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Deep Impact: Geo-Simulations as a Policy Toolkit for Natural Disasters

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Summary. — Adverse post-natural disaster outcomes in low-income regions, like elevated internal migration levels and low consumption levels, are the result of market failures, poor mechanisms for stabilizing income, and missing insurance markets, which force the affected population to respond, and adapt to the shock they face. In a spatial environment, with multiple locations with independent but inter-connected markets, these transitions quickly become complex and highly non-linear due to the feedback loops between the micro individual-level decisions and the meso location-wise market decisions. To capture these continuously evolving micro–meso interactions, this paper presents a spatially explicit bottom-up agent-based model to analyze natural disaster-like shocks to low-income regions. The aim of the model is to temporally and spatially track how population distributions, income, and consumption levels evolve, in order to identify low-income workers that are "food insecure". The model is applied to the 2005 earthquake in northern Pakistan, which faced catastrophic losses and high levels of displacement in a short time span, and with market disruptions, resulted in high levels of food insecurity. The model is calibrated to pre-crisis trends, and shocked using distance-based output and labor loss functions to replicate the earthquake impact. Model results show, how various factors like existing income and saving levels, distance from the fault line, and connectivity to other locations, can give insights into the spatial and temporal emergence of vulnerabilities. The simulation framework presented here, leaps beyond existing modeling efforts, which usually deals with macro long-term loss estimates, and allows policy makers to come up with informed short-term policies in an environment where data is non-existent, policy response is time dependent, and resources are limited.

Key words — agent-based model, geography, migration, food insecurity, Pakistan, earthquake

1. INTRODUCTION

According to the latest Global Assessment Report on Disaster Risk Reduction (UNISDR, 2015), in the last three decades alone, over 1.6 million people have died as a result of natural disasters, of which 80% reside in low- and middle-income countries. Additionally, the total population displaced between 2008 and 2015 is estimated to be 26.4 million of which 95% live in low-income regions (IDMC, 2015). 80% of the population in disaster-prone regions is considered food insecure and depends on agriculture as a main source of livelihood, a sector that is highly vulnerable to disaster-like shocks (FAO, 2013; UNU-EHS, 2015; WFP, 2015; FAO, 2015).

Adverse post-shock outcomes in low-income regions, like elevated internal migration levels, and low consumption levels are the result of market failures, poor mechanisms for stabilizing income, and missing insurance markets, which force the affected population to respond, and adapt to the shock they face (Kahn, 2005; Kellenberg & Mobarak, 2008; Noy, 2009; Cavallo & Noy, 2010; Schumacher & Strobl, 2011). If individuals and markets are able to hedge against the shock, or policies are efficiently implemented, then vulnerabilities can be better managed and adverse post-shock outcomes can be contained (Dückers, Frerks, & Birkmann, 2015). Reasons for poor policy responses in low-income regions are the lack of, first, reliable pre- and post-natural disaster data on various disaster-related indicators and, second, effective policy planning tools that allow for some reasonable prediction of post-natural disaster outcomes in the short-run (Okuyama, 2007; Toya & Skidmore, 2007; Noy, 2009; Cavallo & Noy, 2010).

Literature suggests that any tool that aims to analyze shocks scenarios, especially in the short-run, needs to address three key issues: time, geography, and feedback loops (Okuyama, 2007). In order to construct a useful modeling framework, the processes following a natural disaster scenario need to be systematically understood and modeled. Natural disasters can have direct and indirect (or second-round) effects. The direct effects are the immediate losses resulting from the destruction of productive capital and loss of human life (Skoufias, 2003). In a natural disaster setting, these immediate losses to output and labor, are not uniformly distributed across a region. The highest damage is near the epicenter, which dissipates as one moves away from the origin of the shock. Assuming markets exhibit stable trends pre-shock, a sudden, spatially localized change in capital and labor ratios results in an immediate disequilibrium in one part of the region. As a consequence of these sudden losses, the regional economy enters into a second-round adjustment phase where labor and goods (assuming capital stock is fixed in the very short-run) respond to gaps created by the shock. Labor and goods respond to market signals from across the region, causing the economy to transition to a new equilibrium, and in the process, potentially cascading the shock to the rest of the region. As a result, new or additional vulnerabilities can be created, such as low consumption levels resulting from either low incomes caused by excess labor supply, or rising food prices caused by output losses, or a combination of both. In a spatial environment, with multiple locations with independent but inter-connected markets, these transitions quickly become complex, and highly non-linear, as a result of the

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feedback loops between the micro individual-level decisions and the meso location-wise market decisions.

To deal with these complex transitions, this paper presents an application of a spatially explicit agent-based model (ABM), or a "geo-simulation", of spatial non-linear short-run adjustment processes following a natural disaster-like shock scenario. The goal of this model is to allow policymakers to identify levels of post-shock displacement and spatial clusters of "food insecure" populations in low-income regions especially in the absence of reliable data. This leaps beyond the existing modeling efforts on natural disasters that usually deal with macro aggregated loss estimates in the long-run. Standard modeling tools, for example Input–Output models, CGE models, and Social Accounting Matrices (SAMs), lack the ability to analyze heterogeneous and spatial micro- and meso-level impact of shocks, and the short-run transitions where vulnerabilities can emerge in short time span.

This paper builds on the agent-based model presented in Naqvi and Rehm (2014) where the interaction of six decision-making modules – *Production, Wages, Consumption, Buying, Selling, Migration* – form a complete economy with decentralized labor and goods markets with a focus on the decision making process of low-income workers. The original model is extended through two channels. First, market interactions are updated to allow for a more innovative search-and-match algorithm which allows supply networks to continuously adapt to a rapidly changing environment. Second, the model allows for a more dynamic migration decisions through endogenous location-wise probability assignments which go through several iterations to avoid completely arbitrary outcomes. In addition to updating the two behavioral rules, the model is extended to allow for incorporation of spatial data, bringing it one step closer to actual policy analysis.

The model framework is applied to the 2005 earthquake in Pakistan which resulted in a massive loss of output and human life. A large fraction of the population was displaced while majority of the inhabitants in the region were left "food insecure" within weeks of the earthquake shock (ADB-WB, 2005; ERRA-UN, 2006). The region required immediate policy response to target vulnerable populations especially those facing food insecurity, but lacked reliable data for any type of evidence-based policy planning. This region is selected for two reasons. First, the region is fairly closed, both geographically and economically, comprising a large rural agrarian sector with simple economic dynamics and decision-making rules which are easy to implement in an agent-based modeling environment. Second, baseline data on population ratios, income, and consumption levels for pre-shock trends exist allowing for model calibration. Additionally, the event was an isolated large-scale natural disaster incident in 2005 which received unprecedented attention from local and international organizations. Given the focus on the region, the level of aid disbursed, and the involvement of various national and international disaster management institutions in this "best-case" response scenario, the effectiveness of policy response is still being debated a decade after a earthquake.[1]

The model is set up using actual GIS data on village and city locations, and road networks. Using the actual location of the fault line, the spatially defined artificial economy is subjected to a calibrated earthquake-like shock to determine loss of output and labor. Model results are spatially and temporally tracked on demographic changes, and on changes in income and consumption patterns which allow for identification of food insecure populations in the short-run. The results show how geo-simulations can provide one plausible way of replicating natural disaster-like shock scenarios in a lab-like setting for a more informed policy planning in the short-run where data is non-existent, policy response is time dependent, and resources are limited.

The remaining paper is structured as follows. Section 2 discusses relevant literature and the role of geo-simulations in the analysis of natural disasters. Section 3 presents stylized facts from the 2005 earthquake affected region of northern Pakistan. Section 4 describes the model framework and behavioral rules in detail. Section 5 presents the simulations setup and Section 6 gives the results of the earthquake experiment. Section 7 concludes. Appendices discuss the complete model and present results from sensitivity analyses.

2. LITERATURE

Two broad strands of literature are discussed in this section. The first strand discusses existing modeling efforts of natural disasters and the related empirical literature, both of which focus on a long-period analysis. The second strand summarizes the literature on micro household adaptation strategies in the face of natural disaster-like shocks. The last subsection provides a rationale for using geo-simulations as a modeling tool that can fill in the short- to medium-run gap for disaster-related modeling and policy planning.

(a) *Models of natural disasters and long-period analysis*

Existing modeling frameworks on natural disasters focus on long-run loss estimations using three popular techniques; Input–Output (I-O) models, Computational General Equilibrium (CGE) models, and Social Accounting Matrices (SAMs). I-O models of natural disasters stem from the pioneering work of Dacy and Kunreuther (1969) and focus on long-run direct and indirect loss estimations. While the initial I-O models mainly focused on western high-income economies (Cochrane, 1974; Wilson, 1982; Rose & Benavides, 1998; Cho, Gordon, & Richardson, 2000), focus quickly shifted to other parts of the world (for example, the 1995 Kobe earthquake and the 2004 Indian Ocean Tsunami Okuyama (2004, 2007)). These models have recently been expanded to accommodate inter-regional dependencies as more data has become available (Okuyama & Santos, 2014). I-O models have been criticized on restrictive assumptions of linearity, and lack of sensitivity to parameter changes. As a result they assume very little adaptation in behavior to shock-like scenarios and tend to over-estimate economic losses (Rose, 2004).

To overcome some of the limitations of I-O models, Computational General Equilibrium (CGE) models were introduced in the 2000s and have been extensively used in disaster analysis at the national (Ueda, Koike, & Iwakami, 2001; Rose & Guha, 2004; Rose & Liao, 2005) and at the regional level (Tsuchiya, Tatano, & Okada, 2007; Hallegatte & Ghil, 2008; Hallegatte & Dumas, 2009). CGE models in their standard formulation of optimizing firms and households assume a long-run steady-state equilibrium which is achieved through smooth transitions based on agile reactions. Therefore, the models tend to estimate rather minimal losses. The issue, of whether households and firms even optimize in a highly uncertain environment, has been raised several times in literature (Rose, 2004; Okuyama, 2007).

To further advance modeling efforts, a third wave of models based on Social Accounting Matrices (SAMs) were developed to bring in some of the structural and institutional aspects of economies which dealt with inter-sectoral interactions, for example between households and firms (Cole, 1995, 1998,

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