**Social Policy and Operations Management**

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# ABSTRACT

This dissertation strengthens planning and policy analysis by using concepts from operations management to examine production and distribution of goods and services for disadvantaged groups. Building on the introduction, chapter two tells a cautionary tale, investigating how scholars and decision makers used operations management methods to consider operations in planning and policy analysis in the 1970s in ways that further marginalized already vulnerable residents. The tools and concepts of operations management, however, if sufficiently framed by concerns about equity and advocacy, are powerful instruments in solving production and distribution problems with social consequences. Chapter three explores how these concepts can be used to descriptively *identify disparities* in access to goods and services by socio-economic status, examining the distribution of irrigation equipment in Senegal. The core question is about the allocation of risk and inventory across levels of a supply chain that extends far into Senegal's farming regions. Chapter four identifies how these concepts can be used to causally *explain disparities*, tracing policies and plans that aggregative or ameliorate them. It focuses on the main program that subsidizes affordable housing construction in the United States, a durable necessity that is unevenly available and exposed to environment risks across space. The core question is about patterns over space and time in building affordable housing stocks, relative to where and when disasters occur. Chapter five shows how these concepts can be used to prescriptively *remedy disparities*. It investigates quality risks in the US international food assistance supply chain in Eastern Africa. The core question is about what levers can be pulled in supply chain design to improve food aid quality. Chapter six concludes.

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# Chapter 1

## Introduction

Planning and policy analysis scholars and activists have long been attentive to racial and economic and geographic inequality in relation to goods and services. Designing plans and policies concerning goods and services is often a matter of distributive justice and rests on the principle of strict equality, the premise that each person should have the same opportunity to produce, distribute, and consume goods and services. In examining the intersection of racial inequality and operations, one could look to Pan-African leader and entrepreneur Marcus Garvey. For Garvey, production and distribution economics were a means towards economic equality and political power for black workers and consumers. More recently, planner and political scientist James DeFilippis (2003) drew a connection between economic inequality and operations, tracing how often manage operations to extract value from already marginalized communities, and arguing that local governments can repurpose operations to improve residents' economic opportunities. The work of poverty scholar Amartya Sen foregrounds a link between geographic inequality and operations, identifying how production, access to food, and public aid varies with geography, leading to differential outcomes in famine relief for groups such as Fulani herders and Wallo farmers in the Senegal River Valley during the 1973 Sahel drought (Sen, 1981).

Borrowing a frame from planning scholar John Friedman (1987), who positions the work of public and voluntary sector planners and analysts relative to their private sector counterparts, this dissertation suggests how planning and policy analysis could be enriched by concepts from operations management. The core disciplinary innovation in this dissertation is to show how operations management can responsibly offer conceptual leverage that is relevant to planning and policy analysis problems.

Operations management holds that producing and distributing basic goods and services is an exercise in planning inventory, capacity, and information. These plans determine where and when production and distribution, and hence consumption, occur. Alongside planning and policy analysis, operations management was influenced by the scientific management tradition (Rittel & Webber, 1973). Aside from briefly being motivated by social concerns after World War II, it has been mainly motivated by commercial concerns. Operations management brings clarity to production and distribution problems with clear constructs such as inventory (e.g., a good); capacity (e.g., an ability to process a job or store a product); and information (e.g., a degree of uncertainty). Operations management next brings clarity to decisions by offering basic models that characterize tensions in production and distribution systems—between responsiveness and uncertainty, having too much or little capacity, adding capacity or holding

inventory, and other fundamental tensions. These concepts can be used to describe the unevenness in inventory, capacity, and information across geography and time, relative to disadvantaged groups. These are groups that experience higher rates of poverty, social exclusion, and discrimination. These concepts can also be used to prescribe how inventory, capacity, and information should be made more even.

**History of operations in planning and policy analysis**

The challenge of responsibly considering operations in planning and policy analysis first appeared after World War II. Scholars in thinktanks such as RAND and decision makers at public agencies saw promise in bringing *methods* from operations management to public decision making, particularly in domestic social policy (Light, 2003). These methods or "mathematical techniques" as termed by Ackoff (1979), are predictive, descriptive, and prescriptive models of inventory and capacity systems that are solved with optimization, simulation, learning, and analytical approaches. These methods were helpful in some contexts. For example, local ambulance services adopted operations concepts to route and dispatch trucks in the 1960s-1980s (Simpson & Hancock, 2009). Or, for example, an information management system improved the U.S. postal service's operations (Wildermuth & Foote, 1979).

These scholars and decision makers also found operations management *concepts* to be promising. As described above, these concepts capture the core tensions in production and distribution systems, helping by characterizing variability and trade-offs in operations. Foundational operations management articles explicitly recognize the application of operations management concepts to public, social problems. For example, Arrow, Harris, & Marschak (1951) in the original analysis of the tension between overage- and underage-costs in planning inventory orders note applications to nonprofit settings.

Decision makers relying on mathematical techniques, such as simulation and optimization, took actions that proved to be injurious. These methods exacerbated segregation in American cities, enabling top-down decisions on policy issues such as transportation planning (Light, 2003). These methods also reinforced injurious policies in the Vietnam War, allowing high-level decisions to be based on sophisticated mathematical techniques not always appropriate for strategic decision making (deLeon, 1987; see also Schrader, 2006, p. 14). Critics in government and in communities charged that the use of such techniques lacked norms that ensured equity was considered in formulating problems and implementing solutions (D. Wallace & Wallace, 1998). At the core of critics' charges were concerns over the use of sophisticated mathematical models to preclude stakeholder engagement and generation of practical insights (see, e.g., a discussion of modeling for the Canadian court system in Walker, 1982). Some operations management scholars themselves were also critical of these methods. Questioning such method's appropriateness for social problems, Liebman (1976) argues there are "conflicts among

members of society over goals and methods" that cannot be address by mathematical techniques (see also, Walker, 1982). This debate resembles the current today over the appropriateness of using mathematical techniques in government decisions, such as using learning to grant bail, probation, and parole.

Of the instances where decision makers used these methods in harmful ways, one that stands out is New York City planners using model developed by the RAND Corporation to decide where firehouses should be located (for the initial article, see, Chaiken, 1978). The model optimized a narrow objective of cost-efficiency in solving the question, where should firehouses be located? Decision makers ignored questions of equity and equality, and did not consider how the data, model, and results came together to disproportionately expose non-white residents of New York City to fire (D. Wallace & Wallace, 1998). City planners, guided by the model, closed firehouses in neighborhoods with a majority of Black and Latinx residents. The public outcry culminated on the pages of *Management Science* in a heated exchange between operations scholars and community advocates in which advocates called the research "irresponsible" (Chaiken, Ignall, Kolesar, & Walker, 1980; R. Wallace & Wallace, 1980). More broadly, as Deborah Wallace & Rodrick Wallace (1998) document, public decision makers prioritizing efficiency in operations made access to public services more uneven along racial and class and geographic lines throughout the 1970s with devastating consequences for already-disadvantage groups.

Since the 1970s, operations management, with some exceptions, has continued to become increasingly mathematical and has focused primarily on the private sector, as supply chains lengthened, service operations grew, and new business models emerged (like Uber and Amazon). The discipline has continued to develop powerful conceptual insights into production and distribution system. And in the past decade, it has demonstrated a renewed interest in social problems, framing the poor as producers and distributors with operations challenges (Sodhi & Tang, 2014; Tang, 2018). Thus far, however, operations management has yet to set clear norms for acceptable methods (or questions or partners) that will prevent this second wave of interest in social problems from mirroring the first one and exacerbating inequality.

Planning and policy analysis, by contrast, began to develop new methods and concepts through the 1970s and beyond to inform scholarship and research on operations questions. Rittel & Webber in 1973 note of this methodological shift, "These analysts are coming to realize how valid their model really is." Anticipating this shift, Lindblom's 1959 landmark article *The Science of Muddling Through* codifies an approach to planning and policy decisions that consists of incremental comparisons of policy options rooted in a few crucial empirical insights instead of reliance on mathematical techniques that attempt to characterize uncertainty and many trade-offs in a system. Practical and empirical methods to collect and represent data may better reflect the complexities of research and decision making with social implications (Ackoff, 1979; Walker, 1982). Ideally, these methods are more attentive to the equity implications of such scholarship and decisions.

**The continued relevance of supply in planning and policy analysis**

What, then, would be entailed in planning and policy analysis scholarship revisiting concepts from operations management? To answer this question, this dissertation explores a set of operations problems with empirical methods and production and distribution concepts.

First, I investigate operations problems in ways that are consistent with concerns about redressing inequality. These problems sit at the intersection of two trends. Growing concentrations of corporate power, especially given the privatization of public functions, pattern the production, distribution, and consumption options and decisions of disadvantaged individuals. And increasing exposure of operations to shocks—disasters, pandemics, war, depressions—complicate the availability of goods and services in all sectors.

Second, in each study I use an empirical approach to produce and, where possible, validate (or confirm) models of production and distribution systems. My intent is to develop models that best encompass the interests of stakeholders in social problems, relying on mathematical formulations only to the extent that concerns about disadvantaged groups can still be brought to the forefront of analysis.

Finally, with each study, I aim to bring new clarity on pressing policy issues by using straightforward operations constructs and models. More broadly, without such clarity, planning and policy analysis scholars will work to formulate and solve operations questions without relying on the extensive and helpful body of relevant scholarship on inventory, capacity and information. In doing so, they risk sacrificing impact on the systems they are studying. But with such clarity, a research agenda employing these concepts can document, explain, and remedy inequalities in production and distribution systems.

*Focusing on basic necessities*

In the twentieth century, globally and within the United States the standard of living increased with more accessible and available basic necessities—food, housing, and medical care. Yet these gains were unevenly distributed as there persist significant disparities along race, class, nationality, and geographic lines in how these goods and services are produced and consumed. This research agenda, motivated by the idea of distributive justice, aims to document, explain, and remedy disparities over the most basic goods. Tying this agenda to public policy objectives, one starting point is that individuals should enjoy a ‘freedom from want’ of basic necessities, a notion which underpinned the 1940s US social policy agenda and persists today in debates on redistributive policies. More recent starting points are declarations that all individuals should enjoy productive agricultural systems (NEPAD, 2014) and food

aid when those systems falter (WFP/FAO, 1996). A need is to develop nuanced operations insights that can help turn these declarations into impactful policies.

**A research agenda on production and distribution systems**

How would operations management concepts responsibly inform planning and policy analysis today? As a baseline, scholars would *define what constitutes responsible operations management.* Next, scholars would *descriptively document disparities* in basic goods and services through the analysis of inventory, capacity, and information, relative to disadvantaged groups. Then, scholars would *causally explain the disparities* by attributing how plans and policies—in all sectors—affect those systems. Finally, they would design mechanisms to *prescriptively remedy disparities*, such as rearranging incentives and risks to reallocate power in systems.

*Defining responsible operations management*

As a starting point, this agenda defines what constitutes responsible operations management. Closely reflecting the arguments above, a responsible operations management agenda is cautious as it recognizes that in history decisionmakers used operations in ways that furthered inequality and injurious policies. Accordingly, such an agenda is based on an empirical and transparent, public sector- and community-oriented, and political understanding of operations challenges. The main principle of the agenda is that operations questions with distributional implications should be solved using empirical and transparent methods with public and community partners. This agenda subtlety but significantly differs from recent work in operations management that, broadly, examines the poor as buyers and sellers of goods and services. *The first paper in my dissertation defines how concepts from operations management can be responsibly employed to document, explain, and resolve social problems.*

*Documenting disparities*

A next step in such an agenda entails documenting how inventory, capacity, and information shape the economic opportunity of disadvantaged groups. Further, the agenda illustrates the consequences of disparities. Broadly there are disparities in the opportunity to produce, distribute, and consume, such as grow food, sell basic medicines, and access decent housing units, respectively. This research goes beyond just an analysis of production and distribution economics. Instead, it identifies where, when, and to what extent production and distribution occur relative to disadvantaged groups. A helpful template for operations work that documents disparities is Rydell, Mulford, & Kozimor (1979), who, looking over time, characterize participation rates in public transfer programs. Social problems that can be documented range from how safety nets for basic medical services work, which provide care to one in five people in

the United States (and more in other contexts), to how opportunity to work public jobs is distributed, which employ one in six Americans (and again more in other contexts).

*The second paper in my dissertation documents how irrigation equipment inventory, and risk associated with it, is distributed across the irrigated zones of Senegal.* Supply chain risk drives what and how much firms are willing to source, stock, and sell, affecting what is available to customers. This paper reports findings from a census conducted of known firms that constitute the irrigation equipment supply chain in Senegal. These firms source, stock, and sell pumps and pipes and do business in 35 cities in Senegal's irrigated areas. In the census, we pose open-ended interview questions about perceived risks. We find that contractual and quality risks are the most cited. Such risks are more prevalent in firms in the supply chain that are at lower echelons and located in small cites. A lower-echelon firm is closer to customers; a higher one is closer to manufacturers. We also find that firms mainly use reactive strategies, instead of proactive strategies, to manage risks. We document that downstream firms that use proactive risk-management strategies hold more inventory and set higher targets. Based on the observation that risk differentially burdens downstream firms and those in small cities, we recommend how policy interventions should be targeted and designed to support these firms in the supply chain. Our recommendations are generalizable for the improvement of supply chains on which public and voluntary sector programs rely, allowing those programs to benefit the poor.

*Explaining disparities*

The next step in this agenda entails explaining how policies and plans across public, voluntary, and private sectors cause disparities in opportunities to produce, distribute, and consume. In response to charges that production and distribution exacerbate inequalities (beyond those inequalities generated by a consumer's wealth), public and private sector organizations often proffer the defense that decision makers are well intentioned and that any inequality generating consequences of operations are unexpected and regrettable. Holding decision makers accountable for inequality is especially important and difficult as private firms have taken over functions once held by public agencies, albeit are intertwined with the public sector through public loans, subsidies, regulations, and other instruments. The goal of this research is to reveal discrimination in operations and to characterize unequal, even if unintentional, impacts of production and distribution across race and class and geographic lines. A useful template for operations work that explains disparities is Savas (1973), who, at the request of the Mayor of New York, empirically showed the extent to which "middle class" residents of the outer boroughs had less access to snowplowing than those in Manhattan, in part because population density helps explain variation in snowplowing availability. Social problems exacerbated by operations, that must be explained range from

uneven patterns in stocking healthy food to analyses of information that banks make available about loans for homes, cars, small business, etc.

*The third paper in my dissertation explains where and when a housing program subsidizes construction of affordable housing inventories, relative to where and when disasters occur.* Recent hurricanes and wildfires have made clear the disruptive effect of disasters on housing markets, aggravating underlying geographic disparities in available, affordable, and disaster-exposed rental-housing inventories in the United States. Where and when policy makers respond to environmental shocks by allocating resources to lower-income households and stabilizing neighborhoods is understudied, despite being a major policy concern. The main federal program that has the potential to rebuild affordable housing inventories, given its flexibility and scope, is the Low-Income Housing Tax Credit Program (LIHTC). The questions at the core of studying this quickly evolving safety net are when, where, and to what extent do decision makers use LIHTC respond to disasters? With insufficient affordable housing stocks nationally, the question of where and when stocks are expanded is of importance. Our results indicate that LIHTC is a powerful tool for state policymakers and private developers in shaping affordable housing markets after disasters. Disasters lead state policymakers to allocate more LIHTC units in affected areas, a higher share of which are not in floodplains than in floodplains, hence lessening the exposure of renters in these affordable housing units to disasters. LIHTC is an important tool in post-disaster housing and climate policy by creating low-income housing inventories outside of floodplains.

*Resolving disparities*

The final step in this agenda resolves disparities by rearranging risk and incentives, and ultimately power, in production and distribution systems. This agenda is consistent with the expansive line of prescriptive research that, as supply chains have lengthened over the last half century, suggests how to coordinate incentives and risks across many stakeholders. The goal of this research, however, is to act on these prescriptive insights by advocating in front of legislatures and courts, working with public agencies, presenting to corporate boards and unions, and other public, political fora. In studying political problems, there is an obligation to amplify the voices of people disadvantaged by operations and provide insights to decision makers for business and policy fixes to inequalities. Echoing Paul Davidoff's (1965) advocacy planning approach, inventory and capacity planners in all sectors have an obligation—and the opportunity—to advocate for durable solutions to inequality. A starting point for operations work that aims to resolve inequalities is Brill (1979), who discusses the extent to which prescriptive techniques allow for scholarship to impact public programs.

*The fourth paper in my dissertation resolves a quality risk in international food aid supply chains, possibly improving timeliness.* International food assistance reaches more than 90 million people per year, much of it through in-kind programs that distribute food. Several key aspects of in-kind programs—what food is shipped, when and from where it is sourced—have been changed to improve program effectiveness and efficiency, becoming helpful tools in the modernized in-kind food assistance toolbox. Packaging—in what food is shipped—remains an unstudied and underused tool despite more than 50 million bags per year passing through in-kind supply chains, affecting program effectiveness and efficiency. We conduct an experiment with 46 shipments using different packaging materials and sizes to measure the effect of packaging on shipment quality, cost, and timeliness. Analyzing the data with randomization tests, we find that, relative to the current materials, new materials maintain shipment quality and cost while improving timeliness and, in some cases, reducing cost. One promising material that balances cost and effectiveness is a bag with a biopesticide applied, designed to prevent insects from reproducing. We also find that, relative to the current size, larger bags improve costs at least in the domestic portion of the supply chain. Donors and their partners should consider packaging as one more tool in the modernized food assistance toolbox. As the toolbox continues to fill, the coming opportunity and challenge to identify situations where the various tools work in complementary ways.

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# Chapter 2

## Responsible operations management: racial, class, and geographic considerations

**Abstract**

This commentary proposes strengthening social operations management scholarship by identifying norms and methods necessary to responsibly investigate production and distribution, relative to vulnerable and marginalized groups. Our starting point is the history of Operations Management and related disciplines. In Operations Management's first interaction with social problems after World War II, scholars furthered policies that disparately affected disadvantaged groups. The current interaction with social problems requires a responsible research agenda with norms and methods that can help scholars avoid the pitfalls of post-war Operations Management. Scholars, aware of the discipline's history, then must work to document, explain, and resolve social production and distribution problems. They should embrace public sector partners, the politics of social operations, advocating for disadvantaged groups, and using insights generated by empirical methods and applied research strategies. A social research agenda along these lines has the potential to transform the landscape of goods and services for the vulnerable and marginalized in society, as the late-century commercial research agenda did for the growing middle class.

**Key words**: responsible operations management, operations management history, equity

### 1. Introduction

In the past decade, Operations Management scholars have renewed their attention to problems of social concern. Problems of social concern are operations issues that are animated by social, instead of commercial, interests. Disaster relief and farmer livelihood problems are particularly prominent in current research, indicating how social problems can be addressed through study of the public, private, or voluntary sectors. This attention is apparent from special issues, calls for research, and conference mini-tracks. Mirroring this renewed scholarly attention are major companies' efforts to consider the social consequences of their operations. Yet the landscape of goods and services continues to be shaped by operations that perpetuate disparities in the opportunity to produce (e.g., to farm profitably), distribute (e.g., to stock medicines in developing countries), and consume (e.g., to call 911 systems).

Borrowing a frame from Planning scholar John Friedman (1987), who positions the work of public and voluntary sector planners and analysts relative to their private sector counterparts, this

commentary suggests that social operations management scholarship could be enriched by clear norms and context-appropriate methods used by public and voluntary sector planners and analysts. The need for such norms and methods becomes apparent in reviewing Operations Management's interaction with social problems from the 1950s through 1970s. It also becomes apparent in examining the trajectory of Planning, Policy Analysis, and Public Administration, neighboring disciplines concerned with social problems and that also emerged from the 'scientific management' tradition (Rittel & Webber, 1973). As discussed below, examining the history of Operations Management and that of neighboring disciplines can provide scholars insight in advancing racially and economically just operations.

**2. The continued relevance of Operations Management**

Operations Management holds that producing and distributing basic goods and services is an exercise in planning inventory, capacity, and information. These plans determine where and when production and distribution, and hence consumption, occur. The descriptive side of the social operations management research agenda sets forth the goal of describing the unevenness in inventory, capacity, and information across geography and time, relative to disadvantaged groups. The prescriptive side of the agenda attempts to make inventory, capacity, and information more even. The goal is to increase the opportunities to produce (e.g., work shifts), distribute (e.g., maintain a small business), and consume (e.g., access decent food). The challenge comes in translating this goal into responsible scholarship and action.

The challenge of conducting socially responsible scholarship is persistent and first appeared after World War II. Scholars and decision makers saw promise in bringing mathematical techniques to social decision making, particularly in domestic social policy (Light, 2003). Mathematical techniques, as termed by Ackoff (1979), are predictive, descriptive, and prescriptive models that are solved with optimization, simulation, learning, or analytical methods. For example, in this period local emergency services adopted operations concepts to route and dispatch trucks and locate stations (Simpson & Hancock, 2009).

Critics of Operations Management in the post-war era, though, saw an "irresponsible" approach to public decision making. They charged it lacked norms, and hence neglected equity; it relied on highly sophisticated methods, and hence precluded community engagement (Chaiken, Ignall, Kolesar, & Walker, 1980; D. Wallace & Wallace, 1998). By the 1970s, decision makers found that mathematical techniques may only be responsibly applied to narrow situations in the public sector (Light, 2003).

The missed opportunity to engage with social problems has persisted since the 1970s. Since then, though, the neighboring disciplines of Policy Analysis, Public Administration, and Planning have continued to grow and study these problems. Like Operations Management, these neighboring disciplines are in part traceable to Frederick Taylor's (1911) concept of "scientific management." Policy analysts engage in the "systematic and empirical" study of social problems (DeLeon, 2009; McCool, 1995).

Planners turn public and voluntary sector objectives into action, which is the focus of Planning as a discipline (Friedmann, 1987). Administrators use plans to put policies into effect by delivering goods and services to residents, which is the focus of the discipline of Public Administration (Stillman, 1992).

This second interaction between Operations Management and social problems is an opportunity to interface with and learn from these disciplines. Scholars and activists in these disciplines have long been attentive to racial and economic inequality in relation to goods and services, and developed norms and methods to do such research responsibly. In Planning and in Policy Analysis, scholars concerned with racial inequality and operations look to the foundational work of Marcus Garvey. For Garvey, production and distribution economics are a means towards advantaging black workers and consumers. Those concerned with economic inequality rely on, more recently, political scientist James DeFilippis, (2003). DeFilippis traces how firms manage operations to extract and oppress communities, while local governments and community organizations can repurpose operations to improve residents' opportunities. These disciplines may also be strengthened by the conceptual leverage that Operations Management offers. Operations Management brings clarity to decisions by offering basic models that characterize tensions in production and distribution systems—between order and variable costs, overage and underage costs, adding capacity and holding inventory, etc.

Today, Operations Management is reexploring the opportunity for scholarship and action on social problems, after decades of work on commercial problems as supply chains lengthened, service operations grew, and new business models (like Uber and Amazon) emerged, etc. Growing concentrations of corporate power create systems with a few powerful firms and many disadvantaged producers, distributors, and consumers. Increasing exposure of operations to shocks—disasters, pandemics, war, depressions—complicate the distribution of goods and services from all sectors. This reconsideration is enabled by new data, a growing openness among public decision makers to operations approaches, and the availability of "low-hanging" social problems.

A major challenge for operations scholars is that the norms and methods for responsible research and action are still not fully codified—across journals, associations, departments, and conferences. In the next sections in this commentary we review the history of operations management and related disciplines in order to propose norms and methods for responsible social operations management research. Such norms and methods, we argue, can bring new clarity. Without clarity, scholars risk less impact, as they are more likely to study second-order social operations problems, and more likely to generate insights that inadvertently further inequality if not do harm. With clarity, a normative research agenda can focus on first-order social operations problems—documenting, explaining, and resolving inequalities in production and distribution systems.

## 3. History of social operations

During World War II, researchers in universities, the defense industry, and the U.S. armed services developed conceptual and computational tools to address operations problems (William, 2015). After the war, defense contractors and researchers from thinktanks such as the RAND Corporation, with mathematical techniques in hand, began to advance a social operations management research agenda in areas such as public administration and city planning (Light, 2003). These tools were helpful in places—for example, an information management system improved the U.S. postal service's distribution operations, amid suburbanization (Wildermuth & Foote, 1979). Some foundational operations management articles even explicitly recognize applications to social problems. For example, the original newsvendor analysis notes that the overage-underage cost tension is apparent in nonprofit as well as commercial settings (Arrow, Harris, & Marschak, 1951).

The operations management research agenda was in tension by the 1970s, over both the questions being asked, a matter of norms, as well as the techniques being used, a matter of methods. Scholars were being pulled between two understandings of production and distribution economics, as represented by Ackoff (1979) in *The Future of Operations Research Is Past*. One understanding was based on "sophisticated" techniques providing decisions to questions that lent to being solved with mathematical techniques. The other was based on "contextually" appropriate methods that weighed input from "all stakeholders" in formulating problems, solving models, and implementing solutions. This tension dates back to WWII when there was debate in the military between the theoretical and empirical operations analysts (William, 2015).

This tension was particularly thick in social operations management research after several missteps in social policy and war planning spilled into public view. Decision makers relying on mathematical techniques took actions that produced inequality and exacerbated segregation in the United States, and reinforced injurious policies in the Vietnam War, of which lower-income Americans bore the burden (Light, 2003). In addition to doing harm, other studies were done without attempts at implementation (e.g., see an example of modeling for the Canadian court system, Walker, 1982). These missteps taken together left decision-makers and the broader public with the impression that the discipline could not responsibly engage social problems.

### 3.1 A need for norms on problem selection and formulation

History shows a responsible social research agenda must balance equity and efficiency in operations (and other criteria such as security and privacy). As political scientist Charles Hyneman (1939) observed, in a democracy there are other criteria beyond "efficiency in operation." A normative version of this agenda prioritizes equity over efficiency, in selecting and formulating problems. Concern for equity is

necessary for picking research partners, identifying questions, and implementing solutions that will lead to racially and economically just insights.

The consequences of a narrow focus on efficiency in operations management through the 1970s were stark. Of the public debacles that harmed vulnerable and marginalized groups in the interests of efficiency, the outcry in 1980 over the RAND fire-house model stands out (for the initial article, see, Chaiken, 1978). The model optimized a narrow objective of cost-efficiency in solving the question, where should firehouses be located? City decision makers left aside equity in not considering how the data, model, and results came together to disproportionately expose black residents of New York City to fire (D. Wallace & Wallace, 1998). Planners, guided by the model, closed firehouses in minority neighborhoods. The public outcry culminated on the pages of *Management Science* in a heated exchange between researchers and community advocates in which advocates called the scholars "irresponsible" (Chaiken et al., 1980; R. Wallace & Wallace, 1980). More broadly, as D. Wallace & Wallace (1998) document, public decision makers prioritizing efficiency in operations made access to public services more uneven along racial and class lines throughout the 1970s.

What constitutes responsible Policy Analysis, Planning, and Public Administration was defined during the 1970s, in part in response to this issue. In a pivotal *Policy Sciences* article, Horst Rittel and Melvin Webber (1973) recognize that efficiency dominated the disciplines that emerged from scientific management—Operations Management, Policy Analysis, Planning, and Public Administration. Focused on Planning, they called for an equity-focused approach to scholarship and action: "We have come to think about the planning task in very different ways in recent years. We have been learning to ask whether what we are doing is the right thing to do." In doing so, they declare that Planning scholarship and practice are not apolitical exercises. Since then, Planning has adopted equity as a core principle and "equity planning" has become a dominant paradigm. Equity planning holds the planner responsible for ameliorating disparities in the built environment across racial and class lines (Krumholz, 1982).

In light of history, how should equity be incorporated into the operations approach to social problem solving? The norm should be that scholarship makes more available to disadvantaged groups the opportunity to produce, distribute, and consume. This commentary argues for identifying problems that most dramatically improve equity in production and distribution systems. With an important problem identified, it may (or may not) be helpful to solve it in mathematical ways that are sensitive to equity, as is helpfully done in organ transplant and blood research. Embracing a normative Operations Management research agenda may not be that uncomfortable. Jon Liebman (1976) writing *Interfaces* about public sector problems recognizes that operations management is already normative, noting, "Once a model has been constructed, optimization answers, 'What *should* I do'." In general, Operations Management adheres to the "doctrine of efficiency" (Dahl, 1947). In other words, problems are usually formulated around

efficiency concerns. But, perhaps identifying problems with meaningful equity issues in order to propose just solutions is not so different from solving problems in order to propose efficient solutions.

**3.2 A need for empirical methods and validated approach**

History shows a research agenda on equity in operations must rely on empirical methods and validated (or tested) studies that rely on an applied and collaborative research strategy. As Ackoff (1979) observes, methods determine what operations problems are solved: in the 1970s research was "dictated by the [mathematical] techniques it has at its command" instead of the "problematic situations faced." For social problems in particular, Rittel & Webber (1973) note, "These analysts are coming to realize how valid their model really is." In particular, this commentary proposes that responsible OM research requires an empirical and validated approach to produce racially and economically just insights.

The impact of mathematical techniques, as operations management made its first interaction with social problems through the 1970s, was injurious. One example is the operations planning in the Vietnam War. Measures such as the "kill ratio"—the number of enemy forces killed divided by the number of friendly forces lost—were being used to model and drive policy-level decisions (Schrader, 2006). Mathematical techniques crowded out unit-level officers from the decision-making process and invited in operations experts with no battlefield experience. The main input in decision-making from unit-level officers was data, which was rolled-up to parameterize and model aspects of the war and produce policy recommendations. Operations over-reached in trying to parameterize factors and to model decisions with mathematical techniques that were better solved by less complex methods. An U.S. Army General noted, "Our experience was the large operational or tactical problems overwhelmed the analytical approach" (Schrader, 2006).

What constitutes reasonable methods for Policy Analysis, Planning, and Public Administration was defined through the 1970s, in part in reaction to this operations management's mathematical over-reach. That operations scholars were over-reaching with mathematical methods is the thesis of Lindblom's (1959) landmark *The Science of Muddling Through*, in which he argues policy decisions should be made with successive and narrow comparisons of alternative options. His approach seeded the incrementalist planning paradigm. It is also the basis of the variety of policy analysis taught at policy schools today, which is similar to the relative, incremental analysis taught with cases in business schools (e.g., Quinn, 1978).

In light of history, how should empirical methods and validation (or testing) be incorporated into the operations approach to social problem solving? The norm should be that scholarship uses empirical methods to produce and validate models of production and distribution systems. This commentary argues for models that best encompass the interests of stakeholders in social problems, using mathematical formulations only to the extent that the concerns of vulnerable and marginalized groups can still be

brought to the forefront of analysis. In problems outside the private sector, there are inherently "conflicts among members of society over goals and methods" (Liebman, 1976; see also, Walker, 1982). Accordingly, using methods that can "take all stakeholders into account" is essential (Ackoff, 1979). Embracing an empirical and validated research agenda will not be unfamiliar. Operations scholars already encourages, especially in the last decade, empirical methods (e.g., Terwiesch, 2019) and validated models (e.g., Gallien, Graves, & Scheller-Wolf, 2016).

## 4 A normative responsible operations research agenda

What would constitute a responsible operations management research agenda today? First, it would *document disparities* in basic goods and services through the analysis of inventory, capacity, and information, relative to vulnerable and marginalized groups. Second, it would *explain the disparities* by attributing how policies—in all sectors—affect those systems. Third, it would determine mechanisms to *resolve disparities*, such as rearranging incentives and risks to reallocate power in systems. A core premise of this research agenda is that scholars must build over years (if not decades) a deep descriptive understanding of social operations problems in order to do responsible prescriptive analyses. In other words, scholars must document and explain disparities before attempting to responsibly resolve them.

### 4.1 Documenting disparities

First, a normative, responsible operations management research agenda requires documenting how inventory, capacity, and information shape the economic opportunity of marginalized and vulnerable groups. Further, it illustrates the consequences of disparities. There is the opportunity to produce, such as grow food; to distribute, such as sell basic medicines; and to consume, such as access decent housing units. The goal of this research goes beyond just an analysis of production and distribution economics. Instead, it seeks to understand where, when, and to what extent production and distribution occur relative to disadvantaged groups. An helpful template for work that documents disparities is Rydell, Mulford, & Kozimor (1979), who, looking over time, characterize participation rates in public transfer programs.

What norms and methods underpin responsibly documenting disparities? The norm should be that, to the large extent that public production and distribution systems shape disparities, the public sector be a partner and area of study. Inequities in operations cannot be understood without studying the role of public production and distribution systems. Yet in contrast to the 1960s and 1970s, there is currently less attention to social problems in the public sector as compared to in the private and voluntary sectors. Less attention may be a thoughtful and conscientious reaction to the failures of the discipline's first interaction with social problems. Or it may reflect a deeply political perspective that the private and voluntary sectors are the more efficacious means to improve social conditions. The research strategy, then, should be

empirical and validated work with public agencies that which can be easily understood by public decision makers.

Social problems that can be documented, then, range from how safety nets for basic medical services work, which provide care to one in five people in the US (and more in other contexts), to how opportunity to work public jobs is distributed, which employ one in six Americans (and again more in other contexts). One contemporary example of scholarship on resolving disparities, and that studies a public problem and advances an empirical approach, is Kretschmer, Spinler, & Van Wassenhove's (2014) framework on school feedings. A crucial next step beyond documenting disparities is to illustrate their effect. One recent example of scholarship along this line is Gooding, Spiliotopoulou, & Yadav's (2019) analysis of the effect of vaccine stockouts on immunizations in Nigeria.

**4.2 Explaining disparities**

Second, a normative, responsible research agenda explains how policies and plans across all sectors cause disparities in opportunities to produce, distribute, and consume. The defense for decades of operations in all three sectors, especially as private firms have taken over functions once held by public agencies, is that decision makers are well intentioned but operations produce unexpected, regrettable outcomes. The goal of this research is to reveal discrimination in operations and to characterize unequal, even if unintentional, impacts of operations across race and class lines. A useful template for work that explains disparities is Savas (1973), who, at the request of the Mayor of New York, empirically showed the large extent to which "middle class" residents of the outer boroughs had less access to snowplowing than those in Manhattan. He then shows that population density helps explain the variation in snowplowing access.

What norms and methods underpin responsibly explaining disparities? The norm should be that explanations of disparities are inherently political. An explanation for inequities assigns a cause that, whether the disparity is deliberate or not, is a political statement, as Savas (1973) observed. This political step is more straightforward in the public and voluntary sectors than the private sector. In scholarship on the private sector, the link between disadvantaged groups and operations is fuzzy. In the contemporary social operations management research agenda, the link is clearer, in that it assumes that operations determine opportunity for disadvantaged groups. Yet, it remains apolitical, framing operations more as a promising solution to disparities instead of a cause of disparities (e.g., Sodhi & Tang, 2014). What is needed is political scholarship that also treats operations as a cause of disparities, tracing exploitation and racism in private operations, as well as in public and voluntary operations. Systems of production and distribution have long been used to oppress along race and class lines, which operations management can help dismantle by offering nuanced, conceptual tools. Such work is almost necessarily empirical and can

be validated with organizations that dismantle exploitation and racism, such as impact litigation firms that work to explain these disparities in front of courts.

Social problems, then, that must be explained range from uneven patterns in stocking healthy food to analyses of information that banks make available about loans for homes, cars, small business, etc. One powerful contemporary example of scholarship that makes race a central explanatory variable is Cui, Li, Li, & Yu (2020), who work to understand racial patterns in wholesale pricing.

### 4.3 Resolving disparities

Third, a normative, responsible research agenda works to resolve disparities by rearranging risk and incentives, and ultimately power, in production and distribution systems. Such an agenda is consistent with the expansive line of prescriptive research that, as supply chains lengthened over the last half century, suggests how to coordinate incentives and risks across many stakeholders. The goal of this research, however, is to act on these prescriptive insights by advocating in front of legislatures and courts, working with public agencies, presenting to corporate boards and unions, etc. In studying political problems, there is an obligation to amplify the voices of people disadvantaged by operations and provide insights to decision makers for business and policy fixes to inequalities. Echoing Paul Davidoff's (1965) advocacy planning approach, inventory and capacity planners and scholars have an obligation—and the opportunity—to advocate for durable solutions to inequality. A starting point for work that aims to resolve inequalities is Brill (1979), who discusses the extent to which prescriptive techniques allow for scholarship to impact public programs.

What norms and methods underpin responsibly resolving disparities? The norm should be that scholars use empirical analyses of inventory, capacity, and information to illustrate how production and distribution systems can be changed. These models should be empirical if not validated (or tested) with partners. The challenge with this norm is that data behind social problems is often, at first glance, scant. Systems like Enterprise Resource Planning do not often track the operations relevant to social problems, e.g., the retail firms that sell school books in developing economies. Sometimes systems do, but the politics of accessing that data are fraught. Perhaps as a reaction, operations scholarship on social problems relies heavily on mathematical techniques. The issue is mathematical techniques limit who can use operations scholarship (Liebman, 1976). Public and voluntary sector decision makers would be no more likely to use mathematical techniques than inventory planners at Proctor and Gamble, which excels with spreadsheet-based inventory models (see e.g., Farasyn, Perkoz, & Van de Velde, 2008). The other issue is that such techniques only work for a narrow set of social problems, e.g., those with clear decision variables, estimable parameters, and characterizable variation. For instance, Simpson & Hancock (2009) question the reliance on mathematical techniques in public sector emergency response, given how

difficult those problems can be to formulate mathematically. Left unstudied with these methods, then, are core operations problems, e.g., the inventory issues in the small firms that implement safety net programs.

One contemporary example of scholarship and advocacy on resolving disparities that is consistent with this commentary in terms of norms and methods is a series of studies on food aid transport. These studies document the costs and consequences on beneficiaries of an inefficient ocean shipping practice and trace the influence of an ocean shipping lobby on keeping the practice as a law (Bageant, Barrett, & Lentz, 2010; Nikulkov, Barrett, Mude, & Wein, 2016). This line of work culminated with testimony in the US Senate Committee on Foreign Relations in 2017 about how to resolve the issue.

**6. Conclusion**

Operations management has not taken a clear stand to address racial and economic disparities in production and distribution systems. The discipline must continue to develop clarity on what constitutes a responsible social operations management research agenda; otherwise, this second wave of social operations management may mirror the first one and exacerbate inequality. It is our intent that this commentary help starts a discussion on norms and methods for responsible scholarship.

Operations management should document disparities, paying close attention to the role the public sector plays in determining production, distribution, and consumption. It then should explain disparities without timidity, making hypotheses of racial discrimination and economic exploitation. Finally, it should resolve disparities, identifying solutions and advancing them through advocacy. Journals, departments, conferences, and associations all have a role to play in encouraging this responsible research and facilitating the debates that will set the responsible agenda. Journals can lead by prioritizing research that is political in nature, that has been validated and that gives appropriate consideration to the public sector in framing the problem and proposing solutions. Departments can lead with doctoral training that adopts norms and methods from Public Administration, Planning, and Policy Analysis. These norms and methods, after all, are how those disciplines understand the problems of the people, communities, and institutions in which production and distribution systems are embedded.

Operations management can no longer avoid the political realities associated with understanding, diagnosing and addressing social problems. Recognizing that operations management is now a political discipline will help bring into focus the methods and norms necessary to solve what are ultimately political questions, a reckoning which has already occurred in operations management's disciplinary neighbors. For example, by the close of World War II, leading Public Administration scholars rejected that "administrative questions are not political questions," changing the face of administration research going forward (Simon, Smithburg, & Thompson, 1950). Today, many operations questions are political questions. Operations management has no choice but to embrace the political implications of inventory,

capacity, and information. Not engaging in social problems or to do so superficially is political. Continuing to study commercial problems, given extreme concentrations of power in markets and persistent operations shocks from disasters, recession, pandemics, and wars, is also political.

It will not always be comfortable or familiar to allow operations management to become politicized. For instance, while norms point scholars toward issues of equity, they also point scholars *away from* certain problems or solutions. With a strong disciplinary norm about equity, we may debate studies that advance efficiency in powerful firms whose sourcing and selling decisions determine the production and consumption choices of hundreds of millions of vulnerable and marginalized individuals. For instance, qualitative empiricism runs contrary to the doctoral training in operations management programs. Programs will need to balance the methodological trajectory on which they set doctoral students with the need for responsible social operations management research.

A responsible agenda will significantly enlarge the impact of the discipline. In the 2020s, we will have to decide to what extent, and with how much impact, we want to engage with the pressing social challenges that are, at their core, politicized operations problems. Decision makers in private, public, and voluntary sectors will address growing concentrations of power in markets and the impact of shocks ranging from conflict to depressions, pandemics, and disasters. Operations management can offer powerful insights on these challenges, informing and advocating for plans and policies that favor disadvantaged groups. A social research agenda on these lines has the potential to make more equitable the landscape of goods and services for the vulnerable and marginalized in society, as the late-century commercial research agenda brought down production and distribution costs and enabled middle classes to grow.

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# Chapter 3

## Managing risks in lower-income economy supply chains: evidence from agricultural firms in Senegal


### Abstract

*Problem definition:* How risks are distributed across firms in a supply chain is a major management and public policy concern. Little is documented, however, awbout how such risks are distributed across firms in lower-income countries, especially the small firms that serve poor, rural households.
*Relevance:* Supply chain risk drives what and how much firms are willing to source, stock, and sell, affecting what is available to customers. Documenting these risks, then, is necessary for policymakers and program managers to design interventions that spread risk in ways favoring firms that serve poor, rural households.
*Methods:* Our research strategy is descriptive and empirical. We report findings from a census of known firms that constitute the irrigation equipment supply chain in Senegal. These firms do business in 35 cities in Senegal's irrigated areas. In the census, we pose open-ended interview questions about perceived risks.
*Results:* We find that contractual and quality risks are the most cited. Such risks are more prevalent in firms in the supply chain that are downstream and located in small cites. We also find that firms mainly use reactive strategies, instead of proactive strategies, to manage risks. We document that the downstream firms that do use proactive risk-management strategies set higher inventory targets and hold more inventory than firms that only use reactive strategies.
*Managerial implications:* Based on the observation that risk differentially burdens downstream firms and those in small cities, we recommend how policy interventions should be targeted and designed to support these firms in the supply chain. Our recommendations are generalizable for the improvement of supply chains on which public and voluntary sector programs rely, allowing them to benefit the poor.



**Key words**: supply chain management, risk management, developing economy, empirical methods


### 1. Introduction

How risks are distributed across firms is a core management concern. Integrating activities (Chandler 1977) and outsourcing activities (Prahalad and Hamel 1990) redistribute risks along a supply chain. Many companies coordinate and manage risks with formal contracts, which redistribute the costs that come

from uncertainty about supply, demand, and production (e.g., Corbett, Zhou, and Tang 2004). How risks are distributed among firms is also a major policy concern. A policymaker's toolbox includes interventions that manage firms' exposures to various risks associated with supply and price volatility, information access and openness of markets (Hood 1986; Vedung 1998). In the agriculture sector, one example of a common, contemporary policy intervention is sharing information with downstream firms about suppliers that provide quality goods (e.g., Barriga and Fiala 2020). By targeting and supporting firms that enable goods to get to vulnerable populations, these policy interventions can help achieve economic and social policy objectives. However, these policy tools prove most useful when the distribution of risk in a supply chain is well understood, so that they may be differentially targeted toward firms in particular echelons and locations.

How, then, are risks distributed across a supply chain in a lower-income country? There is a body of scholarship on how risks are, and should be, distributed in higher-income economies. However, what is known from higher-income economies does not necessarily transfer to lower-income economies, because financial, legal, and built environments differ (for reviews see, e.g., Lee and Tang 2017; Sagasti 1974; Tang 2018). Thus, the existing characterizations of supply chain operations may not apply to the majority of the firms in the world (as noted in Mckenzie and Woodruff 2017). While there will always be uncertainty around supply, production, and demand, the specific types, extents, and impacts of risks may be different in lower-income countries and must be characterized. This study, using a descriptive and empirical research strategy, is a crucial first step in documenting these risks and their allocation. Our intent is to offer a helpful starting point for causal work that aims to explain, and prescriptive work that aims to resolve, differential allocations of risk among firms in such settings.

The arrangement of risk in supply chains has social implications because it influences the affordability and availability of decent quality goods for the poor. In lower-income countries, such as those in West Africa, major structural reforms in the 1980s shifted economic activity into private rather than public supply chains (Gore 2000). This resulted in the creation of private supply chains that serve poorer households with agricultural, food, and even health goods (e.g., Crook and Ayee 2006). Thus, public and voluntary program managers, in attempting to influence affordability and availability of such goods, must rely on private supply chains to do so. The arrangement of risk in these supply chains hence moderates how effectively public and voluntary sector programs reach the poor. Local supply chain issues, like the only retailer in a city lacking working capital to finance inventory, and national disruptions, like the country's railroad closing, affect affordability and availability of goods. Consequently, supply chain coordination has become a necessary aspect of contemporary development programs (de Janvry and Sadoulet 2020).

In Senegal, a country of 16 million in West Africa, the irrigation equipment supply chain is one important example of an essential supply chain managed by the private sector. How and if the irrigation equipment supply chain reaches rural customers determines the effectiveness of Senegalese food security and economic policies. In this study we characterize the distribution of risks in the irrigation equipment supply chain in Senegal by asking a set of fundamental questions:

- *What are the supply chain risks faced by firms and what are their strategies to address those risks?*
- *How do these supply chain risks and strategies vary with location and supply-chain echelon?*
- *To what extent are the inventory practices aligned to these supply chain risks and strategies?*

We inform our hypothesis with insights from social science scholarship on development. A second contribution is to demonstrate how social science field methods apply to the study of supply chains in low income settings.

To explore these questions, we generate firm-level data from a census in the 35 cities that span Senegal's irrigated areas or that are major commercial hubs nearby. Here, a supply chain census refers to attempting to identify and interview the entire population of firms that make up the chain. We interview 60 shop keepers at their firms, asking open-ended questions about risk and risk-management strategies. We broadly define risk for respondents as the "uncertainties" that come from being involved in the irrigation pump and/or pipe business, following Tang (2006). Similarly, we define risk-management strategies as being how a firm manages a risk or its "impacts." We study firms by location and echelon, terms that we discuss in **Section 4**. Broadly, we use location to describe whether a firm is in a big or small city. We use echelon to describe whether the firm is upstream or downstream in the supply chain. The census data lets us tally risks by location and echelon, allowing for relative and absolute comparisons in analysis. Another secondary contribution of this study is demonstrating how census data may be used to more effectively design programs that rely on private supply chains.

The intent of this study is to help fill the gap in understanding about supply chain risk in lower-income economies and, building on that understanding, to offer practical insights for policy makers and program managers on how to manage risk in supply chains that support crucial public and voluntary programs. The Malabo Declaration, the current, common agricultural plan for African economies, finds coordinating commercial activities necessary to facilitate irrigation and "suitable, reliable, and affordable mechanization" for small farmers (NEPAD 2014).

In our results, we document the extent and types of risks in an agricultural supply chain that is made up of small firms. In our discussion, we relate this understanding of risk to two core challenges in public policy—carefully targeting interventions and identifying suitable interventions. Targeting, or selecting who to serve, is a core step in implementing an intervention. In observing that risk varies meaningfully with echelon and location, we propose that these two factors are useful for grouping and targeting firms.

And, given the type and extent of risk, we propose interventions built from concepts in operations management that may be used to address the major risks in the supply chain. Our data and insights are being used by a major farmers association and a national agricultural agency.

In Section 2 we provide background on irrigation equipment supply chains. We show that irrigation equipment supply chains are important to implement food security and economic policies. Understanding the design of these supply chains and their risks is the first step toward improving their effectiveness to distribute goods in support of policies. In Section 3 we introduce the concepts of supply-chain risk and of proactive and reactive risk management. These concepts theoretically inform the study design and data collection that we describe in Section 4. In Section 5 we present the relationships across location and echelon and risks, risk-management strategies, and inventory measures. In Section 6 we report our managerial insights and discuss the relevance to and use by policy makers. We conclude in Section 7.

## 2. Background

Agricultural supply chains in lower-income countries shape the availability of goods to three in four of the world's poor people (The World Bank 2003a:37). These supply chains are made up of the 25-30 million firms in lower-income economies (IFC 2013: 13). These firms distribute agricultural inputs (e.g., seeds) and equipment (e.g., irrigation pump and pipes) that are necessary for rural economies and diets (see for overview, Reardon, Lu, and Zilberman 2019). In Africa, there are 51 million smallholder farmers who rely to varying degrees on agricultural supply chains (Lowder, Skoet, and Raney 2016). Five million of those farmers use one million irrigation pumps to irrigate more than one million hectares (De Fraiture and Giordano 2014). There remain 30 million hectares of irrigable land in Sub-Saharan Africa that is suitable for pump irrigation that are not being irrigated as of 2014 (Xie et al. 2014). Hence there are clear social and commercial interests in expanding the reach of these private supply chains.

### 2.1 Irrigation in Senegal

Farmers in Senegal have practiced surface-water irrigation alongside Senegal's extensive river network for hundreds, if not thousands, of years. Irrigation is essential in Senegal because rainfall in the Sahel is unpredictable. As irrigation practices evolved to include pumping and piping water, the Senegalese government began in the 1960s to distribute large pumps and pipes to farmers and their associations (Ndiaye 2013:116). The flow and then ebb of the government in the irrigation equipment supply chain are consistent with the evolving role that many African governments played in agricultural supply chains in the 1970s through 1990s (Kherallah et al. 2000). Starting in 1984, as a result of economic reforms, the government reduced its role in the supply chain (Ndiaye 2013:45). Distributing equipment was left to private firms and running and maintaining the pumps was left to farmers' associations. From the 1980s through the 1990s, the amount of irrigated land remained unchanged at

about 0.07 hectares (FAO 2019). As of 2016, an estimated 0.10-0.12 million hectares are irrigated in Senegal, out of 0.40 million irrigable hectares (FAO 2016, 2019).

Currently, the irrigation equipment supply chain in Senegal consists primarily of private firms. The government does some limited distribution of irrigation equipment, giving or loaning pumps and pipes to farmers (Ndiaye 2013:139). In addition, the government, along with non-governmental organizations, provides grants and loans to some farmers and their associations to buy equipment.

Shifts on the supply and demand sides of agriculture markets in the 2000s and 2010s re-primed irrigation equipment supply chains in lower-income economies and in Senegal in particular. On the supply side, global supply chains extended into lower-income economies. In particular, Chinese- and Indian-produced gasoline-powered pumps became affordable for small firms to import and sell, and for institutions and individual farmers to buy (De Fraiture and Giordano 2014).

On the demand side, four factors primed the market. First, international development policy refocused on agriculture sector growth, a component of which is irrigated farming (The World Bank 2008). As an example, irrigation is necessary for programs, such as farmer credit initiatives, to be effective (Hanjra, Ferede, and Gutta 2009; Nakano and Magezi 2020). Second, global food prices spiked, prompting countries to try to produce enough crops domestically to achieve self-sufficiency. Senegal added a second, irrigated rice growing season, though with limited benefits for national food security (Van Oort et al. 2015). Third, international and local demand has spurred vegetable production, which is often irrigated at larger scales in Senegal (Van den Broeck, Van Hoyweghen, and Maertens 2018). Fourth, rain in the Sahel is expected to become more unpredictable with climate change, making irrigation a necessary part of climate-sensitive agricultural policy (Burney and Naylor 2012). Given the promise of irrigation, a pressing matter is how public and voluntary programs can target and support particular firms.

**2.2 Irrigation equipment distribution and use**

The irrigation equipment supply chain is not well understood as it differs across countries and continues to evolve over time. In general the irrigation supply chain is made up of private firms operating with commercial purposes and limited intervention by the public and voluntary agencies. For this reason, it is a useful point of entry to study commercial risk in a lower-income economy. Colenbrander and van Koppen's (2013) landmark survey of 21 pump retailers in Zambia documents one supply chain. In this instance, importers in a national capital procure pumps from off shore manufacturers, typically from Asia (De Fraiture and Giordano 2014), and then serve as distributors for a few rural retailers (Colenbrander and van Koppen 2013). These firms sell pumps that are often of poor quality and offer limited after-sales services such as repairs (Giordano and de Fraiture 2014). The end-customers include farmers, their associations, and institutional buyers that loan, sell, or give equipment to farmers. The structure of the

Zambia supply chain is generally consistent with what we describe in **Section 5**, though we do find substantial supply chain activity in other big and even smaller cities besides the capital.

In contrast, the use of irrigation equipment is better understood than its supply chain. Most irrigation comes from surface water (Camara and Sally 2010). Mechanically, irrigation from surface water in Sub-Saharan Africa entails moving water from low-lying rivers to farmers' fields by pumping it through pipes. Depending on the scale of the irrigation system, the water is moved through pipes into secondary canals, tertiary canals, or right onto crops. In Senegal, irrigation is from surface water and is found throughout the irrigable areas, though is less prevalent in poorer areas (SE-CNSA 2015). Starting in the 1980s, across Africa farmers and farmer associations operate the equipment and are often responsible for contracting repairs and maintenance to private firms (Woodhouse et al. 2017).

## 3. Framing and Hypotheses

How risk is allocated across firms in a supply chain is a longstanding area of interest in operations management in the contexts of sourcing, production, and distribution. Supply-chain risk is important to understand and manage because it shapes the performance and effectiveness of a supply chain.

*Risk is central to operations problems.* We categorize risks as operational, reputational, contractual, and disruptive. Operational risk is defined by Tang (2006) as the 'inherent uncertainties' around demand, supply, and production in a supply chain (e.g., Bowden 1995; Calvo and Martínez-De-Albéniz 2016; Jiang, Baker, and Frazier 2009). It can be managed through coordination mechanisms such as contracts (e.g., Cachon 2004). Reputational risk is possible damage to brand and relationships (e.g., Chen and Lee 2017; Knittel and Stango 2014). Contractual risk is the uncertainty about agreements related to demand, supply, and production being appropriately executed (e.g., Aral, Bakos, and Brynjolfsson 2018; Shou, Zheng, and Zhu 2016). Disruptive risk, in contrast to operational risk, is the uncertainty of large events impacting demand, supply, and production (e.g., Dong and Tomlin 2012; Knemeyer, Zinn, and Eroglu 2009).

Operations management research in lower-income economies mainly examines two types of risk. First, there are contractual risks such as those identified in Shou et al. (2016) and Wang et al. (2016). Second, there are operational risks identified in Mitra et al. (2015), such as uncertain quality (e.g., Amoako-Gyampah and Boye 2001), demand (e.g., Castañeda, Brennan, and Goentzel 2019), and supply (e.g., Gui, Tang, and Yin 2019; Iyer and Palsule-Desai 2019). These risks are empirically examined in the context of production (i.e., Amoako-Gyampah and Boye 2001; Castañeda et al. 2019; Sreedevi and Saranga 2017), or with respect to emerging markets such as those of China and India (i.e., Dong, Ju, and Fang 2016; Iyer and Palsule-Desai 2019; Shou et al. 2016; Sreedevi and Saranga 2017; Wang et al. 2016). In this study we examine risks that small wholesale and retail firms face in an African market, and hence

address a wide contextual gap in scholarship on the 3.5-4.3 million (IFC 2013:13) firms in some of the fastest growing economies globally (Naidoo and Wallace 2019). There are two adjacent areas of scholarship. One examines the price, information, production, and supply uncertainty on small farms, a common form of enterprise in lower-income economies (e.g., An, Cho, and Tang 2015; Gupta et al. 2017; Tang, Wang, and Zhao 2015). The other examines the risks to big firms sourcing and selling to smaller firms or to the poor, which entails supply uncertainty as well as reputational and quality risks (e.g., Chen and Lee 2017; Chen, Shanthikumar, and Shen 2013).

Our core hypothesis about risk is that there is more risk downstream and in small cities. In general, the extent and types of risk vary with echelons (e.g., Osadchiy, Gaur, and Seshadri 2011). Likewise, risk varies with location (e.g., Gray, Roth, and Leiblein 2011). Our hypothesis reflects the notion that downstream and small-city activities are likely to occur amid different and riskier financial, legal, and built environments. This notion is consistent with the observations in development studies that the provision of goods and services from public organizations in rural environments is different among lower levels of government (Pepinsky, Pierskalla, and Sacks 2017) and is challenging (Brinkerhoff, Wetterberg, and Wibbels 2018; Kosec and Wantchekon 2020). In fact, these differences motivate an active area of scholarship on rural bureaucracies, voluntary organizations, and, where those fail to provide, informal groups (e.g., Grindle 2007; Tsai 2007; Watkins, Swidler, and Hannan 2012). It makes a similar broad observation about the rural environment with respect to firms (Herbst 2000; Poulton, Kydd, and Dorward 2006). At the center of our hypothesis is the notion that location and echelon determine the extent and type of risk.

*Risk-management strategies address risk.* Firms can manage risk proactively or reactively. Proactive management means addressing a risk before it occurs (e.g., Knemeyer et al. 2009). Reactive management means responding to a realized risk (e.g., Thun and Hoenig 2011). Both types of strategies affect demand, supply and/or information, through mechanisms such as better tracking of information or sharing the burden of uncertainty with others in the chain, in order to manage risk (Tang 2006). In this study we document the variation in and type of risk-management strategies across the supply chain.

Our core hypothesis about risk-management is that reactive strategies are more common than proactive risk-management strategies along the supply chain and in particular for downstream and small-city activities. Most major strategies for managing risk entail "coordinating" the chain (Tang 2006). Proactive risk-management strategies in particular tend to require coordination with suppliers or with customers (e.g., Krause 1999). Our hypothesis reflects the notion that coordination between supply chain partners, and in particular for downstream and small-city activities, is likely more difficult and so less common. Motivating this hypothesis is a long-standing question of interest in development studies about the extent to which bureaucrats effectively coordinate the distribution goods and services across main-

and sub-offices, which are usually located in large and small cities, respectively. This question was posed in The World Bank's (2003) Annual Development Report. Since then scholarship has observed that coordination (e.g., ensuring accountability and enforcing rules) often prove difficult across distance. At the center of this hypothesis is the notion that location and echelon drive the extent and type of strategies.

*Inventory practices reflect, among other operational considerations, risk exposure.* Inventory practices can offset risks such as uncertainty with supply (e.g., Ancarani, Di Mauro, and D'Urso 2013) and demand (e.g., Pinçe and Dekker 2011; Song and Zipkin 1996). Inventory practices, however, can also expose firms to risk. Hence we study inventory practices to illustrate one way that risk affects operations and how much inventory is available. We specifically examine the extent to which the inventory-on-hand matches the desired (or target) inventory on-hand.

Our core hypothesis is with regard to the association between risk exposure and inventory practices. In particular, we hypothesize that a proactive risk-management strategy does better than a reactive strategy at helping a firm to control its inventory and meet desired (target) levels. Our hypothesis reflects a notion that the effectiveness of inventory control, as a risk management strategy, varies with echelon and location. Supporting this hypothesis is the insight from development studies that bureaucrats from small offices in small cities struggle to meet their service targets (Tummers et al. 2015). In response, some of these bureaucrats develop strategies to overcome constraints and achieve their service targets (Maynard-Moody and Musheno 2000).

**4. Design and Analysis**

We conduct a supply chain census to generate firm-level data across the supply chain. Firm-level census data is used in some areas in management science and related ones in economics, and is usually collected by public agencies. Sometimes, when a census is not possible or necessary, stratified surveys are used. Firm-level data is often used to answer firm location, productivity, and turnover questions in developed economies and emerging economies such as those of China and India (e.g., Alcácer and Delgado 2016; Bloom and Reenen 2007; Foster, Haltiwanger, and Syverson 2008; Hsieh and Klenow 2009). Some major studies, many run by the World Bank, collect their own firm-level data in lower-income economies. They use stratified surveys and tend to focus on manufacturing and services firms (The World Bank 2009). A growing area of management science research uses convenience samples to generate firm-level data. These studies use data in which firms are recruited through opportunities such as business plan competitions (e.g., Mckenzie and Woodruff 2017). These firms are often upstream, in manufacturing and services (e.g., Amoako-Gyampah et al. 2019; Amoako-Gyampah and Boye 2001; Mckenzie and Woodruff 2017; Shou et al. 2016; Wang et al. 2016).

What is distinctive about our firm-level data-collection strategy is that it is a census of the entire supply chain. Census data let us fundamentally and with a degree of generality illustrate aspects of how a supply chain works in a lower-income economy. Given that most supply chain scholarship on lower-income nations has focused on the emerging economies of China and India, we select Senegal as an example of a medium-sized lower-income economy. Senegal's economy is structurally similar to that of many of the other 46 least developed countries in the world (UNCDP 2018). We interview firms along the supply chain instead of focusing on a particular echelon, such as manufacturing, and at many locations instead of focusing on one, such as the capital. Doing so brings into focus distribution and retail at the rural tails of the supply chain. Crucially, we aim to interview all firms in the population instead of using a convenience sample. Convenience samples can have limited external validity, even if they offer internal validity (McCutcheon and Meredith 1993).

To design the study, and specifically set effective protocols for city selection and firm recruitment, we held 16 unstructured interviews with stakeholders in the agricultural sector (e.g., think tanks, universities, importing firms, national agencies, farmers associations). These conversations let us better understand the challenges of and operations in the supply chain.

**4.1 City Selection**

The main effort in designing the census is identifying the relevant cities to canvas. In identifying cities that reasonably host the firms of interest, we use the administrative divisions of the Senegalese public sector to guide us because they demarcate where irrigation and commerce occur. Thus we:

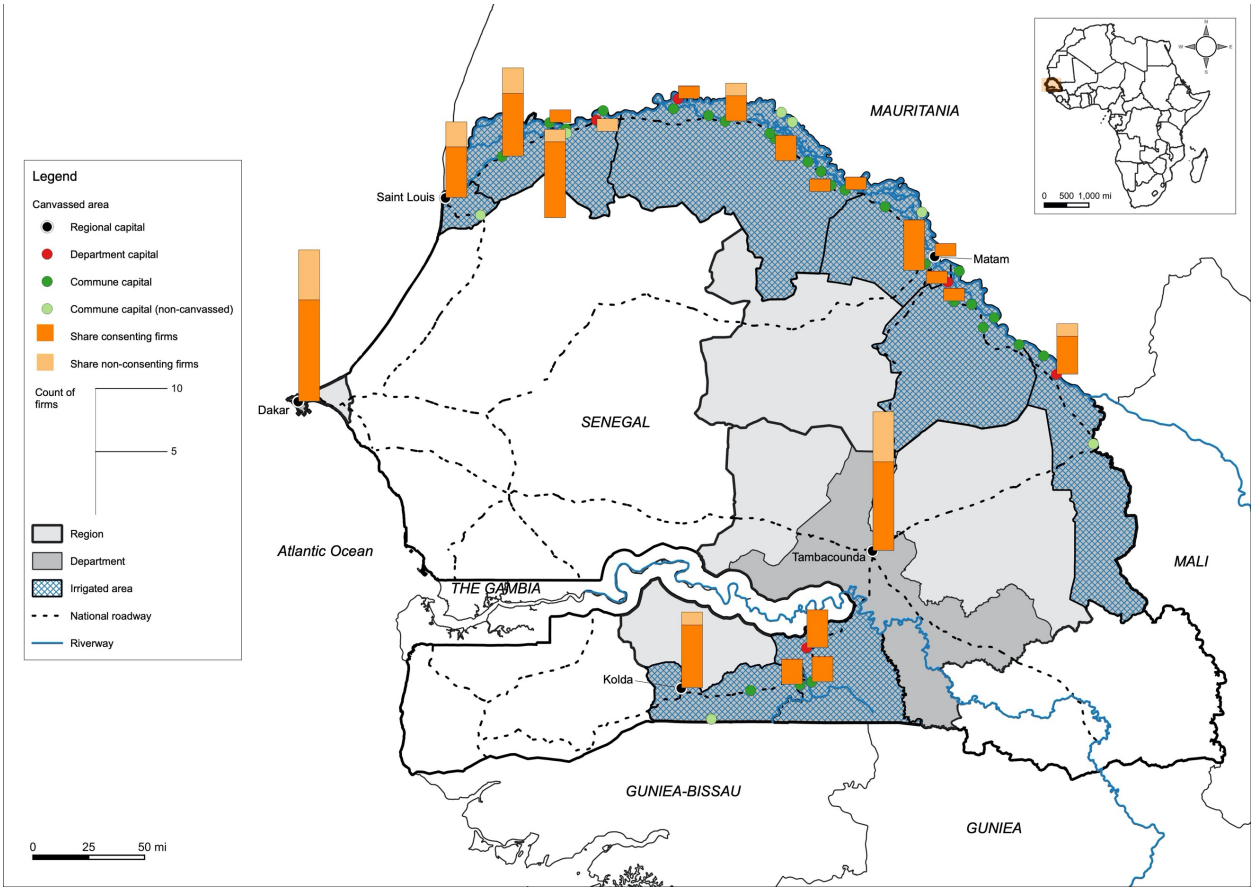
1. *Consider the irrigated areas:* We consider the two main areas where there is surface-water irrigation. Each area is managed by a national irrigation agency. One area is the Senegal River Basin, which runs 720 kilometers through the North and East. The other is the Anambé River Basin in the South. These areas are where 78 percent of rice and 43 percent of all cereals are produced (ANSD 2017). The South is historically more poor (WFP 2018).
2. *Identify cities in irrigated areas*: We identify cities in the irrigated areas. Patterns of commerce reflect jurisdictions in public administration. In general, cities that have bigger markets are regional capitals while those that have smaller markets are departmental and commune capitals. Those that are not administrative capitals tend to have very small or no markets. We canvas 33 cities in these two areas. We select these cities because they are commune, department, or region capitals. These are the cities where commerce occurs. We initially had identified 42 cities. We removed five cities that are not reasonably accessible from the irrigated areas (i.e., a day's travel). We excluded four additional (small) cities that were too difficult to access.
3. *Add national and regional cities that are 'upstream'*: We add two cities in the design because they are major commercial hubs. First, we add the national capital. Its firms mainly serve downstream firms

across the country and in particular in the North and East. Second, we add Tambacounda, which is a regional capital. Its firms mainly serve downstream firms in the South and East. Tambacounda is on the main National Road that leads to both irrigated areas.

This process produces a final design of 35 cities, which is presented in **Figure 1** along with counts of the number of firms recruited in each city.

Based on the above criteria, the cities included are mostly small. The population of the cities at the top of the first and third quartiles are 6,100 and 17,600 residents, respectively. The smallest city has 2,700 residents. The five most populous cities have more than 50,000 residents. The share of population living in urban areas in the four canvased regions (excluding the Dakar Region) is between 24 and 48 percent.

**Figure 1: Cities Selected and Firms Recruited**




## 4.2 Commercial Quarter Identification, Firm Approach and Recruitment, and Questionnaire Administration

In the field, the research team is made up of two researchers each paired with an enumerator. Upon arriving in each city, the team first identifies the commercial neighborhoods; second, the team approaches firms that fit the criteria for possibly selling pumps and/or pipes; third, it recruits firms that are found to be selling pumps and/or pipes; and fourth, it administers the questionnaire to the recruited

firms that consent to be interviewed. The main effort in administering the census is identifying all the neighborhoods in the cities to canvas and then firms within those neighborhoods to approach, recruit, and interview.

First, in each city, the team finds commercial neighborhoods. These are the neighborhoods that can reasonably be expected to host the firms of interest. (Our approach is different in Dakar. In Dakar, we canvas the five main commercial neighborhoods.) In finding those neighborhoods the team uses criteria, which usually overlap, that indicate where commerce occurs:

- The city's major paved and unpaved roads.
- The city's market(s).
- The religious and civic center(s) of town, e.g., the *grande mosque* and mayor's office.

Second, in each commercial quarter, the team approaches three types of enterprises with a storefront. These enterprises, which we call "firms," can be reasonably expected to sell pumps and/or pipes:

- Agricultural firms that sell seeds, fertilizer, pesticides, etc.
- Machining firms that sell and repair agricultural and non-agricultural equipment
- Hardware firms that sell machines and sometimes electronics.

The team approaches these firms based on their names, signs and advertisements, and products on display, being repaired, or in stock and visible. See **Figure 2** for typical examples of the firms.

We determine from piloting the questionnaire in three cities in January and June 2018 that firms that sell pumps and pipes almost always are in those neighborhoods and have those features. For completeness, the team asks each firm if there are other firms in the city that should be interviewed (Szajnfarber and Gralla 2017). From the response, the team rarely identifies additional firms that had not already been interviewed or were not already on the list to be interviewed. In other words, visually identifying firms in these neighborhoods seems to effectively lead the team to interview the population of firms in each city, because 'snowball' identification (i.e., asking one firm to help us identify others) very rarely pointed the team to firms of which they were unaware. The number of firms that the team approaches but do not recruit (as it turns out those firms do not sell pumps and/or pipes) is several times the number that the team approaches and recruits (as they do sell pumps and/or pipes).

Third, among the approached firms, the team identifies 77 firms that do sell pumps and/or pipes, and are recruited to be interviewed. The interviewee must have knowledge of the firm's operations but not necessarily the firm's financials (e.g., margins).

Fourth, 60 of the 77 recruited firms consent to the interview. Thus we work with a dataset of 60 consenting firms. Firms consent at comparable rates across cities, with the exception of the two major commercial hubs, Dakar and Tambacounda, where about half of all the declined interviews occurred.

The interview includes 69 questions. It is available in **Supplement Table S1**. It focuses on the 'middle range' pump and/or pipe in terms of price. It covers the firm's products; its customers, suppliers, and partners (e.g., the government); its ordering and stocking practices; and its risks and risk-management strategies. We ask open-ended questions about risks and risk-management strategies, offering definitions (Schaeffer and Presser 2003) and clarifications (Singleton and Straits 2009). Our research interests do not require asking questions about their core business model (e.g., profit), which can lead to distrust or apprehension (Leech 2002). Those questions would also require that we speak to somebody with deep knowledge of the firms' financials, which is sometimes not possible. We sequence our questions to avoid giving any impression that we also want to buy equipment (Leech 2002), which was an issue in piloting.

The interview takes 30-45 minutes to complete, including interruptions as respondents serve customers. The interviews are administered in French, Wolof, or Pulaar by the researchers and translators. All answers are recorded on *Qualtrics*, an electronic platform. Open-ended answers are recorded in *Qualtrics* in short-hand, edited after the interview, and coded after fieldwork by three researchers. 1.4 percent of answers are missing; 0.9 percent were declined; and 0.7 percent could not be answered.

**Figure 2: Firms Selling Irrigation Equipment Recruited**


Agriculture shop Machining shop Hardware shop

### 4.3 Variables

*Independent Variables*

Through *firm location* we study how the spatial position of a firm is associated with a firm's risk exposure and risk-management strategies. The size of the city is one important dimension of location. We obtain city size from the 2016 population census (ANSD 2016). In Senegal, small cities are situated in sprawling rural areas and big cities, by definition, make up peri-urban and urban areas. We define big cities as those with more than 50,000 residents. City size follows a power law distribution in Senegal, and the cutoff of 50,000 is a reasonable differentiator between the few big and many small cities.

Through *supply-chain echelon*, we study how economic position in the supply chain is associated with a firm's risk exposure and risk-management strategies. For the supply-chain echelon we designate

each firm as being upstream or downstream in the supply chain. Upstream firms source equipment from a domestic or foreign manufacturer or foreign exporter. Downstream firms source equipment from a domestic importer or wholesaler. An alternative way to partition the firms into echelons could be by their customers instead of suppliers. For example, we might partition the firms based on upstream firms selling to downstream firms and downstream firms selling to farmers and their associations. One feature of this supply chain, however, appears to be that half of the firms sell equipment to other firms but not exclusively, and all firms sell some of their product direct to famers. The supply chain thus is not cleanly partitionable into echelons by customer (which is indirectly noted in Colenbrander and van Koppen 2013). We expand on this observation in **Section 4.4.**

*Dependent Variables*

We define *risks* to be the uncertainties that can arise from being in the pump and/or pipe business. We then ask the respondents to cite any risks that they face: operational, reputational, contractual, disruptive, or another type. We prompt the respondent that a risk and a problem are different, i.e., a risk can be well managed and so need not also be a problem.

We define *strategies* to manage risks as how the firm addresses a risk or its impacts. After providing this definition, we let respondents cite their strategies. After the interview we categorize those strategies as proactive or reactive.

We define *target-inventory on-hand* to be the desired, average amount of inventory to have on-hand on any day. We prompt the respondent that target-inventory is how much would be 'good' in general to have on-hand. If needed, we clarify that target-inventory is not necessarily an order-up-to quantity, nor is it just a safety stock level. We define *inventory on-hand* as the amount on-hand that day.

*Unit of Analysis*

Our main unit of analysis is an *activity*. In this supply chain, there are two types of activities. One activity is sourcing, stocking, and selling pumps; the other activity is sourcing, stocking, and selling pipes. Each firm either performs two activities (source, stock, and sell both pumps and pipes), or does one activity (source, stock, and sell either pumps or pipes, but not both). Activities have risks for which there are risk-management strategies. An activity is a useful unit since it lets us study risks and strategies across both types of equipment in analysis. An alternative unit of analysis is the firm. While intuitive, using the firm as the unit of analysis offers no clean way to presents results for the nearly one in two firms that do both activities. A limited analysis by firm is available from the authors upon request.

**4.4 Population for Analysis**

*Firm characteristics*

- *Firm type*: The 60 firms in the population for analysis are primarily hardware stores. In the population, 38 firms sell pumps; 49 firms sell pipes; and 27 firms sell both.

- *Firm staff, ownership, and history*: The median number of employees per firm is three. 80 percent of firms have six or fewer employees. Almost all firms are Senegalese-owned. Approximately half of the managers identify with a generally urban and coastal ethnic group, and the others identify with an inland ethnic group. The median age of the firm is 12 years.
- *Firm ethos*: 28 percent of the firms provide some advice about irrigation practices and 13 percent of firms work with the government in some way (e.g., doing pump demonstrations for farmers). The majority of firms do not do provide these services, identifying 'only' as 'commerçants' or 'traders'.
- *Firm inventory:* The median number of pumps on-hand is one and the median value of pump inventory-on-hand is $408. The median number of pipes eaches on-hand is 4.2 and the median value of on-hand pipe inventory is $90. We treat 10m of pipe as an each because a pump requires about 10m of pipe to move water over the canal or river embankment. (Recall, we focus the interview on the 'middle range' pump and/or pipe.)

*Network characteristics*

- *Firms:* There are 60 firms in the population for analysis.
- *Locations of firms:* The firms are concentrated in big cities. Exactly half the firms are located in the five largest cities in the census (Dakar, Tambacounda, and three others). The other half of the firms are located in 15 small cities. The remaining 15 small cities have no firms.
- *Locations of suppliers*: One in four suppliers for activities are international. International suppliers are split with one third in China; one third in Europe; and one third elsewhere, such as the UAE. Three in four suppliers are based in Senegal. About 90 percent of domestic suppliers are based in Dakar. These suppliers are pipe manufacturers in Dakar's industrial zones and pump and pipe distributors in Dakar's commercial zones. There are no domestic pump manufacturers. The other 10 percent of domestic suppliers are based in four other cities, three of which we canvas (as discussed in **4.5 Design Assumptions**).
- *Suppliers:* In the network there are 80 activities. Of these, there are 31 upstream activities with the suppliers being international exporters or domestic or international manufacturers. And there are 49 downstream activities with upstream suppliers in Senegal.
- *Customers:* The firms sit along a spectrum from B2B to B2C. Half of the firms do some B2B sales, selling equipment to other firms. However, all firms sell directly to farmers and two in three firms sell to farmers' associations. Fifteen percent of the firms sell to institutional customers, i.e., non-governmental organizations and the government.
- *Network inventory:* Inventory amounts, values, and turns in the network by echelon and location are described in **Table 1.** The first set of columns in the table is the count of pump and pipe eaches on-hand for an echelon and location, e.g., there are 46 pumps on-hand at downstream firms in big cities.

The second set of columns is the sum of the value of pump units or pipe eaches on-hand for an echelon and location. The third set of columns is an estimate of inventory turns per year for an echelon and location.

**Table 1: Inventory Amount, Value, and Turns**

| | | Inventory-on-hand (Sum) | | Value-on-hand (USD) (Sum) | | Inventory Turns (Ratio) | |
|---|---|---|---|---|---|---|---|
| | | Echelon | | Echelon | | Echelon | |
| | Location | Downstream | Upstream | Downstream | Upstream | Downstream | Upstream |
| Pumps | Big | 46 | 21 | 14,348 | 18,275 | 1.5 | 4 |
| | Small | 48 | 0 | 67,652 | 0 | 1.8 | - |
| Pipes | Big | 87 | 162 | 1,938 | 6,687 | 1.5 | 0.7 |
| | Small | 195 | 62 | 4,499 | 1,496 | 0.8 | 1.1 |

**Note** (inventory): Pumps are counted in units at each location-echelon; pipes are counted in eaches of 10m at each location-echelon. An each is a bundle of saleable units.
**Note** (echelon): Values counted in USD at each location-echelon.
**Note** (turns): To estimate demand for equipment we use custom tables from the 2018 restricted-use Senegalese agricultural census data (ANSD 2018). There are 76,124 farming households in the two irrigated areas of interest and of those about 1 percent use a motor pump.
Pumps break after 2-4 years so on average there is replacement demand of 234 pumps per year. New demand, assuming the market is growing at 4 percent on 703 households, could be an additional 28 pumps per year. Total yearly demand would be 262 pumps. With demand evenly spread across the pump activities reported by echelon-location in Table 2 would mean on average 7 pumps sold per year per firm.
Pipes break after 1-2 years so on average there is replacement demand of 486 pipe eaches per year. New demand, assuming the market is growing at 4 percent on 703 households, could be an additional 28 pipe eaches per year. Total yearly demand would be 514 pipe eaches. With demand evenly spread across the pipe activities reported by echelon-location in Table 2 would mean on average 11 pipe eaches sold per year per firm.

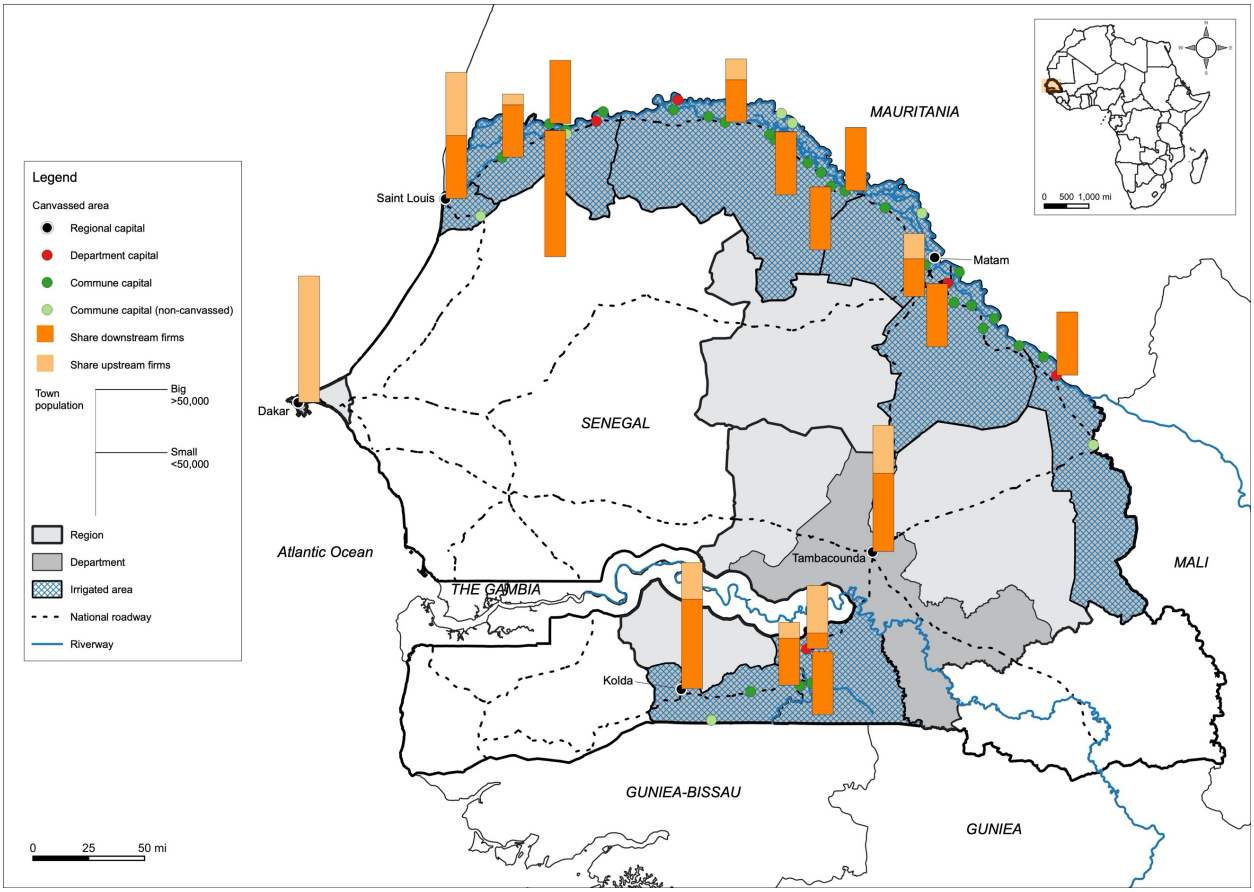
### 4.5 Study assumptions

Our study design rests on two assumptions, which we developed in consultation with a range of stakeholders in the agriculture sector (See **Section 6.3**). First, we assume that we canvas cities that actually host the firms in the supply chain. In other words, that we select cities of the right size and in the right location. With respect to size, we note that just four firms are in the sixteen smallest canvased cities. Hence it would not be fruitful to canvas even smaller cities, and we already canvas all of the big cities. With respect to location, we select all administrative capital cities in irrigated areas and add the big commercial, administrative capitals on National Roads leading to an irrigated area. With hindsight, however, we would have also canvased Touba, a big commercial, administrative capital city that is on a National Road indirectly leading to an irrigated area. It is the only city that we did not canvas but in which firms cite having suppliers (two percent of all domestic suppliers are based there).

Second, we assume that firm recruitment should focus on firms with storefronts, as distribution and retail occurs through firms with storefronts. One check on this assumption is asking in recruitment and during the interview: “Who else sells pumps or pipes around here?” We were almost always pointed to

merchants with storefronts. Another check on this assumption is that we find that 'traveling traders' account for only three percent of all suppliers.

**Figure 3: Locations and Echelons**




## 5. Results

*We show first what types of activities firms do and how they vary by echelon and location.* The counts in **Table 2** are of activities, e.g., there are 10 downstream activities in big cities. There are 80 activities, most of which are downstream activities. There are notably few upstream activities in small cities. The distribution of all activities across locations and echelons is significant. In other words, observing such a severe distribution of activities across location and echelon by chance is negligible.

**Table 2: Activities by Echelon and Location**

| | | Echelon | | |
|---|---|---|---|---|
| Counts | Location | Downstream | Upstream | P-value |
| Activities - Pump | Big | 10 | 12 | 0.033 |
| | Small | 12 | 2 | |
| Activities - Pipe | Big | 12 | 11 | 0.228 |
| | Small | 15 | 6 | |
| Activities - All | Big | 22 | 23 | 0.012 |
| | Small | 27 | 8 | |

**Test**: We use the Fisher Exact Test of Independence. It is a test of association between a discrete factors—location and echelon.

**5.1 Risks**

*First, we illustrate what types of risks firms face.* **Table 3** illustrates the more common risks in the supply chain (i.e., that are present at more than one activity). The counts are of activities for which a risk is present, e.g., the most prevalent risk is present at 32 activities. Firms cite risks specific to each activity, in the interview.

Contractual risk permeates the supply chain as seen in **Table 3**. One type of contractual risk is *nonfeasance*: not taking actions that should be taken. Failing to ensure product quality is a relatively common form of nonfeasance. Another type is *misfeasance*. Misfeasance is taking inappropriate actions that break a contract. Customers not paying back credit lines or suppliers not sending what is ordered can be misfeasance. These risks are less common. A final type is *malfeasance*: taking actions with an intent to harm. Suppliers defrauding firms by taking payment without delivering products or delivering knockoff products are malfeasance. These risks are not common. Our result that contractual risk is important is consistent with recent attention in scholarship (e.g., Shou et al. 2016; Wang et al. 2016). Our results though indicate that less insidious types of contractual risk, nonfeasance and misfeasance, are more common in this context than more insidious types of contractual risk, malfeasance.

Quality risk is also common as seen in **Table 3**. The specific quality risks are products being broken on arrival, during storage, and after selling. Firms must handle the financial, logistical, and reputational impacts of quality risks with suppliers and customers. Our results emphasize that there are three distinct varieties of quality risk in this context. Relatedly, the risk that low quality products pose to farmers is well treated in the development studies literature (e.g., Burney and Naylor 2012). Financial risk is a final, major type of risk.

**Table 3: Risks**

| Risk | Counts | Risk Type |
|---|---|---|
| Customer repayment with credit sales | 32 | Contractual (Misfeasance) |
| Product is broken (on arrival) | 20 | Contractual (Nonfeasance)/Quality |
| Product is broken (after selling) | 18 | Quality |
| Working capital tied in inventory | 11 | Financial |
| Product is broken (during storage) | 5 | Quality |
| Repaying supplier for credit purchases | 5 | Financial |
| Supplier shipment is delayed | 5 | Contractual (Nonfeasance) |
| Product is stolen (during storage) | 4 | Other |
| Supplier defrauds him | 4 | Contractual (Malfeasance) |
| Customer relationship (providing after-sales services) | 3 | Other |
| Product is knockoff | 3 | Contractual (Malfeasance) |
| Supplier sends not what ordered | 3 | Contractual (Misfeasance) |
| Competitors have low quality products | 2 | - |
| National market affected by exchange rate | 2 | Financial |
| Product is stolen (at port) | 2 | Other |
| Supplier stockout | 2 | Other |

**Note**: This set of risks is limited to those that are present at least for two activities. The full set of risks can be found in **Supplement Table S2**.

*Next, we analyze to what extent these risks vary by echelon and location.* There are 23 distinct risks that are present at 128 activities along the supply chain. Each firm faces on average two risks. **Table 4** shows the distribution of risk across locations and echelons. The counts are of activities for which a risk is present, e.g., there are 33 activities for which a risk is present for a downstream activity in a big city.

Risks are comparably distributed across locations—big and small cities. One risk that is an outlier, however, is products failing after selling. This reputational concern is mainly an issue for big-city activities, perhaps where most institutional purchasing, and hence possible reputational damage, occurs.

There are more risks downstream, reflecting the fact that there are more downstream than upstream activities. There are 1.4 times more downstream than upstream risks. One risk that particularly illustrates this pattern is working capital being tied up in inventory. A possible explanation is pooling. Downstream firms pool their demand across fewer customers relative to upstream firms. Pooling across fewer customers produces a less stable demand, which explains why a higher portion of their working capital could be tied up in inventory.

The ratio of risks relative to activities, however, is greater upstream than downstream. The ratio of the risks relative to activities is 1.5 downstream while it is 1.7 upstream. The activities, hence, with the most risk exposure are upstream.

Finally, risk is significantly arrayed across locations and echelons. Observing such a severe distribution of risk across location and echelon by chance is negligible. For example, instances of

customer repayment with credit sales and the product being broken on arrival vary significantly with location and echelon.

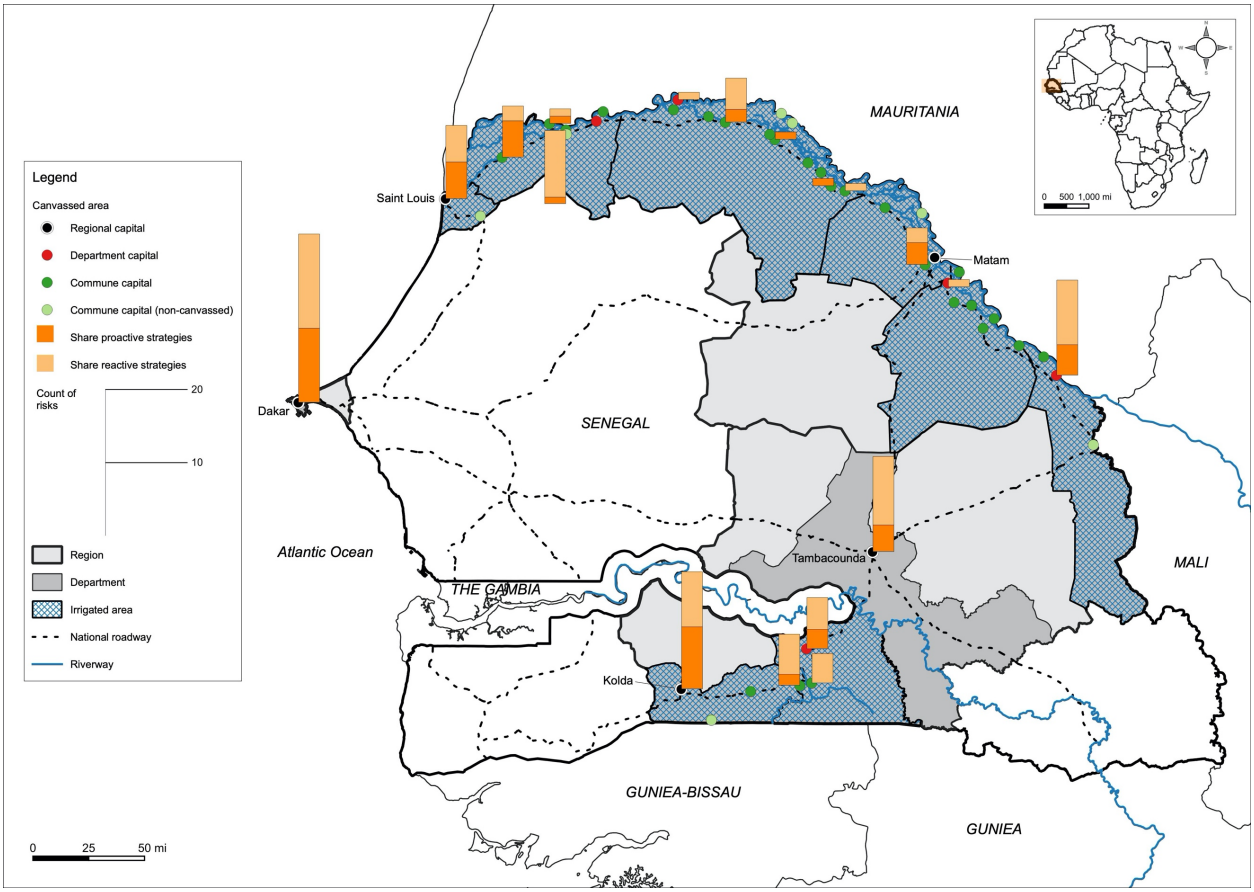
**Table 4: Risks by Echelon and Location**

| | | Echelon | | |
|---|---|---|---|---|
| | Location | Downstream | Upstream | P-value |
| All risks | Big | 33 | 39 | 0.002 |
| | Small | 41 | 15 | |
| Risks – Top four | Big | 21 | 23 | 0.000 |
| | Small | 32 | 5 | |
| Customer repayment with credit sales | Big | 8 | 9 | 0.028 |
| | Small | 13 | 2 | |
| Product is broken (after selling) | Big | 4 | 8 | 0.131 |
| | Small | 5 | 1 | |
| Product is broken (on arrival) | Big | 4 | 6 | 0.057 |
| | Small | 9 | 1 | |
| Working capital tied in inventory | Big | 5 | 0 | 1.000 |
| | Small | 5 | 1 | |
| Ratio of risks to activities | | | | |
| All risks to all activities | Big | 1.5 | 1.7 | |
| | Small | 1.5 | 1.9 | |

**Test**: We use a Fisher Exact Test. We use the Fisher Exact Test of Independence. It is a test of association between a discrete factors—location and echelon.

### 5.2 Risk-management strategies

**Figure 4: Risks and Strategies**




*First, we illustrate what strategies firms use to manage risks.* **Table 5** illustrates the strategies for the four most common risks in the supply chain. The counts are of activities for which a strategy is used, e.g., the strategy of pressuring customers to repay lines of credit is used for 8 activities for which customer repayment is a problem.

Firms heavily rely on reactive strategies for the four most common risks. One explanation for the reliance on reactive strategies is that the firms in this supply chain may not hold bargaining power via-a-vis their suppliers or customers (e.g., Cachon and Laiviere 2005); proactive strategies require some coordination with one's suppliers or customers, and inevitably this requires some negotiation to get an agreement.

The strategies in the supply chain are also generally informal instead of formal. We build this distinction from development studies scholarship on formal and informal goods and services provision (Helmke and Levitsky 2004; Pepinsky et al. 2017; Tsai 2007). We define formal as strategies that are officially authorized and enforceable through contracts, permits, regulations, laws, or policies. We define informal strategies as those that rely on norms, customs, and relations for their authorization and enforcement. Few firms cite the government as a way of enforcing a risk-management strategy. Beyond

strategies relying on the government, we observe creative strategies that rely on cooperation with suppliers, customers, and civic and community actors (e.g., Poulton et al. 2006).

In listing risk management strategies, firms rarely cite inventory management as a strategy, as seen in **Table 5** and **Table A2**. In part, this practice could be due to the type of risks that are present, for which more or less inventory does not directly help.

**Table 5: Strategies by Risk**

| Risk | Strategy | | | |
|---|---|---|---|---|
| | Elaborated | Coded | Coded | Counts |
| Customer repayment with credit sales | Pressure customer | Reactive | Informal | 8 |
| | Limit to whom you sell on credit | Proactive | - | 8 |
| | Pressure customer via local leaders | Reactive | Informal | 3 |
| | Negotiate repayment | Reactive | Informal | 3 |
| | Require a guarantee | Proactive | Formal | 3 |
| | Only sell on credit to projects | Proactive | - | 3 |
| | Report to law | Reactive | Formal | 3 |
| | Require down payment | Proactive | Informal | 2 |
| | No longer sell on credit | Proactive | - | 2 |
| Product is broken (after selling) | Let customer return or exchange product | Reactive | Informal | 8 |
| | Repair product for customer | Reactive | Informal | 6 |
| | Advise farmers on how to use product | Proactive | Informal | 2 |
| | Trial product with customer at sale | Proactive | Informal | 2 |
| Product is broken (on arrival) | Dispose of product | Reactive | - | 6 |
| | Repair product and then sell | Reactive | Informal | 6 |
| | Return product to supplier | Reactive | Informal | 6 |
| | Sell product at loss | Reactive | - | 5 |
| Working capital tied in inventory | Hold product (do not reduce price) | Reactive | Informal | 5 |

**Note**: This set of strategies is those associated with the four most common risks. The full list of strategies is available in **Supplement Table S23** We only code strategies as being formal or informal if they involve a customer or supplier (and/or others).

*Next, we analyze to what extent strategies vary by echelon and location.* There are 50 distinct strategies that are used in response to the 158 risks along the supply chain. Each firm uses on average 2.6 strategies. **Table 6** shows the distribution of these strategies across locations and echelons. The counts are of strategies used for a risk, e.g., there are 40 strategies used for downstream activities in a big city.

The risk management strategy for a particular risk can differ across echelons and/or locations. One risk that shows this pattern is the risk of the product being broken after selling. The risk is experienced at both upstream and downstream activities, yet the nature of the mitigation strategies differ by echelon. For the upstream activities, 75% of the strategies are reactive, compared to 58% for the downstream activities.

Some risks are managed more reactively than other risks, irrespective of location or echelon. One risk that illustrates this point is the product being broken on arrival, for which 27 or 28 of the risk strategies were reactive.

Taken together, for many risks, management strategies are significantly arrayed across echelons and locations, in that observing such a severe distribution of strategies across location and echelon by chance is negligible. For example, instances of strategies to address customer repayment with credit sales and the products being broken vary significantly with echelon and location.

**Table 6: Strategies by Echelon and Location**

| | | | Echelon | | |
|---|---|---|---|---|---|
| | | Type | Downstream | Upstream | P-value |
| All strategies | Big | - | 40 | 47 | 0.000 |
| | Small | - | 51 | 16 | |
| All strategies – Proactive | Big | - | 10 | 24 | 0.007 |
| | Small | - | 16 | 8 | |
| All strategies - Reactive | Big | - | 30 | 23 | 0.015 |
| | Small | - | 35 | 8 | |
| Customer repayment with credit sales | Big | Reactive | 7 | 3 | 0.582 |
| | Small | Reactive | 9 | 1 | |
| | Big | Proactive | 4 | 9 | 0.057 |
| | Small | Proactive | 6 | 1 | |
| Product is broken (after selling) | Big | Reactive | 3 | 8 | 0.106 |
| | Small | Reactive | 4 | 1 | |
| | Big | Proactive | 2 | 3 | 0.196 |
| | Small | Proactive | 3 | 0 | |
| Product is broken (on arrival) | Big | Reactive | 6 | 5 | 0.054 |
| | Small | Reactive | 14 | 1 | |
| | Big | Proactive | 0 | 1 | 1.000 |
| | Small | Proactive | 0 | 0 | |
| Working capital tied in inventory | Big | Reactive | 4 | 0 | 1.000 |
| | Small | Reactive | 4 | 0 | |
| | Big | Proactive | 1 | 0 | 1.000 |
| | Small | Proactive | 1 | 1 | |
| Ratio of strategies to risks | | | | | |
| All strategies to all risks | Big | - | 1.8 | 2.0 | |
| | Small | - | 1.9 | 2.0 | |

**Test**: We use the Fisher Exact Test of Independence. It is a test of association between discrete factors—location and echelon.

### 5.3 Inventory Practices

*Finally, we study inventory on-hand and targets.* In the first two sets of rows in **Table 7** we show the median value of on-hand and target inventory for activities across echelons and locations and with and without any proactive risk management strategy. The next set of rows shows the median ratio of inventory on-hand to the inventory target.

We observe that firms hold substantially less inventory than their target. Using proactive strategies downstream is associated with more inventory being on-hand and with higher targets. The opposite is true for using proactive strategies upstream. Recall that upstream activities are risker than

downstream; one explanation may be that decision makers weigh many versus few risks differently and, even with proactive strategies, react with lower on-hand and target inventory levels.

**Table 7: Inventory Practices**

| | | Echelon | | Echelon: Downstream | | | Echelon: Upstream | | |
|---|---|---|---|---|---|---|---|---|---|
| Median | | Downstream | Upstream | Any Proactive | Only Reactive | P-value | Any Proactive | Only Reactive | P-value |
| On-hand (USD) | | | | | | | | | |
| All Activities | Big | 34 | 393 | 102 | 12 | 0.54 | 64 | 680 | 0.51 |
| | Small | 175 | 51 | 271 | 128 | 0.48 | 26 | NA | - |
| Target (USD) | | | | | | | | | |
| All Activities | Big | 1,530 | 4,250 | 3,485 | 1,190 | 0.35 | 2,401 | 5,772 | 0.06 |
| | Small | 578 | 2,295 | 1,488 | 425 | 0.18 | 2,295 | NA | - |
| Ratio | | | | | | | | | |
| All Activities | Big | 0.05 | 0.12 | 0.15 | 0.00 | 0.63 | 0.03 | 0.50 | 0.69 |
| | Small | 0.39 | 0.03 | 0.28 | 0.39 | 0.69 | 0.03 | - | - |

**Test**: We use a Wilcoxon rank sum test. It tests whether the medians of two distributions are significantly different, given their distributions. We look at the distributions of the on-hand, target, and ratios of on-hand to target inventory.

## 6. Discussion

This discussion proposes policy responses to redistribute activities and the risks among them, presents the operational challenges created by the distribution of activities and risks across the supply chain, and suggests methods necessary to collect data to address these risks.

### 6.1 Policy responses and managerial implications

We review the policy implications of our assessment of risk—for program managers who must identify and support firms and for scholars examining how this support can be made practical and effective.

Who to target with a given policy is a common class of problem for program managers, one that is often considered in the context of determining which individuals are vulnerable and would benefit from the intervention (see for agriculture interventions e.g., Marivoet, Ulimwengu, and Sedano 2019). The Malabo Declaration, for instance, aims to increase "agricultural productivity with social protection initiatives focusing on vulnerable social groups" by "targeting priority geographic areas and community groups for interventions" (NEPAD 2014). Targeting firms is another important context, especially when they distribute essential goods or implement public and voluntary programs. Yet it remains an under-studied variety of targeting. A standard approach to target firms in lower-income economies, e.g., for financing and job-growth interventions, is based on the number of people working in the firms (for a discussion of such interventions, see, e.g., Grimm and Paffhausen 2015).

We argue that targeting firms based on their spatial and economic position in the supply chain, in addition to their workforce, is appropriate for supply chain management interventions. Risk varies meaningfully with location and echelon but not necessarily by the number of employees—almost three in

four firms have four or fewer employees. Program managers can tractably target firms based on echelon and location, which, as we show in this study, are identifiable groupings. To the extent that upstream firms in small cities have more risks per activity than others, these may even be seen as the most 'vulnerable' group of firms, which are worth prioritizing in an intervention.

What intervention to use in a program is another common class of policy problem. Interventions with firms consist of shaping their information and resources and regulating their activities (i.e., Hood 1986; Vedung 1998). A necessary step in program design is finding practical pairings between interventions and risk management principles that are context appropriate. Among interventions, exchanging information and offering modest subsidies are appropriate, as both are consistent with the politics of the contemporary development agenda. Both still entail private firms supplying agricultural goods (e.g., Benson and Mogues 2018; Kelly, Adesina, and Gordon 2003). And both may improve "resilience" in the supply chain (USAID 2018). Among risk management principles, more coordination and specifically proactive risk-management strategies are appropriate, given the extent of risk and firm's reliance on reactive strategies.

We argue that three interventions can help managers of public and voluntary programs address the main risks in the supply chain:

- Public and voluntary agencies can *provide grants or loans* to farmers associations in coordination with the 22 firms with downstream activities in small cities. Doing so could tractably avoid the risk to the retailer of them not repaying lines of credit, the major contractual issue in the supply chain. The non-repayment risk is two times as prevalent downstream than upstream and is a particular issue for downstream activities in small cities. This grant or loan program would shift the risk of repayment issues to the lenders and from the firms. A concern here is that irrigation manages some uncertainty in farming, but loans present new risks to farmers if crop yields fall short (Clapp and Isakson 2018).
- Likewise, these agencies can offer to the 34 firms in big cities the chance to participate in a supplier certification program, a mechanism to *share information* (Chen and Lee 2016 and see specifically for food, Coulter and Onumah, 2002). It could address the most common product quality risks in the supply chain. As the supply chain spans multiple markets in Senegal and abroad, firms source from far-away suppliers selling unreliable equipment. Quality risk is 1.3 times more common in activities in the five big cities than in small cities. A program would entail providing them with information about, and requiring firms to source from, a handful of reliable suppliers (abroad and domestically). It would require providing the 26 firms in smaller cities information on participating firms and, to not advantage firms in big cities, the same information about reliable suppliers. This supplier certification program would provide firms with a proactive risk-management strategy.
- Finally, these agencies can *insure activities* with a buy-back program to address the cash-flow issues at downstream firms, a main financial uncertainty in the supply chain. This program would be modest

and in line with "new" input subsidy programs with "careful targeting" and private partners (Jayne et al. 2018). 90 percent of activities with this risk present are downstream. A buy-back program for the 40 downstream firms could help firms satisfy demand while managing working capital. For instance an agency could buy excess inventory from a downstream firm, recalling that inventory turns are 1 to 2 per year. This program would shift the risk of tied-up working capital away from the downstream firms toward agencies.

These interventions have potential to improve supply chain efficiency. Furthermore, they indicate that complementary policy efforts outside of the supply chain should bolster rural financial institutions, invest in hard infrastructure, develop regional and national legal systems and business networks, and further de-risk farming via-a-vis novel technology packages such as better equipment and planting information.

**6.2 Operational challenges and opportunities**

We present the core operational insights of our analysis—for managers of programs that rely on, and for scholars doing descriptive and prescriptive research on, private supply chains.

*In the supply chain, 75% of upstream activities are in big cities and distribute equipment to downstream activities that are evenly arrayed across small and big cities.* This observation means that efforts to analyze and shape prices and availability in small cities near farmers must acknowledge the reliance of most activities on an upstream supplier that intermediates with an exporter or manufacturer.

*Upstream activities are more risky than downstream activities and buffer downstream activities to an extent from some risk.* Taken with the preceding observation, pricing and availability in intermediated downstream activities must be considered in light of the useful role that upstream intermediaries play in managing and absorbing risk. Relatedly, upstream activities in small cities face 1.3 times more risks per activity than downstream activities. This observation may explain the few upstream activities in small cities: it is possibly too risky a business. How policy can enable upper echelon activities to be competitive in small cities, making available to nearby farmers disintermediated pricing, is a question that we explore in **Section 6.1.**

*Contractual and quality risks permeate the supply chain.* Two core uncertainties in this supply chain are softer contractual risks such as misfeasance and quality risks among small, local firms. Thus far operations scholarship on lower-income economies treats harder contractual risk (e.g., Shou et al. 2016; Wang et al. 2016) and quality risk between international and local firms (Chen and Lee 2017). Development studies scholarship, however, has recently explored quality risk between small, local firms (e.g., Barriga and Fiala 2020).

*We observe a supply chain that is laden with risk and mainly manages risk reactively and informally.* For every proactive strategy used there are 1.7 reactive strategies used in the supply chain. This observation suggests that the principles of risk management in developed economies do not fully apply to

lower-income economies. For example a common risk management strategy in developed economies is an "administratively burden[some]" contract, which requires built and legal environments that permit monitoring and enforcement (Cachon and Lariviere 2005).

*Having proactive risk-management strategies is associated with holding more inventory downstream.* Whether firms with proactive strategies manage inventory closer to targets depends on echelon and location. Having inventory on-hand in local shops is important; Colenbrander and van Koppen (2013) note that traveling to a large city can constitute one third the cost of a pump.

### 6.3 Methodological template

This study provides a template for generating supply chain census data in a lower-income economy—this template may be of use for managers designing programmatic responses to operations challenges and for scholars further characterizing risk and coordination across firms.

Collecting census data is useful in a lower-income economy where public and private data may be fewer, especially among the more informal tails of supply chains. This data then can be used to generate insights with a degree of external validity, which is helpful for informing policy in new contexts (Bloom and Reenen 2007). The challenge, though, in collecting is data is doing so efficiently and effectively, correctly identifying where to recruit firms. We relied on partners in designing the survey, in canvasing, and in validating results. Over the course of the study, we consulted with the two main agricultural agencies, the national university, two farmer associations, a large importing firm, and one think tank. We also had the benefit of the authors having collectivity nearly three years field research experience in Senegal. A result of this partnered and empirical research strategy is that a national agency and a farmers association validated the helpfulness of our insights and data, using them in an irrigation season.

## 7. Conclusion

In this supply chain contractual and quality risks permeate all activities though disproportionality burden upstream activities, especially given the reliance on reactive instead of proactive risk management strategies. In Senegal, as in other lower-income economies, policy reforms in the 1980s shifted supply chain roles and associated risks to private firms from government and voluntary agencies. As a result, a set of private firms appeared for sourcing, stocking, and selling essential goods, connecting suppliers as far away as China and India with downstream retailers in Senegalese cities as small as 4,500 people. But in doing so, these firms have faced a wide range of risks. We present results from a supply chain census of the 60 small firms that make up the Senegalese irrigation equipment supply chain. These firms mainly operate in the 35 cities that span Senegal's irrigated areas. Their most commonly cited risks are defaults or delays in customer loan repayments, sourcing or selling unreliable equipment, and having working capital tied in inventory. These risks are mainly downstream in the supply chain, reflecting where economic activity occurs. Reactive risk-management strategies are the most common across the supply

chain. Downstream firms using a proactive strategy for an activity seem to hold more inventory and to better manage their inventory relative to firms using only reactive strategies. The policy implications of our result are that location and echelon are meaningful groups toward which policies can be differentially targeted and that operations concepts, such as information sharing and buy-back contracts, can be used to build policy interventions that that aim to make more even allocations of risk in the supply chain.

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# Chapter 4

## In Harm's Way? The Effect of Disasters on the Magnitude and Location of Low-Income Housing Tax Credit Allocations

**Abstract**

This paper analyzes the effect of disasters on affordable housing construction. Exploiting the exogenous timing of flooding disasters and 25 years of housing data, we derive causal estimates of the effect of disasters on county-level Low-Income Housing Tax Credit (LIHTC) allocations nationwide. We find that states respond to flooding disasters by increasing the number of LIHTC units allocated to a disaster-struck county by 73 percent in the year after the disaster, compared to other years. We suggest that this increased allocation of LIHTC units is indicative of a process of institutional or policy conversion, in which states are repurposing the three-decade old housing tax credit program to meet disaster assistance and recovery needs. These additional LIHTC units can meet the pressing needs of disaster survivors for affordable rental housing, but, given that the program was not designed with disasters in mind, do the new units ameliorate or exacerbate renter's exposure to disaster risk? To answer this question, we analyze whether these post-disaster LIHTC allocations are more or less likely to be located in the floodplain than pre-disaster LIHTC allocations in that county. Results indicate that, after a disaster, more units are allocated both inside and outside of the floodplain relative to prior years. On an absolute level, the average number of units allocated outside of the 500-year floodplain in a disaster-struck county increases more than the average number inside the floodplain. The relative increase in units after a disaster, however, is larger in the floodplain than outside of the floodplain, relative to other years. Results are robust to an array of alternative specifications and assumptions about the sample. The findings highlight the tension between supporting the recovery of disaster-struck low-income residents in their existing communities and encouraging rebuilding outside of floodplains.

### 1. Introduction

Recent hurricanes, floods, and wildfires have highlighted the devastating effect of disasters on individuals and communities, as well as the importance of programs to meet survivors' housing needs in the short and the long term. Disasters disproportionately affect low-income households and renters, yet existing federal and state disaster assistance disproportionately benefits homeowners (Fothergill and Peek 2004; Furman Center 2017a, 2017b; GAO 2009; Howell and Elliott 2019; Lee and Van Zandt 2019). In 2015-2017, 324,000 renters were displaced by natural disasters and more than 500,000 units of rental

stock required disaster-related repairs (JCHS 2020). When low-income units are damaged or destroyed, it raises two crucial policy questions. First, how, if at all, do state governments facilitate the rebuilding of affordable rental housing inventories after disasters? Second, to what extent does rebuilding occur in disaster prone areas, such as floodplains, versus less hazardous areas?

Congress has given the Federal Emergency Management Agency (FEMA) the power to provide financial assistance for the first 18 months after a disaster so that affected households can rent alternate housing accommodations and so that homeowners can repair their homes. In some cases, FEMA can also temporarily lease units for occupancy by disaster survivors. After 18 months, however, FEMA's authorization to provide housing aid ends. Further assistance depends on, first, whether Congress appropriates funding for a Community Development Block Grant Disaster Recovery and, second, if such funding is appropriated, how the state or territory decides to use those resources. Generally, the bulk of the funding is used to support homeowners' repairs, leaving affected renters with few options and an increased likelihood of outmigration (Government Accountability Office, 2010; Elliott, 2015).

The main federal program to support the construction of affordable rental housing is the Low-Income Housing Tax Credit (LIHTC) program (McClure 2008). Congress included the LIHTC provisions in the Tax Reform Act of 1986 in order to leverage federal tax credits for private investment in the construction of affordable housing. More than 3 million subsidized housing units have been placed in service through the LIHTC program since 1987. Each year, the Department of the Treasury transfers approximately $9 billion worth of tax credits to states and territories, each of which develops an allocation plan that outlines the criteria by which the state will distribute the credits among projects proposed by developers (Ellen, Horn, and Kuai 2018).

To what extent do states turn to the LIHTC program to address disaster recovery needs in addition to the affordable housing production objectives it was originally designed to serve? In this paper, we assemble a panel dataset on LIHTC unit allocations, disasters, and the social and built environment for all U.S. counties between 1990 and 2015. To characterize the effect of disasters on LIHTC unit allocations, we specify a distributive lag model. We exploit the exogenous timing of disasters to interpret our results causally.

Our results indicate that LIHTC is a powerful tool for state policymakers to intervene in housing markets after disasters in order to catalyze recovery. First, we establish the extent and timing of LIHTC unit allocations relative to disasters. Specifically, we estimate the effect of a severe disaster in a county on allocations of LIHTC units in the following years. We find that, on average, a severe disaster leads to 22 units allocated in the year following a disaster. This result is significant and substantial. The median county by total units has on average 30 units allocated annually, so the disaster represents a 73 percentage average increase. Next, we focus on where within disaster-affected counties relative to floodplains these

LIHTC unit allocations occur. We find that severe floods in a county drive fourfold more allocations outside of 500-year floodplains than inside 500-year floodplains. Nevertheless, states allocate 1.65 times more units in the floodplain after a disaster relative to units allocated to the floodplain in other years, compared to 1.14 times more units outside of the floodplain relative to out-of-floodplain units in other years. These findings highlight the tensions between investing in housing production to help communities rebuild and recover in place and investing in housing production that can help households move out of the floodplain.

These insights into American disaster-housing policy contribute to two lines of scholarship. First, a central empirical matter in policy analysis is how public programs support vulnerable groups through societal shocks (Bitler, Hoynes, and Kuka 2017; Klerman and Danielson 2011). This question is timely given the disasters, pandemics, and recessions in the past decade, which have disproportionately negatively impacted low- and moderate-income households. By showing when, where, and the extent to which LIHTC unit allocations respond to disasters, we provide evidence on how a broader social safety net program responds to disaster specific shocks.

Second, a central theoretical interest in institutions scholarship is how safety net institutions or policies change over time, especially in light of emerging needs and legislative inaction (Hacker, Pierson, and Thelen 2015). Theorists in political science have identified processes of drift, through which static policies have different effects in changing contexts, and conversion, through which institutional actors adapt existing policies to serve originally unintended ends. Existing disaster housing assistance programs have failed to keep up with changing housing market and wage trends and currently contribute to widening wealth inequality between renters and homeowners after disasters (Howell and Elliott 2019). Created in 1986 to leverage private investment to produce affordable housing, there is no evidence that Congress created LIHTC with disaster housing needs in mind. But over the past three decades, state and local governments, along with developers, have adapted the program to be an important part of the disaster recovery programs. Looking forward, there is opportunity for empirical and theoretical work on housing and food programs that have dual uses in the poverty- and disaster-safety nets. Understanding those programs is necessary to understand the extent to which social safety nets assist vulnerable groups.

Section 2 summarizes US disaster housing policy and the implications of disasters on renters . Section 3 presents our panel dataset and specifies our model, as well as a suit of robustness checks. Section 4 describes our results, in which we pay particular attention to the timing, location, and extent of LITHC allocations after disasters. Section 5 discusses the disaster- and housing-policy implications. Section 6 concludes.

## 2. Background

Climate related disasters have increased in frequency and severity in the past three decades (Barthel and Neumayer 2012; Kunkel et al. 2013; Smith and Katz 2013). At the same time, the share of household budgets, especially low-income household budgets, going to pay for housing has been rising and the homeownership rate has been declining. These intersecting trends make understanding the relationship between disasters and affordable housing production increasingly important.

**2.1 Implications of disasters for vulnerable renters**

Severe flooding disasters often have substantial effects on housing, and particularly housing occupied by lower income households. Recovery measured in terms of population, housing, or economic growth takes years, if not decades. The recovery from Hurricane Katrina is an extreme, but well-documented, example of the destruction of housing, the displacement of residents, and the transformation of much of the city's affordable housing stock. Before Katrina, the population of New Orleans was 452,000 residents. One year after the storm, the population was approximately 230,000 residents. By 2016, New Orleans had grown by roughly 160,000 residents from its post-storm low, but many of those additional residents were not returnees but new movers into the city (Fussell 2015). Hurricane Katrina destroyed nearly all of the homes in the primarily African-American neighborhood of the Lower Ninth Ward and the majority Vietnamese neighborhood of Village de l'Est in New Orleans East (Kamel 2012). A decade later, housing repair and rebuilding remained unfinished in many low-income neighborhoods, including these two areas (Adams, Van Hattum, and English 2009; Seidman 2013). Part of the net out-migration of lower-income residents from New Orleans can be attributed to the damage to homes and the slow pace of housing recovery. The extent of damage is a crucial factor in individuals' decisions to relocate permanently (Myers, Slack, and Singelmann 2008). Further, increases in the cost of housing in New Orleans after Katrina made returning impossible for many low-income renters (Vigdor 2008).

A substantial literature focuses on the importance of housing in disaster recovery. Much work focuses on the temporary sheltering needs of survivors as well as differential access to shelter and to housing aid based on class and race or ethnicity (Bolin and Stanford 1991; Nigg, Barnshaw, and Torres 2006; Peacock et al. 2014). But few studies look simultaneously at the effects of multiple disasters at the local level. The most relevant here is Boustan, Kahn, Rhode, & Yanguas, (2017), who estimate the effect of disasters on home values, as well as migration and poverty. They find that over the past century, counties in the United States struck by severe disasters have experienced net out-migration, on average (Boustan et al. 2017). As populations decline, counties in the United States that experience severe disasters also experience long-term declines in home values. At the same time, poverty rates in disaster-hit counties increase, on average (Boustan et al. 2017; Boustan, Kahn, and Rhode 2012; Strobl 2011). This increase in poverty may be explained by the out-migration of the non-poor, who have more

resources to move; by the in-migration of the poor, attracted by lower housing costs; or by a transition of the existing population into poverty because of economic dislocation caused by the disaster (Boustan et al. 2017). In short, demographic shifts and local affordable housing markets are intertwined as places recover from disasters. With demographic shifts increasingly understood, we turn to affordable housing markets and investigate what effect disasters have on the subsequent creation of federally subsidized housing by private affordable housing developers. On the one hand, declining population size and falling home values might lead us to expect a decline in the construction of subsidized housing. On the other hand, increasing poverty rates might lead us to expect an increase in the construction of subsidized housing.

**2.2 Post-Disaster Housing Policy**

The federal disaster safety net is under increasing strain. Much of the existing disaster relief and recovery infrastructure is three to five decades old, dating to the 1966 Disaster Relief Act and its subsequent amendments or the 1988 Robert T. Stafford Disaster Relief and Emergency Assistance Act (Stafford Act).[1] The major hurricanes of the past 15 years, such as Hurricanes Katrina, Sandy, Harvey, Irma, Maria, and others, have highlighted the need to continually reevaluate and improve disaster recovery programming. The Stafford Act authorizes the Federal Emergency Management Agency (FEMA) to provide temporary financial assistance to affected households to repair owner-occupied private residences or to rent alternate housing for up to 18 months.[2] The Stafford Act also authorizes FEMA to provide direct assistance in the form of temporary housing units, acquired by the federal government through purchase or lease, and provided for up to 18 months directly to households who would be unable to make use of the financial assistance.[3] There is no established program focusing on addressing the need for permanent housing after disasters.

Congress has occasionally supported new approaches, such as the 2006 one-time authorization of the Alternative Housing Pilot Program and the resulting "Katrina Cottages," and HUD's experimentation with the Rebuild by Design and subsequent National Disaster Resilience Competition after Hurricane Sandy.[4] The recent Disaster Recovery Reform Act of 2018 also breaks new ground in directing a share of

[1] Disaster Relief Act of 1966, P.L. 89-769 (Nov. 6, 1966); Disaster Relief Act of 1974, P.L. 93-288 (May 22, 1974); Robert T. Stafford Disaster Relief and Emergency Assistance Act, P.L. 100-707 (Nov. 23, 1988); see also Sandy Recovery Improvement Act of 2013 (SRIA, Division B of P.L. 113-2) and the Post-Katrina Emergency Management Reform Act of 2006 (PKEMRA, P.L. 109-295).
[2] 42 U.S.C. §§ 5174(c)(1) (A), 5174(c)(2-3).
[3] 42 U.S.C. § 5174(c)(1)(B)(i)).
[4] Emergency Supplemental Appropriations Act, 2006, P.L. 109-234 (June 15, 2006); Disaster Relief Appropriations Act, 2013, P.L. 113-2 (Jan. 29, 2013).

funding for disaster mitigation and, in some circumstances, allowing states to administer direct temporary housing assistance.[5]

The closest existing program to a long-term housing recovery program is the periodic Congressional appropriation, since 1993, of Community Development Block Grant Disaster Recovery funds, which affected states can use in flexible ways to fund rebuilding and recovery. If funds are appropriated by Congress, which is uncertain after any given disaster, each state then subsequently designs its own recovery program to use the amount appropriated in compliance with Department of Housing and Urban Development (HUD) guidelines. A Government Accountability Office (2010) study found that overall federal disaster assistance primarily benefited homeowners as compared to renters. When the estimated number of assisted units after Hurricane Katrina were compared to the estimated number of damaged units, 62 percent of damaged homeowner units but only 18 percent of damaged rental units were assisted (GAO 2010). Congress has twice approved special LIHTC allocations to facilitate long-term housing recovery after disasters, through the Gulf Opportunity Zone (GO Zone) Act of 2005 and the Heartland Disaster Tax Relief Act of 2008.[6] The Government Accountability Office study found, however, that "the GO Zone LIHTC program addressed only a small part of the repair and replacement needs of rental properties."

Perhaps in part because there is not an existing program to address permanent housing needs after disasters, states have identified housing as a national area for improvement in every annual National Preparedness Report since the inception of these preparedness reports in 2012. State and local preparedness levels for housing recovery actually appear to be getting worse instead of better (FEMA 2017:13, 88). As the 2019 Report emphasized, "States and territories frequently reported being furthest from their goals for establishing long-term housing [and] relocating individuals affected by disasters" and "more than half of urban areas reported that they are far from their goals to relocate affected individuals and establish long-term housing" (FEMA 2019:11). Especially given the central role that housing plays in efficient and equitable recovery, a focus on improving hazard mitigation and disaster recovery processes for low-income renters is essential.

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[5] Disaster Recovery Reform Act of 2018 (DRRA), P.L. 115-254 (Oct. 5, 2018). Section 1234 of the DRRA allows the President to set aside funding for pre-disaster mitigation from the Disaster Relief Fund (DRF) at an amount equal to 6 percent of the estimated aggregate amount of the grants to be made pursuant to the principal Stafford Act authorizations. Sections 1211, 1212, and 1213 of the DRRA also makes it possible for states to administer direct temporary housing assistance, separate the cap on the maximum amount of financial assistance for housing assistance from that for other needs assistance and remove rental assistance from that cap, and expands the eligible areas for FEMA's multifamily lease and repair program while also removing the requirement that the value of the improvements or repairs not exceed the value of the lease agreement.

[6] Gulf Opportunity Zone Act of 2005, P.L. 109-135 (Dec. 22, 2005); Heartland Disaster Tax Relief Act of 2008, P.L. 110-343 (Oct. 3, 2008).

## 2.3 Affordable Housing Policy and LIHTC

Without an existing federal program focused on catalyzing the construction of rental housing or subsidized rental housing after disasters, it is helpful to focus on the principal federal program and funding to support affordable housing construction in general. Congress created the LIHTC program in 1986 to leverage federal tax credits for private investment in the construction of affordable housing. The U.S. Treasury distributes LIHTC credits to every state and territory roughly in proportion to its population. State, territorial, or municipal housing finance agencies then award the tax credits to affordable housing developers through a competitive application process. The program allows developers to receive federal income tax credits for constructing or renovating rental properties for low-income households and operating the affordable housing development under the Internal Revenue Service's LIHTC guidelines for a certain compliance period, originally 15 years and now 30 years (Freedman & McGavock, 2015). These developers partner with investors who provide equity for the affordable housing development and, in exchange, receive a tax credit annually over 10 years. The partnership with equity investors through the tax credit program significantly reduces a project's debt service costs and allows the projects to operate with below-market rental income.

Federal law sets out a framework for the LIHTC program, requiring allocation plans to give preference to projects that serve the lowest income tenants, that serve these tenants for the longest period of time, and that are located in qualified census tracts in which the project contributes to a concerted community revitalization plan (26 U.S.C. § 42(m)(1)(B)(ii)). Federal law requires that the allocation plans include selection criteria regarding project location, local housing needs, and capacity to house individuals with special needs, among others (26 U.S.C. § 42(m)(1)(C)). The federal statute authorizing LIHTC does not, however, include any requirements related to disaster mitigation, preparedness, response, or recovery.

In practice, the Internal Revenue Service has recognized that LIHTC may be a useful tool for disaster recovery and sometimes temporarily suspends some of the statutory LIHTC requirements for affected buildings after federal disaster declarations.[7] The Internal Revenue Service also sometimes temporarily suspends certain income limitations for individuals displaced by a major disaster, allowing owners of LIHTC buildings to rent units to households even if their income does not fit within the LIHTC requirements. Nevertheless, there are no federal statutes, rules, or permanent guidance regarding the use of LIHTC allocations for disaster recovery.

[7] See for instance, IRS Rev. Proc. 2007-54; IRS Rev. Proc. 2014-49; IRS Rev. Proc. 2014-50; IR-2017-165.

### 2.4 Institutional Change

This background understanding of the context of post-disaster housing assistance and affordable housing policy raises the question of what happens when policymakers fail to change policies to meet the demands of changing contexts. Scholarship on institutions generally has noted that institutions are not fixed, but evolve over time (Hacker et al. 2015). The question, then, is "what kinds of institutional changes propelled by what kinds of social processes are most likely under what kinds of political configurations" (Hacker et al. 2015:180). One common process of institutional change is "drift," when institutions or policies are bound in place even as the setting in which they operate changes, thus limiting or changing the institution's effect. Another common process of institutional change is "conversion," in which actors are able to repurpose and apply existing institutions or policies toward a new and originally unintended aim. The focus on institutional drift and conversion highlights the role of administrative agencies and their staff in powerfully, but often less visibly, shaping policy outcomes over time beyond the common public focus on voters or legislators, whose effects are more visible in the overt political reforms that create or expressly change institutions or policies at a given moment. The attention to the power of these institutional actors also helps explain the common observation in industrialized states of relative stability in formal institutions yet often marked changes in political outcomes (Hacker et al. 2015).

## 3. Data and Methods

### 3.1 Data

The dependent variable in the analysis is the LIHTC units allocated in a county in a given year, drawn from the Department of Housing and Urban Development LIHTC Database of all LIHTC projects in American states and territories from 1987 to 2018.[8] For each of the 45,905 projects, the dataset includes the number of housing units, allocation year, 2010 census tract, and longitude and latitude of the project.[9] Roughly 1.3 percent of counties have more than 10,000 units each, and the units in those counties comprise 36.6 percent of the total number of units.

The independent variables related to disasters are gathered from the Spatial Hazard Events and Losses Database (SHELDUS) database compiled by scholars at Arizona State University. For each county and year and Presidentially Declared Disaster in the continental United States, the dataset includes detailed information about and the value of estimated damage and the number of deaths caused by the disaster.

[8] Data available at https://lihtc.huduser.gov/.
[9] Observations missing data for any of those variables make up 15 percent of the dataset and are removed.

The primary independent variables of interest are the number of severe disasters in a county each year and that number lagged for one through six years. We define severe disasters as the 1,167 presidentially declared disasters with a value of property damage in the top 5 percent of all disaster events between 1987 and 2018. One in four counties experience a severe disaster over the 25 years studied. It is important to note that because the disaster declaration process includes multiple factors and is not immune from political pressure, there are some major disasters that do not receive federal declarations and there are some minor events that do receive federal declarations (Salkowe and Chakraborty 2009; Schmidtlein, Finch, and Cutter 2008).[10]

Drawing from the U.S. Census Bureau data, Brown University's Diversities and Disparities Project provides measures of demographics and housing market characteristics for each 2010 census tract in the United States in 1980, 1990, 2000, and 2010 (Logan, Xu, and Stults 2014).[11] Data for these variables for 1980, 1990, and 2000 comes from the decennial census, while data for 2010 comes from the 5-year American Community Survey, centered on 2015. We linearly interpolate between decades, which is a common strategy despite making a strong assumption about how demographic and housing market measures change. We group the dataset so that each observation is a county-year, and then construct variables representing population density; percent of people who are in poverty, percent of the population identifying as non-Hispanic white, and share with a four-year college degree or higher. We also include variables describing housing characteristics, including the percent of units that are owner-occupied, vacant, and in multi-family buildings, as well as median rent and home value.[12] We fill in missing values for each county using the values from the subsequent Census or Survey.[13]

Using FEMA floodplain maps from 2018, we identify, using the geographic information systems (GIS) ArcGIS, the share of each county that is located in a floodplain. To measure the share of the county in the floodplain we identify the centroid of each block group and the area of that block group. If the centroid is in the floodplain, we categorize the block group as in the floodplain. We also identify the locations of each specific LIHTC project developed since 1987 and identify whether or not that LIHTC project is located in a floodplain. Finally, we estimate the shares of each county's housing units and

[10] 44 C.F.R. § 206.48 sets out the factors considered when evaluating a Governor's request for a major disaster declaration.
[11] Data available at https://s4.ad.brown.edu/projects/diversity/Researcher/LTBDDload/DataList.aspx
[12] All variables but median rent and home value were reported as counts so we could sum the counts as we group tracts into counties; median rent and home value were reported as medians, so we took the average of the medians across the tracts in a county.
[13] Almost no values were missing in the 1990, 2000, and 2010 census years. We use values from subsequent censuses to populate missing values in the preceding one.

population living in floodplains, identifying any units or people living in block groups in the floodplain. We use the most recent FEMA flood maps available in June 2019.[14]

The unit of analysis is the county-year. Many studies of LIHTC developments use the project, tract-, or city-level to explore different aspects of the program, such as neighborhood economic or demographic characteristics, effects on home values, and other dimensions of the LIHTC program (Baum-Snow and Marion 2009; Dawkins 2013; Deng 2011; Ellen et al. 2018; Ellen, Horn, and O'Regan 2016; Freedman and McGavock 2015; Gould Ellen and Voicu 2006; Woo, Joh, and Van Zandt 2016). Studies of federal disaster programs, however, often focus on the county-level (Berke, Kartez, and Wenger 1993; Bolin and Stanford 1991; Horney et al. 2017; Simo and Bies 2007; Yoon, Youngs, and Abe 2012). The county level is an appropriate scale at which to study disasters because Major Disaster Declarations and the federal programs that come with them are determined at the county-level, and, even in the absence of federal assistance, county governments play crucial roles in disaster response and recovery. Furthermore, federal and state disaster recovery programs often work at the county level, and state and local governments, in particular, have an interest in retaining residents, making it plausible that a disaster in one county would be met with LIHTC unit allocations in the same county. We merge the three datasets by county-year, using the set of 3,143 counties and 25 years common to all datasets.

In Table 1, we present descriptive statistics by county, describing the total number of allocated LIHTC units and disasters from 1990 to 2015 as well as demographic and housing market measures for 2010. We sort the table into quartiles by the total number of LIHTC units between 1990 and 2015. Table 1 confirms that the demographic and housing measures vary substantively with the total number of LIHTC units in ways consistent with existing research, for instance, on the relationship between LIHTC project locations and poverty rates and minority residents (Dawkins 2013; Ellen et al. 2018; Freedman and McGavock 2015).

[14] Data available at https://www.fema.gov/flood-maps and made available on ArcGIS.

**Table 1: Count of Counties by Number of LIHTC Units**

| | 0%-25% (Mean) | 25-50% (Mean) | 50-75% (Mean) | 75-100% (Mean) |
|---|---|---|---|---|
| Counties | 779 | 792 | 786 | 786 |
| LIHTC Units (sum 1990-2015) | 7.09 | 72.88 | 249.22 | 2831.54 |
| Population | 8991.49 | 21039.9 | 44875.79 | 333421.1 |
| Population Density | 22.26 | 68.52 | 103.46 | 885.49 |
| Share Households in Poverty | 14.98 | 16.84 | 17.16 | 14.95 |
| Share non-Hispanic White | 80.75 | 80.61 | 76.31 | 69.38 |
| Share BA or Higher | 12.92 | 11.55 | 12.94 | 17.88 |
| Share Multi-Family Housing | 3.49 | 4.45 | 6.83 | 14.28 |
| Median Rent ($) | 637 | 660 | 719 | 919 |
| Median Home Value ($) | 112272 | 119067 | 136814 | 196891 |
| Count Flood Damage ($1000s., 1990-2015) | 47727.1 | 53842.26 | 112807.9 | 434074.6 |
| Count Flood Events (sum 1990-2015) | 4.13 | 5.42 | 5.42 | 6.05 |
| Count Severe Flood Events (sum 1990-2015) | 0.07 | 0.17 | 0.25 | 0.52 |
| Count LIHTC Units in 100-yr Floodplain | 0.22 | 2.34 | 8.5 | 132.58 |
| Count LIHTC Units in Floodplain | 0.27 | 3.9 | 14.22 | 295.38 |
| Share LIHTC Units in 100-yr Floodplain of all LIHTC | 0.96 | 3.35 | 3.42 | 4.17 |
| Share LIHTC Units in Floodplain of all LIHTC | 1.28 | 5.25 | 5.67 | 8.13 |
| Share County in 100-yr Floodplain | 7.00 | 11.04 | 11.12 | 10.00 |
| Share County in Floodplain | 7.51 | 12 | 12.4 | 12.64 |
| Share Rental Units in Floodplain of all Units | 1.01 | 1.75 | 2.1 | 2.89 |
| Share Rental Units in Floodplain of all Rental Units | 4.26 | 6.99 | 7.27 | 8.43 |
| Share LIHTC Units of all Rental Units | 1.00 | 4.81 | 6.94 | 7.52 |
| Share LIHTC Units in Floodplain of all Rental Units | 0.03 | 0.23 | 0.35 | 0.68 |
| Share People in Floodplain of all People | 3.89 | 6.28 | 6.62 | 7.76 |
| Share non-Hispanic White in the Floodplain to all White | 3.97 | 6.34 | 6.76 | 7.77 |
| Share non-Hispanic Black in the Floodplain to all Black | 3.87 | 6.55 | 6.4 | 7.38 |
| Share Hispanic in the Floodplain to all Hispanic | 3.84 | 6.47 | 6.93 | 7.94 |

### 3.2 Methods

We identify the effect of disasters on LIHTC unit allocations using these panel data. The timing of disasters is exogenous to state or county level characteristics, allowing for causal estimation of the effects of disasters on LIHTC allocations.

We estimate a linear panel regression model across 3,143 counties and 25 years to estimate the effect of disasters on LIHTC unit allocations. We specify a distributive lag model, to test whether a disaster in one year has an effect on LIHTC unit allocations in subsequent years. We isolate the effects of disasters on LIHTC unit allocations by including demographic and housing market measures as pre-treatment confounders and specifying county-level fixed effects to control for time-invariant unobserved differences between counties. Our range of pre-treatment confounders vary with time to avoid an estimate biased by omitting variables. We use time-level fixed effects to control for unobservable differences between years.

To account for serial correlation within each county across years, we cluster robust standard errors at the county level.[15]

The model is described in Equation (1):

$$Y_{it} = \beta_0 D_{i,t} + \beta_1 D_{i,t-1} + \ldots + \beta_6 D_{i,t-6} + C_{it} + c_i + y_t, + e_{it}$$

$Y_{it}$ is the number of allocated LIHTC units in county *i* and time *t*. $D_{i,t}$, $D_{i,t-1}$, etc. are the severe disasters in county *i* and time *t, t-1,* etc. $C_{it}$ are a collection of time-varying demographic and housing market characteristics. County and year fixed effects are $c_i$ and $y_t$, respectively. The error term is $e_{it}$.

## 4. Results

### 4.1 Descriptive Analysis

In Table 2, we present descriptive data regarding the counties in the dataset with severe disaster damage and those with LIHTC units, finding that 436 counties experienced severe flooding disasters at some point over the 25 years. Of those counties, 213 counties experienced severe damage from a flooding disaster and had some units in a floodplain while 264 counties experienced severe damage from a flooding disaster but had no units located in a floodplain.

**Table 2: Count of Counties by Flood Damage and LIHTC Units in Floodplain**

| | | LIHTC Units | |
|---|---|---|---|
| | | None in Floodplain | Any in Floodplain |
| Flooding Disaster | No Severe Flood | 1741 | 436 |
| | Any Severe Flood | 264 | 213 |

In Table 3, we divide the counties into quartiles by the value of the total disaster damage over the 25 years in the study. As expected, counties with higher disaster damage estimates are more highly populated and more dense than those with lower damage estimates. Counties with higher damage estimates also have higher home values, higher rents, more multifamily housing, and more LIHTC units than counties with lower damage estimates. Renters in counties with higher damage estimates are also more likely to live in the 100 and 500-year floodplain than renters in counties with lower damage estimates. Similarly, counties with higher damage estimates have a higher share of LIHTC units located

[15] To the extent that disasters may catalyze the creation of LIHTC units in neighboring counties without a disaster declaration, that would only suggest that our findings are a conservative estimate of the impact of disasters on allocated LIHTC units.

in the 100- and 500-year floodplains than in counties with lower damage estimates. The likelihood that a renter in a LIHTC unit will be located in a floodplain is lower than the likelihood for a renter overall.

**Table 3: Counties by Total Flood Damage 1990-2015**

| | 0%-25% (Mean) | 25-50% (Mean) | 50-75% (Mean) | 75-100% (Mean) |
|---|---|---|---|---|
| Counties | 786 | 785 | 786 | 786 |
| Count Flood Damage ($1000s., 1990-2015) | 71.84 | 1814.85 | 10629.77 | 635923.7 |
| Population | 48734.79 | 54194.93 | 76097.76 | 229450.3 |
| Population Density | 260.66 | 127.92 | 290.95 | 400.69 |
| Share Households in Poverty | 15.81 | 16.43 | 15.6 | 16.1 |
| Share non-Hispanic White | 74.37 | 78.61 | 82.3 | 71.75 |
| Share College Educated | 13.92 | 12.71 | 13.59 | 15.05 |
| Share Multi-Family Housing | 5.83 | 5.87 | 7.49 | 9.86 |
| Median Rent ($) | 703 | 689 | 720 | 824 |
| Median Home Value ($) | 135109 | 124344 | 137980 | 167677 |
| Count Flood Events (1990-2015) | 1.35 | 4.53 | 6.83 | 8.32 |
| Count Severe Flood Events (1990-2015) | 0.00 | 0.00 | 0.00 | 0.99 |
| Count LIHTC Units | 448.55 | 362.66 | 579.38 | 1771.1 |
| Count LIHTC Units in 100-yr Floodplain | 14.13 | 10.67 | 17.9 | 100.97 |
| Count LIHTC Units in 500-yr Floodplain | 27.21 | 29.1 | 35.94 | 221.59 |
| Share LIHTC Units in 100-yr Floodplain of all LIHTC | 1.2 | 2.28 | 2.91 | 5.53 |
| Share LIHTC Units in 500-yr Floodplain of all LIHTC | 2.22 | 4.02 | 4.91 | 9.21 |
| Share County in 100-yr Floodplain | 5.36 | 9.71 | 11.07 | 13.05 |
| Share County in 500-yr Floodplain | 6.05 | 10.8 | 12.25 | 15.48 |
| Share Rental Units in 500-yr Floodplain of all Units | 1.1 | 1.68 | 1.87 | 3.1 |
| Share Rental Units in 500-yr Floodplain of all Rentals | 3.71 | 5.85 | 6.72 | 10.69 |
| Share LIHTC Units of all Rental Units | 4.54 | 4.79 | 5.2 | 5.78 |
| Share LIHTC Units in 500-yr Floodplain of all Rentals | 0.17 | 0.23 | 0.27 | 0.63 |
| Share People in Floodplain of all People | 3.49 | 5.29 | 5.96 | 9.82 |
| Share non-Hisp. White in 500-yr Floodplain to all NHW | 3.51 | 5.37 | 6.02 | 9.96 |
| Share non-Hisp. Black in 500-yr Floodplain to all NHB | 3.27 | 5.44 | 6.12 | 9.4 |
| Share Hispanic in the 500-yr Floodplain to all Hispanic | 3.57 | 5.25 | 6.16 | 10.23 |

In Table 4, we focus only on counties with at least some land in the floodplain and that experienced a severe flooding disaster over the 25 year study period. We divide the county-year LIHTC allocations into those years proximate to (within the six years following) a disaster and those years distant from a disaster. In those years proximate to a disaster, roughly 85 LIHTC units were allocated annually while in those years distant from a disaster roughly 71 LIHTC were allocated annually. Without adding any controls, this suggests that LIHTC allocations are roughly 20 percent larger overall in the six years after to a disaster compared to other years. Looking specifically at the LIHTC allocations in the 500-year floodplain, we find that allocations within the floodplain are roughly 65 percent larger in the six years after a disaster compared to other years while the share of LIHTC units outside of the floodplain is roughly 14 percent larger in the years after disaster compared to other years.

**Table 4: LIHTC Unit Allocations Given Recent Disasters**

| | Recent Disaster | No Recent Disaster | Ratio Recent to No Recent |
|---|---|---|---|
| Count County-years | 3,958 | 7,950 | 0.50 |
| Count LIHTC Units | 336,473 | 563,606 | 0.60 |
| Count LIHTC Units in Floodplain | 53,992 | 65,802 | 0.82 |
| Count LIHTC Units not in Floodplain | 282,481 | 497,804 | 0.57 |
| Ratio LIHTC Units to County-years | 85.01 | 70.89 | 1.20 |
| Ratio LIHTC Units in Floodplain to County-years | 13.64 | 8.28 | 1.65 |
| Ratio LIHTC Units not in Floodplain to County-years | 71.37 | 62.62 | 1.14 |

### 4.2 Causal Analysis

To estimate the effect of a severe flood disaster on LIHTC allocation, we formulate a linear panel regression model and specify a distributive lag. In Table 5, we find that a severe flooding disaster is positively associated with larger LIHTC allocations in the first two years following the disaster. This finding suggests that states and localities use the LIHTC program in part as a disaster recovery program to facilitate the construction of affordable housing in disaster hit counties. Results in years three through five are positive but not significant. By the sixth year after the disaster, LIHTC allocations to the county decline.

**Table 5: Estimate of Effect of Flood Disasters on LIHTC Unit Allocations**

| | Model 1 | | Model 2 | |
|---|---|---|---|---|
| Severe Flood | 5.9 | | 5.7 | |
| | (6.91) | | (6.8) | |
| Severe Flood | 22.81 | *** | 22.65 | *** |
| Lag 1 | (6.27) | | (6.22) | |
| Severe Flood | 12.27 | * | 12.17 | * |
| Lag 2 | (6.85) | | (6.79) | |
| Severe Flood | 8.85 | | 8.9 | |
| Lag 3 | (5.61) | | (5.62) | |
| Severe Flood | 2.09 | | 2.14 | |
| Lag 4 | (7.44) | | (7.31) | |
| Severe Flood | -4.81 | | -5.21 | |
| Lag 5 | (6.21) | | (6.08) | |
| Severe Flood | -14.4 | ** | -15.14 | ** |
| Lag 6 | (7.06) | | (7.23) | |
| Pop. Density | | | 0.13 | * |
| | | | (0.07) | |
| Share HH in Poverty | | | 0.61 | ** |
| | | | (0.25) | |
| Share non-Hispanic White | | | 0.19 | |
| | | | (0.66) | |
| Share BA or More | | | 3.91 | *** |
| | | | (1.31) | |
| Share Multi-Family Housing | | | 0.06 | |
| | | | (1.03) | |
| Share Owner Occupied | | | 0.6 | |
| | | | (0.43) | |
| Median Rent | | | 43.93 | |
| | | | (32.57) | |
| Median Home Value | | | -0.04 | |
| | | | (0.12) | |
| Errors | HC1 | | HC1 | |
| Effects | FE | | FE | |
| Observations | 61218 | | 61210 | |
| R2 | 0.000 | | 0.014 | |
| Adjusted R2 | -0.039 | | -0.025 | |
| F statistics | 8.129 | | 59.64 | |

The preceding results indicate that LIHTC allocations increase in the two years following severe flooding disasters. This finding raises the question of the extent to which these post-disaster LIHTC allocations to flood-hit counties are for projects that are in the 500-year flood plain and whether these allocations will mitigate or exacerbate disaster exposure for low-income tenants.

The results in Table 6 indicate that LIHTC allocations in the first year after severe flooding disasters are generally associated with a substantial increase in units built both inside and outside of the 500-year floodplain in those disaster-hit counties. In Models 1 and 2, we find that even after controlling

for standard demographic controls, more units are allocated outside of the floodplain in the first and third years after a disaster while more are allocated in the floodplain in the first and second years in the floodplain, relative to other years. In Models 3 and 4, we add controls for the distribution of existing units in that county relative to the floodplain. In Model 3, after adding a measure of the share of units in the floodplain in each county, the results remain unchanged, with significantly more units in the floodplain in years one and two after a disaster and significantly more units outside of the floodplain in years three and four. In Model 4, after adding controls for the number of rental units in the floodplain and the ratio of rental units in the floodplain to all housing units, the significance of years one and three for allocations outside of the floodplain remains while there does not seem to be a significant effect of disaster on allocations inside the floodplain. Following the pattern identified above for LIHTC allocations overall after flooding disasters, the magnitude of the effect generally declines across the years, and becoming negative in the fifth and sixth years, though only significant in the sixth year.

**Table 6: Estimate of Effect of Flood Disasters on LIHTC Unit Allocations Relative to Floodplain**

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | In FP | | Not in FP | | In FP | | Not in FP | |
| Severe Flood | 0.21 | | 5.7 | | 0.12 | | 5.58 | |
| | (-1.64) | | (-6.52) | | (-1.62) | | (-6.42) | |
| Severe Flood | 4.63 | * | 18.18 | *** | 4.54 | * | 18.11 | *** |
| Lag 1 | (-2.44) | | (-5.34) | | (-2.44) | | (-5.32) | |
| Severe Flood | 4.83 | * | 7.44 | | 4.72 | * | 7.45 | |
| Lag 2 | (-2.82) | | (-6.06) | | (-2.81) | | (-6.01) | |
| Severe Flood | 0.74 | | 8.11 | * | 0.64 | | 8.26 | * |
| Lag 3 | (-2.39) | | (-4.68) | | (-2.42) | | (-4.63) | |
| Severe Flood | 1.36 | | 0.73 | | 1.24 | | 0.9 | |
| Lag 4 | (-2.66) | | (-7.03) | | (-2.64) | | (-6.89) | |
| Severe Flood | 0.14 | | -4.95 | | -0.03 | | -5.18 | |
| Lag 5 | (-2.85) | | (-5.43) | | (-2.79) | | (-5.34) | |
| Severe Flood | -4.7 | * | -9.7 | | -4.89 | * | -10.24 | * |
| Lag 6 | (-2.48) | | (-5.96) | | (-2.53) | | (-6.04) | |
| Pop. Density | | | | | 0.02 | *** | 0.11 | |
| | | | | | (-0.01) | | (-0.07) | |
| % HH in Poverty | | | | | 0.06 | | 0.55 | ** |
| | | | | | (-0.05) | | (-0.22) | |
| % non-Hisp. white | | | | | -0.02 | | 0.2 | |
| | | | | | (-0.13) | | (-0.59) | |
| % BA or More | | | | | 0.46 | *** | 3.45 | *** |
| | | | | | (-0.16) | | (-1.19) | |
| % Multi-Family Housing | | | | | -0.11 | | 0.17 | |
| | | | | | (-0.16) | | (-0.94) | |
| % Owner Occup. | | | | | 0.08 | | 0.52 | |
| | | | | | (-0.1) | | (-0.39) | |
| Median Rent | | | | | 8.4 | * | 35.53 | |
| | | | | | (-4.97) | | (-29.43) | |
| Median Home Value | | | | | -0.02 | | -0.03 | |
| | | | | | (-0.02) | | (-0.1) | |
| Units in FP to Units Rental Units in FP to Units in FP # Rental Units in FP | | | | | | | | |
| Errors | HC1 | | HC1 | | HC1 | | HC1 | |
| Effects | FE | | FE | | FE | | FE | |
| Observations | 61218 | | 61218 | | 61210 | | 61210 | |
| R2 | 0 | | 0 | | 0.005 | | 0.012 | |
| Adjusted R2 | -0.039 | | -0.039 | | -0.034 | | -0.028 | |
| F statistic | 7.376 | | 5.737 | | 22.346 | | 49.654 | |

**Table 6 (continued): Estimate of Effect of Flood Disasters on LIHTC Unit Allocations Relative to Floodplain**

| | Model 1 (repeated) | | | | Model 4 | | | |
|---|---|---|---|---|---|---|---|---|
| | In FP | | Not in FP | | In FP | | Not in FP | |
| Severe Flood | 0.21 | | 5.7 | | 0.07 | | 5.51 | |
| | (-1.64) | | (-6.52) | | (-1.62) | | (-6.43) | |
| Severe Flood Lag 1 | 4.63 | * | 18.18 | *** | 4.48 | | 18.08 | *** |
| | (-2.44) | | (-5.34) | | (-2.42) | | (-5.32) | |
| Severe Flood Lag 2 | 4.83 | * | 7.44 | | 4.63 | | 7.45 | |
| | (-2.82) | | (-6.06) | | (-2.8) | | (-6.03) | |
| Severe Flood Lag 3 | 0.74 | | 8.11 | * | 0.53 | | 8.3 | * |
| | (-2.39) | | (-4.68) | | (-2.45) | | (-4.65) | |
| Severe Flood Lag 4 | 1.36 | | 0.73 | | 1.07 | | 0.98 | |
| | (-2.66) | | (-7.03) | | (-2.62) | | (-6.89) | |
| Severe Flood Lag 5 | 0.14 | | -4.95 | | -0.26 | | -5.09 | |
| | (-2.85) | | (-5.43) | | (-2.73) | | (-5.31) | |
| Severe Flood Lag 6 | -4.7 | * | -9.7 | | -5.14 | | -10.12 | * |
| | (-2.48) | | (-5.96) | | (-2.58) | | (-6.02) | |
| Pop. Density | | | | | 0.02 | *** | 0.11 | |
| | | | | | (-0.01) | | (-0.07) | |
| % HH in Poverty | | | | | 0.07 | | 0.56 | ** |
| | | | | | (-0.05) | | (-0.22) | |
| % non-Hisp. white | | | | | 0.06 | | 0.22 | |
| | | | | | (-0.11) | | (-0.57) | |
| % BA or More | | | | | 0.44 | *** | 3.45 | *** |
| | | | | | (-0.15) | | (-1.19) | |
| % Multi-Family Housing | | | | | -0.07 | | 0.2 | |
| | | | | | (-0.15) | | (-0.94) | |
| % Owner Occup. | | | | | 0.09 | | 0.48 | |
| | | | | | (-0.11) | | (-0.38) | |
| Median Rent | | | | | 7.18 | | 35.31 | |
| | | | | | (-4.71) | | (-29.17) | |
| Median Home Value | | | | | -0.02 | | -0.03 | |
| | | | | | (-0.02) | | (-0.1) | |
| Units in FP to Units | | | | | 0.1 | | 1.39 | * |
| | | | | | (-0.4) | | (-0.78) | |
| Rental Units in FP to Units in FP | | | | | -0.05 | * | -0.19 | |
| | | | | | (-0.03) | | (-0.16) | |
| # Rental Units in FP | | | | | 0.00 | ** | 0.00 | |
| | | | | | (0.00) | | (0.00) | |
| Errors | HC1 | | HC1 | | HC1 | | HC1 | |
| Effects | FE | | FE | | FE | | FE | |
| Observations | 61218 | | 61218 | | 61207 | | 61207 | |
| R2 | 0 | | 0 | | 0.007 | | 0.012 | |
| Adjusted R2 | -0.039 | | -0.039 | | -0.032 | | -0.028 | |
| F statistic | 7.376 | | 5.737 | | 26.92 | | 41.666 | |

From the preceding regressions, we now know that severe flooding disasters are associated with an increase in LIHTC unit allocations in the first two years after the disaster and that more LIHTC units are allocated outside of the 500 year floodplain in the first and third years after a disaster compared to other years. We also find that, relative to other years, more LIHTC units are allocated inside the floodplain in the first and third years after a disaster, although the significance of this result disappears once we control for the number of already existing rental units in the floodplain and the share of all units in the floodplain that are rentals.

### 4.3 Sensitivity

To evaluate the robustness of these models, we conduct several additional tests, presented in the appendix. We evaluate the stability of results using alternative measures of the independent and dependent variables and alternative constructions of the model presented above. These results are available on request.

First, we focus on evaluating changes to the central independent variables of interest. Instead of measuring severity relative to all other disasters in the United States we measure it relative to all other disasters in the state. This alternative measure of disasters has significant and positive effects on the number units allocated, parallel with the results presented.

Second, we focus on evaluating changes to the dependent variable. We transform it with an inverse hyperbolic sin transformation, a helpful transformation for variables with some extreme values and also many zero values. We also transform the dependent variable by dividing allocations by the population in the county. These alternative dependent variables produce results that are parallel to those presented. As an alternative to transforming the dependent variable, we remove the 1.3 percent of counties (45 counties) that have more than 10,000 units allocated over the 25 years studied and that together account for 37 percent of all LIHTC allocations.

Third, we validate our specification. We specify a time-trend at the state level to account for any time-variant but unobserved confounders, which would undermine our model specification strategy. It does not produce results substantively different from ours. Next, to assess whether the lagged results may be the product of spurious correlations, we add placebo leads for up to six years prior to the disaster. The test generates modestly significant coefficients on two of the placebo leads. A final check is to include a control for the counties and years in which the Go Zone LIHTC allocations were distributed, to adjust for any effect it had on total allocations. This check produces results still parallel to our initial ones.

## 5. Discussion and Conclusion

The findings here suggest that in the absence of a federal disaster housing program that creates permanent housing for renters, states are turning to the LIHTC program to catalyze affordable housing production after disasters. We find that the year after a severe flooding disaster is associated with a 73 percent increase in disaster-hit county LIHTC allocations relative to other years. For the average county, this means that a disaster is associated with the production of 23 additional LIHTC units in the year following a severe flooding disaster.

In the context of federal disaster assistance, the central housing programs have remained essentially the same since 1988. The Stafford Act favors temporary financial assistance over direct housing assistance and generally prohibits FEMA from providing permanent housing.[16] The increasing frequency of flooding disasters that significantly affect housing, the disproportionate vulnerability of renters, and the increasing cost of rental housing relative to wages over the past three decades all mean that even as the programs have remained the same, the context has changed. Renters, and especially low-income renters, struggle to find and to afford nearby comparable housing after disasters and, the more aid that an area receives from FEMA, the wider wealth inequality between renters and homeowners increases after disasters (Howell and Elliott 2019). Here we see policy drift at the federal level, where the federal disaster housing policy remains the same, even as the context of disasters and housing changes, and the statute intended to help disaster survivors ends up disproportionately helping homeowners and leaving renters behind.

This policy drift at the federal level has been met with policy conversion at the state level. The LIHTC program was created in the Tax Reform Act of 1986 to encourage private investment in affordable housing. It has come to serve as a fundamental part of the social safety net for millions of low-income households seeking a more affordable home. The results above suggest that states have also converted the program to serve a new and originally unintended aim: disaster recovery. With the existing statutory framework for temporary disaster housing assistance failing to meet renters' long term needs, states have turned to LIHTC to fund the construction of affordable, multi-family rental housing after disaster and to catalyze disaster recovery.

A limitation of converting existing policies to meet new objectives is that when programs are used to serve needs that do not reflect their original legislative purposes, they may not be designed to allow agencies to equitably and efficiently meet those new objectives. A central tension in disaster policy, and safety net policies more broadly, is the degree to which the policy not only addresses current vulnerability or harm but also functions to reduce future vulnerability. This tension is central to any disaster-housing program and is especially acute in the context of affordable housing after disasters. After a flooding

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disaster, land in potential flood hazard areas is likely to be sold at a discount, enabling the creation of more affordable units or more deeply subsidized units, even as it places those subsidized renters at greater risk. To what extent has states' conversion of the LIHTC program to a disaster recovery tool ameliorated or exacerbated disaster risk for subsidized renters? Another central tension in disaster recovery policy is the extent to which aid should focus on recovery in place, recognizing the importance of fragile social networks and of the cultural and historical significance associated with specific places, or whether it should focus on encouraging migration to less hazard prone locations.

The findings here indicate that, after a flooding disaster states allocate more units to affordable housing projects both inside and outside of the 500-year floodplain relative to prior years. As in prior years, many more units are allocated outside of the floodplain than inside of it—specifically more than fivefold more LIHTC units are allocated outside of a floodplain than inside of a floodplain in the six years after a disaster. At the same time, the share of units allocated inside the 500-year floodplain increases by roughly 65 percent after a flooding disaster, substantially larger than the 14 percent increase for units outside of the floodplain after a flooding disaster.

Together, these findings suggests that states are using LIHTC to catalyze recovery and potentially doing so in a nuanced way, placing an emphasis on increasing the units allocated to disaster-hit communities even if in the floodplain while also increasing units allocated to that same county but outside the floodplain, in order to reduce the flooding hazards that future subsidized renters face. The fact that states and affordable housing developers are largely making these difficult decisions on a state by state and project by project basis highlights the need for more explicit conversations the role that the LIHTC program plays role in disaster recovery.

The results also suggest there may be a role for federal guidance that can help states and affordable developers weigh more clearly the competing goals of catalyzing disaster recovery, meeting the affordable housing needs of low-income renters, and protecting renters from future harms. The existing drift of relatively static disaster-housing policies combined with substantial shifts in disaster-housing needs and renters' housing cost burdens has disproportionately harmed renters (Howell and Elliott 2019). While state conversion of the existing federally funded and state managed LIHTC program to meet rental housing needs after disasters has helped fill this policy gap, federal policy could do more. For instance, adjusting federal LIHTC allocations automatically to meet disaster housing needs would allow states to act more quickly to allocate more units for subsidized permanent rental housing after disasters.

Future research could qualitatively and quantitatively explore state variation in LIHTC locations relative to the floodplain and look specifically at how states balance competing disaster recovery priorities in the context of housing.

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# Chapter 5

## One More Tool for the Food Assistance Toolbox? Experimental Evidence on Food Assistance Packaging

**Abstract**

International food assistance reaches more than 90 million people per year, much of it through in-kind programs that distribute food. Several key aspects of in-kind programs—what food is shipped, when and from where it is sourced—have been changed to improve program effectiveness and efficiency, becoming helpful tools in the modernized in-kind food assistance toolbox. Packaging—in what food is shipped—remains an unstudied and underused tool despite more than 50 million bags per year passing through in-kind supply chains, affecting program effectiveness and efficiency. We conduct an experiment with 46 shipments using different packaging materials and sizes to measure the effect of packaging on shipment quality, cost, and timeliness. Analyzing the data with randomization tests, we find that, relative to the current materials, new materials maintain shipment quality and cost while improving timeliness and in some cases may reduce cost. One promising material that balances cost and effectiveness is a bag with a biopesticide applied, designed to prevent insects from reproducing. We also find that, relative to the current size, larger bags may improve costs at least in the domestic portion of the supply chain. Donors and their partners should consider packaging as one more tool in the modernized food assistance toolbox. As the toolbox continues to fill, the coming opportunity and challenge to identify situations where the various tools work in complementary ways.

**Key words**: food assistance; in-kind; humanitarian supply chain; packaging; design of experiments

### 1. Introduction

Acute food insecurity affected 108 million people in 2016 and is a major policy concern (UNOCHA, 2018). In response, food assistance programs provide in-kind food and, increasingly, cash and food vouchers. In the past two decades, the goal of food assistance programs has shifted from surplus disposal in developed economies to ensuring food security in developing economies (Barrett & Maxwell, 2005; Christensen, 2000). And food assistance programs have responded to pressures to be more efficient and effective (Barrett & Maxwell, 2005). As a result, many new tools have been introduced to the donor and humanitarian organization's toolbox. These tools have changed what foods are shipped (Marchione,

2002, Huybregts *et al.*, 2012; Isanaka et *al.*, 2010; Karakochuk *et al.*, 2012), where food is bought (Harou *et al.*, 2013; Lentz *et al.*, 2013a; Lentz *et al.*, 2013b; USGAO, 2009; Violette *et al.*, 2013), and when food is shipped (USGAO, 2014). These tools can improve efficiency and effectiveness vis-à-vis shipment quality, cost, and timeliness, and recipient satisfaction and wellbeing. The question of packaging—in what packaging food assistance is shipped—remains unexplored, despite the potential for substantial efficiency and effectiveness gains in a range of situations.

As the first study on food assistance packaging in decades, we ask a causal and empirical question: To what extent does new packaging improve food assistance shipment quality, cost, and timeliness? We design a study as a factorial experiment, applying different packaging material and size 'treatments' to 46 shipments in the US Agency for International Development's (USAID) food assistance supply chain. A factorial experiment is a systematic way to estimate the effect that factors (e.g., packaging size) made up of levels (e.g., big and small bags) have on response variables (e.g., shipment quality, cost). The shipments in our study are made up of three commodities going to two destinations. To our knowledge, this approach to studying humanitarian food shipments is novel, and it may be useful to practitioners and other researchers evaluating the variety of new tools that rely on public and private supply chains. We find that one material, a bag to which a chemical called a biopesticide is applied, maintains shipment quality while improving timeliness. For shipments of cereals and pulses, that bag may reduce costs. We also find that large bags may reduce costs at least in the domestic portion of the supply chain where there is adequate machinery to handle them, though likely require machinery investments abroad to make them cost-effective across the whole supply chain.

Packaging thus should be added to the food assistance toolbox, and its addition is a useful point of entry to an imminent issue in food assistance program and supply chain design: different tools require different supply chain designs that sometimes work in complementary or conflicting ways. Innovative efforts in food assistance in the last two decades were largely focused on filling the toolbox: identifying and evaluating the efficiency and effectiveness of new tools, and documenting conditions under which they work (e.g., Hidrobo *et al.*, 2014, Maxwell *et al.*, 2013). The opportunity and challenge of this coming decade will be to evaluate in what range of situations and what combinations of these tools are useful. In our discussion, we address the important interactions between packaging and prepositioning, local and regional procurement, and cash and voucher programs.

Section 2 reviews the current food assistance toolbox and introduces the importance of packaging. Section 3 introduces the study design and data collected, and presents the variables used in the analysis after reviewing evaluations of other tools. Section 4 studies the relationship between packaging and shipment quality, cost, and timeliness. Section 5 presents policy recommendations. We discuss how

packaging works in complementary and sometimes conflicting ways with major tools in the toolbox. Section 6 concludes.

## 2. Background

Packaging has been a feature of food assistance programs since they began after World War II. At that time, the main programmatic objective was supporting domestic agriculture by exporting surplus commodities to developing economies (Barrett & Maxwell, 2005; Christensen, 2000; Diven, 2001). In some years, more than half of all packaged powdered milk exports were aid shipments (Barrett & Maxwell, 2005). In the 1970s and 1980s, US Department of Agriculture staff, having recognized the potential of packaging to improve quality and cost of US food assistance exports, experimented in labs with different insecticides on packaging and in shipments from Wisconsin to the Philippines with various materials (Twede & Miteff, 2017).

In the 1990s, innovation in food assistance packaging slowed, while large policy changes unfolded: government surplus programs were eliminated and food assistance policies became more humanitarian in nature (Barrett & Maxwell, 2005). Program and supply chain designs now reflect those shifts. Prepositioning food assistance abroad (e.g., USGAO, 2014) and procuring food assistance locally or regionally (e.g., Lentz *et al.*, 2013a) have changed when and from where assistance is shipped. Programming more fortified food has changed the mix of what is shipped (e.g., Isanaka *et al.*, 2010). As food assistance programs and their supply chains have evolved, packaging remains unchanged, despite the operational and programmatic benefits of improved packaging.

There are operational benefits to improving in what packaging assistance is shipped, since packaging moderates food assistance efficiency and effectiveness, as it does for consumer packaged goods distribution (e.g., McDonald, 2016), vaccine programs (e.g., Pagliusi *et al.*, 2018) and development interventions (e.g., Hellström & Olsson, 2017). This study tests the hypotheses that new packaging materials or sizes improve food assistance shipment quality, cost, and timeliness. Packaging can improve quality by avoiding insect infestation, moisture damage, and tearing (which leads to the former two). An increase in moisture content is an issue since it can lead to mold growth, the byproducts of which can harm human health. Packaging can improve cost by reducing or avoiding the need for fumigation if it reduces or avoids insect infestation. In 2017, fumigation cost at least $6 million and bag costs $12 million in US food assistance programs, which shipped abroad 1.5 million metric tons (MT) valued at an estimated $1 billion.[1] Another benefit of reducing or avoiding the need for fumigation is that if misapplied, fumigation adversely affects human health (USAID, 2013). Packaging can improve timeliness, also by reducing or avoiding the need for fumigation, which requires shipments to rest inert for 2-7 days per application. Food assistance shipped from the United States takes three to six months, of

which one to two weeks may be attributable to fumigation. Packaging that prevents tearing can also directly improve cost and timeliness by reducing the need to re-bag the contents of torn bags into new bags.

The operational gains from packaging can translate to programmatic benefits. Packaging helps maintain shipment quality, which can expand the potential mix of foods shipped and stored, and thus the range of emergencies and populations which receive that assistance. For example, wheat flour is prone to insect infestation during shipping and storage, to the extent that some organizations use it under a narrow range of conditions. Food insecure populations in countries such as Yemen and Afghanistan often eat wheat flour (World Bank, 2017; USDA, 2013), and milling flour locally is not always feasible (FEWSNET 2019, WFP, 2019a). By helping maintain shipment quality, better packaging could enable, when appropriate, the easier and wider use of wheat flour in in-kind programs. Just as the US Department of Agriculture staff studied packaging in the 1970s and 1980s in support of expanding US export markets, new packaging today can expand to whom and the conditions under which some aid is delivered.

## 3. Data and Methods

The analysis in this study uses quality, cost, and timeliness data generated from an experiment with 46 observations, each of which is a food assistance shipment in USAID's supply chain. The treatment is new packaging materials and sizes; the control is the current material and size. Each shipment is packaged in one material and size combination. Each shipment is made up of 20 metric tons of one commodity (which fits in one 20-foot container) that is going to one destination.

To evaluate new packaging, we review studies of other program changes to identify how those changes are evaluated. Studies commonly evaluate changes in food assistance programs along five dimensions: shipment quality, cost, and timeliness (e.g., Lentz *et al.*, 2013b; USGAO, 2014) and recipient satisfaction and wellbeing (e.g., Isanaka *et al.*, 2010; Violette *et al.*, 2013, Nikulkov *et al.*, 2016). We focus on quality, cost, and timeliness, and develop specific measures to evaluate packaging along these three dimensions. Studies evaluating shipments primarily use observational data (e.g., Harou *et al.*, 2013) and studies evaluating recipients primarily use experimental data (e.g., Huybregts *et al.*, 2012; Karakochuk *et al.*, 2012). Though we study the effect of packaging on shipment quality, cost, and timeliness, we use an experimental approach that resembles those approaches used to evaluate recipients' outcomes. An objective of this paper thus is to document our experimental approach, so that it may be used to evaluate other changes in food assistance programs.

### 3.1 Design

With USAID and the US Department of Agriculture (USDA), we designed an experiment in which they procured different commodities and shipped them to different destinations to test different packaging materials and packaging sizes.[2]

We used a commonly shipped and prepositioned grain (sorghum), pulse (yellow split peas), and milled product (corn soy blend plus). These commodities accounted for 28, 10, and 2.5 percent of US food aid shipped in FY 2016, respectively. They each have different costs and quality attributes such as baseline moisture contents and infestation propensities. Lentz *et al.* (2013b) also group commodities in their study by grains, pulses, and milled products.

We used two USAID overseas warehouses at two ports, Durban and Djibouti. The ports are different in two respects. First, at the time of the pilot—between November 2016 and April 2017—Durban had an average humidity 4.8 percentage points higher than Djibouti and an average temperature 3.6°C lower. Second, Durban has a greater degree of mechanization in and around the port, which was noted by key informants and confirmed during tours of both facilities. The ports have roughly comparable shipping times (about 30 days) from the Gulf of Mexico. Nearly one fifth (by weight) of all US in-kind food assistance passes through a USAID warehouse.

We used four types of materials:

1. Control-materials bags—the control-materials bags are polypropylene-based or paper-based bags. Yellow split peas and sorghum are currently shipped in woven polypropylene bags, while corn soy blend plus is shipped in five-ply paper bags. The large 1000-kilogram bags (discussed below) are also made of woven polypropylene, though with a durable material along the edges for structural support.
2. Biopesticide bags made of the control materials with a chemical called a biopesticide that is applied as an exterior film or in the extruded polypropylene, and which is designed to inhibit insect reproduction (e.g., Jenson *et al*., 2009). Other varieties of chemically treated bags exist, but these others have handling requirements that make them impractical for use in the food assistance supply chain.
3. Lined bags made of the control materials with an interior polyethylene plastic lining inserted, which is designed to limit water and oxygen permeability to reduce moisture damage and insect growth.
4. Control-materials bags shipped in a lined container. The liner is made of the same polyethylene plastic material as the liner in the lined bag.

We designed the experiment with a fifth material treatment, bags made of the same material of the liner, but which is essentially twice as thick and so acts as both a bag and a liner. As discussed in Section 3.5, we removed it from the study immediately after tendering the shipments. For clarity, we do not discuss it more in this sub-Section.

The shipments of control-materials bags were to be fumigated ‘as usual.’ This means planned fumigations before ocean shipping for each shipment and during storage for any shipments in a

warehouse with a scheduled, warehouse-wide fumigation. This also means un-planned fumigations during storage, either when a shipment or the entire warehouse gets infested to the point of needing a fumigation. The treatment materials were not to be fumigated (unless they became infested to the point of needing a fumigation, which had to be reported). Like the other treatment shipments, the shipments of lined containers were not to be fumigated during shipping when the plastic lining was affecting quality, but were to be fumigated 'as usual' during storage when the lining was no longer affecting quality. Specifications for each material given during the contracting process are available in **Table A1**.

We used two sizes of bags:

1. Control-size bags—50 or 25 kilograms. Control-size polypropylene-based bags for yellow split peas and sorghum are 50 kilograms, and paper-based bags for corn soy blend plus are 25 kilograms.
2. Large bags—1000 kilograms. Many industries use these large, 1000-kilogram bags to improve handling efficiency.

The contents of these large bags were re-bagged into 50- or 25-kilogram bags on arrival at the overseas warehouse. Specifications for each size given during the contracting process are also available in **Table A1**.

The experiment resembled a standard food assistance procurement. USAID and USDA issued solicitations for each shipment. Six commodity suppliers placed 85 bids and several ocean carriers likewise placed bids. Four suppliers and three carriers received awards for 46 shipments. Each shipment was then filled at one of four plants or at a coastal warehouse, containerized at one of four American ports, and transported on one of seven ships. Two warehousing companies – under an existing contract with USAID that was amended for the experiment – stored the shipments abroad for three months.

Treatment or control packaging was assigned to each shipment before solicitations were issued; firms needed to know which shipments corresponded to which packaging because they had to buy, fill, and handle that packaging.

### 3.2 Dependent Variables

To evaluate food quality we use three variables. These variables were measured for each shipment by USDA in the United States before shipping ($t=0$), and again overseas by a USAID contractor on arrival ($t=1$) and after three months of storage ($t=2$). The first quality variable is a shipment's insect infestation status, which is a binary measure for each shipment determined by visual inspection by an expert. Infestation status was assessed by randomly measuring with a probe ten bags plus two percent of the total bags in the shipment; that rule of thumb is from entomology and mycology. The second quality variable is the change in percent moisture content for each shipment between before shipping and on arrival, and between before shipping and after storage. Percent moisture content was reported as an

average of the measured bags in the shipment. Percent moisture content was assessed using the same rule of thumb to sample bags. The third quality variable is the number of torn bags after unloading the container on arrival. The number of torn bags for each shipment was determined by observing all bags in the shipment being unloaded from the container. Details about these data, including potential biases and missing data, are presented in **Table A2**.

To evaluate cost we use four variables. The cost variables are the shipment's contracted commodity, freight, and warehousing costs, and the sum of those three costs—the shipment's total contracted cost. These costs were documented in USAID and USDA procurement records. Details about these data, including potential biases and missing data, are presented in **Table A3**. Shipment cost is presented per metric ton.

To evaluate timeliness we use three variables. The first timeliness variable is the number of days a shipment remains in fumigation, which is counted before shipping ($t=0$), on arrival ($t=1$), and during storage ($t=1$ to $t=2$). These data rely on USAID contractors reporting any fumigations. Infestation does not always require fumigation. Similar to determining infestation, declaring that fumigation is needed requires judgement of an expert. These are subjective measures, but the study's goal is to understand how packaging affects infestation and fumigation as they are defined in practice. The remaining two timeliness variables are the number of days the USAID warehouses spend re-bagging on arrival ($t=1$) large bags into small bags for distribution, as well as re-bagging on arrival ($t=1$) small torn bags into small untorn bags. These data rely on estimates from the USAID warehouses. Details about these data, including potential biases and missing data, are presented in **Table A4**.

We use these quality and timeliness measures because they are of concern to USAID and humanitarian organizations like the UN World Food Programme.

### 3.3 Independent Variables

The explanatory variables of interest are packaging material and packaging size. Other independent variables are commodity, US load port, destination, and base material (i.e., paper or polypropylene). We identify these variables for our analysis from USAID and USDA shipment records and procurement records.

One set of independent variables that we do not use is combinations of factors—packaging material, packaging size, commodity, destination, and/or base packaging material. Analysis along these lines could provide useful commodity- or destination-specific insights about packaging. We do not present results using those variables though, because such a granular analysis is not useful with our moderately sized study. Analysis with these independent variables is available on request from the authors.

### 3.4 Qualitative information

To help interpret these experimental results, we administered semi-structured interviews with individuals from 17 firms, ports, and humanitarian organizations in the United States, Djibouti and Ethiopia (which serve the Horn of Africa), and South Africa (which serves Southern Africa). We selected those respondents because they often participate in the US food aid supply chain. With each organization, we toured their facilities and traced their filling and/or handling processes, documenting labor, machinery, and throughput rates at each step. The interview guide is available in **Table A6**. We also had unstructured key informant conversations with individuals from divisions, services, and missions in USAID and USDA; packaging suppliers and fumigation providers; and agricultural associations. Just within USAID and USDA, the pilot involved getting feedback from and working with over 30 individuals. These interviews and conversations are crucial for interpreting the practical significance of results, as we are working with a relatively small number of shipments. A full list of respondents is given in **Table A5**. Finally, we reviewed key documents that set standards for and describe food quality in in-kind programs (e.g., USDA 2013c, 2014, 2015; WFP 2019b). We refer to this qualitative data throughout our results and discussion.

### 3.5 Analyses Sample

We initially proposed a balanced experiment made of 180 shipments. Each shipment was composed of a unique combination of one of five materials; one of two sizes; one of three commodities; one of two shipping methods; and one of three destinations. In other words, this was a 5x2x3x2x3 factor design. This initial design was balanced, meaning that it was made up of all 180 possible combinations of levels across factors. This initial design had no replicates, meaning that no combinations were duplicated. Each combination was made up of a material treatment, a size treatment, a shipping method, a commodity, and a destination. The first row of **Table 1** shows this design.

We tendered 60 shipments, reflecting a balanced 5x2x3x1x2 factor design with no replicates. We revised the design with USAID and USDA from 180 shipments to 60 shipments, because many of the initially proposed shipments were not feasible, such as using bulk shipping for shipments of 100 metric tons of a commodity when the minimum size for bulk shipments is often 5,000 metric tons. The second row in **Table 1** shows this change.

Next, 46 shipments were awarded. The experiment changed from 60 to 46 shipments because while tendering we learned that one packaging material was not available in the United States, and that no corn soy blend plus suppliers bid on one size-material combination. Semi-structured interviews with commodity suppliers show that size-material combination would have required the corn soy blend plus suppliers, but not sorghum and yellow split pea suppliers, to buy a new machine for their filling line. Thus, the experiment became a 4x2x3x1x2 factor *un*balanced design with no replicates. The third row in

**Table 1** shows this change. The cost analysis is based on these 46 awarded shipments and, because it is based on procurement records, there is no missing data.

During the shipping process, the next step of the experiment, we learned that 10 shipments of large bags of corn soy blend plus could not physically be filled. We substituted those 10 shipments with shipments of (mostly) the same material type in the control-size bag to maintain a degree of balance across material types for analysis. Thus, the experiment that was procured, shipped, and stored reflects a 4x2x3x1x2 factor unbalanced design with some replicates. This design differs from the initial design, which was balanced and had no replicates. The fourth row of **Table 1** summarizes this change. The quality analyses are based on these 36 unique shipments and 46 total shipments; there are some randomly missing data, and in Djibouti no large bags were measured after storage due to a contractor's error.

**Table 1: Design of Experiment**

| | | Material | Size | Commodity | Shipping Method | Destinations | Reason(s) for Change | Unique Shipments | Replicated Shipments | Balance in Design | Replicates in Design |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | Program-wide | 1 | 1 | >15 | 2 | >50 | - | >1,500 | 0 | Y | N |
| 1 | Start of Design | 5 | 2 | 3 | 2 | 3 | - | 180 | 0 | Y | N |
| 2 | End of Design | 5 | 2 | 3 | 1 | 2 | Selected commodities not used in Malaysia. Bulk shipping only available for sorghum; not cost-effective in such small quantities. | 60 | 0 | Y | N |
| 3 | End of Tendering | 4 | 2 | 3 | 1 | 2 | One material not available in US. No corn soy blend plus suppliers bid on one material. | 46 | 0 | N | N |
| 4 | End of Shipping | 4 | 2 | 3 | 1 | 2 | Cannot physically fill large bags with corn soy blend plus. | 36 | 10 | N | Y |

*Notes*: US load port is omitted in this table because it is a noise factor; we could not specify the load port through which a shipment passes.

### 3.6 Analyses methods

This study uses a randomization test to analyze the effect of packaging material or size on shipment quality, cost, and timeliness. A non-parametric approach, randomization is a common test to use with data from factorial experiments. An approximate randomization test shows the likelihood of observing a test statistic for a level relative to an empirical distribution of test statistics for that level (Montgomery 2017: 39). The distribution is generated by randomizing the order of the outcomes for all levels and recalculating the test statistic for that level many times (Montgomery 2017: 39). The null hypothesis under this randomization test is that the test statistic and the mean of the randomization distribution are the same. For a two-sided test, the p-value is the percentage of test statistics from the randomization distribution that are as-or-more extreme than the actual test statistic. It is valid to use randomization tests on unbalanced designs, though an unbalanced design is less powerful for randomization tests than a balanced design. In other words, it is more difficult to detect any effects when using this test on an unbalanced versus a balanced design.

We operationalize this test by calculating means of shipment quality, cost, and timeliness outcomes by packaging material and by packaging size. Our null hypotheses are that a packaging material or size has no effect on a shipment quality, cost, or timeliness measure. We randomize the observed outcomes for these measures $1x10^4$ times, each time calculating new means by packaging material and by packaging size to generate a distribution of means for each material and size. An exact test would consider the 46! possible permutations of observed outcomes; we use an approximate test with $1x10^4$ randomly generated permutations of the observed outcomes. Next, we calculate the probability of observing the actual means for each level given the distributions of means, and report a p-value that is the share of that distribution that is as-or-more extreme than the actual mean. We use a two-sided test, i.e., if 0.01 or 0.99 percent of sampled means from the randomization are smaller than the actual mean, we would report a p-value of 0.02.

### 3.7 Considerations in experimental design

In selecting a unit of analysis, we navigated a trade-off between doing what was practical to implement and observing the treatment effect over time and scale. Our a unit of analysis is a shipment of 20 metric tons of food. It was practical, since it was large enough to be procurable and shippable at standard costs. It was also practical since it was small enough such that the losses would be minimized if, for instance, one material ruined the food. The disadvantage of just 20 metric tons was that we did not observe learning and scale effects that several and larger shipments may have provided: firms may get better at new processes, affecting quality, and may invest in machinery to do them more efficiency, affecting cost. Lentz *et al.* (2013b), evaluating a local and regional procurement pilot, also note that a similar lack of scale may affect their results.

Selecting a useful but ethical control was another challenge. We could not have (and should not have) sent shipments with no fumigation, which have been be the equivalent of giving no food in an evaluation of recipient wellbeing. The unfumigated commodities would have become inedible—and all shipments were destined for distribution to beneficiaries. Rather, we let the most useful comparison for decision makers guide our choice of a control: USAID needed information to choose between what they were doing at the time (shipments of fumigated materials) and alternative options (shipments of treatment materials).

## 4. Results

### 4.1 Shipment Quality

For infestation, change in moisture content and torn bags, we test the null hypotheses that each packaging material or size does not affect these outcomes. Results are reported in **Table 2** and graphs of these data are presented in **Figure A1**.

The first set of rows of **Table 2** shows that moisture content varies significantly with packaging sizes but not with packaging materials. Supplier interviewees and key informants report that a one percentage point change in moisture content is substantial. The moisture content of shipments of control-size bags significantly decreased 0.37 percentage points from before shipping to on arrival, and decreased 0.12 further from on arrival to after storage.

The moisture content of shipments of large bags significantly decreased 0.06 percentage points between before shipping and on arrival, and then significantly increased 0.61 percentage points between on arrival and after storage. Re-bagging shipments of large bags into control-size bags just after arrival may be responsible for the increased moisture content, since the food can aerate during re-bagging. Re-bagging machinery, which interviewees citied not having, could speed up re-bagging. For example, after re-bagging and then storage in Durban—the more humid destination—the average moisture content in sorghum shipments in control-size bags is 12.60 percent, and the average for sorghum shipments in large bags is 12.78 percent. Sorghum should have a moisture content of about 12.00 percent or less for storage of one to two months (Sadaka & Bautista, 2014; McNeill & Montross, 2003; ASAE, 2002).

The next set of rows in **Table 2** shows that the count of torn bags per shipment does not vary significantly with packaging size, though it does with packaging material. Shipments of control-size bags have moderately more torn bags. Probing this result, we find that it is shipments of the control-size paper-based bags, not the control-size polypropylene-based bags, that tear so often. Interviewees at USAID warehouses cite using laborers instead of forklifts to unload containers with control-size bags, which may lead to tearing. Since there are 20 or 40 times more bags in shipments of control-size bags than of large bags, we also consider the total kilograms in torn bags per shipment. Shipments of large bags have more

kilograms in torn bags. We also see that shipments of lined bags have significantly fewer torn bags; these bags are likely stronger.

**Table 2: Quality and New Packaging**

| | | Material Treatment | | | | Size Treatment | |
|---|---|---|---|---|---|---|---|
| Measure | Analysis | Control (WPP/MWP) | Biopesticide applied | Liner inserted | Liner hung | Control (25/50kg) | Large (1000kg) |
| | Tendered N | 12 | 12 | 12 | 12 | 24 | 24 |
| | Shipped N | 16 | 12 | 8 | 10 | 30 | 16 |
| Moisture content Δ | Mean | -0.24 | -0.36 | -0.18 | -0.23 | -0.37 | -0.06 |
| per shipment | P-value | 0.89 | 0.37 | 0.64 | 0.75 | 0.03 | 0.04 |
| t=1-0 | Measured | 15 | 12 | 8 | 10 | 29 | 16 |
| Moisture content Δ | Mean | 0.09 | -0.10 | -0.06 | 0.14 | -0.13 | 0.61 |
| per shipment | P-value | 0.60 | 0.43 | 0.67 | 0.50 | 0.00 | 0.02 |
| t=2-1 | Measured | 14 | 10 | 6 | 8 | 30 | 8 |
| Torn bags | Mean | 0.94 | 1.25 | 0.00 | 1.40 | 1.37 | 0.19 |
| per shipment | P-value | 0.95 | 0.63 | 0.00 | 0.56 | 0.10 | 0.06 |
| t=1 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Kg in torn bags | Mean | 23.44 | 125.00 | 0.00 | 230.00 | 39.17 | 187.50 |
| per shipment | P-value | 0.49 | 0.71 | 0.00 | 0.31 | 0.20 | 0.21 |
| t=1 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Infestation | Percent | 6% | 33% | 38% | 30% | 10% | 50% |
| of shipment | P-value | 0.04 | 0.66 | 0.51 | 0.99 | 0.02 | 0.05 |
| t=1 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Infestation | Percent | 0% | 0% | 0% | 13% | 0% | 13% |
| of shipment | P-value | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.33 |
| t=2 | Measured | 14 | 10 | 6 | 8 | 30 | 8 |

*Source*: USAID monitoring and evaluation contractor.
*Notes:* Woven polypropylene bags (WPP) and multi-wall paper bags (MWP).
*Notes* (torn bags): No bags were torn between *t=1* and *t=2*, because they were untouched. Measuring

kilograms in torn bags is equivalent for the purposes of the randomization test to the percent of torn bags per shipment.

The final set of rows of **Table 2** shows that shipments of control-material bags are moderately un-infested on arrival and all shipments (but those with liners hung) are significantly un-infested after storage. We also find that shipments of control-size bags are significantly un-infested on arrival and after storage.

### 4.2 Shipment Cost

We test the null hypotheses that each packaging material or size does not affect cost. **Table 3** contains the cost analysis results**.** Graphs of these data are presented in **Figure A2**.

The first set of rows shows that the total contracted cost of shipments does not vary significantly with treatment materials or sizes. Our conversations with key informants suggest that while we do not detect an effect on the total contracted cost, different materials and sizes likely drive costs at different stages of the supply chain. For this reason, the next three sets of rows present the individual commodity, freight, and warehousing contracted costs. However, we still detect no significant effect of any packaging material or size on cost. This is not to say that packaging does not affect cost. Instead, key informant conversations also suggest that the commodity and freight contracted costs are noisy because of the load port's effect on cost, which makes the (slighter) effect of packaging on cost difficult to detect.

The variation in costs is, however, directionally consistent with what key informant conversations suggested that we would find. In particular, the data hint at two key trade-offs.

First, using a more expensive new packaging material that is bought under the commodity contract offsets fumigation costs that occur under the freight and warehousing contracts. For example, consider shipments of polypropylene-based control-size bags, which is the base-material and size used in more than 90 percent (by weight) of USAID's shipments. Shipments of that type of bag with a biopesticide applied cost $438.52 per metric ton under the commodity contract, while shipments of that type of bag made only of the control material cost $15.94 *less* per metric ton under the commodity contract. But shipments of that type of bag with a biopesticide applied have a total contracted cost of $618.86 per metric ton, while shipments of that type of bag made of the control material have a total contracted cost of $16.84 *more* per metric ton.

These contracted commodity costs, which include sourcing bags, are generally consistent with quotes from bag suppliers. For example, consider the case of polypropylene-based bags. Sourcing control-size bags with a biopesticide applied costs $0.02 more per bag (or $0.40 more per metric ton) than

control-material bags, and sourcing bags with a liner inserted costs $1.58 more per bag (or $31.06 more per metric ton). Procuring a large bag costs roughly $9.00 per metric ton, plus an extra estimated $9.20 per metric ton for the control-size bags for re-bagging.

**Table 3: Cost and New Packaging**

| | | Material Treatment | | | | Size Treatment | |
|---|---|---|---|---|---|---|---|
| Measure | Analysis | Control (WPP/MWP) | Biopesticide applied | Liner inserted | Liner hung | Control (25/50kg) | Large (1000kg) |
| | Tendered N | 12 | 12 | 12 | 12 | 24 | 24 |
| | Awarded N | 12 | 12 | 10 | 12 | 22 | 24 |
| Total cost ($/metric ton) | Mean | 655.60 | 664.28 | 670.82 | 678.22 | 668.48 | 665.79 |
| of shipment | P-value | 0.83 | 0.90 | 0.73 | 0.82 | 0.85 | 0.85 |
| t=0, t=1, t=2 | Measured | 12 | 12 | 10 | 12 | 22 | 24 |
| Commodity cost ($/metric ton) | Mean | 461.81 | 485.95 | 479.92 | 462.87 | 471.93 | 472.69 |
| of shipment | P-value | 0.83 | 0.86 | 0.42 | 0.52 | 0.77 | 0.77 |
| t=0 | Measured | 12 | 12 | 10 | 12 | 22 | 24 |
| Freight cost ($/metric ton) | Mean | 180.56 | 167.07 | 179.00 | 201.95 | 186.88 | 178.06 |
| of shipment | P-value | 0.79 | 0.45 | 0.76 | 0.19 | 0.61 | 0.60 |
| t=1 | Measured | 12 | 12 | 10 | 12 | 22 | 24 |
| Warehousing cost ($/metric ton/3mo) | Mean | 12.14 | 10.22 | 11.01 | 12.14 | 8.78 | 13.79 |
| of shipment | P-value | 0.45 | 0.30 | 0.55 | 0.29 | 0.00 | 0.00 |
| t=2 | Measured | 12 | 12 | 10 | 12 | 22 | 24 |

*Sources* (commodity cost): USDA procurement records, which typically include the commodity, packaging, inland (domestic) freight, and fumigation costs.
*Sources* (freight cost): USAID procurement records, which typically include the ocean freight, port handling, and fumigation costs.
*Sources* (warehousing cost): USAID-contracted warehouse managers reported fumigation costs and re-bagging costs. Warehousing cost in Djibouti and Durban are from Djibouti Free Zone Authority and the South African Department of Trade and Industry.
*Notes:* Woven polypropylene bags (WPP) and multi-wall paper bags (MWP).

Second, efficient domestic warehouse handling and container loading for shipments of large bags under the freight contract is nearly offset by the cost of container un-loading and manually re-bagging their contents into control-size bags under the warehousing contract. The freight contracted costs that reflect the efficiency from mechanized handling in the United States point toward, with additional investments in handling and re-bagging machinery at overseas warehouses, warehousing contracted costs decreasing. Based on interviews, on average handling and re-bagging abroad occurs at a rate of 5.41 50-kilogram bags per minute and requires seven laborers; in the United States, bagging relies on some simple machines and three to four laborers, and rates are about 10 bags per minute.

**4.3 Shipment Timeliness**

For timeliness, we test the null hypotheses that each packaging material or size does not affect timeliness. Summary statistics of timeliness are reported in **Table 4.**

**Table 4** shows that shipments of control-material bags spend significantly fewer days in unplanned fumigations, but spend significantly more days in planned fumigations. The trade-off among materials between time in fumigation and the degree to which that fumigation can be planned for must be weighed by donors and humanitarian organizations. **Table 4** also shows that shipments of large bags (re-bagged because of their size) spend significantly more days being re-bagged: a shipment of large bags takes 2.92 working days to be re-bagged.

**Table 4: Timeliness and New Packaging**

| | | Material Treatment | | | | Size Treatment | |
|---|---|---|---|---|---|---|---|
| Measure | Analysis | Control (WPP/MWP) | Biopesticide applied | Liner inserted | Liner hung | Control (25/50kg) | Large (1000kg) |
| | Tendered N | 12 | 12 | 12 | 12 | 24 | 24 |
| | Shipped N | 16 | 12 | 8 | 10 | 30 | 16 |
| Fumigation days | Mean | 5.00 | 0.00 | 0.00 | 0.00 | 2.00 | 1.25 |
| of shipment | P-value | 0.00 | 0.00 | 0.00 | 0.00 | 0.46 | 0.10 |
| t=0 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Fumigation days | Mean | 0.00 | 0.83 | 1.25 | 1.00 | 0.50 | 0.94 |
| of shipment | P-value | 0.00 | 0.92 | 0.50 | 0.83 | 0.22 | 0.67 |
| t=1 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Fumigation days | Mean | 2.19 | 0.00 | 0.00 | 3.00 | 1.50 | 1.25 |
| of shipment | P-value | 0.28 | 0.00 | 0.00 | 0.05 | 0.75 | 0.17 |
| t=1 to t=2 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Total fumigation days | Mean | 7.19 | 0.83 | 1.25 | 4.00 | 4.00 | 3.44 |
| of shipment | P-value | 0.00 | 0.01 | 0.00 | 0.95 | 0.64 | 0.31 |
| t=0 to t=2 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Re-bagging days | Mean | 0.73 | 0.97 | 1.46 | 1.17 | 0.00 | 2.92 |
| of shipment (large) | P-value | 0.35 | 0.81 | 0.60 | 0.88 | 0.00 | 0.00 |
| t=1 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Re-bagging days | Mean | 0.00 | 0.03 | 0.00 | 0.05 | 0.01 | 0.05 |
| of shipment (torn) | P-value | 0.34 | 0.66 | 0.00 | 0.34 | 0.20 | 0.21 |
| t=1 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |
| Total re-bagging days | Mean | 0.73 | 1.00 | 1.46 | 1.22 | 0.01 | 2.96 |
| of shipment | P-value | 0.36 | 0.98 | 0.61 | 0.69 | 0.00 | 0.00 |
| t=1 | Measured | 16 | 12 | 8 | 10 | 30 | 16 |

*Notes* (fumigation days): Fumigations at *t=0* were planned and shipments were not fumigated because of any observed infestation; fumigations at *t=1* were un-planned, with shipments fumigated because of observed and extreme infestation; fumigations at *t=2* were planned, in that the shipments in the study were not infested but the entire warehouse was being fumigated because of other infested shipments.
*Sources* (fumigation days): Fumigations at *t=0* were documented through contracting records; fumigations at *t=1* and from *t=1* to *t=2* were reported by USAID-contracted warehouse managers. The warehouse managers and USAID staff report that fumigation takes between three and seven days; we use five days.
*Notes* (re-bagging days): Re-bagging at *t=1* was planned for large bags, but not for torn bags.
*Sources* (re-bagging days): USAID-contracted warehouse managers report re-bagging occurs at rates of 1 minute to fill one 50 kg bag in Djibouti and 6 minutes to fill one 50 kg bag in Durban. We assume a working day is eight hours.
*Notes:* Woven polypropylene bags (WPP) and multi-wall paper bags (MWP).

## 5. Policy Implications

This paper has two main objectives. First, to present the extent to which packaging affects shipment quality, cost, and timeliness, proposing packaging and, in particular, biopesticide bags and possibly large bags as useful tools in the modernized in-kind toolbox. Second, to conceptualize three tests that should be used to evaluate a tool, such as packaging. This study more broadly has the objective of changing the bags used in US in-kind food assistance, and we conclude this Section with a summary of initial steps that have been taken because of these results. Throughout this section we propose directions for future research.

### 5.1. Test 1: To what degree does the tool work?

When any tool is considered for the in-kind food assistance toolbox, the first test used to evaluate the tool is whether it is effective and/or efficient in at least some situations. In short, to what degree does a tool work? Food policy literature and practice offers a basis for how to measure if a tool works, which, as noted above in the Data and Methods Section, focuses on evaluating shipment and recipient outcomes. This test is applied to any tool, ranging from interrogating shipment quality in local and regional procurement (e.g., Harou *et al.*, 2013; USGAO, 2009) to targeting effectiveness in cash and voucher programs (e.g., Burchi *et al.*, 2018; Handa *et al.*, 2012; WFP-UNHCR, 2013).

In applying this first test, studying the gains from new packaging relative to gains from other tools suggests that to modernize packaging is to work on the margin. The most promising cost and timeliness improvements from packaging come from shipments of control-size polypropylene-based bags with a biopesticide applied. Those shipments cost $16.84 per metric ton less and spend 6 fewer days in fumigation than shipments of the control-size and -material polypropylene-based bags. In contrast, cost gains from locally and regionally procured cereals and pulses are $432.41 and $259.07 per metric ton, respectively (Lentz *et al.*, 2013b). Timeliness gains from pre-positioning and local and regional

procurement are ten and fourteen weeks, respectively (Lentz *et al.*, 2013b; USGAO, 2014). Those tools' gains, measured in dollars or days per metric ton shipped, are an order of magnitude larger than packaging's gains. The difference is consistent with the fact that changing the packaging in which food is shipped is a modest adjustment that requires no new statutes and is less politically charged, as compared to a major change such as procuring locally and regionally.

**5.2. Test 2: In what situations does the tool work?**

We argue that the second test to evaluate a tool should be determining the full range of situations in which the tool is effective and/or efficient. The basis for this test comes from the supply chain management literature.

In supply chain management, segmentation is the notion that different situations – different customers, products, and supplies – often require different supply chains. A supply chain that is designed for particular customers, products, and supplies will be more effective and efficient than a "one-size-fits-all" supply chain (Protopappa & Thonemann, 2017). Segmenting the supply chain by customer (e.g., Gattorna *et al.*, 1991) can mean differentiating it for recipients that have emergency or programmatic needs. Segmentation by product (e.g., Fisher, 1997) can mean partitioning the supply chain into one for therapeutic/fortified foods and one for commodities. Segmentation by supply (e.g., Dyer *et al*., 1998) can be sourcing from local, regional, international, or prepositioned inventories. Our second test comes out of the observation that new tools almost always segment the supply chain, and so it is necessary to evaluate the range of situations in which a tool work. Some good tools that are carefully tailored to customer, product, or supply only work in or are appropriate for a few situations.

In applying this second test, reviewing the gains from new packaging relative to gains from other tools better shows how modernized packaging is a helpful tool. Packaging is useful in most situations. About 90% (by weight) of domestically-bought food assistance can be packaged in polypropylene-based bags with a biopesticide applied, so the modest timeliness and cost per metric ton gains can accrue over a large share of US-sourced assistance.

Applying this second test, local and regional procurement and prepositioning are still more powerful tools than packaging, although they are relatively less powerful when viewed through the lens of this test. Within the American food assistance system, an estimated half of all food assistance (by value) is locally and regionally procured and one fifth (by weight) of domestically-bought food assistance is prepositioned. For example, prepositioning is an estimated 16-fold more timely per metric ton compared with new packaging, though considering the share of the US-sourced supply chain that each intervention affects, prepositioning is an estimated three-fold more timely compared to new packaging.[3] **Table 5** summarizes these tools, the share of assistance they affect, and their gains.

The policy implication of this second test is that donors and humanitarian organizations must experiment with tools that are less powerful but broadly applicable, and thus have substantial aggregate effects on the supply chain. The implication for research is that systematically estimating and comparing the aggregate effects of tools is needed in order to identify new program and supply chain designs.

**Table 5: Packaging and Other Tools**

| Tool | Primarily Changed | Cost gains per metric ton | Timeliness gains per shipment | Share of supply chain |
|---|---|---|---|---|
| Local and regional procurement | Where food is bought | $432.41/MT (cereals)<br>$259.07/MT(pulses) | 10 weeks | 52% (by value of all American assistance) |
| Prepositioning | When food is bought | NA | 14 weeks | 19% (by weight of US-sourced American assistance) |
| Packaging<br>(Bag with biopesticide applied) | In what food is shipped | $16.84/MT (cereals and pulses) | 0.85 weeks | 90% (by weight of US-sourced American assistance) |

*Sources*: Data on cost and timeliness for local and regional procurement from Lentz *et al.* (2013b) and prepositioning from USGAO (2014). Share of the total network funded by the U.S. International Disaster Assistance mechanism for FY2017, which includes local and regional procurement (including cash programming), is from the Food Aid Consultative Group Fall 2017 meeting; share of the in-kind network that passes through the prepositioning system is reported by Food for Peace for FY2016; and share of the in-kind network that can be packaged in polypropylene-based bags with a biopesticide applied is estimated by us, using FY2016 shipment data provided by Food for Peace.

### 5.3 Test 3: To what extent does the tool work well with other tools?

We argue that, as the toolbox fills, the third test should be: to what extent does the tool in question work in complementary—or conflicting—ways with other tools? This question is increasingly relevant as the toolbox fills. Already, Lentz *et al.* (2013b) indirectly consider it: analyzing how local and regional procurement interacts with a therapeutic food, they show that it is not always cost-effective to regionally procure a fortified milled product. Again, the supply chain management literature offers a basis for this test.

Segmenting the supply chain along more than one line can be helpful (e.g., Christopher & Towill, 2002; Aitken *et al.*, 2005; Childerhouse *et al*., 2002). Yet segmentation, especially along several lines, can

produce a complex supply chain that is less flexible, transparent, and predictable. With the proliferation of food assistance tools that each further segments the supply chain, the mid- to late-century supply chain of almost-interchangeable commodity shipments from North Atlantic countries is no longer. Instead, each tool requires pulling program and supply chain levers – funding sources and legal biases; bi- and multi-lateral transfers; supplier and transporter sizes; ocean, sea, and air transportation methods; procurement locations and times; *en route* warehouses locations and shipment diversions; packaging materials and sizes; and more – that together make for an effective yet complex operation. Our third test comes out of the observation that new tools, and the degree of segmentation that each requires of the supply chain, are not always complementary to one another.

In applying this third test, we explore how the situations in which new packaging offers substantial and practical gains depends on the other tools in use. We consider the interaction of packaging and prepositioning (the main other tool in our study), local and regional procurement (a common tool), and cash and voucher programs (another common tool).

### 5.3.1 The case of prepositioning and packaging

Packaging and prepositioning are largely complementary. First, new materials like bags with a biopesticide applied can help ensure quality in prepositioned inventories. Prepositioned commodities are susceptible to infestation because of the duration of storage and the storage environment (USAID 2013a). Second, using new packaging for shipments to the few but high-throughput prepositioning warehouses can let USAID make large bags feasible and cost-effective. The several prepositioning warehouses are destinations for up to one fifth (by weight) of US-sourced assistance. Regulations in some countries restrict packaging sizes (and materials), for example preventing re-bagging of large bags from occurring at some ports, unless humanitarian exemptions are in place. Investing in machinery at warehouses may make large bags cost-effective across the supply chain, enabling the efficiencies accrued under the freight contract to also be accrued under the warehousing contract. For these reasons, prepositioning may also be practical for other bag sizes that are used in commercial contexts, such as 20,000-kilogram bags that essentially line a container.

Packaging—specifically large bags—and prepositioning operate in conflict in one crucial way. While prepositioning is a mechanism to store inventory closer to recipients, it is also a mechanism to get shipments into the ‘pipeline’ that are then available to divert to satisfy needs arising from sudden-onset emergencies. Over six years, 568 of 947 shipments destined for prepositioning warehouses were diverted to humanitarian organizations in dozens of recipient countries (USGAO, 2014). It would not be possible to satisfy regulatory and machinery requirements for large bags in all recipient countries on sudden notice, thus limiting the extent to shipments could be diverted. To partially avoid this issue, large bags

could be used in some but not all shipments to prepositioning warehouses, but further study would be needed to answer whether the added supply chain complexity is worth the cost savings.

### 5.3.1 The case of new modalities and packaging

We consider to what extent better packaging such as bags with a biopesticide applied works in complementary ways with cash and voucher programs or local and regional purchases. In general, the extent to which tools that work well in North Atlantic-sourced in-kind programs—improved packaging, regional inventories to respond to crises, fortified and therapeutic foods—can be used in conjunction with local and regional purchases or cash and voucher programs is an open and important issue. It is a challenge because donors and humanitarian organizations shape the cash, voucher, and local and regional procurement supply chains to a lesser degree than in-kind supply chains that start in North Atlantic markets.

We look to micronutrient fortification, another variety of food assistance that relies mainly on private supply chains, to consider how improved packaging can be introduced in programs where donors and humanitarian organizations only partially shape the supply chain. Both interventions require targeting the few and usually large upstream firms in the supply chain. Both interventions entail minor manufacturing adjustments. And both interventions are inexpensive, with, for example, iodine fortification costing $0.05 per person per year (Barrett 2002) and bag treatment costing $0.02 or about 4% more per 50-kilogram bag.

Donors and humanitarian organizations can use carrots and sticks to shape the supply chain. Incentivizing bag manufacturers, which has been done in fortification programs (Lentz & Barrett, 2013), may be one way to encourage treated bags. Regulating bag manufacturers may be another way to ensure treated bags, though while fortification has been required with firms such as mills and salt producers (Lentz & Barrett, 2013), regulation has not always worked (Barrett 2002). Technical assistance to the bag manufacturers would be a necessary part of any packaging intervention, though working closely with mills and salt producers to fortify foods has not always been possible in complex emergencies (Young *et al.,* 2004).

The policy implications of this third test is that as the number of tools grows, opportunity will be identifying points of intervention in supply chains (e.g., bag manufacturers) to arrange tools in complementary ways. This is particularly important for situations where donors and humanitarian organizations have limited ways to shape the supply chain. Future research should consider the conditions under which different tools work well together, and especially how tools that are helpful in North Atlantic-sourced in-kind programs can be helpful when used with new modalities.

## 5.4 Current and future program impact of packaging

We suggested that USAID, and more generally donors and humanitarian organizations, consider three packaging changes that would improve shipment outcomes. First, apply biopesticides to polypropylene-based bags and continue to fumigate shipments as needed, because taken together those adjustments are a cost-effective alternative to frequent fumigations. At the time of submission, there was a humanitarian shipment of wheat flour to the Middle East in bags with a biopesticide applied. Second, use large bags with shipments to select ports, conditional on machinery investments at those ports that make large bags clearly cost-effective across the supply chain. To allow diversions to continue to occur, only a share of the shipments could be sent in large bags. It is an open question for donors and humanitarian organizations whether that increase in supply chain complexity would overshadow any cost advantages of large bags. Finally, reconsider using paper-based bags, because they break more often than polypropylene-based bags. Some alternatives to paper-based bags were discussed at the second Michigan State University Food Aid Packaging Conference.

The natural next area for program design and research is the effect of packaging on recipient welfare and satisfaction outcomes. After all, any in-kind food transfer is of food and the packaging that holds it. Theoretically, packaging is an unnoted aspect of transfers in Sen's (1981) approach to food access, even though packaging works as an asset and affects production or exchange entitlements. Empirically, even though US food assistance programs alone distribute over 50 million bags per year, there is scant evidence on what recipients do with packaging and how it affects their satisfaction and wellbeing.[4] For instance, some of the vegetable oil tins that are used today are not designed to resist corrosion, which limits their reusability. With a better understanding of how packaging can improve welfare and satisfaction, bags that are not very efficient may become more attractive options. For instance, control-size lined bags are about $15.22 per metric ton more expensive than the control-size and -material bags. But the lining and the outer layer with the lined bags means that twice the material gets transferred to a recipient as compared to the control bags, which could be useful for recipients. Deliberately using packaging to support livelihoods is a natural way to link relief and resilience work (e.g., Pingali, Alinovi, and Sutton 2005). Future studies of new materials or sizes may even first identify packaging that best serves recipients, and work back through its impact on shipment cost, quality, and timeliness.

## 6. Conclusion

Major aspects of in-kind programs—what food is shipped, when and from where it is sourced—have been reformed in the past three decades to improve program effectiveness and efficiency. Packaging—the material in which food is shipped—is one of the last major aspects of food assistance programs that remains unstudied and underused. This study shows the extent to which packaging affects shipment cost, quality, and timeliness using a novel experimental study design. Shipments of biopesticide

bags with pulses and cereals may improve cost while improving timeliness relative to shipments of control-material bags. Large bags may reduce costs conditional on machinery investments that may make them cost-effective across the supply chain. Improving effectiveness and efficiency in food assistance programs as the toolbox fills will be conditional upon how well tools complement one another.

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**Appendix**

**1. Information about study design**

**Table A1:** Specifications of Tendered Packaging *(abbreviations explained below)*

| | Material | | | Size | | | Awarded | Shipped |
|---|---|---|---|---|---|---|---|---|
| | Base | Other | Control-material | Primary (kg) | Secondary (kg) | Control Size | | |
| 1 | WPP | - | X | 50 | - | X | X | X |
| | MWP | - | X | 25 | - | X | X | X |
| 2 | WPP | Liner | | 50 | - | X | X | X |
| | WPP | Liner | | 25 | - | X | | |
| 3 | WPP | Biopesticide | | 50 | - | X | X | X |
| | MWP | Biopesticide | | 25 | - | X | X | X |
| 4 | PE | - | | 50 | - | X | | |
| | PE | - | | 25 | - | X | | |
| 5 | WPP | Cont. liner | | 50 | 20,000 | X | X | X |
| | MWP | Cont. liner | | 25 | 20,000 | X | X | X |
| 6 | WPP | - | X | 1,000 | - | | X | X |
| 7 | WPP | Bag liner | | 1,000 | - | | X | X |
| 8 | WPP | Biopesticide | | 1,000 | | | X | X |
| 9 | WPP | Cont. liner | | 1,000 | 20,000 | | X | X |

*Notes:*

Woven polypropylene (WPP) bag (50 kg):

- Material: Made of woven polypropylene. The polymer in the fabric shall be 100 percent virgin polypropylene with no recycled material.
- Permeability: The bag in an unstressed state shall permit a minimum airflow of 3 cubic feet per minute per square foot and a maximum of 30 cubic feet per minute per square foot, when tested in accordance with ASTM Test Method D737, as amended.

Multi-wall paper (MWP) bag (25 kg):

- Material (two options):
    1. Made of 1 ply inner film liner guaranteed 2.5 mil. minimum thickness linear low density polyethylene, 4 plies of 50-pound natural multiwall kraft (NMK) paper, and 1 outer ply of 60-pound wet strength natural multiwall kraft (WSNMK) paper. The use of recycled materials is not required if performance or food safety is jeopardized.
    2. Made of 3.1 mil. (70 grams per square meter) film consisting of two or more layers of co-extruded polyolefin film with alternating angles of orientation, laminated together and biaxially oriented, two (2) plies of 50- pound NMK paper, and one (1) outer ply of 60-pound WSNMK paper. The bag shall be heat-sealed at the bottom, by the bag manufacturer. The top of the liner shall be heat-sealed by the packer once the bag has been filled with products. The use of recycled materials is not required if performance or food safety is jeopardized.
- Permeability: The bag shall not exceed a maximum average water vapor permeability of 0.65 grams per 100 square inches in 24 hours at 90 percent relative humidity and a temperature of 100 degrees F plus or minus 5 degrees.

Biopesticide (BP) applied:

- Material: Consist of insect growth regulator (e.g., S-Hydroprene (128966), S-Kinoprene (107502), Methoprene (105401), S-Methoprene (105402)).
- Application for MWP-based bags:
    1. Applied by flexographic printing.
    2. Applied by gravure printing.
    3. Applied by rod printing.
- Application for WPP-based bags:
    1. Applied as a coating as an externally laminated film
    2. Applied by incorporation into the fabric.

Polyethylene (PE) liner inserted:

- Material: Made of 78 μm or greater continuous sheet polyethylene. The polymer in the bag shall be 100 percent virgin high density polyethylene with no recycled material.
- Permeability: The liner should have an oxygen transmission rate at or below 3 cm3/m2/day as tested by ASTM D1434. A water vapor transmission rate at or below 4 g/m2/day as tested by ASTM E96.

PE container liner hung:

- Material: Made of a continuous sheet polyethylene that shall be 100 μm or greater. The polymer in the liner shall be 100 percent virgin high density polyethylene with no recycled material.

- Permeability: The liner should have an oxygen transmission rate at or below 3 cm3/m2/day as tested by ASTM D1434. A water vapor transmission rate at or below 4 g/m2/day as tested by ASTM E96.

PE bag:

- Material: Made of 150 μm or greater continuous sheet polyethylene. The exterior of bag shall be finished by coating or other suitable method to prevent slippage. The polymer in the bag shall be 100 percent virgin high density polyethylene with no recycled material.
- Permeability: The bag should have an oxygen transmission rate at or below 3 cm3/m2/day as tested by ASTM D1434. A water vapor transmission rate at or below 4 g/m2/day as tested by ASTM E96.

WPP (1000 kg) bag:

- Material: Made of 100 percent virgin polypropylene with no recycled material. Shall include a 2.5 mil. or greater thickness linear low-density polyethylene liner.
- Permeability: The bag in an unstressed state shall permit a minimum airflow of 3 cubic feet per minute per square foot and a maximum of 30 cubic feet per minute per square foot, when tested in accordance with ASTM Test Method D737, as amended.

**2. Information about data**

**Table A2:** Quality Data

| Measure | Infestation | | Moisture | | | Tearing |
|---|---|---|---|---|---|---|
| Time | On Arrival | After Storage | Before Shipping | On Arrival | After Storage | On Arrival |
| Runs Shipped | 36 | 36 | 36 | 36 | 36 | 36 |
| Replicates Shipped | 10 | 10 | 10 | 10 | 10 | 10 |
| Obs. Shipped | 46 | 46 | 46 | 46 | 46 | 46 |
| Obs. Measured | 46 | 38 | 46 | 45 | 38 | 46 |
| Type of measurement | Binary | Binary | Continuous | Continuous | Continuous | Discrete |
| Unit of measurement | Live insects | Live insects | % by wt. | % by wt. | % by wt. | Torn bags |
| Collection Method | Randomly measure 10 + 2%*X bags per shipment, X = total bags per shipment | | Randomly measure 10 + 2%*X bags per shipment, X = total bags per shipment | | | Measure all bags per shipment |
| Provided by | USDA via contractor | USAID contractor | USDA via contractor | USAID contractor | USAID contractor | USAID contractor |
| Standard Testing and Reporting Practice | Yes | No | Yes | No | No | Yes |
| Biases and missing data | Different thresholds for declaring infestation. | Large bags not measured in Djibouti. | - | One missing observation. | Large bags not measured in Djibouti. | Tears more obvious on the few large bags. |

**Table A3**: Cost Data

| Data Source | Commodity Contract | Freight Contract | Warehousing Contract | |
|---|---|---|---|---|
| | | | Standing | Amendment |
| Relevant Costs Included | Material, fumigation, handling | Material, handling, fumigation | Fumigation | Handling (i.e., re-bagging) |
| Runs Tendered | 60 | 60 | 2 | 2 |
| Runs Awarded | 46 | 46 | 2 | 2 |
| Replicates Awarded | 0 | 0 | - | - |
| Obs. Measured | 46 | 46 | 46 | 46 |
| Unit | $/metric ton | $ /metric ton | $/metric ton | $/metric ton |
| Collected by | USDA | USAID | MIT | MIT |
| Collected through | Tendering records | Tendering records | Self-reporting | Self-reporting |
| Biases and missing data | Firms may under-bid to win the contract to gain a first mover advantage with the new packaging. Firms may over-bid to buffer themselves from unanticipated expenses. | | Costs are self-reported. | |

**Table A4:** Timeliness Data

| Data Source | Fumigation in the US | Fumigation upon arrival | Fumigation during Storage |
|---|---|---|---|
| Reported by | Freight Contractor | USAID warehousing contractor | USAID warehousing contractor |
| Runs Observed | 46 | 46 | 46 |
| Biases and missing data | The USAID contractors may have under-reported the cases of fumigation, because it was not a part of their normal routine to report fumigation to a third party such as us. | | |

**Table A5:** Qualitative Data Collection

| | | Organization | Count | Organization | Count |
|---|---|---|---|---|---|
| | | Semi-structured interviews | | Key informant conversations | |
| US | | Milled commodity suppliers | 2 | USAID divisions | 2 |
| | | Pulse supplier | 1 | USDA services | 2 |
| | | Grain supplier | 1 | Ag. associations | 3 |
| | | Port warehouse | 2 | Packaging suppliers | 4 |
| South Africa | | Bulk port | 1 | Fumigation provider | 1 |
| | | USAID prepo. warehouse | 1 | M&E contractor | 1 |
| Ethiopia | North | PIO/PVO warehouse | 1 | - | - |
| | East | PIO/PVO warehouse | 1 | - | - |
| | Central | PIO/PVO warehouse | 2 | USAID mission | 1 |
| Djibouti | | Bulk port | 1 | M&E contractor | 1 |
| | | Container port | 1 | USAID mission | 1 |
| | | USAID prepo. warehouse | 1 | - | - |
| | | PIO/PVO warehouse | 2 | - | - |

**Table A6:** Interview Questionnaire

1. *Current Process*

Can you walk us through the current process that you use for a food aid shipment, noting the machinery, labor, and time involved at each step?

| | | Step 1 | Step 2 | … |
|---|---|---|---|---|
| Name of Step | | | | |
| Machinery | Description | | | |
| | Value | | | |
| | Unit | | | |
| Labor | Description | | | |
| | Value | | | |
| | Unit | | | |
| Time | Description | | | |
| | Value | | | |
| | Unit | | | |

2. *Introduce new packaging*

3. *Prospective changes to current process with new packaging*

Let's walk through each of the packaging types that we discussed. How do you expect it would change your processes, noting how machinery, labor, and time involved at each step may change?

| Tech | Process | Step 1 | Step 2 | … |
|---|---|---|---|---|
| Woven polypropylene bags (50kg) (If applicable.) | Describe | | | |
| | Capital | | | |
| | Labor | | | |
| | Time | | | |
| Multiwall paper bags (25kg) (If applicable.) | Describe | | | |
| | Capital | | | |
| | Labor | | | |

| | | | | |
|---|---|---|---|---|
| | Time | | | |
| Large bags (1,000kg) | Describe | | | |
| | Capital | | | |
| | Labor | | | |
| | Time | | | |
| Container with liner | Describe | | | |
| | Capital | | | |
| | Labor | | | |
| | Time | | | |
| 25kg and 50kg woven polypropylene bag with liner | Describe | | | |
| | Capital | | | |
| | Labor | | | |
| | Time | | | |

4. *Other questions*

How often do you run the line for food aid?

How many food aid contracts do you win per year?

Which of these new ten products looks most feasible? How large do you think its change would be relative to the others?

## 3. Graphical depiction of data

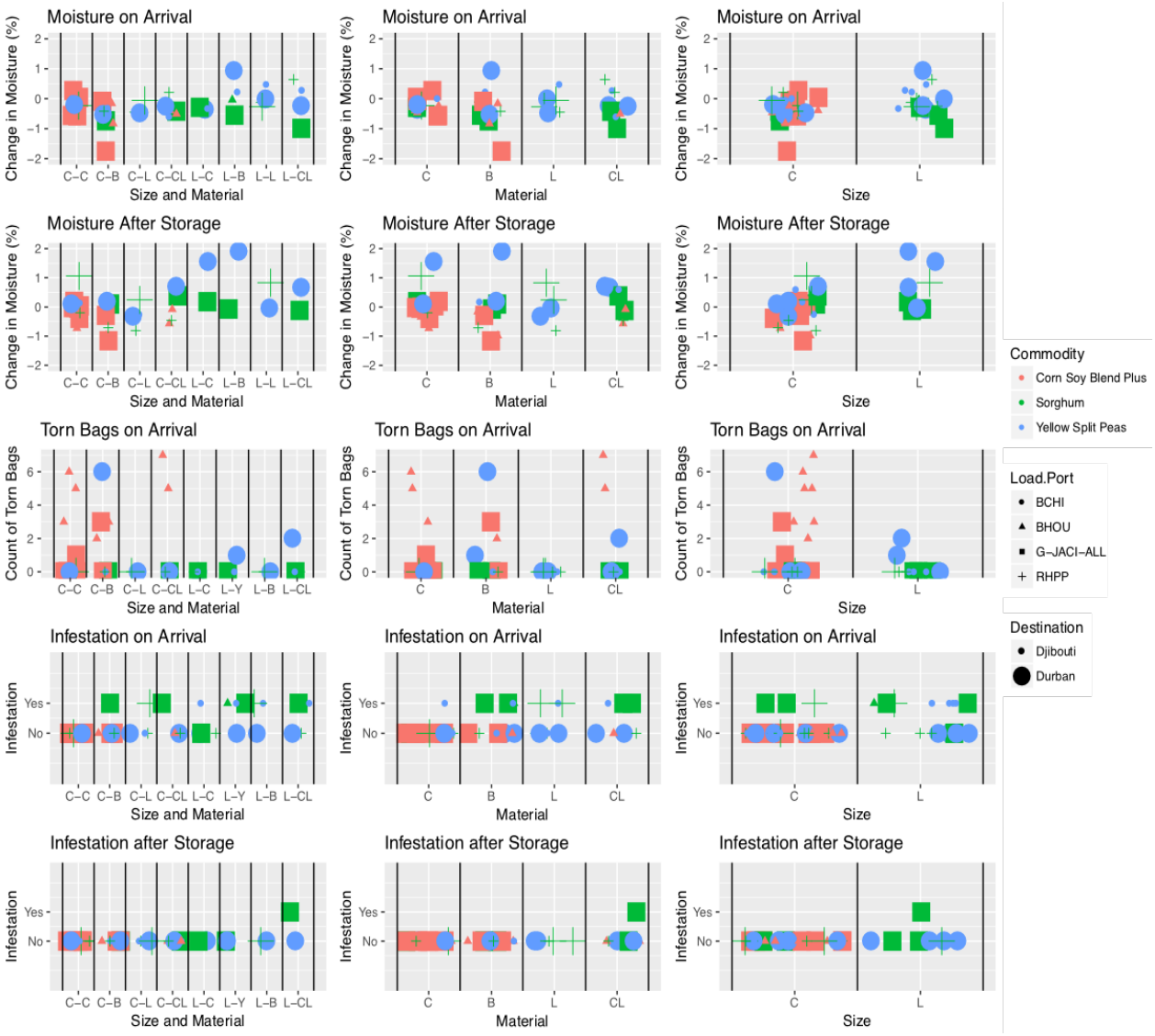


**Figure A1:** Quality Data by Material and Size

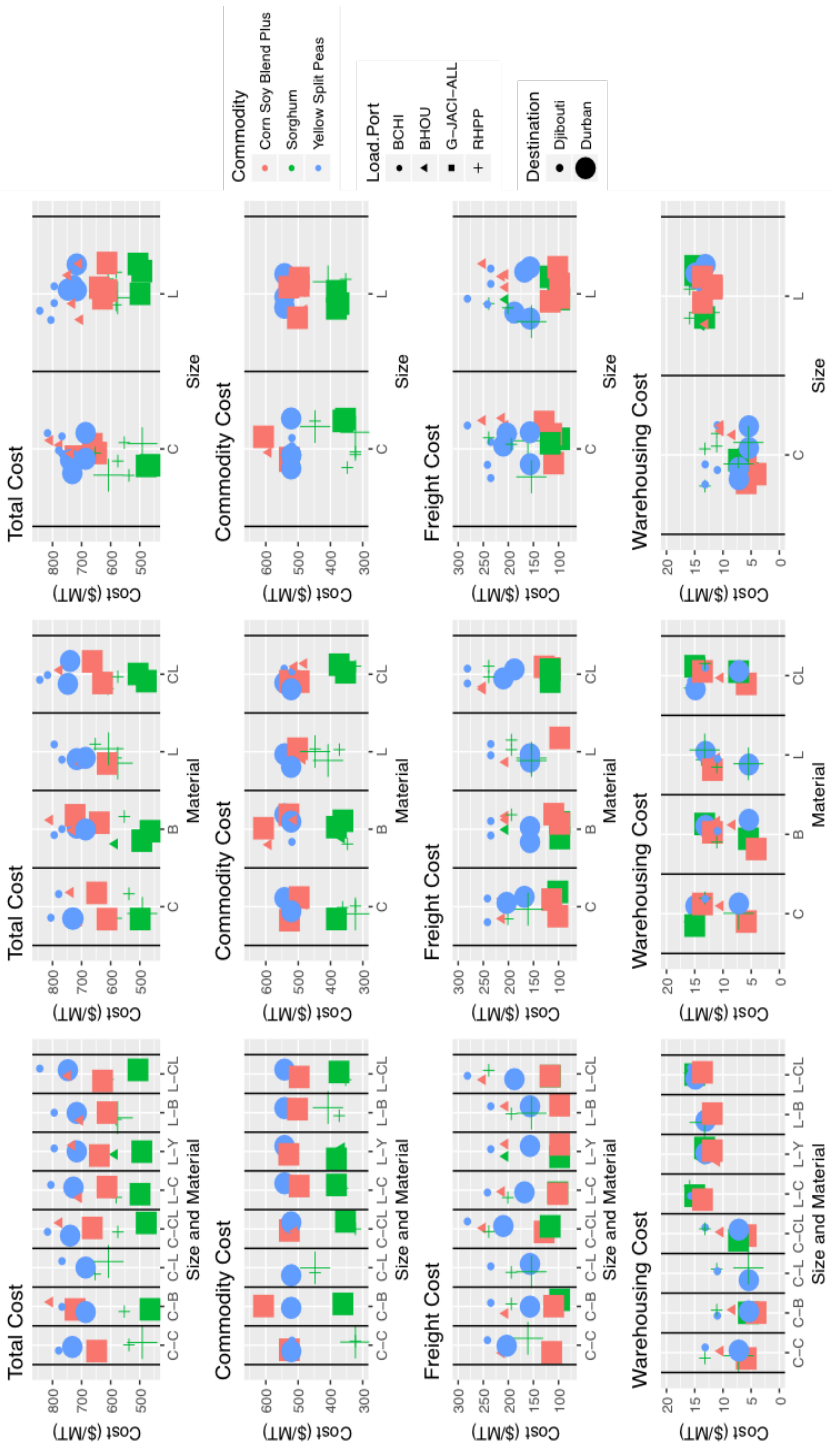


**Figure A2:** Cost Data by Material and Size

**End Notes**

[1] This comparison uses FY 2016 data furnished by USAID. First, it is based on the average procurement cost for all bulk and bagged wheats, sorghum, rice, and peas and lentils ($525) and shipping cost for all bulk and bagged shipments to Red Sea, South East Africa, and South East Asia ports ($142). Second, it uses a packaging cost of $0.46 per 50-kilogram bag, the bag used with 90 percent (by volume) of shipped commodities. And finally, it uses a fumigation cost of $2.05 per metric ton per application and two applications across the supply chain, based on the average cost of fumigation of three USAID-contracted warehouses and one estimate of the number of applications per shipment from USAID. This comparison and more generally this study does not consider how avoiding quality loss affects the cost-effectiveness of packaging. Here, we define quality loss as when food is disposed of because it is "unfit for human consumption" (USDA, 2018). While quality loss is an issue in any food supply chain, the quality, cost, and timeliness issues that primarily stem from fumigating bags and secondarily reconstituting bags are our main focus. Other forms of loss include diversions and theft. USAID indicates that all loss is about one percent (by weight) of shipped commodities (USAID, 2013) though does not specify what share of all loss is quality loss. One percent is on par with the loss observed in commercial supply chains. In general, there is limited evidence about loss in the food assistance supply chain (Barrett & Maxwell, 2005).

[2] In a report to USAID on the study that precedes this paper, we (1) analyze all shipments but those of corn soy blend plus, which makes results not quantitatively match those of the paper, and (2) use only descriptive statistics instead of a randomization analysis, which leads us to highlight different quality, cost, timeliness trade-offs, though which produces results qualitatively consistent with those which we report in this paper.

[3] The 16-fold timeliness saving estimate is based on prepositioning saving 14 weeks (USGAO, 2014) and packaging saving 0.85 weeks (i.e., 14 weeks/0.85 weeks). The 3-fold timeliness saving estimate comes from noting that prepositioning, which accounts for about 19 percent of US-sourced food, in expectation saves 2.7 weeks (i.e., 14 weeks*19% + 0 weeks*81%), while biopesticide packaging, which applies to 90% of US-sourced food, saves 0.8 weeks (i.e., 0.85 weeks*90% + 0 weeks*10%).

[4] USAID alone provided 2.5 million metric tons of in-kind food assistance in FY2018, inclusive of local and regional procured assistance and US-sourced assistance.

# Chapter 6

## Conclusion

Planning and policy analysis stand to benefit from operations management's concepts in working against racial and economic disparities in production and distribution systems. Systems of production and distribution have long unevenly exploited individuals and communities in both extracting labor through production and extracting wealth through consumption, often along racial and class and geographic lines. Decision makers in the private, public, and voluntary sectors increasingly seek to address growing concentrations of power in markets and the impact of shocks ranging from conflict to depressions, pandemics, and disasters. There is no choice but to embrace in scholarship and action the distributional implications of inventory, capacity, and information. Not engaging more in operations problems, or to do so superficially without careful accountings of inventory, capacity, and information, will constrain impact.

Planning and policy analysis should document disparities, paying close attention to the role the public sector plays in determining production, distribution, and consumption. It should explain disparities without timidity, problematizing racial and class and geographic disparities. Finally, it should resolve disparities, identifying solutions and advancing them through advocacy. Necessary for this exercise is understanding, based on decades of operations scholarship, the core tensions in production and distribution systems—between responsiveness and uncertainty in services, over- and under-stocking goods, holding inventory or expanding capacity, and other fundamental tensions in operations.

Operations management likewise stands to benefit from the methods and concepts that enable planning and policy analysis scholarship to responsibly investigate racism and exploitation in production and distribution. But first, operations management must determine what constitutes responsible scholarship on social problems; least the pressing policy problems for which operations management may be helpful be under-studied or the second wave of social operations management, as laid out by Sodhi & Tang (2014) (and Tang, 2018, among other calls for research), mirror the first wave of scholarship and exacerbate inequality.

Operations management must, then, acknowledge that operations questions are inherently political questions. Planning and policy analysis have had such a reckoning. Writing about planners who used mathematical techniques , Alan Black (1979) notes, "The avoidance of politics, which is characteristic of rationalists, proved to be their downfall." Policy analysis had a comparable realization

with politics, for instance concerning its role in determining feasibility and use of results (e.g., Lewin & Shakun, 1971). Another adjacent discipline, public administration, had its reckoning with politics after World War II. Its rejection of a pretended isolation from politics changed the face of administration research going forward, allowing it to step well beyond studies of administrative efficiency (Simon, Smithburg, & Thompson, 1950).

How and if operations management rejects that 'operations questions are not political questions' has yet to be seen. The groundwork for this rejection may be found in early operations management scholarship, a moment when it was closer to public administration and planning, which questions the discipline's apolitical stance (see e.g., the discussion on schoool bussing, Stimson & Thompson, 1975). Ultimately, accepting operations questions are political is a precondition to responsible research and meaningful engagement with planning and policy analysis.

A planning and policy analysis research agenda that uses concepts from operations management will significantly enlarge impact. From concerns over power in markets and to the impacts of resource-constrained public services and a changing climate, a planning and policy analysis research agenda attuned to operations has the potential to make more equitable the landscape of goods and services for the disadvantaged in society.

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