for the poultry production infrastructure sector, we gathered examples of poultry production disruptions in northwest Arkansas after an ice storm impeded traffic flow so badly that the poultry farms ran of feed on-hand, and the birds were unable to eat until the transportation network was operable. Despite the poultry feed delivery disruptions, the response in productivity levels was nonbinary. In this case, the birds did not reach market weight on time and the producers had to make the choice whether to process low-yielding birds or to keep the flock on feed for a brief time until they had reached market weight.

This interesting harvest-time production dynamic prevalent in the row crop and livestock production infrastructures provides a reasonable context to more accurately model and study the true nonbinary responses to disruption due to the infrastructure's operational nature. This discussion of an infrastructure's nonbinary response to a disruption is necessary due to the time-varying production schedules and operational activities found throughout the sector as opposed to a poultry processing facility's generic, consistent requirements for energy and water. If a generic food production facility does not receive water or energy from the utility providers, then production stops at the immediate onset of the disruption and, generally, the food being processed throughout the facility must be thrown away resulting in a true binary response to disruption. The variability and diversity of production in the food and agriculture infrastructure sector has developed structural complexity throughout the operating environment and, in turn, exhibits interesting characteristics with possible applications throughout each of the critical infrastructure sectors.

Chapter 8

Conclusions and Further Work

Our study of the food and agriculture infrastructure sector identified more than 100 examples of interdependence across 13 critical infrastructure sectors. We identified interdependencies through interviews with 39 industry stakeholders across the state of Arkansas. Interdependencies were first classified utilizing the existing taxonomy, and then further characterized using five new, distinct interdependence classes that account for variations in temporal and geographic scales affecting resource requirements and productivity.

In future work, we can expect these interdependencies to be generalized and applied throughout the critical infrastructure sectors to more accurately portray complex infrastructure interactions. Furthermore modeling restoration tasks in the food and agriculture infrastructures is necessary to ensure productivity and reduce food scarcity that attributes to civil unrest and societal tumult. Considering complexity and creating general characterizations for each of these complicating factors is necessary to provide deeper, poignant insights into infrastructure interdependence.

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Appendix A

Well-Studied Interdependencies

Table A.1: Aggregation of well-studied infrastructure interdependencies. Prominent interdependency taxonomies are aggregated in chronological order by publication.

Publication	Classification	Description
Rinaldi et al. [24]	Physical	The state of an infrastructure is dependent on the material output(s) of the other.
	Cyber	The state of an infrastructure depends on information transmitted through the digital information infrastructure.
	Geographic	A local environmental event can create state changes in a collection of infrastructures.
	Logical	The state of an infrastructure depends on the state of another via a connection that is not physical, cyber, or geographic.
Zimmerman [23]	Functional	Infrastructures can be dependent on one another operationally.

Table A.1: (continued)

Publication	Classification	Description
	Spatial	Infrastructures become more dense and compact as distributed networks occupy the same conduits in cities.
Wallace et al. [25]	Input	An infrastructure requires one or more services, as an input, from another infrastructure to provide another service.
	Shared	Physical components or activities of infrastructures are shared to provide some service.
	Exclusive-or	Only one of the two or more services can be provided by an infrastructure.
	Mutually dependent	Infrastructures mutually depend on an output of one another.
	Co-located	Any physical components or activities are situated within an established geographical area.
Dudenhoeffer et al. [26]	Physical	$(a, b)_e$ defines a requirement of b on a.

Table A.1: (continued)

Publication	Classification	Description
	Informational	$(a,b)_i$ defines an informational or control requirement between a and b. Information from asset a, not necessary for the existence of node b, is essential for certain functionality in node b, $\sim a \rightarrow \sim f(b)$ where $f(b)$ is a function of operation for asset b.
	Geospatial	$(a,b)_g$ defines a relationship that exists entirely due to the proximity of nodes a to b, (e.g. $(a,b)_g \rightarrow d(a,b) < \varepsilon$ for some predefined distance ε). Thus a physical event occurring at node a represented as $E(a)$, $E(a) \rightarrow E(b)$.[1]
	Policy/Procedural	$(a,b)_p$ defines an interdependency that exists due to policy or procedures relating an event or state of change for node a to a subsequent effect on node b or $E_j(a) \rightarrow E_k(b)$.[1]

Table A.1: (continued)

Publication	Classification	Description
	Societal	$(a,b)_s$ defines interdependencies or influences that an event, physical or otherwise, on an infrastructure component may impart on societal factors which may be time sensitive in nature, decaying as the time from the original event grows. So for $(a,b)_s$, $E_j(a) \rightarrow E_k(b,t)$, a decaying effect over time t.
Chang et al. [33]	Cascading	The disruption of the power system directly causes the disruption in the impacted system.
	Escalating	The disruption of the power system exacerbates an already-existing disruption in the impacted system, increasing the severity or outage time.
	Restoration	The power outage hampers the restoration of the impacted system.

Table A.1: (continued)

Publication	Classification	Description
	Compound damage propagation	The power system disruption leads to a disruption that then causes serious damage/accidents/problems in the impacted system.
	Substitutive	A system is disrupted due to demands placed on it to substitute for the power system.
Zhang and Peeta [27]	Functional	Functionality of an infrastructure system requires inputs from another system, or can be substituted, to a certain extent, by the other system.
	Physical	Infrastructure systems are coupled through shared physical attributes and share flow right of way.
	Budgetary	Infrastructure systems rely on some level of public financing leading to resource allocation budget interdependencies.
	Market and Economic	Infrastructures share market resources in the same economic system.

Table A.1: (continued)

Publication	Classification	Description
Sharkey et al. [10]	Traditional precedence	(A, B) : A restoration task in infrastructure B cannot be started until a restoration task in infrastructure A is complete.
	Effectiveness precedence	(A, B) : A restoration task in infrastructure B is not as effective until a restoration task in infrastructure A is complete.
	Options precedence	A restoration task in infrastructure B can be completed by accomplishing a restoration task in one of a set of possible infrastructures $A_1, A_2, \ldots, A_n$.
	Time-sensitive options	A restoration task in infrastructure B must be completed only if a restoration task in infrastructure A is not completed by a certain (unknown) deadline. Therefore, the restoration task in A must be completed by its deadline or the task in B must be completed.

Table A.1: (continued)

Publication	Classification	Description
	Competition for resources	Restoration tasks in infrastructures $A_1, A_2, \ldots, A_n$ compete for the same set of scarce resources.

Appendix B

Observed Physical Interdependencies

Recall a *physical infrastructure interdependency*, (A, B), exists when the operational state of infrastructure A depends on a material output of infrastructure B [24].

Table B.1: Enumeration of *physical interdependencies* observed in the food and agriculture sector denoting infrastructure A^{A} and infrastructure B^{B} in the description of each example.

A	B	Description
Chemical	Food and agriculture	Ethyl alcohol manufacturing$^{\text{A}}$ depends on grains produced by the crop production$^{\text{B}}$ infrastructure.
Food and agriculture	Chemical	Crop production$^{\text{A}}$ depends on fertilizer, herbicides, pesticides, and other agricultural chemicals produced by the agricultural chemical manufacturing$^{\text{B}}$ infrastructure.
Food and agriculture	Chemical	Food manufacturing$^{\text{A}}$ adheres to sanitation standards that depend on chlorine dioxide and other cleaning chemicals produced by the chemical manufacturing$^{\text{B}}$ infrastructure.

Table B.1: Physical interdependencies (continued)

A	*B*	Description
Food and agriculture	Critical manufacturing	Animal production$^{\text{A}}$ and crop production$^{\text{A}}$ depend on industrial equipment and farm machinery manufactured in the agricultural implement manufacturing$^{\text{B}}$ infrastructure.
Food and agriculture	Critical manufacturing	Food manufacturing$^{\text{A}}$ processes depend on industrial equipment manufactured in the food product machinery manufacturing$^{\text{B}}$ infrastructure.
Food and agriculture	Dams	Crop production$^{\text{A}}$, grain milling$^{\text{A}}$, and food manufacturing$^{\text{A}}$ infrastructures are vulnerable to flooding and depend on floodwater impoundment and diversion operations of the water supply and irrigation systems$^{\text{B}}$ infrastructure.
Food and agriculture	Energy	Crop production$^{\text{A}}$ equipment and vehicles depend on gasoline and diesel fuel from the petroleum manufacturing$^{\text{B}}$ infrastructure.
Food and agriculture	Energy	Refrigerated storage$^{\text{A}}$ refrigeration systems prolonging the shelf-life of perishable food products depend on the electric power generation$^{\text{B}}$ infrastructure.

Table B.1: Physical interdependencies (continued)

A	*B*	Description
Food and agriculture	Energy	Grain elevators and storage$^{\text{A}}$ facilities are monitored and ventilated by equipment that depends on the electric power generation$^{\text{B}}$ infrastructure.
Food and agriculture	Energy	Grain milling$^{\text{A}}$ boilers depend on dedicated transmission lines from the natural gas distribution$^{\text{B}}$ infrastructure.
Food and agriculture	Energy	Grain milling$^{\text{A}}$ industrial equipment relies on dedicated transmission lines from the electric power generation$^{\text{B}}$ infrastructure.
Food and agriculture	Financial services	Animal production$^{\text{A}}$ financing depends on credit extended by commercial banks or the Farm Credit System in the credit intermediation$^{\text{B}}$ infrastructure.
Food and agriculture	Food and agriculture	Animal food manufacturing$^{\text{A}}$ feed formulations depend on cereal grains produced by the grain farming$^{\text{B}}$ infrastructure.
Food and agriculture	Food and agriculture	Food manufacturing$^{\text{A}}$ perishable goods spoilage prevention depends on refrigeration provided by the refrigerated storage$^{\text{B}}$ infrastructure.

Table B.1: Physical interdependencies (continued)

A	*B*	Description
Food and agriculture	Healthcare	Animal production$^{\mathrm{A}}$ healthcare and animal welfare standards depend on pharmaceuticals and vaccinations from the pharmaceutical and medicine manufacturing$^{\mathrm{B}}$ infrastructure.
Food and agriculture	Healthcare	Animal production$^{\mathrm{A}}$ healthcare and biological security standards depend on animal diagnostic testing services from the veterinary services$^{\mathrm{B}}$ infrastructure.
Food and agriculture	Transportation	Food manufacturing$^{\mathrm{A}}$ shipments and deliveries depend on transportation from the air transportation$^{\mathrm{B}}$, rail transportation$^{\mathrm{B}}$, water transportation$^{\mathrm{B}}$, and truck transportation$^{\mathrm{B}}$ infrastructures.
Food and agriculture	Transportation	Soil preparation and cultivation$^{\mathrm{A}}$ operations performed aerially depend on commercial pilots, aircraft, and airports in the air transportation$^{\mathrm{B}}$ infrastructure.

Table B.1: Physical interdependencies (continued)

A	*B*	Description
Food and agriculture	Water	Food manufacturing$^{\mathrm{A}}$, animal production$^{\mathrm{A}}$, and crop production$^{\mathrm{A}}$ depend on municipal water supplies, irrigation reservoirs, and distribution of potable water from the water supply and irrigation systems$^{\mathrm{B}}$ infrastructure.
Food and agriculture	Water	Food manufacturing$^{\mathrm{A}}$, animal production$^{\mathrm{A}}$, and crop production$^{\mathrm{A}}$ operations typically are unable to appropriately treat wastewater byproduct and then depends on collection and treatment provided by the wastewater treatment$^{\mathrm{B}}$ infrastructure.
Transportation	Food and agriculture	Rail transportation$^{\mathrm{A}}$, water transportation$^{\mathrm{A}}$, and truck transportation$^{\mathrm{A}}$ long-haul grain shipments rely on fumigation for vermin control provided by the postharvest crop activities$^{\mathrm{B}}$ infrastructure.

Appendix C

Observed Cyber Interdependencies

Recall a *cyber infrastructure interdependence* exists when A is dependent on a material output of B that is transmitted directly or indirectly through the information technology or communications infrastructure sectors [24].

Table C.1: Enumeration of *cyber interdependencies* observed in the food and agriculture sector denoting infrastructure A^{A} and infrastructure B^{B} in the description of each example.

A	B	Description
Dams	Information technology	Water supply and irrigation systems$^{\text{A}}$ floodwater impoundment and diversion activities are planned using real-time environmental data in the Damwatch web-application that depends on the data processing, hosting, and related services$^{\text{B}}$ infrastructure.
Dams	Communications	Water supply and irrigation systems$^{\text{A}}$ floodwater impoundment and diversion activities are planned using real-time environmental data disseminated by the Damwatch web-application that depends on the wired telecommunications carriers$^{\text{B}}$, wireless telecommunications carriers$^{\text{B}}$, and satellite telecommunications$^{\text{B}}$ infrastructures.

Table C.1: Cyber interdependencies (continued)

A	*B*	Description
Information technology	Communications	Data processing, hosting, and related services$^{\mathrm{A}}$ aggregation, analysis, and dissemination of environmental data from across the country in real-time depends on data transmission through the wired telecommunications carriers$^{\mathrm{B}}$, wireless telecommunications carriers$^{\mathrm{B}}$, and satellite telecommunications$^{\mathrm{B}}$ infrastructures.
Food and agriculture	Information technology	Grain farming$^{\mathrm{A}}$ remotely operated, on-farm grain drying and storage systems depends on the ability to digitally manage operations and equipment through the computer facilities management service$^{\mathrm{B}}$ infrastructure.
Food and agriculture	Communications	Farm management services$^{\mathrm{A}}$ that remotely monitor and operate farm equipment such as grain bins depend on the wireless telecommunications carriers$^{\mathrm{B}}$ infrastructure to transmit digital communications in rural areas.

Table C.1: Cyber interdependencies (continued)

A	*B*	Description
Food and agriculture	Information technology	Food manufacturing$^{\mathrm{A}}$, animal production$^{\mathrm{A}}$, and crop production$^{\mathrm{A}}$ enterprise resource planning software integral to productivity depends on software consultants developing and maintaining functionality through the computer systems design services$^{\mathrm{B}}$ infrastructure.
Food and agriculture	Information technology	Food manufacturing$^{\mathrm{A}}$, animal production$^{\mathrm{A}}$, and crop production$^{\mathrm{A}}$ enterprise resource planning software depends on managed technology services provided by the data processing, hosting, and related services$^{\mathrm{B}}$ infrastructure.
Food and agriculture	Information technology	Agricultural research and development$^{\mathrm{A}}$ depends on physical and cybersecurity measures in the security systems services$^{\mathrm{B}}$ and data processing, hosting, and related services$^{\mathrm{B}}$ infrastructures to protect proprietary technology and intellectual property from unauthorized access as a matter of corporate security and national security.

Appendix D

Observed Geographic Interdependencies

Recall a *geographic infrastructure interdependence* exists among a collection of infrastructures "if a local environmental event can create state changes in all of them" [24].

Table D.1: Enumeration of *geographic interdependencies* observed in the food and agriculture sector denoting infrastructures $A_1 \ldots A_n{}^{A_1 \cdots A_n}$ in each example's description.

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture^{A_1}, Commercial facilties$^{A_2 \cdots A_4}$	Restaurants and other eating places^{A_1} are collocated with commercial facilities housing performing arts and spectator sports^{A_2}, museums and historical sites^{A_3}, amusement parks, gambling, and recreation^{A_4}.
Dams^{A_1} , Food and agriculture$^{A_2 \cdots A_4}$, Transportation^{A_5}, Water^{A_6}, Energy^{A_7}, Emergency services$^{A_8 \cdots A_1 0}$	Floods in the Arkansas delta affect water supply and irrigation systems^{A_1}, grain farming^{A_2}, grain milling^{A_3}, animal production^{A_4}, water transportation^{A_5}, water supply and irrigation systems^{A_6}, electric power generation^{A_7}, emergency road services^{A_8}, emergency medical transportation services^{A_9}, and emergency relief services$^{A_1 0}$ infrastructures.

Table D.1: Geographic interdependencies (continued)

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture$^{A_1, A_2}$, Water^{A_3}, Healthcare$^{A_4, A_5}$, Emergency services^{A_6}	Food manuacturing^{A_1} and animal production^{A_2} pollution affects water treatment and distribution^{A_3}, health care services^{A_4}, hospitals^{A_5}, and emergency relief services^{A_6} operations to treat the polluted water, healthcare and testing for ill residents, and emergency relief for those without potable water.
Food and agriculture$^{A_1 \cdots A_3}$, Transportation^{A_4}	Grain farming^{A_1}, grain milling^{A_2}, and grain elevators and storage^{A_3}, and the road transportation^{A_4} infrastructures used in crop production are typically within a 25 mile radius.
Water$^{A_1, A_4}$, Food and agriculture^{A_2}, Emergency services$^{A_3, A_6}$, Transportation^{A_5}	Drought and wildfires disrupting the water supply^{A_1} for animal production^{A_2} require emergency relief services^{A_3} deliver water from neighboring water supplies^{A_4} using truck transportation^{A_5} and fire departments^{A_6}.

Table D.1: Geographic interdependencies (continued)

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture$^{A_1 \cdots A_4}$, Transportation^{A_5}, Energy^{A_6}	Ice storms in Arkansas simultaneously disrupt animal production^{A_1}, animal production support activities^{A_2}, animal food manufacturing^{A_3}, food manufacturing^{A_4}, truck transportation^{A_5}, and electric power distribution^{A_6}.
Food manufacturing$^{\mathrm{A}_1}$, Water$^{\mathrm{A}_2}$	Food manufacturing$^{\mathrm{A}_1}$ facilities consume large amounts of potable water and require high volumes of wastewater collection and hence tend to be geographically clustered in regions where distribution networks and wastewater treatment facilities in the municipal water and sewage systems$^{\mathrm{A}_2}$ infrastructures are well established.

Appendix E

Observed Logical Interdependencies

Recall a *logical infrastructure interdependence* exists when the state of A is dependent on B by some mechanism that is not physical, cyber, or geographic in nature [24].

Table E.1: Enumeration of *logical interdependencies* observed in the food and agriculture sector denoting infrastructure A^{A} and infrastructure B^{B} in the description of each example.

A	B	Description
Chemical	Food and agriculture	Agricultural chemical manufacturing^A depends on grain farming^B infrastructures challenging the regulatory bans on the use of the dicamba herbicide.
Food and agriculture	Financial services	Animal production^A and crop production^A depend on agriculturally-focused credit services^B, the Farm Credit System, created, operated, and regulated by the federal government.
Transportation	Emergency services	Road transportation^A depends on government emergency planning^B to lift working time limitations during states of emergency.

Table E.1: Logical interdependencies (continued)

A	B	Description
Water	Food and agriculture	Water supply and irrigation system^A infrastructures depend on crop production^B to self-report groundwater usage to conservation districts monitoring groundwater use and forecasting groundwater availability for future growing seasons.

Appendix F

Observed Dynamic Physical Interdependencies

Recall a *dynamic physical infrastructure interdependence* exists when the time-varying operational activities of infrastructure sector A depend on different amounts of material outputs of infrastructure sector B over time.

Table F.1: Enumeration of *dynamic physical interdependencies* observed in the food and agriculture sector denoting $\underline{\text{infrastructure } A}^{\mathrm{A}}$ and $\underline{\text{infrastructure } B}^{\mathrm{B}}$ in the description of each example.

A	B	Description
Food and agriculture	Food and agriculture	$\underline{\text{Broiler chicken production}}^{A}$ depends on $\underline{\text{poultry hatcheries}}^{B}$ for chick placement at the beginning of every seven week flock grow-out period.

Table F.1: Dynamic physical interdependencies (continued)

A	*B*	Description
Food and agriculture	Transportation	Broiler chicken production[A] production cycles last approximately 10 weeks where the cycle begins with the placement of live chicks to begin a seven week grow-out period that ends when the mature birds are processed. Cleaning and sanitation tasks are completed in the final three weeks of the cycle while the house is empty, hence broiler chicken production depends on truck transportation[B] to deliver poultry feed from the feedmill to poultry farms only during the seven week grow-out period when the house is occupied.

Table F.1: Dynamic physical interdependencies (continued)

A	*B*	Description
Food and agriculture	Water	Broiler chicken production^{A}production cycles last approximately 10 weeks where the cycle begins with the placement of live chicks to begin a seven week grow-out period that ends when the mature birds are processed depends on water supply and irrigation systems^{B} to deliver water for drinking and cooling systems on poultry farms housing a flock during the seven week grow-out period when they occupy the chicken houses..
Food and agriculture	Energy	Broiler chicken production^{A} depends on electric power generation^{B} to deliver uninterrupted power for feeding, drinking, monitoring, and cooling systems on poultry farms housing a flock during the seven week grow-out period when they occupy the chicken houses..
Food and agriculture	Healthcare	Broiler chicken production^{A} depends on veterinary services^{B} to test and monitor flock health during the seven week grow-out period when they occupy the chicken houses..

Table F.1: Dynamic physical interdependencies (continued)

A	B	Description
Food and agriculture	Healthcare	Animal food manufacturing^{A} depends on pharmaceutical and medicine manufacturing^{B} for specific antibiotics and vitamins necessary for individual flock health and feed-mass conversion during the seven week grow-out period when they occupy the chicken houses..
Food and agriculture	Food and agriculture	Truck transportation^{A} of market weight broiler chickens must be caught and loaded into trucks through processes that depend on poultry catching^{B} infrastructures on the final day of the seven week grow-out period when they occupy the chicken houses..
Food and agriculture	Food and agriculture	Animal slaughtering and processing^{A} of market weight broiler chickens depends on poultry catching^{B} infrastructures to catch and load broiler flocks on the final day of the seven week grow-out period when they occupy the chicken houses..

Table F.1: Dynamic physical interdependencies (continued)

A	*B*	Description
Food and agriculture	Water	Rice farming^A depends on water supply and irrigation systems^B to deliver ground water for irrigating crops from May through September.
Food and agriculture	Energy	Rice farming^A depends on electric power generation^B and natural gas distribution^B to power water pumps that irrigate rice fields in the hottest months of June, July, and August.
Food and agriculture	Energy	Grain milling^A depends on electric power generation^B and natural gas distribution^B to power fans and heaters drying wet rice harvested in October and November to a moisture content of 14%.
Food and agriculture	Information technology	Grain milling^A depends on data processing, hosting, and related activities^B to monitor grain drying operations and remotely control equipment responsible for the grain drying process.

Table F.1: Dynamic physical interdependencies (continued)

A	B	Description
Food and agriculture	Transportation	Grain milling^{A} depends on truck transportation^{B} in September - November to deliver large amounts of freshly harvested grain from the fields to grain milling facilities or on-farm grain drying and storage systems.
Transportation	Food and agriculture	Truck transportation^{A} depends on grain milling^{B} efficiency in September - November to efficiently unload grain deliveries preventing long queues that disrupt truck flow from grain mills to farms.
Energy	Food and agriculture	Electric power generation^{A} depends on radio transmitters installed on crop production^{B} irrigation pumps to stop irrigation and divert power to other customers during peak usage hours in the hot summer months.

Appendix G

Observed Dynamic Geographic Interdependencies

Recall a *dynamic geographic infrastructure interdependence* exists when the geographic or spatial scales of interdependent infrastructure operations are altered by some process, event, or circumstance.

Table G.1: Enumeration of *dynamic geographic interdependencies* observed in the food and agriculture sector denoting infrastructures $A_1 \ldots A_n^{A_1 \cdots A_n}$ in each example's description.

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture$^{A_1 \cdots A_3}$, Transportation^{A_4}	The geographic scale of crop production^{A_1}, grain milling^{A_2}, grain elevators and storage^{A_2}, and truck transportation^{A_4} infrastructures interdependence shrinks as on-farm grain drying storage systems become more prevalent.
Food and agriculture$^{A_1, A_2}$, Chemical^{A_3}, Transportation^{A_4}	The geographic scale of crop production^{A_1}, soil preparation and cultivation^{A_2}, agricultural chemical manufacturing^{A_3}, and air transportation^{A_4} infrastructure interdependence increases as the herbicide dicamba volatilizes during aerial application drifting several miles to other fields and affecting non-resistant crops.

Table G.1: Dynamic geographic interdependencies (continued)

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture$^{A_1 \cdots A_4}$, Healthcare^{A_5}, Emergency services^{A_6}, Financial services^{A_7}	The geographic scale of crop production^{A_1}, animal production^{A_2} and food manufacturing^{A_3} laborers dependence on food and beverage stores^{A_4}, health care services^{A_5}, emergency medical transportation services^{A_6}, and financial services^{A_7} increases as rural populations become smaller and local businesses close throughout the Arkansas delta.
Food and agriculture$^{A_1, A_2}$, Transportation^{A_3}	The geographic scale of animal production^{A_1}, animal food manufacturing^{A_2}, and truck transportation^{A_3} infrastructure interdependence increases when a feedmill is disrupted and unable to manufacture feed creating dependence on neighboring feedmills for the production and transportation of feed.

Table G.1: Dynamic geographic interdependencies (continued)

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture$^{A_1, A_2}$, Transportation^{A_3}	The geographic scale of animal production^{A_1}, animal slaughtering and processing^{A_2}, and truck transportation^{A_3} infrastructure interdependence increases when a animal slaughtering and processing facility is disrupted and unable to operate creating dependence on neighboring facilities for animal slaughtering and processing.
Food and agriculture$^{A_1 \cdots A_3}$, Transportation$^{A_4, A_5}$	The geographic scale of crop production^{A_1}, grain milling^{A_2}, grain elevators and storage^{A_3}, truck transportation^{A_4}, and rail transportation^{A_5} infrastructure interdependence increases when a grain mill is disrupted and unable to operate creating dependence on neighboring grain mills to mill, store, and distribute harvested grain.

Table G.1: Dynamic geographic interdependencies (continued)

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture$^{A_1, A_2}$, Transportation^{A_3}	The geographic scale of food manufacturing^{A_1}, refrigerated storage^{A_2} and truck transportation^{A_3} infrastructure interdependence increases when a food manufacturing plant is disrupted and unable to operate creating dependence on neighboring manufacturing plants and storage facilities to manufacture, store, and distribute products.
Food and agriculture$^{A_1 \cdots A_4}$, Water^{A_5}, Transportation^{A_6}	The geographic scale of animal production^{A_1}, food manufacturing^{A_2}, animal slaughtering and processing^{A_3}, animal food manufacturing^{A_4}, water treatment and distribution^{A_5}, and truck transportation^{A_6} infrastructure interdependence increases as manufacturing facilities are unable to expand operations or increase productivity when municipal water utilities are unable to process higher volumes of wastewater.

Table G.1: Dynamic geographic interdependencies (continued)

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture^{A_1}, Healthcare$^{A_2 \cdots A_4}$, Emergency services^{A_5}	The geographic scale of animal production^{A_1}, veterinary services^{A_2}, pharmaceutical and medicine manufacturing^{A_3}, health care services^{A_4}, and government emergency planning^{A_5} infrastructure interdependence increases as pathogen-carrying migratory birds infect animal flocks requiring veterinary testing and epidemic prevention, and emergency services planning and health care services if the pathogens infect human population.

Table G.1: Dynamic geographic interdependencies (continued)

$S = \{A_1, \ldots, A_n\}$	Description
Food and agriculture$^{A_1, A_2}$, Critical manufacturing$^{A_3, A_4}$, Chemical^{A_5}, Communications^{A_6}, Information technology^{A_7}	The geographic scale of agricultural production^{A_1}, agricultural research and development^{A_2}, agricultural implement manufacturing^{A_3}, food product machinery manufacturing^{A_4}, agricultural chemical manufacturing^{A_5}, wireless telecommunications carriers^{A_6}, and data processing, hosting, and related services^{A_7} infrastructure interdependence increases as advances in information technology and communication create cybersecurity vulnerabilities in food and agriculture systems exploitable from remote locations.

Appendix H

Observed Deadline Interdependencies

Recall a *deadline infrastructure interdependence* exists when infrastructure A depends on resources provided by infrastructure B by a deadline $\bar{t}$.

Table H.1: Enumeration of *deadline interdependencies* observed in the food and agriculture sector denoting infrastructure A^{A} and infrastructure B^{B} in the description of each example.

A	B	$\bar{t}$	Description
Food and agriculture	Transportation	10 hours	Poultry production^A and animal slaughtering and processing^A depends on truck transportation^B of live birds from poultry farms to processing plants as the birds lose mass during transit and perish if not processed within 10 hours.
Food and agriculture	Energy	24 hours	Rice farming^A depends on electric power generation^B and natural gas distribution^B to power irrigation pumps so that no rice fields are not flooded or irrigated for longer than 24 hours.

Table H.1: Deadline interdependencies (continued)

A	B	$\bar{t}$	Description
Food and agriculture	Healthcare	36 hours	Animal production^{A} depends on veterinary services^{B} and pharmaceutical medicine manufacturing^{B} infrastructures for testing and vaccinations to stop disease spread within 36 hours of detection.
Food and agriculture	Energy	14 days	Grain milling^{A} depends on electric power generation^{B} and natural gas distribution^{B} infrastructures to dry grain to 14% moisture content within 14 days of harvest.
Food and agriculture	Dams	7 days	Crop production^{A} depends on water supply and irrigation systems^{B} infrastructure to alleviate floodwaters in low-lying fields before crops drown in seven days.

Table H.1: Deadline interdependencies (continued)

A	B	$\bar{t}$	Description
Food and agriculture	Chemical	March 31	Soil preparation and cultivation^A depends on agricultural chemical manufacturing^B so that fertilizer and nutrients may be sowed into the fields by the end of March before planting begins.
Food and agriculture	Food and agriculture	June 30	Rice farming^A depends on crop production^B infrastructure to cultivate and distribute rice seeds to be planted by June 30.

Table H.1: Deadline interdependencies (continued)

A	B	$\bar{t}$	Description
Food and agriculture	Financial services	January 31	Soil preparation and cultivation[A] and crop production[A] depend on credit services[A] and fund disbursement by January 31 to purchase seed, fertilizer, chemicals, and other inputs necessary for the upcoming crop year.

Appendix I

Observed Delay Interdependencies

Recall a *delay infrastructure interdependence* exists when the operational state of infrastructure A experiences a delayed onset disruption δt time after a disruption in infrastructure B.

Table I.1: Enumeration of *delay interdependencies* observed in the food and agriculture sector denoting infrastructure A^{A} and infrastructure B^{B} in the description of each example.

A	B	δt	Description
Food and agriculture	Transportation	24 hours	Poultry production^{A} experiences a delayed onset disruption when the buffering stock of animal feed is depleted, approximately 24 hours, after a disruption in the truck transportation^{B} infrastructure responsible for delivering feed to poultry houses.
Food and agriculture	Energy	24 hours	Poultry production^{A} experiences a delayed onset disruption when the buffering stock of diesel fuel powering a backup generator is depleted, approximately 24 hours, after a disruption in the electric power generation^{B} infrastructure.

Table I.1: Delay interdependencies (continued)

A	B	δt	Description
Food and agriculture	Water	24 hours	Poultry production^A experiences a delayed onset disruption when the buffering stock of reserve-tank water, approximately 24 hours, after a disruption in the water supply and irrigation^B infrastructure.
Water	Food and agriculture	years	Water supply and irrigation systems^A experiences a delayed onset disruption when pollution is detectable in the water supply, up to several years after polluting begins, after a disruption in the animal production^B, crop production^B, and food manufacturing^B infrastructures allows the pollutants to reach a water supply.

Table I.1: Delay interdependencies (continued)

A	B	δt	Description
Food and agriculture	Food and agriculture	3 months	Rice farming^A experiences a delayed onset disruption when herbicide resistant seed production fails to meet demand, approximately 3 months, after a disruption in the crop production^B infrastructure causing rice farming productivity loss until the following crop year.
Financial services	Food and agriculture	3 months	Credit services^A financing row crop operations experiences a delayed onset disruption when farmers' harvest proceeds fail to meet financial obligations, approximately 3 months, after a disruption in the crop production^B infrastructure reducing crop yield.

Appendix J

Observed Human, Economic, and Natural Resource Interdependencies

Recall a *human, economic, and natural resource infrastructure interdependence* exists when the operational state of infrastructure A is affected by changes in human, economic, or natural resources provided by infrastructure B.

Table J.1: Enumeration of *human, economic, and natural resource interdependencies* observed in the food and agriculture sector denoting infrastructure A^A and infrastructure B^B in the description of each example.

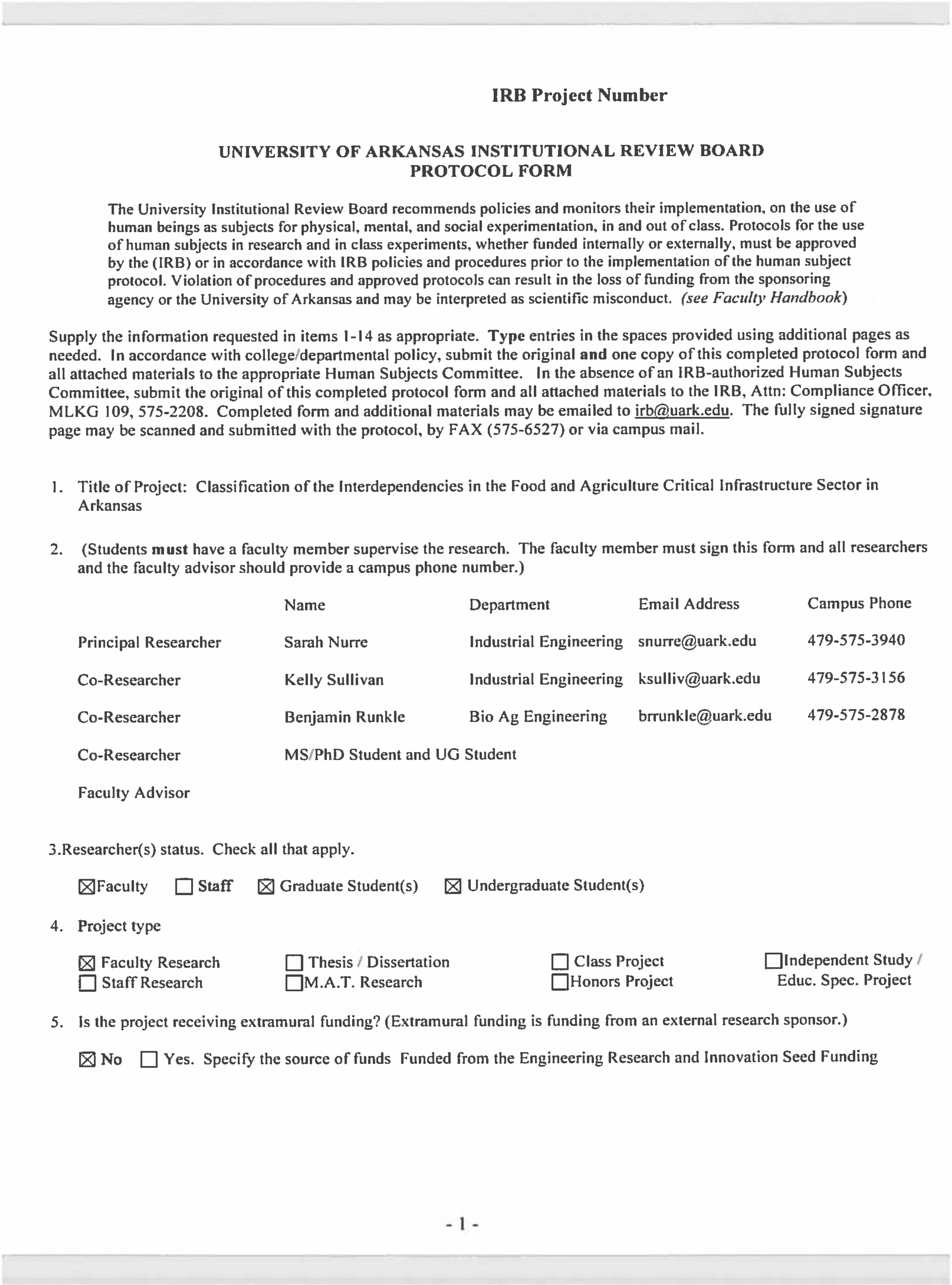
A	B	Description
Financial services	Food and agriculture	Availability and accessibility of agricultural credit services^A to finance row crop operations, equipment purchases, and farmers' living expenses on an annual basis is affected by crop production harvest volumes.
Food and agriculture	Energy	Grain crop production planting decisions are affected by petroleum merchants in OPEC due to a positive correlation of grain prices and commodity oil prices.
Food and agriculture	Information technology	Crop production labor force within the food and agriculture sector is becoming smaller due to increased productivity from information technology innovations allowing farmers to work at older ages.

Table J.1: Human, economic, and natural resource interdependencies interdependencies (continued)

A	*B*	Description
Food and agriculture	Transportation	Grain milling infrastructures require increased volumes of barge and truck transportation affected by the increased maintenance costs of rail transportation.
Food and agriculture	Water	A majority of irrigation for row crop production$^{\mathrm{A}}$ draws large amounts of water from groundwater aquifers and surface water reservoirs$^{\mathrm{B}}$.
Food and agriculture	Commercial facilties	The average age of row crop producers$^{\mathrm{A}}$ continues to increase as populations in rural areas continue to decline as residents leave in response to fewer commercial facilties$^{\mathrm{B}}$ operating in typically poor, rural areas that ultimately leads to generational information loss as fewer families are able to maintain farm production with sufficient financial support through the generations.

Appendix K

Institutional Review Board Protocol



IRB Project Number

UNIVERSITY OF ARKANSAS INSTITUTIONAL REVIEW BOARD
PROTOCOL FORM

The University Institutional Review Board recommends policies and monitors their implementation, on the use of human beings as subjects for physical, mental, and social experimentation, in and out of class. Protocols for the use of human subjects in research and in class experiments, whether funded internally or externally, must be approved by the (IRB) or in accordance with IRB policies and procedures prior to the implementation of the human subject protocol. Violation of procedures and approved protocols can result in the loss of funding from the sponsoring agency or the University of Arkansas and may be interpreted as scientific misconduct. *(see Faculty Handbook)*

Supply the information requested in items 1-14 as appropriate. **Type** entries in the spaces provided using additional pages as needed. In accordance with college/departmental policy, submit the original **and** one copy of this completed protocol form and all attached materials to the appropriate Human Subjects Committee. In the absence of an IRB-authorized Human Subjects Committee, submit the original of this completed protocol form and all attached materials to the IRB, Attn: Compliance Officer, MLKG 109, 575-2208. Completed form and additional materials may be emailed to irb@uark.edu. The fully signed signature page may be scanned and submitted with the protocol, by FAX (575-6527) or via campus mail.

1. Title of Project: Classification of the Interdependencies in the Food and Agriculture Critical Infrastructure Sector in Arkansas

2. (Students **must** have a faculty member supervise the research. The faculty member must sign this form and all researchers and the faculty advisor should provide a campus phone number.)

	Name	Department	Email Address	Campus Phone
Principal Researcher	Sarah Nurre	Industrial Engineering	snurre@uark.edu	479-575-3940
Co-Researcher	Kelly Sullivan	Industrial Engineering	ksulliv@uark.edu	479-575-3156
Co-Researcher	Benjamin Runkle	Bio Ag Engineering	brrunkle@uark.edu	479-575-2878
Co-Researcher	MS/PhD Student and UG Student			
Faculty Advisor				

3.Researcher(s) status. Check all that apply.

☒Faculty ☐ **Staff** ☒ Graduate Student(s) ☒ Undergraduate Student(s)

4. Project type

☒ Faculty Research ☐ Thesis / Dissertation ☐ Class Project ☐Independent Study / Educ. Spec. Project
☐ Staff Research ☐M.A.T. Research ☐Honors Project

5. Is the project receiving extramural funding? (Extramural funding is funding from an external research sponsor.)

☒ No ☐ Yes. Specify the source of funds Funded from the Engineering Research and Innovation Seed Funding

IRB Project Number

6. Brief description of the purpose of proposed research and all procedures involving people. Be specific. Use additional pages if needed. (**Do not** send thesis or dissertation proposals. Proposals for extramural funding must be submitted in full.)

Purpose of research:

Food and agriculture is a critical infrastructure making up almost 20% of the economic activity in the US. In spite of its importance, researchers have overlooked food and ag when classifying infrastructure interdependencies. We will fill this need by identifying and classifying the interdependencies of the food and ag sector within the state of Arkansas with the aim of strengthening its resilience. Ag is the top industry in AR wherein rice and poultry comprise two of the top commodities. Using rice and poultry as case studies, we will interview key personnel in the food and ag industry such as farmers, packaging managers, researchers, and members of the AR Division of Ag. Complementing this effort, we will interview managers of interdependent infrastructures (e.g., water). We will augment the interview data with data from GIS and literature to classify and create visualizations for the types and characteristics of interdependencies within food and ag in AR.

Procedures involving people:
We will conduct interviews, which involve the participation by people. Each person will have the option to consent or not consent to audio and/or video recording of the interviews.

7. Estimated **number of participants** (complete all that apply)

__0___ Children under 14
____0__ Children 14-17
__0___ UA students (18yrs and older)
__30___ Adult non-students

8. Anticipated dates for contact with participants:

First Contact ___August 1, 2017________________ Last Contact ________June 30, 2018______

9. Informed Consent procedures: The following information must be included in any procedure: identification of researcher, institutional affiliation and contact information; identification of Compliance Officer and contact information; purpose of the research, expected duration of the subject's participation; description of procedures; risks and/or benefits; how confidentiality will be ensured; that participation is voluntary and that refusal to participate will involve no penalty or loss of benefits to which the subject is otherwise entitled. See *Policies and Procedures Governing Research with Human Subjects*, section 5.0 Requirements for Consent.

☒ Signed informed consent will be obtained. **Attach copy of form.**
☐ Modified informed consent will be obtained. **Attach copy of form.**
☐ Other method (e.g., implied consent). **Please explain on attached sheet.**
☐ Not applicable to this project. **Please explain on attached sheet.**

10. Confidentiality of Data: All data collected that can be associated with a subject/respondent must remain confidential. Describe the methods to be used to ensure the confidentiality of data obtained.

All information will be kept confidential to the extent allowed by applicable State law, Federal law, and the Freedom of Information Act in Arkansas. No transcription of any recordings will be conducted. All data and results summarized in reports and publication will not include identifiable information. Unless an agreement is made between the research team and interviewee, specific statements will not be attributed to an individual or organization. All paper notes will be kept securely locked in the research team members' offices. Text-based electronic records will be documented in a OneNote project that only the research team has access to. Audio and video based electronic records will be secured in a password-protected folder that only the research team has access to. All electronic and paper records will be shredded and/or deleted 5 years after the study is complete.

11. Risks and/or Benefits:

Risks: Will participants in the research be exposed to more than minimal risk? No Minimal risk is defined as risks of harm not greater, considering probability and magnitude, than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests. Describe any such risks or discomforts associated with the study and precautions that will be taken to minimize them.

The participants will not be exposed to more than minimal risk.

Benefits: Other than the contribution of new knowledge, describe the benefits of this research, especially any benefits to those participating.

With the participants, we will share the classifications of agricultural interdependence deduced as a result of the study. Additionally, we will share any appropriate data that has been input into a GIS visualization representation displaying the connections and interactions between and within critical infrastructure sectors. These two key pieces of information will benefit the participants by providing a system-wide perspective on how infrastructure interact.

12. Check all of the following that apply to the proposed research. Supply the requested information below or on attached sheets:

☐ A. Deception of or withholding information from participants. Justify the use of deception or the withholding of information. Describe the debriefing procedure: how and when will the subject be informed of the deception and/or the information withheld?
☐ B. Medical clearance necessary prior to participation. Describe the procedures and note the safety precautions to be taken.
☐ C. Samples (blood, tissue, etc.) from participants. Describe the procedures and note the safety precautions to be taken.
☐ D. Administration of substances (foods, drugs, etc.) to participants. Describe the procedures and note the safety precautions to be taken.
☐ E. Physical exercise or conditioning for subjects. Describe the procedures and note the safety precautions to be taken.
☐ F. Research involving children. How will informed consent from parents or legally authorized representatives as well as from subjects be obtained?
☐ G. Research involving pregnant women or fetuses. How will informed consent be obtained from both parents of the fetus?
☐ H. Research involving participants in institutions (cognitive impairments, prisoners, etc.). Specify agencies or institutions involved. Attach letters of approval. Letters must be on letterhead with original signature; electronic transmission is acceptable.
☐ I. Research approved by an IRB at another institution. Specify agencies or institutions involved. Attach letters of approval. Letters must be on letterhead with original signature; electronic transmission is acceptable.
☐ J. Research that must be approved by another institution or agency. Specify agencies or institutions involved. Attach letters of approval. Letters must be on letterhead with original signature; electronic transmission is acceptable.

13. Checklist for Attachments

The following are attached:

☒ Consent form (if applicable) or

☒ Letter to participants, written instructions, and/or script of oral protocols indicating clearly the information in item #9.

☐ Letter(s) of approval from cooperating institution(s) and/or other IRB approvals (if applicable)

☒ Data collection instruments

*Note, we have attached the informed consent form. Additionally, we include an attachment with the link to the web-based form and a list of the questions we will ask in-person. We will use computer software and phone applications to record interviews with permission of participants.

14. Signatures

I/we agree to provide the proper surveillance of this project to insure that the rights and welfare of the human subjects/respondents are protected. I/we will report any adverse reactions to the committee. Additions to or changes in research procedures after the project has been approved will be submitted to the committee for review. I/we agree to request renewal of approval for any project when subject/respondent contact continues more than one year.

Principal Researcher Sarah G. ______ Date 8/4/2017

Co-Researcher ______ Kelly Sullivan Date 8/4/2017

Co-Researcher ______ Date 8/4/17

Co-Researcher ______ Date

Faculty Advisor ______ Date

PROTOCOL APPROVAL FORM

(To be returned to IRB Program Manager with copy of completed protocol form and attachments)

Human Subjects Committee Use Only (In absence of IRB-authorized Human Subjects Committee, send protocol to IRB.)

Recommended Review Status

9 Human Subjects Committee can approve as exempt because this research fits in the following category of research as described in section 9.02 of the IRB policies and procedures **(Cite reasons for exempt status.)**:

Printed Name and
Signature of the HSC Chair ____ Date

****
**

9 Expedited Review by a designated member of the IRB because this research fits in the following category of research as described in section 9.03 of the IRB policies and procedures **(Cite reasons for expedited status.)**:

Printed Name and
Signature of the HSC Chair ____ Date

****
***

9 Requires Full Review by the IRB because this research fits in the following category of research as described in section 9.04 of the IRB policies and procedures **(Cite reasons for full status.)**:

Printed Name and
Signature of the HSC Chair ____ Date

IRB/RSCP Use Only

Project Number ________________________________ Received RSCP

Sent to: ____ Date:

Final Status

9 Approved as **Exempt** under section 9.02 of the IRB Policies and Procedures (**Cite reasons for exemption.**):

9 Approved as **Expedited** under Section 9.03 of the IRB Policies and Procedures because **(Cite reasons for expedited status.)**

Printed Name and
Signature: ____ ______________ Date ________________
IRB (for the Committee)

9 Approved by **Full** review under Section 9.04 of the IRB as meeting requirements of the IRB Policies and Procedures.

Printed Name and
Signature: ____ Date
IRB Chairperson

UNIVERSITY OF
ARKANSAS

Office of Research Compliance
Institutional Review Board

August 31, 2017

MEMORANDUM

TO:	Sarah Nurre Kelly Sullivan Benjamin Runkle
FROM:	Ro Windwalker IRB Coordinator
RE:	New Protocol Approval
IRB Protocol #:	1708017910 (previously 17-07-012)
Protocol Title:	*Classification of the Interdependencies in the Food and Agriculture Critical Infrastructure Sector in Arkansas*
Review Type:	☐ EXEMPT ☒ EXPEDITED ☐ FULL IRB
Approved Project Period:	Start Date: 08/31/2017 Expiration Date: 08/24/2018

Your protocol has been approved by the IRB. Protocols are approved for a maximum period of one year. If you wish to continue the project past the approved project period (see above), you must submit a request, using the form *Continuing Review for IRB Approved Projects*, prior to the expiration date. This form is available from the IRB Coordinator or on the Research Compliance website (https://vpred.uark.edu/units/rscp/index.php). As a courtesy, you will be sent a reminder two months in advance of that date. However, failure to receive a reminder does not negate your obligation to make the request in sufficient time for review and approval. Federal regulations prohibit retroactive approval of continuation. Failure to receive approval to continue the project prior to the expiration date will result in Termination of the protocol approval. The IRB Coordinator can give you guidance on submission times.

This protocol has been approved for 50 participants. If you wish to make *any* modifications in the approved protocol, including enrolling more than this number, you must seek approval *prior to* implementing those changes. All modifications should be requested in writing (email is acceptable) and must provide sufficient detail to assess the impact of the change.

If you have questions or need any assistance from the IRB, please contact me at 109 MLKG Building, 5-2208, or irb@uark.edu.

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