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Evolutionary modelling of the macro-economic impacts of catastrophic flood events

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ABSTRACT

This paper examines the possible contribution of evolutionary economics to macro-economic modelling of flood impacts to provide guidance for future economic risk modelling. Most macro-economic models start from a neoclassical economic perspective and focus on equilibrium outcomes, either in a static or dynamic way, and describe economic processes at a high level of aggregation. As a consequence, they typically fail to account for the complexity of social interactions and other behavioural responses of consumers and producers to disasters, which may affect the macroeconomic impacts of floods. Employing evolutionary principles and methods, such as agent-based modelling, may help to address some of the shortcomings of current macro-economic models. We explore and discuss the implications of applying consumer and producer heterogeneity, bounded rationality, network effects, social and technological learning, co-evolution and adaptive policy-making concepts into existing economic frameworks for the assessment of macro-economic impacts of floods.

1. Introduction

The economic losses caused by natural disasters have increased significantly over the past decades (Munich Re, 2009). Many regions and economic sectors are vulnerable to increasing disaster risks because of a lack of resources to implement cost-effective loss-reduction and risk transfer measures. Several studies have attempted to estimate the economic damages associated with climate change and include them in integrated models, of which FUND (Tol, 2002a,b) and DICE (Nordhaus, 1992, 2008) are probably best known. Potential catastrophic events like floods are by far the most important factor in these total damages (Nordhaus and Boyer, 2000). However, indirect economic effects from increased extreme weather events and associated catastrophes are usually not included in existing integrated assessment models (Patt et al., 2010). There is increasing dissatisfaction with existing macro-economic models used for the assessment of flood damages and risks. They rely on assumptions of market equilibrium and behavioural rationality of market participants, which are not considered realistic in the context of catastrophic events.

In this paper, we explore the potential contribution of an alternative theoretical perspective and methodological tools from evolutionary economics to address some of the shortcomings associated with current macro-economic modelling approaches to study the impacts of floods. The focus on flood risk is motivated by the fact that floods have been identified as the most common hazard for the entire European area among different natural and technological disasters (Schmidt-Thome and Kallio, 2006). The unprecedented 2002 large-scale flooding in central Europe and other events have placed adaptation to climate change at the top of the political agenda (see, for instance, the EU White Paper on Adaptation COM 2009).

The main challenge ahead lies in integrating different types of non-economic knowledge and information, such as geophysical land use data, with economic data and equations related to changing risk perceptions and behavioural adjustments. Exposure to natural disaster risk such as floods, and ultimately economic damage costs, are a function of both an individual's private choices and government decisions over land use zoning and infrastructure investments (Boustan et al., 2012; Hallegatte and Dumass, 2009). Empirical studies emphasize the role of socio-economic factors (personal characteristics, risk perception, behaviour in relation to flood damage) in reducing flood damage, in addition to structural measures (Botzen et al., 2009; Shaw et al., 2005). However, heterogeneity of individual responses to perceived and actual risks cannot be easily incorporated into existing macro-economic models, which rely on aggregate equations and do not discriminate between different behavioural rules. This relates to the fact that these macro models entail a simplifying assumption that the diversity of agents within a specific sector can be described as one "representative" utility maximizing agent, whose preferences coincide with aggregate choices of individuals. This simplification may be unjustified as the reaction of the representative to changes can be very different from the aggregate reaction of the individuals he 'represents' (Kirman, 1992).

In the paper, we discuss how employing evolutionary principles and methods, such as agent-based modelling, can help to address shortcomings of current macro-economic models. Evolutionary economics

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replaces assumptions of representative, rational agents, exogenous preferences and utility-maximization by populations of diverse, boundedly rational and interacting individuals, whose preferences evolve over time. As a consequence, it may provide a useful approach to study adaptation and mitigation policies aimed at stimulating changes in behaviour and technologies prior to and after the disasters. We provide an overview of evolutionary-economic building blocks for researchers working on disaster modelling, who may be interested, but not familiar with recent developments in evolutionary-economic modelling. Evolutionary models allow studying macro outcomes emerging from interactions of many agents on multiple markets. In particular, the agent-based modelling technique has been increasingly employed to model such interactions, for instance in financial (e.g. Arthur et al., 1996; Caldarelli et al., 1998; LeBaron, 2001; Levy et al., 2000) or electricity markets (e.g. Bunn and Oliveira, 2001; Safarzynska and van den Bergh, 2011). In such models, behavioural rules of agents are deduced from empirical studies and psychology experiments. Agent-based models have proved to be capable of generating aggregate macro regularities, while allowing at the same time at the micro level of the individual decision maker to explore feedback mechanisms that underlie economic dynamics. In this context, providing macro models with explicit micro foundations enriches the analysis of economic outcomes and policies. Designing agent-based models for flood damage and risk assessments requires theory development, micro and macro data collection to validate model assumptions and to design behavioural rules of agents prior to and after disasters. Our paper aims to offer a starting point for such an endeavour and provide guidelines for future flood risk modelling.

The remainder of the paper is as follows. In Section 2, we discuss current approaches to integrated macro-economic modelling of flood risks and their theoretical underpinning. In Section 3, we present an overview of the key concepts and methods in evolutionary economics, while Section 4 elaborates and further details the specific contribution of evolutionary building blocks to existing macro-economic systems to provide a more realistic account of economic dynamics during and after a catastrophic flood event.

2. Integrated Macroeconomic Modelling of Catastrophic Flood Events

Integrated models of catastrophic flood events attempt to combine all relevant physical and economic aspects related to a water flow in a single framework. They provide a conceptual basis for the assessment of flood damages and cost-benefit comparisons of climate change mitigation and adaptation measures (e.g. Jonkman et al., 2008; Zhu et al., 2007). In many of such models, economic analysis of flood protection measures is carried out at the expense of hydrological detail, while social and technological learning are rarely addressed (Brouwer and Hofkes, 2008). On the contrary, in Geographical Information System (GIS)-based models, the flood event is described in more detail and geographically linked to a set of financial and economic assets (e.g. houses, factories, infrastructure) based on available land cover and land use maps. These models are used to simulate alternative flood event scenarios, for which economic values of damages are then computed based on available land cover and land use data. In such frameworks, no assumptions about behaviour of economic actors (consumers or producers) are being made. This simplification is problematic as the value of economic losses is expected to be sensitive to flood protection and other adaptation measures undertaken by firms and households as a result of experience and learning along with changes in perceived flood risks.

Input–output and general equilibrium models predominate among economic approaches employed for assessing flood risk and damages. Input–output models enable modelling of the interdependencies between different sectors in the economy. Here, natural disasters are often conceptualized as a shock to technological coefficients. The input–output approach has been criticized for its lack of explicit resource constraints and responsiveness of economic variables to changes in prices (Rose, 2004). Moreover, it does not allow modelling of behavioural responses of consumers and producers to stochastic shocks or the substitution of inputs in production. These shortcomings can be partially addressed by general equilibrium models. Contrary to I-O models, general equilibrium models allow introducing more sophisticated dynamics, describing price-quantity relationships, supply–demand adjustments towards equilibrium, input substitution and trade relations.

In general equilibrium models currently used to assess the impacts of flood events, deterministic equations describe optimizing behaviour of a representative producer and consumer, whose activities are disturbed by flood events (e.g. Narayan, 2003). Typically, their behaviour is invariant to natural disasters, i.e. characterized as business as usual after a catastrophic event, and the analysis focuses on relatively small incremental changes towards equilibrium. However, disasters can be a source of long-term structural change and behavioural adjustment to post-disaster situations. For instance, the size and composition of the population may change (Vigdor, 2008), firms may upgrade their capital (Hallegatte and Dumass, 2009) or consumers may reduce demand as a sign of sympathy for individuals affected by disasters (Okutama, 2004). Such behavioural responses and changes in the population and consumption patterns are not yet well understood, let alone modelled properly.

Typically, in input–output and general equilibrium models, natural disasters are modelled as stochastic shocks disturbing economic dependencies or exogenous changes in coefficients describing pre- and post-disaster situations (Rose and Liao, 2005; Steenge and Bokarjova, 2007). To illustrate this with an example, the technological coefficients in the input–output model by Steenge and Bokarjova (2007) change in a post-disaster situation, so as to reflect losses of industrial capacities. Modifying the matrix of coefficients yields a new equation, describing relations between labour, output and prices, called the Basic Equation. Different adjustment pathways of consumption and production after the catastrophe can be analysed using this approach. The restoration path always involves a transition between two equilibriums. The Basic Equation has also been employed in Jonkman et al. (2008) to evaluate the indirect damage of flooding in the Netherlands. In the model, a hydrodynamic module generates input information that is translated into different flood scenarios. Estimation of the direct losses is based on the damage equation: $D = \sum_{i=1}^{m} \sum_{r=1}^{n} \alpha_i(h_r) D_{\max,i} \eta_{i,r}$, where $D_{max,i}$ is the maximum damage for an object or land use category i, m is the number of damage categories, n the number of flooded locations in an area, h_r captures the hydraulic characteristics of the flood at a particular location, $\alpha_i(h_r)$ is a damage function that expresses the fraction of maximum damage for category i as a function of flood characteristics at a particular location r and $\eta_{i,r}$ is the number of objects of damage category i at location r. Here, damages are evaluated with reference to a static equilibrium, which does not allow accounting for behavioural and technological change occurring after the disaster. Okuyama et al. (2004) extend the I–O table with the sequential industry framework to introduce dynamic and spatial dimensions into the model.

Alternatively, scenarios are simulated with the help of hydraulic and hydrological models that are translated into different flood probabilities (e.g. Brouwer and van Ek, 2004; Jonkman et al., 2008). In the latter case, flood probabilities can be used to compute expected economic damages based on land cover and land use maps. In particular, geographical information systems (GIS) can be used to map flood risk areas (Harou et al., 2009). For instance, in models developed by Tol and co-authors to assess the economic impacts of sea-level rise, GIS provides information on the type of land lost across regions for different climate scenarios (Bosello et al., 2007; Darwin and Tol, 2001; Tol, 2007). However, economic modules in such models are mostly deterministic, based on optimization procedures for a representative, rational agent, focusing