Exploring Regional Agglomeration Dynamics in Face of Climate-Driven Hazards: Insights from an Agent-Based Computational Economic Model

Alessandro Taberna, Tatiana Filatova, Andrea Roventini, and Francesco Lamperti

Abstract By 2050 about 80% of the world's population is expected to live in cities. Cities offer spatial economic advantages that create agglomeration forces and innovation that foster concentration of economic activities, but for historic reasons cluster along coasts and rivers that are prone to climate-driven flooding. To explore tradeoffs between agglomeration economies and the changing face of hazards we present an evolutionary economics model with heterogeneous agents. Without climate-induced shocks, the model demonstrates how advantageous transport costs that the waterfront offers lead to the self-reinforcing and path-dependent agglomeration process in coastal areas. The likelihood and speed of such agglomeration strongly depend on the transport cost and magnitude of climate-driven shocks. In particular, shocks of different size have non-linear impact on output growth and spatial distribution of economic activities.

Keywords Agglomeration · Path-dependency · Climate · Flood · Shock · Relocation · Migration · Agent-based model

1 Introduction

Rapid urbanization and climate change exacerbate natural hazard risks worldwide. In the stable climate, which humanity has enjoyed for centuries, coastal and delta regions historically grew faster than landward areas, with all current megacities flourishing along the coast. The richness of natural amenities and resources coupled with transportation advantages created agglomeration forces that have enabled this boom [14]. Yet, the escalation of climate-induced hazards fundamentally reshape

A. Taberna (✉) · T. Filatova
Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628, BX, Delft, The Netherlands
e-mail: a.taberna@tudelft.nl

A. Roventini · F. Lamperti
Institute of Economics, Scuola Superiore Sant' Anna, piazza Martiri della Libertá 33, 56127 Pisa, Italy

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the trade-offs which firms and households have to take while choosing a location [6]. Increasingly, managed retreat becomes plausible for all types of coasts even under low and medium sea level rise scenarios [5], raising a hot debate on how to make this a positive transformation. Understanding the location and agglomeration of productive activities has been at the core of spatial economics for almost two hundred years [27]. The "new economic geography" [20] literature has proposed a coherent analytical framework grounded in general equilibrium analysis of the spatial distribution of economic activities. New economic geography linked international trade and economic geography giving rise to models that produce emergent spatial structures without any assumed agglomeration economies [19]. These models traditionally assume a unique equilibrium and rational representative agents with perfect information. Yet, heterogeneity of technologies, resources and preferences as well as the fundamental uncertainty necessitating dynamic expectations and adaptive behavior [1], challenge these assumptions. Agent-Based Models (ABMs) has risen as a method to accommodate heterogeneity, learning, interactions and out-of-equilibrium dynamics [26], also in environmental and climate change economics [2, 22] and economic geography [13, 23]. ABMs are increasingly versatile in modeling disaster scenarios, and flooding in particular [24]. However, an ABM of an economy shaped by locations of economic activities and agglomeration forces and altered by climate-induced risks is missing. To address this gap, we design a model to study the spatial distribution of economic agents, both firms and households, in face of the costliest climate-induced hazard: flooding. Our goal is to explore how the complex trade-offs between agglomeration economies and a changing severity of location-specific flood hazards affect the economic performance and attractiveness of regions and steer their development. In particular, we aim to address two research questions: (1) How do agglomeration forces shape economic centers in coastal areas? (2) What are the effects of climate shocks of various severity on this agglomeration dynamics? Following previous work on evolutionary macroeconomic ABMs [9, 11], we use R&D investment and a "Schumpeterian" creative (innovative) destruction process as the engine of economic growth. Our model is characterized by two spatial regions, safe Inland and hazard-prone Coastal, and explores the economic dynamics in the two regions under different climate shocks. Our simulation results show that in the absence of floods when the Coastal region holds a natural spatial advantage, such as being on a transportation route and hence paying a lower transportation cost to trade with the rest of the world (RoW), it will experience an inflow of economic activities from the Inland region. The likelihood and the speed of such agglomeration strongly depend on the extent of the location advantage. In particular, in line with empirical evidences, our model confirms that, because of the trade stickiness, the concentration of economic activities decreases as transport costs increase [25]. Nonetheless, when climate shocks are introduced, they play an important role on the final distribution of economic activities between the regions as well as the economic growth of the whole economy.

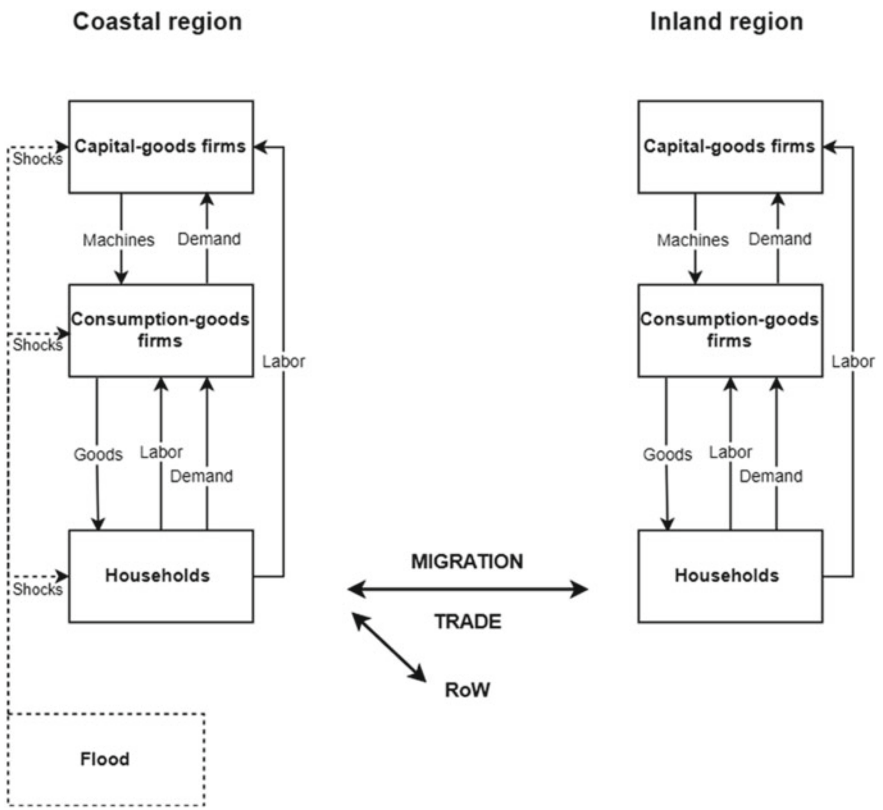

Fig. 1 A stylized representation of the model

2 Methodology

Previous attempts of ABMs for modelling agglomeration dynamics in an out-of-equilibrium fashion highlighted the need to depart from the neoclassical economic framework [13, 23]. Hence, we adopted the evolutionary economic engine of a well validated macroeconomic ABM, the "Keynes + Schumpeter" [8–11, 21]. Furthermore, we added two differentiated spatial regions, migration actions and climate hazards. The two regions, namely Coastal and Inland, feature a two-sector economy with three classes of heterogeneous interacting agents. Specifically, the economy of region r consists of heterogeneous boundedly-rational F_i^r capital-good firms (CP Firm agents), F_j^r consumption-good firms (CS Firm agents) and L_h^r Households agents (consumers/workers). Capital-good firms produce heterogeneous machines and invest in R&D to stochastically discover more productive technologies. Consumption-good firms combine labour and machineries bought from the capital sector to produce a final homogeneous consumer product. There are two local labour markets, hence firms can only hire workers from their own region. In contrast, the goods market is global: firms from both sectors are able to sell in the other region and export to the rest of the world economy bearing a regional and international iceberg transport cost respectively. Furthermore, all agents are mobile and can migrate across the two regions. Migration is costly and increasing with size for firms, while is costless for workers. A one-time climate shock hits the Coastal region at time ts, with average magnitude Dc. We model climate damages heterogeneously at the microeconomic level, hitting workers' labor productivity, capital stock and inventories of firms. Households reduce consumption to undertake repair costs. Figure 1 provides a schematic representation of the model dynamics.

2.1 The Capital Good Sector

The structure of the capital-good sector in each country takes the basic form of the K + S model [9].

Each firm i is endowed with labor productivity (A_i^τ, B_i^τ). The former coefficient indicates the productivity of the machines produced by firm i, while the latter stands for the productivity used by firm i to produce its machines. Capital-good firms determine their price by applying a fixed markup μ_1 to their unit cost. The unit cost is the ratio between individual nominal wage and productivity coefficient. Capital firms aim to improve both their productivity coefficients. To do so, they actively invest in R&D a fraction ν of their past sales. Furthermore, firms split their R&D between innovation (IN) and imitation (IM) according to the parameter $\xi \in [0, 1]$ and follow a two steps procedure. In both cases, the first step is a draw from a Bernoulli distribution, $\theta_i^{in}(t) = 1 - e^{-\zeta_1 IN_i}(t)$ for innovation and $\theta_i^{im}(t) = 1 - e^{-\zeta_2 IM_i}(t)$ for imitation, which determines whether the firm i gets access to the second step with $0 \leq \zeta_{1,2} \leq 1$. Hence, the probability of a positive outcome depends on the amount of resources invested. If the innovation draw is successful, the firm discovers a new set of technologies, (A_i^{in}, B_i^{in}), according to $A_i^{in}(t) = A_i(t)(1 + x_i^A(t))$ and $B_i^{in}(t) = B_i(t)(1 + x_i^B(t))$. $x^{A,B}(t)$ are independent draws form a $Beta(\alpha_1, \beta_1)$, over the support $[\underline{x_1}, \overline{x_2}]$, with $\underline{x_1} \in [-1, 0]$ and $\overline{x_2} \in [0, 1]$. The supports of the Beta distribution determine the probability of "succesfull" over "failed" innovations, and hence shape the landscape of *technological opportunities*. Furthermore, firms passing the imitation draw get access to the technology of one competitor (A_i^{im}, B_i^{im}). Notably, firms are more likely to imitate competitors located in the same region and with similar technologies. The higher the technological distance with a specific firm, computed with an Euclidean metric, the lower the probability to imitate its technology. Moreover, we augmented the technological distance of firms located in different regions by a factor $\epsilon > 0$. Once both processes are completed, all the firms succeeding in either imitation or innovation select the most efficient production technique they can master according to a payback rule. Finally, capital-good firms send a "brochure" containing price and productivity of their machines to a random samples of potential new clients (NC_i) as well as its historical customers (HC_i)[1].

2.2 The Consumption Good Sector

Consumption-good firms combine labour and capital with constant returns to scale to produce a homogeneous good. In line with K+S tradition [9], adaptive demand expectations ($D_j^e = f[D_j(t-1), D_j(t-2), \ldots, D_j(t-h)]$), desired inventories ($N_j^d$), and the actual stock of inventories (N_j) form the desired level of production ($Q_j^d(t)$). The latter is constrained by firms' capital stock K_j, with a desired capital stock K_j^d required to produce Q_j^d. In case $K_j^d(t) > K_j(t)$, the firm calls for a desired expansionary investment such that:

$$EI_j^d(t) = K_j^d(t) - K_j(t) \tag{1}$$

Furthermore, firms undertake replacement investment RI, scrapping machines with age above $\eta > 0$ and those that satisfy a payback rule. Firms then compare the "brochures" received by capital-good firms and order the machines with the best ratio between price and quality.

Notably, consumption-good firms have to advance both their investments and the worker wages. This implies that capital markets are imperfect. As a consequence, external funds are more expensive than internal ones and firms may be credit rationed. More specifically, consumption- good firms finance their investment first by using their stock of liquid assets (NW_j). When the latter does not fully cover investment costs, firms that are not credit-constrained can borrow the remaining part paying an interest rate r up to a maximum debt/sales ratio of $\Lambda > 1$.

Each firm is characterized by heterogenous vintages of capital-goods with different average productivity (A_j) which reflects in its unit cost of production (c_j):

$$c_j(t) = \frac{w_j(t)}{A_j}$$

where w_j is the average wage paid by firm j. The prices in the consumption-good sector are computed applying a mark-up ($\mu_{2,j}$) on unit cost: $p_j(t) = (1 + \mu_{2,j})c_j(t)$ The evolution of firm's market share (f_j), determines the variation of its markup ($\mu_{2,j}$): $\mu_{2,j}(t) = \mu_{2,j}(t-1)(1 + \nu \frac{f_j(t-1) - f_j(t-2)}{f_j(t-2)}) \quad with \quad 0 \leq \nu \leq 1$

Consumption-good firms compete in three markets, namely the Coastal (Co), the Inland (In) and the export (Exp). In a generic market m, firm's competitiveness (E_j) depends on its price, which can account for inter-regional (τ_1), international (τ_2) transport costs, as well as on the level of unfilled demand (l_j):

[1] For additional detail about the capital good sector see [9]

$$E_j^m(t) = -\omega_1 p_j^m(t)(1+\tau_1+\tau_2) - \omega_2 l_j^m(t) \quad with \quad \omega_{1,2} > 0, m = Co, In, Exp \tag{2}$$

Of course, in the Coastal (E_J^{Co}) and Inland (E_j^{In}) market, $\tau_2 = 0$, while they pay no transport cost to compete in the region where they are located. Regarding the export market, according to the spatial economics literature that indicates ports as hub for international trade [14, 15], we model the competitiveness (E_j^{Exp}) so that firms located in the Coastal region holds a competitive advantage in trade with the rest of the world, i.e. $\tau_1 = 0$, while Inland firms bear it.

In each market (m), the average competitiveness ($\overline{E}^m$) is calculated by averaging the competitiveness of all firms in the corresponding region weighed by their market share in the previous time step:

$$\overline{E}^m(t) = \sum_{j=1}^{F2} E_j^m(t) f_j^m(t-1) \quad with \quad m = [Co, In, Exp] \tag{3}$$

The market shares (f_j) of firms in the three markets evolve according to a quasi-replicator dynamics:

$$f_j^m(t) = f_j^m(t-1)\left(1 + \chi \frac{E_j^m(t) - \overline{E}^m(t)}{\overline{E}^m(t)}\right) \quad with \quad m = [Co, In, Exp], \tag{4}$$

with $\chi > 0$ which measures the selective pressure of the market. In a nutshell, the market shares of the less efficient firms shrinks, while those of the more competitive ones increases (due to lower prices and less unfilled demand). The firm's individual demand in each market is then calculated by multiplying its market share by the total demand. For the two regions, the latter is computed by summing up all the wages and unemployed benefits of their households. Conversely, we assume that the export market grows at a constant rate: $Exp(t) = Exp(t-1)(1+\alpha), \quad \alpha > 0$.

2.3 Labour Market

Consumption-good firms in the Coastal and Inland zones offer heterogeneous wages which depends on their productivity, as well as on regional productivity, inflation and unemployment:

$$w_j(t) = w_j(t-1)\left(1 + \psi_1 \frac{\Delta AB_j(t)}{AB_j(t-1)} + \psi_2 \frac{\Delta \overline{AB^r}(t)}{\overline{AB^r}(t-1)} + \psi_3 \frac{\Delta U^r(t)}{U^r(t-1)} + \psi_4 \frac{\Delta cpi^r(t)}{cpi^r(t-1)}\right), \tag{5}$$

where r is the region where firm j is located, AB_j is its individual productivity, $\overline{AB^r}$ is the regional productivity, cpi^r is the regional consumer price index and U^r is the local unemployment rate. Furthermore, capital-good firms follow the wage dynamics of top-paying consumption firms, as in [10, 11].

Interactions in the local labor markets are decentralized. This process allows to take into account unemployment as a structural disequilibrium phenomenon. As we assume no commuting, households can only work for the firms in the same region where they live. Thus, on the one hand, the labor supply $L^{S,r}$ of region r at time t, is equal to the number of households living in that region. On the other hand, the aggregate labour demand $L^{D,r}$ is given by the sum of individual firms labour demand:

$$L^{D,r}(t) = \sum_{i=1}^{F1^r} \sum_{j=1}^{F2^r} L_f^d \quad with \quad f = [i, j], \tag{6}$$

where $F1^r$ and $F2^r$ are the populations of capital- and consumption-good firms located in region r. The labour demand of capital-good firm i (L_i^d) is equal to: $L_i^d = \frac{Qo_i^r(t)}{B_i^\tau(t)}$ where Qo_i is the quantity ordered to the firm. Similarly, the labour demand of consumption-good firm j (L_j^d) is computed as: $L_j^d = \frac{Qd_j(t)}{A_j(t)}$ where Qd_i is its desired production. The labour market matching mechanism operates as follow:

1. If $L_f^d(t) > n_f(t)$, where $n_f(t)$ is the current labour force of a generic firm f, the firm posts m vacancies on the labour market, with $m = L_f^d(t) - n_f(t)$. Conversely, if $L_f^d(t) < n_f$ the firm fires m employees.
2. Unemployed households are boundedly-rational and have imperfect information. They are aware of a fraction $\rho \in [0, 1]$ of all vacancies posted by the firms in their home region.
3. Unemployed households select the vacancy with highest offered wage in their sub-sample and they are hired by the firm.

The process is completed when either all the households are employed or the firms have hired all the workers they need. Note that there is no market clearing and and involuntary unemployment as well as labor rationing are emergent properties generated by the model.

2.4 Migration

Households and firms can move to the other region. To capture heterogeneous location preferences and imperfect information about regional variables such as wage levels, we model migration as a probabilistic two-step procedure. In the first step, an agent compares several indicators between the two regions, and she/he does consider to migrate only if the region where it is not currently located displays better economic conditions. The probability to migrate depends on a switching test (see [3, 4, 7]) grounded on economic variables. Each household h compares wages and levels of unemployment in two regions and its probability to migrate (Pr) is equal to:

$$Pr_h(t) = \begin{cases} 1 - e^{(W_d(t))}, & \text{if } W_d(t) \text{ and } U_d(t) < 0 \\ 0, & \text{Otherwise} \end{cases}. \quad (7)$$

W_d is the *wage distance* which captures the average salary difference between the two regions: $W_d(t) = \frac{(\overline{W^r}(t-1) - \overline{W^*}(t-1))}{\overline{W^r}(t-1))}$ where r is the region where the agent is located and $*$ is the other one. Similarly, the *unemployment distance* U_d reads: $U_d(t) = \frac{(U^*(t-1) - U^r(t-1))}{U^r(t-1)}$ The mobility choices of firms depends on the local regional demand for their goods, in line with the New Economic Geography models where firms move towards bigger and more profitable markets [20]. More specifically, a generic firm f, calculates the probability to migrate according to:

$$Pr_f(t) = \begin{cases} 1 - e^{(\omega_1 Dd_f(t) + \omega_2 DAd(t))}, & \text{if } Dd_f(t) \text{ and } DAd(t) < 0 \\ 0, & \text{Otherwise} \end{cases}, \quad (8)$$

where $\omega_1 + \omega_2 \leq 1$. Dd is the *demand distance* of firm f between the two regions: $Dd_f(t) = \frac{(D^r_f(t-1) - D^*_f(t-1))}{D^r_f(t-1))}$

Firms also consider the dynamics of their sales with the *"Demand attractiveness"* (DAd): $DAd_f(t) = \frac{(DAd^r_f(t-1) - DAd^*_f(t-1))}{DAd^r_f(t-1)}$ where $DAd^{r,*}_f(t-1) = log(s^{r,*}_f(t-1)) - log(s^{r,*}_f(t-2))$ and s_f are individual firm sales. The economic agents that consider whether to migrate ($Pr > 0$) perform a draw from a Bernoulli distribution. If the draw is successful, the agent migrates to the other region. Households that pass both steps leave their job (if employed) and move to the other region as unemployed. Migrant firms fire all their employees, paying a fixed cost that is equal to the sum of their quarterly wages.

2.5 Climate

In a predetermined time step, t_s a single climate shock, can hit the Coastal region. The hazard is rather stylized, yet for the type of consequences on the economy can be intended as a flood. The shock is heterogeneous among the Coastal region agents. In particular, each agent draws an individual damage coefficient Dc from a $Beta(\alpha_2, \beta_2)$ distribution. The flood affects Coastal firms (indexed here generically as cf) in the following ways:

- A one period labour productivity loss $AB_{fc}(t_s) = AB_{fc}(t_s - 1)(1 - Dc_{cf})$.
- Each vintage of the capital stock go through a draw from a Bernoulli distribution; $\theta^{Dc_{cf}}_{\tau}(t_s)$, whenever the draw is successful the vintage is destroyed.
- A permanent destruction of a fraction of the inventories $INV_{fc}(t_s) = INV_{fc}(t_s - 1)(1 - Dc_{cf})$.

Also, for one step, each Coastal households (ch) decrease their consumption to undergo repair cost in the form $C_{ch}(t_s) = C(t_s)(1 - E(Dc)_{ch})$.

2.6 Timeline of Event

In any given time period (t), the following actions take place in sequential order:

1. Households and firms can consider to migrate across regions.
2. Firms in the capital-good sector perform R&D.
3. Consumption-good firms set their desired production, wages, and, if necessary, order new machines.
4. Decentralized labor market opens in each region.
5. An imperfect competitive consumption-good market opens.
6. Entry and exit occur.
7. Machines ordered are delivered.
8. There is a probability of climate shock in Coastal region.

3 Results

3.1 Agglomeration Dynamics

At the beginning of each experiment, economic activities and population are evenly distributed between the two regions and each agent begins with exactly the same initial conditions. Therefore, the only difference between Coastal and Inland region is the regional transport cost (τ_1) that Inland firms have to consider when calculating export competitiveness (Eq. 2). We start describing the dynamics of our economy without climate hazard. Simulations results show that the model is characterized by a self-reinforcing and path dependency agglomeration process triggered by endogenous technical change. Namely, the discovery of newer and more productive technologies by capital-good firm R&D investments. Because of transport cost and physical distance, consumption-firm located in the same region where the innovation took place are more likely to absorb it. Furthermore, since salaries are indexed to both individual and regional productivity, the region that innovates more will also have the higher average salary. The latter is an attractor of households migration which ultimately results in shift in regional consumption, making the environment less favorable for the firms located in the region with less population. Hence, even more firms will decide to migrate, altering even further job opportunities and wages level. This process continues until all economic activities and population are concentrated in one region. As in new economic geography models [20], labour mobility plays the central role in the agglomeration process. In line with the empirical evidences [12], our evolutionary economic model endogenously determines the direction and speed of the labour mobility triggered by the process of R&D investments and a relative increase in wages in the most technologically-advanced core region versus the periphery. Moreover, since the technological change is stochastic the agglomeration process will materialize in the region which is more "lucky" in the discovery

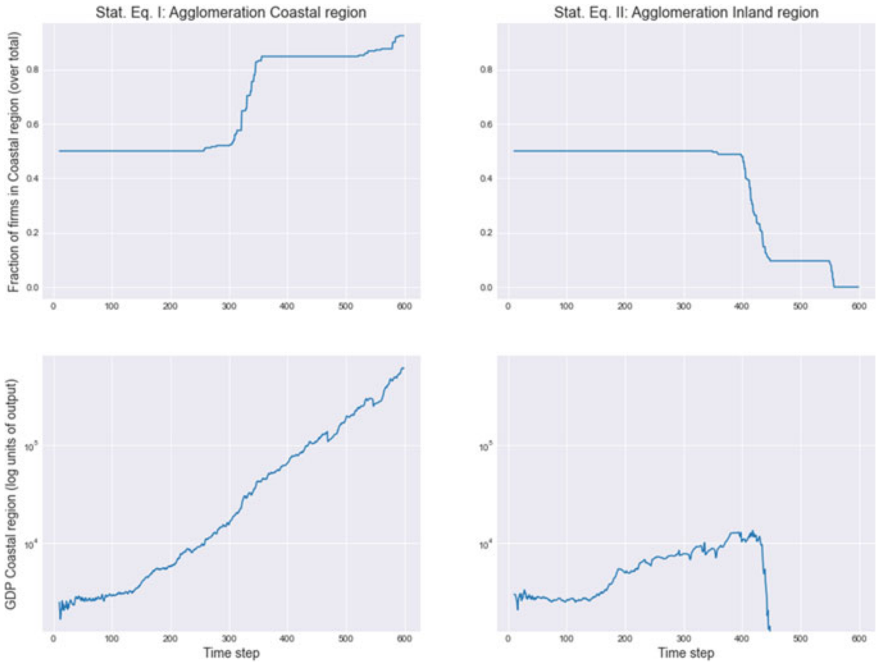

Fig. 2 Population and GDP in Stat. Equation I (left) and Stat. Equation II (right). Note that the Coastal region is used as reference

of newer and more productive technologies. Thus, as typical in complex systems the model produces a non-ergodic behavior characterized by two statistical equilibria: a complete agglomeration of economic activities and population in either Coastal (Eq. 1) or Inland (Eq. 2) region (Fig. 2).

Importantly, the likelihood and speed of the equilibria depend on model calibration. As common in spatial economics, a parameter that plays a major role on the final results is the iceberg transport cost. The regional transport cost affects model dynamics through market competitiveness (Eq. 2). In particular, since competitiveness is inversely proportional to the values of the regional transport cost, the higher the transport cost the more difficult is for the firms to be competitive, and hence gain market share, outside the region where their are located. This has two main implications. The first is on the speed of the process. To consider migration, firms need to have a positive and increasing demand distance (Eq. 8). Yet, the regional transport cost functions as a barrier in inter-regional trade, making it harder for firms to sell outside their region. The second effect is on the likelihood between the two statistical equilibria. As the regional transport cost also measures the competitive advantage that the Coastal firms have in trade with the rest of the world, the higher is this cost, the harder is for Inland firms to be competitive on exports. Furthermore, the lower the competitiveness, the lower the share of export demand allocated to

Table 1 The effects of different transport costs on the speed and the likelihood of final Stat. Eq

τ_1	Fraction of MC runs that have reached final state before step 600	Stat. Eq 1: Agglomeration coastal region (%)	Stat. Eq. 2: agglomeration Inland region (%)
0	1	51	49
0.01	0.71	65	35
0.02	0.45	73	27
0.03	0.33	76	24
0.04	0.27	81	19
0.05	0.22	84	16

the Inland region. In particular, lower demand means less investments in R&D and slower technical change. To analyze the effect of transport cost on agglomeration and to remove the effects of stochastic components, we implement a Monte Carlo (MC) exercises of size 500 on the seed of pseudo random number generator. We will use the same protocol for all the simulation results. In this exercise, we measure the speed, counting the fraction of MC simulations that have reached one of the final equilibria after 600 steps (Table 1). Since a step can be intended as a quarter, the time span of the simulation is 150 years. However, the first 20 years serve as transition phase. Furthermore, the likelihood between final equilibria is calculated only among the sub-sample of MC that have reached a final equilibria. We decide to consider only the latter since if we run the model for an infinite number of steps, one of the two final equilibria will always emerge.

With zero transport cost there are no idiosyncratic differences between the two regions. As expected, since there are no trade barriers, firms easily penetrate outside their regional market and speed up the agglomeration process with all the runs that are agglomerated in either region before step 600. Moreover, with no transport cost the Coastal region has no competitive advantage in trade with export and hence the likelihood between the equilibria is the same with a completely stochastic agglomeration (Table 1). Notably, as the transport cost increases, the trade between the two regions decreases. Consequently, resulting in a slower agglomeration process (only 0.22 with $\tau_1 = 0.05$). Further, as anticipated before, among these smaller samples, the likelihood of Eq. 1 constantly increases. This is due because the competitive advantage in export increases as the transport cost does (Table 1). However, export are only a small fraction of the internal demand. Hence, the gap in resources is not sufficient to completely remove the possibility of Eq. 2.

3.2 Agglomeration Dynamics and Climate Hazard

As second exercise, we analyze the impact of a single climate shock on the agglomeration process. In this experiment, the regional transport cost (τ_1) is equal to 0.01 and the climate hazard hitting the Coastal region is placed at the end of transition phase (80th step). Furthermore, we perform a set of 10 experiments, where the damage coefficient (Dc) ranges from 0 to 0.5, with intervals of 0.05. Our goal is to understand the response of our economy to shocks of different size. Despite being modelled in a stylized manner, such shocks deliver important insights on the feedbacks between climate, economy and the agglomeration forces. In particular, as for transport cost, we look at the impact of climate dynamics on both speed and likelihood between equilibria. In addition, we also consider the flood effect on the whole economy (defined as the sum between Coastal and Inland regions). The results of this set of experiments can be summarize in Fig. 3. A first takeaway is that the lower half of the shocks (0–0.25) has not particular influence on the fraction of MC runs that reach the final state before step 600. Conversely, the latter increases rapidly as the average shocks exceeds 0.25 (Fig. 3-left panel). The reason behind this behavior is that the hazard affects regional productivity both directly and indirectly. In the former case, through the one period productivity cut equal to average size of the shock. While for the latter, the partial destruction of capital stocks forces firms to buy newer machines with different productivity coefficient. In this sense, the shock can act as the trigger for the self-reinforcing and path dependency agglomeration process that characterizes the model, usually generated by endogenous technical change and innovation. However, a mild shock does not systematically produce a sufficient regional productivity gap able to start the agglomeration. Conversely, this effect becomes more evident as the size of Dc passes 0.25, with almost the totality of (0.92) MC sample reaching either equilibria with the highest shock ($Dc = 0.5$).

A second important result is the presence of non-linearity between the size of the shock (Dc) and the likelihood of statistical equilibria as well as global economic performance. In particular, the model displays an higher both probability of agglomeration in Coastal region and overall GDP growth with the presence of a small shock than without a shock. However, as the damage coefficient increases the probability of agglomeration in Coastal region decreases steeply as well as the positive effects on overall economic growth fade out (Fig. 3-central and right panels). The reason behind such non-linearity is the complex interplay between two forces caused by the natural hazard, defined here as "disruptive effect" and "creative destruction effect" [16]. On the one hand, the latter refers to positive economic effect following a natural disaster, which despite being initially counter-intuitive, it is not uncommon in empirical studies [17, 18]. In our model it is generated by the "forced" investment that firms have to undertake following the climate shock. Firms have to replace their capital destroyed with newer and more productive technologies by anticipating future investment. This leap forward, boosts Coastal region productivity and hence the aggregate economy. On the other hand, the former reflects the negative effects that the shock causes to the economy, such as temporal drop in productivity and consumption. Moreover,

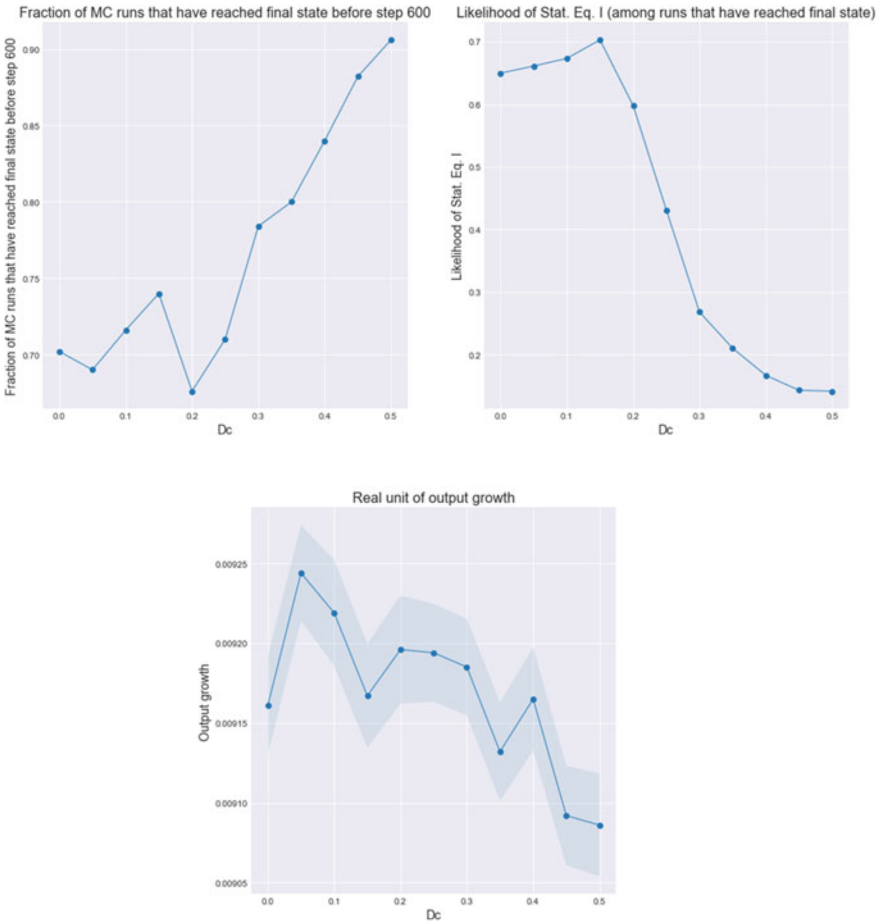

Fig. 3 Response of speed (left), likelihood between equilibria (center) and global GDP growth (right) to shocks of different magnitude. Results are from a MC of size 500

firms are resources constrained and they might not be able to replace their capital stock entirely. Notably, as long as the shock is mild, the "creative destruction" prevails. Since only a small fraction of capital stock and market is affected, firms can afford to buy brand new machines, increase productivity, wages and the likelihood of agglomeration Coastal region (Fig. 3-central panel). Moreover, such technological jump has positive "hysteretic effects" on GDP that display statistically significant higher growth rate when $Dc < 0.15$ (Fig. 3-right panel). However, as the Dc coefficient goes up, so does the fraction of capital destroyed and firms are not able to buy it back entirely because it is beyond their financial capabilities. Thus, they are forced to reduce output and fire the surplus of workers. Moreover, they are not able to fulfill the whole demand, mining long-term competitiveness. The more the firms

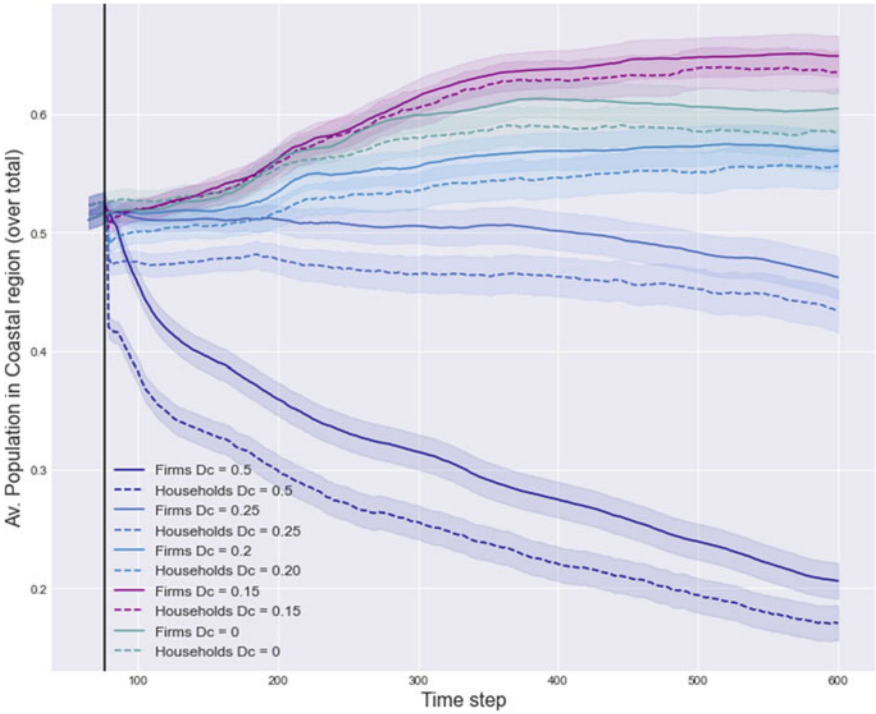

Fig. 4 Population dynamics in response of shocks of different magnitude. Results are the average of MC simulation of size 500

are constrained in production, the higher is the increase of unemployment rate in the Coastal region. This increase of unemployment rate coupled with the temporal decrease of productivity and wages triggers a households migration towards the inland region. As households redistribute between the two regions, also consumption does. Therefore, the volume of out-migration in the aftermath of the natural hazard is crucial to determine future region attractiveness. As shown in Fig. 4, when more than 5% of the total household population leaves the Coastal region ($Dc \geq 0.25$), the demand distribution between the two regions reaches a tipping point that makes the Inland region more attractive for further firms migration. Importantly, for very high values, ($DC \geq 0.45$), the shock not only substantially affects the distribution of economics activities, but it also compromises the development of the whole economy (Fig. 3-right panel). In particular, the economy displays a negative "hysteresis" characterized by a statistically significant lower GDP growth.

4 Conclusion

The amount of people and assets exposed to climate hazards is increasing as a consequence of both urbanization and changing climate. In this work, we have investigated the macroeconomic and spatial consequences of heterogeneous climate shocks in a theoretical agent-based computational economic framework. The model is characterized by two regions, and three classes of mobile agents, namely capital-good firms, consumption-good firms and households that interact in goods and labour markets. We have experimented two types of scenario first, we muted climate shocks and showed the ability of the model to reproduce the self-reinforcing and path-dependency agglomeration process typical of economic geography model.

Importantly, individual investment choices and technical change trigger such process, reinforcing previous literature findings about the correlation between productivity and agglomeration forces. Furthermore, MC simulation results displayed non-ergodic properties, yet a more likely concentration of economies activities in coastal areas because of their competitive advantage in trade with the rest of the world. We have investigated the role of the transport in these dynamics.

In the second scenario, we introduced heterogeneous climate shocks hitting the Coastal region. We found a non-linear response of both spatial distribution of economic activities and global macroeconomic indicators to the size of the shock. In particular, a small shock increased statistically significant the probability of agglomeration in the Coastal region as well as the output of the whole economy. Conversely, big shocks boost agglomeration in the Inland safe region, but also generate negative "hysteretic" effects on global economic growth. Such non-linearity depends on the complex interplay of two forces that we defined as "creative destruction effect" and "disruptive effect". The model showed encouraging first results on the trade-off between natural disasters and agglomeration economies. Moreover, it advanced the economic geography literature by exploring spatial distribution of economic activities in a out-of equilibrium fashion. Further research could include, but not limited to, calibration with empirical data, more realistic representation of natural hazards, introduction of additional industries and multi-level climate change adaptation actions to reduce harm from the shocks.

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