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Abstract

When do multinationals show resilience during natural disasters? To answer this, we develop a simple model in which multinationals and local firms in the host country are interacted through input-output linkages. When natural disasters seriously hit local firms and thus increase the cost of sourcing local intermediates, most multinationals may leave the host country. However, they are likely to stay if they are tightly linked with local suppliers and face low trade costs of importing foreign intermediates. We further provide two extensions of the basic model to allow for multinationals with heterogeneous productivity and disaster reconstruction.

JEL codes: F12; F23; Q54; R11.

Keywords: Foreign direct investment (FDI); Multinational enterprises (MNEs); Input–output linkages; Supply chain disruptions; Multiple equilibria.

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1 Introduction

Multinational enterprises (MNEs) play a vital role in helping developing countries grow by contributing to local employment and productivity improvement in normal times. However, MNEs may play a more crucial role during crisis times, especially in natural disasters. Thailand's experience of large-scale floods in 2011 is a notable example of the destructive effects of a natural disaster on multinationals. The estimated economic damage is 46.5 billion USD across all sectors, and manufacturing alone suffered 32 billion USD of damage (Abe and Ye, 2013; Haraguchi and Lall, 2015). Seven industrial parks and 904 factories were inundated, more than half of which were Japanese MNEs. Thus, the business operation of many factories completely ceased for one to two months. Even non-inundated multinational plants were forced to reduce production due to the lack of parts from damaged suppliers. The disaster-hit economy hopes multinationals to show resilience so that they continue to source local intermediates and help local industry recover. The Bank of Thailand cautioned against this optimistic idea by stating that, unless the government took appropriate measures, the flood would relocate more multinationals to other Asian countries in the long run (BOT, 2012). The exit of footloose multinationals would weaken their input-output linkages with local suppliers, damaging the economy further. Indeed, using country-level data, Escaleras and Register (2011) and Doytch (2019) find that natural disasters have negative effects on aggregate foreign direct investment (FDI) inflows.[1]

Only a limited attention in the literature has been paid to how MNEs respond to natural disasters and little is known about underlying mechanisms, despite its importance in the real world. This paper theoretically investigates under what conditions multinationals leave their host country once it is hit by negative supply shocks such as natural disasters and which factor helps them stay there. To address these, our model takes into account two noticeable characteristics of multinationals: (i) input-output (or vertical) industrial linkages and (ii) footloose-ness. Vertical linkages imply that multinationals have important complementarities with local industry (Markusen and Venables, 1999). Sourcing by multinationals helps the local supply industry grow, leading to a lower price of inputs and thus benefiting themselves. The footloose-ness arises because the location choice of foreign capital is based on the comparison of profits made in different countries. Multinationals are sensitive to negative

[1]Using aggregate data on FDI inflows into Thailand, Anuchitworawong and Thampanishvong (2015) construct a severity index of natural disasters consisting of their frequencies and damages and find that this negatively affects aggregate FDI inflows into Thailand in 1971–2012.

shocks in their location; thus, compared with local firms, they are likely to enter and exit a host country (Görg and Strobl, 2003; Bernard and Jensen, 2007).

Our main findings are threefold. First, multiple equilibria, one in which multinationals enter and the other in which they do not, may exist. Second, a substantial negative supply shock, even if it damages local suppliers only, results in a switch from one equilibrium with multinationals to the other without them. The negative shock reduces the number of local suppliers and hence raises the cost of sourcing inputs. Multinationals may find the damaged country unprofitable and leave, shrinking local industry further. This mechanism helps understand the (sometimes long-lasting) negative disaster impact on FDI found in empirical studies (Escaleras and Register, 2011; Doytch, 2019; Toner-Rodgers and Friedt, 2020). Finally, conditions that prevent multinational relocation are identified. Specifically, they are more likely to stay in the disaster-hit country, if local inputs are more important in multinational production or trade costs of importing foreign inputs are lower. Contrary to the warning by the Bank of Thailand, the 2011 Thailand floods did not cause long-lasting relocation and restructuring by manufacturing MNEs, perhaps because of strong industrial linkages between local and multinational firms and progressive trade liberalization (Milner et al., 2006; Feliciano and Doytch, 2020).[2]

We further extend the basic model to allow for heterogeneous productivity and gradual recovery from disasters, giving similar results and yielding additional implications. Among others, we find that the least efficient multinationals are the first to leave the host country once a disaster hits. Put differently, multinationals staying in the host are likely to be the most efficient ones. This result may help us understand the observation that in the aftermath of the 2011 floods, larger Japanese MNEs in Thailand did not change their local procurement share as much as smaller ones (Hayakawa et al., 2015).

1.1 Relation to the literature

We aim to contribute primarily to the literature investigating the impact of multinationals on industrial development (Alfaro, 2015 for a survey). For example, using Irish micro-level data, Görg and Strobl (2002) find that the presence of multinationals promotes the entry

[2]Using the information on Japanese-Thailand bilateral input-output table, Milner et al. (2006) find a sizable and robust association between the number of Japanese affiliates in Thailand and their linkages with Thailand's industries. Feliciano and Doytch (2020) document the recent development of Thailand's Free Trade Agreements. Using Thailand's firm-level data, they find that reductions in import tariffs improve the performance of both local and foreign-owned firms.

of local manufacturing firms.[3] Among many channels through which multinationals benefit host economies, an important one is vertical industrial linkages (e.g., Javorcik, 2004; Alfaro-Ureña et al., 2020). Alfaro-Ureña et al. (2020) use firm-to-firm transaction data in Costa Rica and find that local firms increase their size and productivity after becoming a supplier to multinationals.

Although many theoretical attempts seek to understand the role of multinationals in vertically linked industries, only a limited number of studies have described (de)industrialization as switches between multiple equilibria in the model economy (Rodríguez-Clare, 1996; Markusen and Venables, 1999; Carluccio and Fally, 2013).[4] Markusen and Venables (1999) numerically illustrate the situation where the entry of downstream MNEs fosters local upstream industry. These studies, however, have analyzed each equilibrium only separately and not explored which shocks trigger a shift from one equilibrium to another or how the transition proceeds. We rely on their framework and take one step further to analytically characterize the conditions under which an exogenous supply shock leads to an equilibrium switch and which factor promotes or prevents it. In doing so, our theoretical results can be related to disaster impacts on multinationals. In contrast to Carluccio and Fally (2013), who model a "technological incompatibility" of local intermediates with multinational production, we deliberately keep the technology side as simple as possible to highlight the impact of negative supply shocks.

Some studies examine the impact of various types of risk on multinational behavior (Aizenman, 2003; Aizenman and Marion, 2004; Russ, 2007; Fillat and Garetto, 2015). Aizenman and Marion (2004) investigate how the volatility of demand and supply shocks affect differently market-seeking FDI and efficiency-seeking FDI. For instance, Fillat and Garetto (2015) model multinational entry as a real-option problem, where multinationals show resilience against negative shocks because of the sunk cost they have paid to enter. Unlike these studies focusing on risk under uncertainty, our model highlights actual physical damages, given the context of developing countries that are vulnerable to severe disasters (ADB, 2013; Sivapuram and Shaw, 2020).

[3]By contrast, studies reporting negative impacts include Aitken and Harrison (1999) for Venezuela; Görg and Strobl (2002) for Ireland; and Lu et al. (2017) for China.

[4]We differ from more recent theoretical studies on MNEs such as Alfaro et al. (2010), Garetto (2013), Ramondo and Rodríguez-Clare (2013), Arkolakis et al., 2018, Adachi and Saito (2020), and Gumpert et al. (2020) in that exogenous shocks always lead to smooth changes in equilibrium in these models unlike in our models. Economic geography models deal with multiple equilibria but typically assume away distinction between local and multinational firms and/or input-output linkages (e.g., Redding and Turner, 2015, Section 20.3.7; Akamatsu et al., 2020; Gaspar, 2020). A few exceptions include Fujita and Thisse (2006), Hsu et al. (2020), and Kato and Okoshi (2020), although disaster impact is outside the scope of these studies.

Simulation studies investigating disaster impact in an economy with industrial linkages are complementary to ours (Okuyama and Chang, 2004; Henriet et al., 2012; Inoue and Todo, 2019; Galbusera and Giannopoulos, 2018 for a survey).[5] In an economy where buyer-supplier relationship constitutes a complex network, Henriet et al. (2012) show how network features such as concentration, clustering and connectedness between subregions either dampen or magnify the effects of a natural disaster. We differ from these studies in terms of both in focus and modelling strategies. They describe regional economies by fixing the location of production, whereas we emphasize the footloose-ness of internationally mobile MNEs in developing countries. Although input-output linkages in our model are admittedly far simpler than theirs, we hope it serves as the first step toward a more comprehensive analysis on disasters and multinationals.

This paper is also related to the vast body of empirical literature assessing disaster impact on firm performance.[6] Recent studies using micro-level data have found that natural disasters destroy enormous amounts of physical capital, which may be a good chance of updating capital (Leiter et al., 2009; Vu and Noy, 2018; Okazaki et al., 2019) or a bad one of decreasing productivity and the survival rates of firms (Tanaka, 2015; Cainelli et al., 2018; Cole et al., 2019).[7]

Only a limited number of empirical studies examined the nexus between natural disasters and multinationals. They find mixed results on whether the disaster effect is positive or negative and short- or long term (Escaleras and Register, 2011; Oh and Oetzel, 2011; Anuchitworawong and Thampanishvong, 2015; Doytch, 2019; Toner-Rodgers and Friedt, 2020). Doytch (2019) examines sectoral FDI inflows in 69 countries from 1980 to 2011. Her dynamic panel regression results show negative effects in general, but also suggest that the effects vary depending on the type of disasters, industries, and regions. Using data from foreign affiliates of 71 European MNEs, Oh and Oetzel (2011) find that major natural disasters have no significant impact on the number of affiliates, whereas terrorist attacks and technological disasters have negative impacts. Closely examining disaster events in India in 2006–2019,

[5]For empirical studies on the impact of negative shocks including natural disasters in supply chains, see Todo et al. (2015), Barrot and Sauvagnat (2016), Carvalho et al. (2020), Dhyne et al. (2021), and Kashiwagi et al. (2021).

[6]Empirical studies on the disaster impact on economic growth are also extensive. For a summary of finding, see Tables 1 and 2 in Cavallo and Noy (2011); and Table 1 in Felbermayr and Gröschl (2013). Theoretical contributions in this line include Hallegatte and Dumas (2009), Ikefuji and Horii (2012), Akao and Sakamoto (2018), and Schubert and Smulders (2019).

[7]Some studies have reported negative impacts on export and import performance of affected firms at least in the short run (Ando and Kimura, 2012; Boehm et al., 2019; Elliott et al., 2019).

Toner-Rodgers and Friedt (2020) report persistent intra-national shifts in multinationals' investment patterns from disaster-affected regions to non-affected regions. Our theory may help sort out these empirical findings by uncovering why and when natural disasters may have a long-term negative impact on multinationals and local industry.

1.2 Disaster impact on FDI: an empirical example

To motivate theoretical analysis, this subsection provides suggestive evidence on natural disasters and FDI. We first check the negative impact of natural disasters on FDI inflows to developing countries. We then confirm that the negative impact on FDI inflows to developing countries is long-term especially when disaster damages are severe. We utilize country-level data on FDI in 1991–2015 from the World Bank Development Indicators (WDI) and data on natural disasters in 1976–2015 from the Emergency Disasters Database (EM-DAT) maintained by the Centre for Research on the Epidemiology of Disasters.[8] Detailed information on data sources is provided in Data Appendix.

Following Escaleras and Register (2011), we regress FDI inflows (as a percent of GDP) from the world to country i in year t on the total number of natural-disaster events that hit country i in $t-1$ to $t-\tau$ years:

$$\mathrm{FDI}_{i,t} = \alpha + \beta \sum_{s=1}^{\tau} (\text{No. of natural disasters})_{i,t-s} + \boldsymbol{x}'_{i,t}\boldsymbol{\gamma} + u_{i,t},$$

where τ takes 5, 10, or 15; $\boldsymbol{x}_{i,t}$ is a column vector of control variables; and $u_{i,t}$ is the error term.[9] We reexamine their analysis by updating the sample period and splitting the sample based on whether a country is a developing/developed one.[10] The estimates of β in developing-countries sample are shown in columns (1) to (3) of Table 1, all of which show a negative sign with strong statistical significance. Although the absolute magnitude of the estimate gets smaller as the time span is longer (from columns (1) to (3)), there seems a long-term impact. The estimates in developed-countries sample are in columns (4) to (6), all of which show a negative sign but without statistical significance. These results suggest that

[8] The EM-DAT database is commonly used in studies on natural disasters (e.g., Escaleras and Register, 2011; Felbermayr and Gröschl, 2013, 2014; Hallegatte, 2015; Doytch, 2019; Kikkawa and Sasahara, 2020)

[9] Control variables include: population growth, inflation, corporate tax and an index of financial development. See Data Appendix for variable descriptions and full regression results.

[10] Following the classification of the World Bank, a developed country is defined as one that belongs to the high-income group, while a developing country as one that falls in the other income groups.

the negative impact of natural disasters is more articulated in developing countries.

Table 1. Disaster impact on FDI: developing vs. developed countries

	Dependent variable: FDI (as % of GDP)					
	Developing countries			Developed countries		
	(1)	(2)	(3)	(4)	(5)	(6)
No. of disasters in the prior 5 years	−0.031**			−0.056		
	(0.014)			(0.052)		
No. of disasters in the prior 10 years		−0.027***			−0.020	
		(0.007)			(0.024)	
No. of disasters in the prior 15 years			−0.020***			−0.007
			(0.005)			(0.014)
Country fixed effects	✓	✓	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
Number of countries	112	112	112	41	41	41
Number of observations	2,000	2,000	2,000	655	655	655
R^2	0.513	0.515	0.515	0.426	0.424	0.423

Notes: Standard errors clustered by country are in parentheses. Developed countries are those belonging to the high-income group, while developing countries to the other income groups, according to the classification of the World Bank. We exclude tax haven countries identified by Hines and Rice (1994) and countries that never experienced natural disasters in 1976–2015. We drop the top 1% and the bottom 1% of the observations of the dependent variable as outliers.
*Significant at 10% level; **Significant at 5% level; ***Significant at 1% level.

Let us check whether disasters have indeed long-lasting effects on the current FDI performance. We explore this by decomposing the number of disaster events in the prior 15 years into recent and past ones. Namely, the modified estimation equation includes three disaster variables such that (i)the number of events in the prior 5 years; (ii)that in the prior 6 to 10 years; and (iii)that in the prior 11 to 15 years, or two variables such that (i)the number of events in the prior 5 years; and (ii)that in the prior 6 to 15 years. We further consider the heterogeneous effect of disasters depending on their intensity. A disaster event is defined as a severe one if it records financial damage as a share of GDP exceeding its median value for all countries that have ever suffered from disasters in 1976–2015. Hence, a non-severe event is defined as one if it is equal to or below the median. Table 2 provides regression results for developing countries. In all columns, the number of disasters more than 5 years ago have negative effect with in general statistical significance, while that in the prior 5 years does show any statistically significant effect. These suggest a long-term negative impact. The negative coefficients in columns (1) to (2) are consistently greater in magnitude than their counterparts in columns (3) to (4), telling that the severe events discourage FDI inflows more.

These observations guide our theory in a way such that the long-term (and perhaps irreversible) impact could be modeled as shifts between multiple equilibria of industrial configurations in the host country. Important aspects are that such shifts may likely be to occur in developing counties and to be brought especially by severe disasters. Building a model describing these aspects, our aim is then to characterize the conditions under which FDI in developing countries shows resilience against substantial disasters.

Table 2. Disaster impact on FDI in developing countries: severe vs. non-severe disasters

	Dependent variable: FDI (as % of GDP)			
	Severe disasters		Non-severe disasters	
	(1)	(2)	(3)	(4)
No. of disasters in the prior 5 years	0.013	0.014	0.019	0.018
	(0.055)	(0.056)	(0.024)	(0.024)
No. of disasters in the prior 6 to 10 years	-0.081^{*}		-0.053^{**}	
	(0.049)		(0.022)	
No. of disasters in the prior 11 to 15 years	-0.095^{***}		-0.031	
	(0.034)		(0.028)	
No. of disasters in the prior 6 to 15 years		-0.088^{***}		-0.042^{***}
		(0.022)		(0.013)
Country dummies	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
Number of countries	112	112	112	112
Number of observations	2,000	2,000	2,000	2,000
R^2	0.516	0.516	0.515	0.515

Notes: Standard errors clustered by country are in parentheses. A severe disaster in country i in year t is defined as one that records financial damages as a share of GDP exceeding its median for all countries that have ever experienced natural disasters in 1976–2015. A non-severe disaster in country i in year t is defined as one that is not severe. We exclude tax haven countries identified by Hines and Rice (1994) and countries that never experienced natural disasters during the sample period. We drop the top 1% and the bottom 1% of the observations of the dependent variable as outliers.

*Significant at 10% level; **Significant at 5% level; ***Significant at 1% level.

The remainder of the paper is structured as follows. The next section describes the model and characterizes conditions under which different industrial configurations emerge. Section 3 examines the impact of natural disasters and characterizes the conditions under which multinationals show resilience. Section 4 presents two extensions of the basic model. The final section concludes the paper.

2 The model

Consider the host country and the foreign country, comprising the rest of the world. There are two sectors: a differentiated-product sector and a homogeneous-product sector. In the differentiated sector, there are three types of firms: domestic, multinational, and foreign firms. The last two are foreign-owned firms. Differentiated varieties have two roles: final goods for consumers in the two countries and intermediate inputs for domestic and multinational firms. To best fit our model in the context of developing-countries, the host-country market is assumed to be small and localized and thus served by only domestic firms, while the foreign-owned firms serve the non-host country market.[11] Foreign capital used as fixed costs of setting up foreign-owned firms is free to choose between the host and the foreign countries. Fig. 1 presents the structure of our model.

In the homogeneous sector, firms use labor to produce a homogeneous good. We assume that the good is freely traded and the unit labor requirement is unity. These imply that the good's price is equal to both a constant world price and wage. We choose the homogeneous good as the numéraire, so that both the good price and the wage are unity. Labor is freely mobile between two sectors, which equalize wages between the sectors.

[11] In an earlier working paper, we analyze the situation where foreign-owned firms serve the host-country market and obtain similar results (Kato and Okubo, 2017).

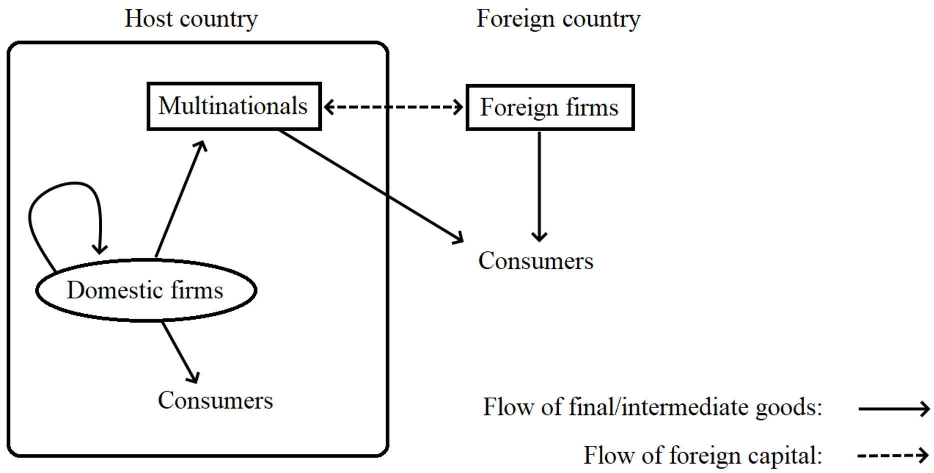

Fig. 1. Model structure.

2.1 Tastes and production

Consumers. The representative consumer in the host country has the following utility function:

$$u = Q^{\alpha}(q^{O})^{1-\alpha}, \tag{1}$$
$$\text{where} \quad Q = \left(\int q(\omega)^{\frac{\sigma-1}{\sigma}} d\omega\right)^{\frac{\sigma}{\sigma-1}},$$

and where Q is the composite of the differentiated final goods and $q(\omega)$ is the demand for an individual variety of ω produced by the domestic firms. q^{O} is the demand for the numéraire good, α is the expenditure share on final goods, and $\sigma > 1$ measures the elasticity of substitution between them. We solve the first-order condition (FOC) of utility maximization to obtain demand function for variety ω:

$$q = \left(\frac{p(\omega)}{P}\right)^{-\sigma} \frac{E}{P}, \tag{2}$$
$$\text{where} \quad P = \left(\int p(\omega)^{1-\sigma} d\omega\right)^{\frac{1}{1-\sigma}},$$

and where p is the price of the variety and E is the aggregate expenditure on differentiated goods, which is equal to α share of income. The income of the representative consumer consists of labor income and excess profits repatriated by domestic firms (if not zero). Noting that domestic firms are symmetric, the price index, P, reduces to

$$P = \left(Np^{1-\sigma}\right)^{\frac{1}{1-\sigma}} = N^{\frac{1}{1-\sigma}}p, \tag{3}$$

where N is the number (or mass) of domestic firms. We will suppress the variety index of ω in what follows.

Our focus is on the host country; hence, we do not fully model the market in the rest of the world, whom multinational and foreign firms serve. The demand functions for a typical variety produced by multinational firms, $i = m$, and foreign firms, $i = f$, are

$$q_i = \left(\frac{p_i}{P^*}\right)^{-\sigma} \frac{E^*}{P^*} \equiv p_i^{-\sigma} D^*, \qquad i \in \{m, f\}, \tag{4}$$

where P^* and E^* are respectively the price index and the total expenditure on differentiated goods in the rest of the world. The market size of the rest of the world is summarized by a constant $D^* \equiv E^*(P^*)^{\sigma-1}$.

Domestic firms. Each domestic firm requires F amounts of labor for setup costs. Once established, they use $\widetilde{a}$ units of a Cobb-Douglas composite input for each unit of output they produce. The composite input comprises foreign intermediates (with share $1-\mu$) and local intermediates produced by the differentiated sector itself (with share μ). The price of foreign intermediates is exogenously given by τp_u^*, where $p_u^* \geq 1$ is a constant free-on-board price and $\tau \geq 1$ represents trade costs between the host country and the rest of the world. The minimized total cost to produce q units of a typical variety is then

$$C(q) = P^\mu w^{1-\mu}\widetilde{a}q + wF = P^\mu \widetilde{a}q + F, \tag{5}$$

noting that the wage is equal to one: $w = 1$. As the demand elasticity is given by σ, which we will see later, the FOCs for profit maximization yield the usual constant-markup pricing:

$$p = \frac{\sigma\widetilde{a}P^\mu}{\sigma-1} = aP^\mu, \tag{6}$$

where we choose $\widetilde{a}$ such that $\widetilde{a} = (\sigma-1)a/\sigma$. From Eqs. (3) and (6), we can rewrite the price index as

$$P = a^{\frac{1}{1-\mu}} N^{\frac{1}{(1-\sigma)(1-\mu)}}, \tag{7}$$

which decreases with N because $\sigma > 1$ and $\mu \in (0, 1)$,

Multinationals. Each multinational firm needs one unit of foreign capital to start operation and $\widetilde{a}_m$ units of a composite input per unit of output. The composite input for multinationals is different from that for domestic firms and is made up of intermediates produced abroad (with share $1 - \mu_m$) and intermediates produced by domestic firms (with share μ_m). The cost function for a typical multinational is then

$$C_m(q_m) = P^{\mu_m}(\tau p_u^*)^{1-\mu_m}\widetilde{a}_m q_m + r_m, \tag{8}$$

where q_m is given by Eq. (4) and π_m is the rental rate of foreign capital. The FOCs give the optimal price:

$$p_m = \frac{\sigma \widetilde{a}_m P^{\mu_m}(\tau p_u^*)^{1-\mu_m}}{\sigma - 1} = a_m P^{\mu_m}(\tau p_u^*)^{1-\mu_m}, \tag{9}$$

where $\widetilde{a}_m$ is chosen such that $\widetilde{a}_m = (\sigma - 1)a_m/\sigma$.

Foreign firms. Each foreign firm needs one unit of foreign capital for setup costs and $\widetilde{a}_m$ units of foreign intermediates per unit of output. They source all inputs from the world market and do not incur trade costs. The cost function for a typical foreign firm is

$$C_f(q_f) = p_u^* \widetilde{a}_m q_f + r_f, \tag{10}$$

where r_f is the rental rate of foreign capital for foreign firms. The optimal price for the variety is simply given by $p_f = a_m p_u^*$.

Finally, we need to consider clearing conditions for goods and labor markets. The total output for the variety produced by each domestic firm, q, must be equal to the sum of consumer demand and the input requirement of domestic and multinational firms. By using Eq. (2) and applying Shepard's lemma to Eqs. (5) and (7), we obtain

$$\begin{aligned} q &= \left(\frac{p}{P}\right)^{-\sigma} \frac{E}{P} + N\frac{\partial C(q)}{\partial p} + N_m \frac{\partial C_m(q_m)}{\partial p} \\ &= p^{-\sigma}\left[P^{\sigma-1}E + N\mu P^{\sigma+\mu-1}\widetilde{a}q + N_m \mu_m P^{\sigma+\mu_m-1}(\tau p_u^*)^{1-\mu_m}\widetilde{a}_m q_m\right], \end{aligned} \tag{11}$$

noting that the demand elasticity is equal to the elasticity of substitution between varieties σ.

Similarly, the labor demand in the differentiated sector can be derived from using Shephard's lemma as $N \cdot \partial C(q)/\partial w = N\left[(1-\mu)P^{\mu}\widetilde{a}q + F\right]$. The labor-market clearing requires that the sum of the labor demand in both the differentiated and the numéraire sectors must be equal to the total workforce in the host country, L. It determines the upper bound of N such that $N \leq \overline{N} \equiv L/F[\sigma(1-\mu)+\mu]$ (see Appendix 1). In the numéraire sector, its labor demand and thus its output are adjusted in a way such that imports/exports of the good are balanced.

2.2 Industry equilibrium

All three types of firms freely enter and exit from the differentiated sector. Let $\Pi \equiv pq - C(q)$ be the excess profit of domestic firms, i.e., operating profits minus fixed costs. Then, entry occurs when $\Pi > 0$, while exit occurs when $\Pi < 0$. This adjustment process stops at the point where domestic firms break even, that is, $\Pi = 0$. Using Eqs. (5), (6), and (10), we can derive the combinations of N and N_m that satisfy $\Pi = 0$ as

$$
\begin{aligned}
&\Pi = pq - C(q) = pq - P^{\mu}\widetilde{a}q - F = 0, \\
&\to N_m = \Theta N^{-\frac{\mu_m}{1-\mu}}\left(N - \alpha\overline{N}\right), \qquad (12) \\
&\text{where} \quad \Theta \equiv \frac{\sigma F[\sigma(1-\mu)+\mu]\left[a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right]^{\sigma-1}}{\mu_m D^*(\sigma-1)}, \qquad \overline{N} \equiv \frac{L}{F[\sigma(1-\mu)+\sigma]},
\end{aligned}
$$

noting that $\overline{N}$ represents the maximum number of domestic firms the host country can support, which depends on its workforce, L. We draw a typical $\Pi = 0$ locus in Fig. 2(a). The locus has an upward slope under a reasonable condition that the expenditure share on varieties is not sufficient small such that $\alpha > 1-(1-\mu)/\mu_m$, which we will assume throughout the paper.[12]

We assume a gradual entry-and-exit process such that the entry cost is proportional to the number of existing domestic firms: $\dot{N} = \Pi$, where the dot denotes the time derivative.[13]

[12] The $\Pi = 0$ locus increases with N if $\partial N_m/\partial N = N^{-1-\frac{\mu_m}{1-\mu}}[\mu_m\alpha\overline{N} + (1-\mu-\mu_m)N]/(1-\mu_d) < 0$, or equivalently $\mu_m\alpha\overline{N} + (1-\mu-\mu_m)N > 0$ holds. A sufficient condition for this inequality is $\alpha > 1-(1-\mu)/\mu_m$.

[13] More rigorous dynamic analyses of location models can be found in Baldwin (2001), Ottaviano (2001), Boucekkine et al. (2013), and Fujishima and Oyama (2021).

The arrows in Fig. 2 indicate the direction of motions. Above the curve, $\Pi < 0$ holds and domestic firms exit. Meanwhile, below the curve, $\Pi > 0$ holds and domestic firms enter. It has an upward slope because an increase in the number of multinationals and hence in local intermediate demand induces the entry of domestic firms. When N is small such that $N \in [0, \alpha\overline{N}]$, the costs of sourcing local intermediates, P, are too high for a positive number of domestic firms to survive. The domestic firms may use up all labor in the host country, that is, $N = \overline{N}$, in which case no further entry is allowed and incumbents make positive profits.

We turn to multinational and foreign firms. Let $\Pi_i = p_i q_i - C_i(q_i)$ be the excess profit of firm $i \in \{m, f\}$. Then, free entry and exit lead to $\Pi_i = 0$, where the rental rate of foreign capital is exactly covered by operating profits: $r_i = p_i q_i/\sigma$. As a result of the arbitrage behavior of foreign investors, foreign capital chooses the type of firms that generates higher rental rate/operating profits. Foreign capital becomes indifferent between becoming a multinational and a foreign firm when the capital-return differential is zero:

$$\begin{aligned} &\Delta r_m \equiv r_m - r_f = p_m q_m/\sigma - p_f q_f/\sigma = 0, \\ &\rightarrow N = a^{\sigma-1}\left[\tau^{\frac{1-\mu_m}{\mu_m}}(p_u^*)^{-1}\right]^{(\sigma-1)(1-\mu)} \equiv N_0, \end{aligned} \tag{13}$$

where we used Eqs. (4), (8) to (10) and $p_f = a_m p_u^*$. A typical $\Delta r_m = 0$ locus is drawn in Fig. 2(b) with arrows indicating the direction of motion, where K_f is the total amount of foreign capital. The locus does not depend on the mass of multinationals, N_m, because the operating profits of both types of firms are independent of N_m. What only matters for the location decision of foreign capital is the price index of local intermediates, P, which is a decreasing function of N. The $\Delta r_m = 0$ locus, or equivalently the $N = N_0$ line is the threshold number of local firms above which foreign capital chooses to enter the host country. When $N > N_0$ holds, multinationals can produce at a lower marginal cost than foreign firms, and thus foreign capital can choose to become a multinational. The opposite is true when $N < N_0$ holds.

Following the gradual relocation process such that $\dot{N}_m = \Delta r_m$ as in the entry-and-exit of local firms, the movement of foreign capital stops at either one of the three points: (i) $\Delta r_m = 0$; (ii) $\Delta r_m > 0$ and all foreign capital becomes a multinational, i.e., $N_m = K_f$; and (iii) $\Delta r_m < 0$ and all foreign capital becomes a foreign firm, i.e., $N_m = 0$.

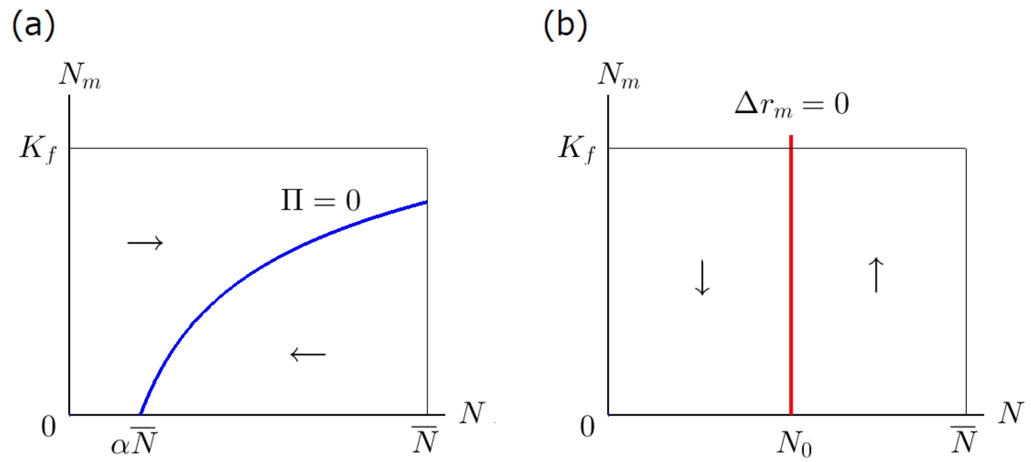

Fig. 2. Equilibrium curves.

Industry equilibrium, in which both the adjustments of N and N_m are completed, is determined by the relative positions of the two curves. When $N_0 < \alpha\overline{N}$ holds, foreign capital finds it more profitable to become a multinational than to become a foreign firm even if there are few local firms and hence P is high. More multinationals demand local intermediates, inducing more domestic firms to enter. Consequently, the economy reaches point $S_1 : (N, N_m) = (\overline{N}, K_f)$, a stable equilibrium where both domestic and multinational firms coexist.

Meanwhile, when $N_0 > \overline{N}$ holds, no foreign capital prefers to become a multinational. The unique stable equilibrium is point $S_2 : (N, N_m) = (\alpha\overline{N}, 0)$, where only domestic firms operate in the host country. Since there are no intermediate demand by multinationals, the number of domestic firms, $\alpha\overline{N} = \alpha L/F[\sigma(1-\mu)+\sigma]$, is constrained solely by the local expenditure on differentiated goods, $E = \alpha L$.

When N_0 is in between $\alpha\overline{N}$ and $\overline{N}$, both points, S_1 and S_2, are stable equilibria. Fig. 3 shows this situation. The foreign-capital-return differential is not large enough; hence, whether becoming a multinational or a foreign firm has no definite answer. Rather, the answer depends on the number of local firms currently prevailing in the host country. This complementarity between multinationals and local firms creates a coordination problem. Foreign capital will enter the host country if local production is expected to expand. If there exists a prospect of multinationals rising intermediate demand, more domestic firms will enter, leading the economy to point S_1. The same reasoning applies to point S_2: local intermediate production is never expected to expand, if no prospect of multinational entry exists. Which of the two equilibria arises depends on the expectations of firms/investors and the initial industry configuration (Krugman, 1991; Matsuyama, 1991). Point U is a saddle but an unstable equilibrium, because our model does not include any jump variables to put the economy on the saddle path.

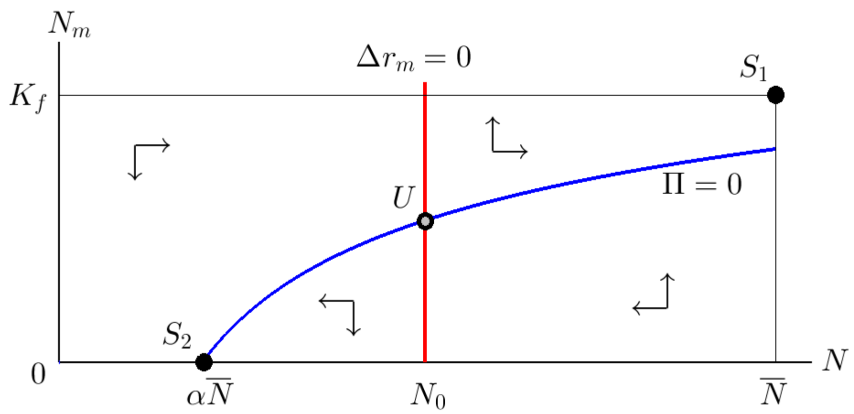

Fig. 3. Multiple equilibria.

As $\overline{N}$ is a function of fixed labor input F, it is convenient to characterize industry equilibrium using F. We assume that (a) the expenditure share on varieties is not too small such that $\alpha > 1 - (1-\mu)/\mu_m$, in which case the $\Pi = 0$ locus has an upward slope, and (b) it never touches the upper limit of N_m, that is, a sufficiently large amount of foreign capital such that $K_f > \Theta\overline{N}^{\frac{1-\mu-\mu_m}{1-\mu}}(1-\alpha)$ (see Eq. (12)). Then we obtain the following proposition.

Proposition 1 (Industry equilibrium). *Using the fixed labor requirement for a domestic firm, F, industry equilibrium is characterized as follows:*

(i) If F is small such that $F < F_a \equiv \alpha L/N_0[\sigma(1-\mu)+\mu]$, the configuration in which domestic and multinational firms coexist, $S_1 : (N, N_m) = (\overline{N}, K_f)$, is the only stable equilibrium.

(ii) If F is large such that $F > F_b \equiv L/N_0[\sigma(1-\mu)+\mu]$, the configuration in which all multinational firms leave, $S_2 : (N, N_m) = (\alpha\overline{N}, 0)$, is the only stable equilibrium.

(iii) If F is intermediate such that $F_a \leq F \leq F_b$, both configurations are stable equilibria.

3 Natural disasters and the resilience of FDI

3.1 Adverse shock to local firms

Let us now consider natural disasters in the host country. A natural disaster to local firms is modeled as an adverse shock to the fixed labor input F, that is, an increase from F to $F+\Delta F$ with $\Delta F > 0$. We examine (i) whether the natural disaster changes the equilibrium configuration, and if so (ii) when such a change is less likely to occur: that is, when the host economy is more likely to be resilient.

Suppose F is in between F_a and F_b and that the economy is at point $S_1 : (N, N_m) = (\overline{N}, K_f)$. Fig. 4(a) depicts this situation and marks the initial point with a double circle. As shown by the thin dashed line in Fig. 4(b), an increase in F raises labor used in each domestic firm and hence reduces the maximum number of firms the host country can support, i.e., a decrease from $\overline{N}$ to $\overline{N}'$. It means that more domestic firms become unprofitable, moving also the $\Pi = 0$ locus left. The $\Delta r_m = 0$ locus does not change, however, as F does not directly enter the operating profits of multinational and foreign firms.

In Fig. 4(b), the shock is so substantial that the new $N = \overline{N}'$ line is located to the left of the $\Delta r_m = 0$ locus. The decline in local supplying industry raises input prices and thus makes multinationals unprofitable. If such an adverse effect reaches a certain threshold, multinationals suddenly start leaving the host country. Multinational exits in turn decreases demand for local input and causes a further decline in local industry. The dotted arrow in Fig. 4(b) traces the industry evolution: it moves left horizontally up to N_0 and then moves lower left, heading for a new equilibrium at point $S_2' : (N, N_m) = (\alpha\overline{N}', 0)$, as indicated by a double mark in Fig. 4(c).

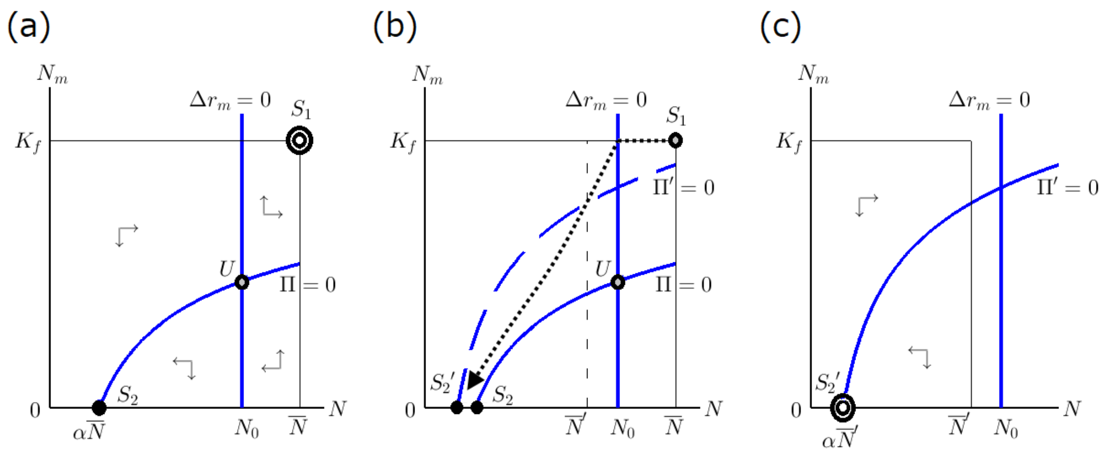

Fig. 4. Equilibrium switch due to a natural disaster (from panel (a) to (c)).

The condition for the equilibrium switch to occur is

$$\overline{N}' \equiv \frac{L}{(F+\Delta F)[\sigma(1-\mu)+\mu]} < N_0 \equiv a^{\sigma-1}\left[\tau^{\frac{1-\mu_m}{\mu_m}}(p_u^*)^{-1}\right]^{(\sigma-1)(1-\mu)},$$
$$\rightarrow F+\Delta F > F_b \equiv \frac{L}{N_0[\sigma(1-\mu)+\mu]},$$
$$\rightarrow \Delta F > F_b - F \equiv \Delta F_{min}. \tag{14}$$

A natural disaster causes a shift in equilibrium only if the magnitude of shock exceeds a certain threshold. In addition, as long as myopic location decision is assumed, the equilibrium shift is permanent.[14] This result echoes the long-lasting negative impact of severe disasters on FDI found by Toner-Rodgers and Friedt (2020) and the motivational observations we laid out in Table 2.

We can see that the threshold level of shock, ΔF_{min}, increases with the Cobb-Douglas share of local intermediate for multinationals μ_m, and decreases with trade costs τ. Put differently, as μ_m is higher or τ is lower, the equilibrium switch is less likely to occur. Multinationals more dependent on low-price local intermediates (higher μ_m) make greater profits, so that they are more likely to stay in the host country despite the decreased number of local suppliers.[15] Lower trade costs play a similar role by reducing the import price of foreign

[14] We consider forward-looking location decision in Section 4.2.

[15] Under the situation where point S_1 can be an equilibrium, the sourcing costs of local intermediates are not higher than those of foreign intermediates, i.e., $P \leq \tau p_u^*$ (see Appendix 2 for the proof). In contrast to μ_m, the effect of domestic firm's input share of local intermediates, μ, on ΔF_{min} is ambiguous. Higher μ

intermediates and thus making multinationals more profitable. Contrary to the concern of the Bank of Thailand, the 2011 flood did not cause drastic long-run changes in the location and production of manufacturing MNEs (Haraguchi and Lall, 2015). This may reflect the fact that Thailand had already established strong linkages with multinationals and engaged in trade liberalization (Milner et al., 2006; Feliciano and Doytch, 2020).

Assuming (a) $\alpha > 1 - (1-\mu)/\mu_m$ and (b) $K_f > \Theta \overline{N}^{\frac{1-\mu-\mu_m}{1-\mu}}(1-\alpha)$ as in Proposition 1, we can prove the following proposition (see Appendix 2 for the proof).

Proposition 2 (Natural disaster). *Suppose that the fixed labor input, F, is intermediate so that multiple equilibria arise, i.e., $F \in [F_a, F_b]$, and that the host economy is initially at point S_1, where multinationals and local firms coexist. If F increases to $F + \Delta F$ due to a natural disaster, then the following holds:*

(i) If the level of shock is substantial such that $F + \Delta F > F_b$, or equivalently $\Delta F > \Delta F_{min}$, the equilibrium switches from S_1 to S_2', where the host country loses all multinationals.

(ii) The threshold level of shock increases with the share of local intermediates for multinationals and decreases with trade costs, i.e., $\partial(\Delta F_{min})/\partial \mu_m \geq 0$ and $\partial(\Delta F_{min})/\partial \tau \leq 0$. That is, the natural disaster is less likely to trigger the equilibrium switch if multinationals are more dependent on local intermediates or they face lower trade costs.

3.2 Other types of shock

The essence of the above analysis is that the negative shock to local firms raises the cost of local sourcing and hence discourages foreign capital to stay in the host country. Other types of shocks that directly or indirectly raises the local-input price would give qualitatively the same result. For example, one can think of additional intra-trade costs that local suppliers have to incur when delivering varieties to multinationals and consumers. Through the destruction of domestic transportation infrastructure, natural disasters may raise intra-trade costs, leading to a higher local-input price. This translates into an upward shift of the $\Pi = 0$ locus and

means that local firms use more roundabout technologies based on intermediates and use less labor. More labor can be devoted to the fixed labor input for potential local firms, leading to more entry and thus making the price index of local intermediates lower. However, higher μ may push the price index up if the local intermediates are more expensive than labor. If the productivity of domestic firms are sufficiently high such that $a \leq e^{\frac{1}{\sigma}}(\alpha \overline{N})^{\frac{1}{\sigma-1}}$, the former effect dominates the latter, so that $\partial(\Delta F_{min})/\partial \mu > 0$ holds. See Appendix 2 for details.

a rightward shift of the $\Delta r_m = 0$ locus (i.e., the $N = N_0$ line); however, it does not change the $N = \overline{N}$ line unlike the case in Section 3.1.[16] Our main results would maintain in this case. That is, if the level of shock is substantial, the equilibrium switches from the one with both local and multinational firms to the one with only local firms (Proposition 2(i)). Multinationals are more likely to stay in the disaster-hit host country if they rely more on local inputs or they face lower trade costs (Proposition 2(ii)).

A more straightforward way to model natural disasters is direct shocks to multinationals, as documented in a number of disaster experiences in developing countries. Supposing that the fixed cost of capital for setting up a multinational increases from one to ΔF_m, other things being equal, the capital return multinationals generate decreases and foreign capital finds it more profitable to leave the host country. This effect results in a rightward shift of the $\Delta r_m = 0$ locus.[17] Applying an analogous reasoning, we can confirm qualitatively the same results as Proposition 2.

4 Extensions

We provide two extensions of the basic model.

4.1 Multinationals with heterogeneous productivity

In the basic model, multinationals are all homogeneous in productivity. In reality, however, productivity differs from multinationals, which may lead to heterogeneous response to disasters. For example, Hayakawa et al. (2015) report that in the aftermath of the Thailand 2011 floods, changes in sourcing patterns of multinationals differ by their age and size, which is

[16] If intra-trade costs are modeled as an iceberg cost, denoted by $\widetilde{\tau} \geq 1$, the price index is modified as $P = [N(\widetilde{\tau}p)^{1-\sigma}]^{\frac{1}{1-\sigma}} = (\widetilde{\tau}a)^{\frac{1}{1-\mu}} N^{\frac{1}{(1-\sigma)(1-\mu)}}$ from Eqs. (3) and (7). Since $\widetilde{\tau}$ and a enter in a multiplicative form, both terms have the same effect on the $\Pi = 0$ curve and the $\Delta r_m = 0$ line (see Eqs. (12) and (13)). An increase in $\widetilde{\tau}$ as a result of a natural disaster shifts the $\Pi = 0$ curve upward and the $N = N_0$ line rightward. If the increase is so substantial that the $N = N_0$ line goes beyond the $N = \overline{N}$ line, the equilibrium switches from point S_1 to S_2' (Proposition 2(i)). Higher μ_m and lower τ would move the $N = N_0$ line left (see Eq. (13)) and hence make the switch less likely to occur (Proposition 2(ii)).

[17] As a result of the disaster, the cost function of a typical multinational is modified as $C(q_m) = P^{\mu_m}(\tau p_u^*)^{1-\mu_m}\widetilde{a}_m q_m + r_m \Delta F_m$ and the capital return as $r_m = p_m q_m/(\sigma \Delta F_m)$. The $\Delta r_m = 0$ locus after shock is thus given by $N_0 = a^{\sigma-1}\left[\tau^{\frac{1-\mu_m}{\mu_m}}(p_u^*)^{-1}\right]^{(\sigma-1)(1-\mu)} (\Delta F_m)^{\frac{1-\mu_m}{\mu_m}}$. It can be seen that an increase in ΔF_m moves the $\Delta r_m = 0$ locus right and higher μ_m and lower τ make the rightward shift smaller, leading to qualitatively the same results as Proposition 2.

often associated with their productivity. We will see that the introducing heterogeneous productive multinationals into the basic model would give richer implications and more realistic equilibrium configurations.

Heterogeneity comes from a stochastic draw of unit input requirements, $\widetilde{a}_m = a_m(\sigma-1)/\sigma$, as in the literature on heterogeneous firm models (Melitz, 2003; Baldwin and Okubo, 2006). We assume that the cumulative density function of $a_m \in [\underline{a}_m, \overline{a}_m]$ takes a truncated Pareto distribution. Namely, the probability of a multinational drawing productivity lower than a_m is

$$G(a_m) = \frac{a_m^\rho - \underline{a}_m^\rho}{\overline{a}_m^\rho - \underline{a}_m^\rho} = \frac{a_m^\rho - 1}{\overline{a}_m^\rho - 1},$$

where $\rho \geq 1$ is the shape parameter. We set $\underline{a}_m$ to one without loss of generality. In addition, it is reasonable to assume that high-productive MNEs (lower a_m) enjoy lower trade costs (lower τ) per-unit of ship than low-productive firms due to scale economies in transportation (Forslid and Okubo, 2015, 2016):[18]

$$\tau(a_m) = a_m^\gamma,$$

implying that most productive firms with $a_m = 1$ is free from trade costs: $\tau(1) = 1$.

The return to foreign capital depends on its productivity and thus its relocation incentive also differs by productivity. Given the number of domestic firms N, Fig. 5 shows a typical capital-return differential: $\Delta r_m(a_m) \equiv r_m(a_m) - r_f(a_m)$, which captures the incentive to locate in the host country. The advantage of locating in the host country is a low cost of sourcing local inputs, whereas its disadvantage is a high cost of sourcing foreign inputs. For multinationals with lower a_m, the advantage is more beneficial because of their larger amount of production, whereas the disadvantage is smaller thanks to scale economies of transportation. Hence more productive multinationals have a greater $\Delta r_m(a_m)$ and thus a stronger incentive to locate in the host country, as shown in Fig. 5.

[18] Forslid and Okubo (2016) document that the export-to-sales ratio of Japanese firms differs greatly among firms and is systematically higher for larger exporters.

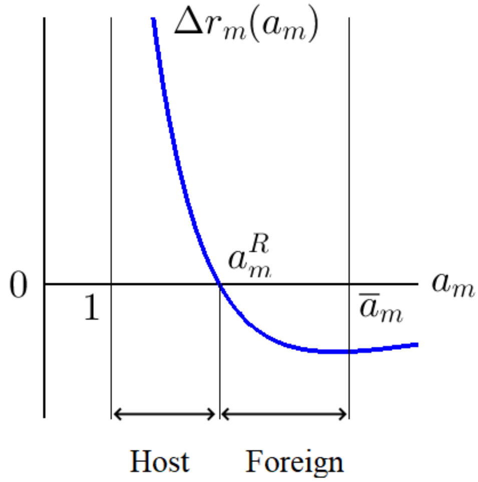

Fig. 5. Location incentives of multinationals.

As in the basic model, we consider a gradual relocation process. Namely, each foreign capital, initially located in the foreign country, incurs migration costs χ to move to the host country. The migration costs is assumed to be proportional to the flow of migrating capital, i.e., $\chi = \dot{N}_m$ (Baldwin and Okubo, 2006). Fig. 5 tells that the first capital ready to pay the relocation costs will be those that have the most to gain, i.e., the most efficient foreign capital. In industry equilibrium where the capital movement ceases, foreign capital with $a_m \leq a_m^R$ becomes a multinational in the host country, whereas foreign capital with $a_m > a_m^R$ remains in the foreign country as a foreign exporter, where a_m^R is the cut-off productivity at which the two locations are indifferent. The number of multinationals is thus given by

$$N_m = G(a_m^R)K_f = \frac{(a_m^R)^\rho - 1}{\overline{a}_m^\rho - 1} \cdot K_f,$$

which is proportional to a_m^R: N_m increases as the host country allows less productive foreign capital to come.[19]

Taking the migration of foreign capital into account, the entry and exit of local firms gradually take place. Fig. 6 illustrates industry equilibria in the (N, N_m) plane, corresponding to Fig. 3. Noteworthily, unlike the basic model, the $\Delta r_m(a_m^R) = 0$ locus is no longer a vertical line. Its upward slope comes from heterogeneous productivity: as the local supplying industry expands and the local-sourcing cost is lower, less productive foreign capital can

[19]The migration costs are thus given by $\chi = \dot{N}_m = \rho a_m^{\rho-1}\dot{a}_m K_f/(\overline{a}_m^\rho - 1)$ and a_m^R is the solution of $\Delta r_m(a_m^R) = \chi$. See Appendix 3 for details.

enter. As a result, a few but very productive multinationals remain in point S_2. In Appendix 3, we can check that multiple equilibria arise if the fixed labor requirement for setting up a domestic firm, F, takes an intermediate value, just like the basic model (Proposition 1(iii)).

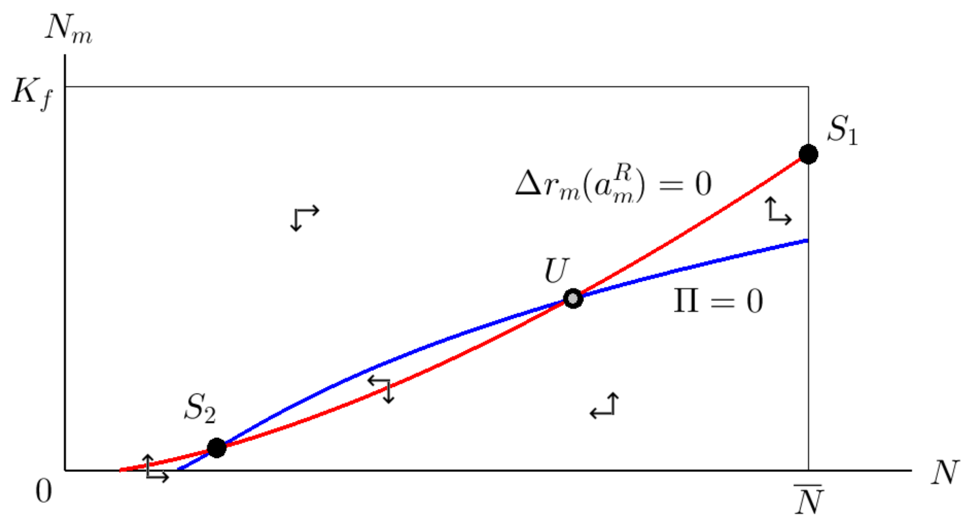

Fig. 6. Industrial configurations under heterogeneous multinationals.

Considering the effect of an increase in F due to a natural disaster as in Section 3.1, we can see in Fig. 7 qualitatively the same changes and the same intuition behind them as in the basic model. That is, the $\Pi = 0$ curve moves up simply because lower profitability shrinks the area where local firms can survive. The total number of local firms that the host country can accommodate decreases so that the $N = \overline{N}$ moves left. As a result of these shifts, the new $\Pi' = 0$ curve may no longer intersect at point U with the $\Delta r_m(a_m^R) = 0$ curve, in which case the equilibrium would switch from S_1 with many multinationals to S_2' with few multinationals. The unique but interesting difference from the basic model is clear from the new equilibrium S_2': the most efficient multinationals are the ones that remain in the disaster-hit country.[20]

[20]This relocation pattern holds also when the disaster does not trigger the equilibrium switch. An increase in F moves the $N = \overline{N}$ line left, thereby decreasing N_m at equilibrium S_1 along the $\Delta r_m(a_m^R) = 0$ locus. The decrease in $N_m = G(a_m^R)K_f$ is equivalent with an decrease in a_m^R, implying that the least efficient multinationals are the first to leave the host country.

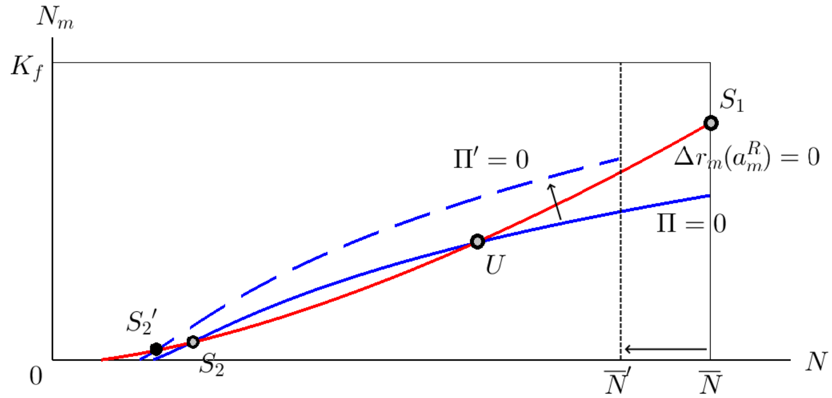

Fig. 7. Impact of a natural disaster under heterogeneous multinationals.

It can also be checked that if multinationals are more dependent on local suppliers (higher μ_m), the disaster is less likely to trigger the equilibrium switch.[21] By imposing assumptions similar to those in Propositions 1 and 2, we can formally prove the following proposition. The proof and explicit expressions are given in Appendix 3.

Proposition 3 (Heterogeneous multinationals). *Assume that multinationals are heterogeneous in a way that is specified in the text. Suppose that the fixed labor input, F, is intermediate so that multiple equilibria arise, i.e., $F \in (\widetilde{F}_a, \widetilde{F}_b]$, and that the host economy is initially at point S_1 with many multinationals. Consider an increase in F due to a natural disaster, then the following holds:*

(i) Multinationals with higher productivity are more likely to stay in the host country.

(ii) The natural disaster is less likely to trigger the equilibrium switch from S_1 to S_2', where the host country loses most of multinationals, if multinationals are more dependent on local intermediates (higher μ_m).

4.2 Reconstruction from disasters

We have so far modeled a disaster as a permanent shock. Let us instead consider a temporal shock and uncover under what conditions foreign capital reenters the gradually recovering host country. To come to the point, the host country re-attract multinationals earlier, as (a)it

[21]This result comes from the fact that a higher μ_m makes smaller the upward shift of the $\Pi = 0$ curve.

recovers from the disaster more quickly, (b)they are more dependent on local intermediates or (c)they face lower trade costs. These conditions have in common with those in Proposition 2(ii) and 3(ii).

As long as myopic relocation decision is assumed as before, no foreign capital relocates to the host country even if it fully recovers from the disaster. To allow for the possibility of reentering, we need to consider far-sighted decision making of foreign capital: it chooses whether to become a multinational or a foreign firm to maximize its lifetime return.[22]

Consider the situation where the host country is hit by a natural disaster at time $s = 0$ and all multinationals leave there, corresponding to point S_2' in Fig. 4(c). Suppose then that the increased fixed-labor input due to the disaster gradually gets back to the pre-shock level after some time T. Specifically, the fixed labor input at time s, denoted by $F(s)$, is given by

$$F(s) = \begin{cases} Fe^{\delta(T-s)} & \text{for} \quad s \in [0, T) \\ F & \text{for} \quad s \in [T, \infty) \end{cases},$$

where δ is the recovery rate and $F(0) = Fe^{\delta T} > F_b \equiv L/N_0[\sigma(1-\mu)+\mu]$ and $F \leq F_b$ are assumed to ensure the situation in Fig. 4(c). Letting t $(\leq T)$ be the time at which foreign capital moves from the foreign to the host country, the lifetime capital return, $v(t)$, is given by

$$v(t) \equiv \underbrace{\int_0^t e^{-\theta s} r_f ds}_{\text{Locate in foreign}} + \underbrace{\int_t^T e^{-\theta s} r_m'(s) ds + \int_T^\infty e^{-\theta s} r_m ds}_{\text{Locate in host}},$$

where $\theta > 0$ is the discount rate. For $s \in [0, t)$, foreign capital becomes a foreign exporter and makes the flow return r_f. It locates in the host country from time t onward. The flow return during recovery period $s \in [t, T)$ is $r_m'(s)$ and is fully recovered to the pre-shock level $r_m (\geq r_m'(s))$ for $s \in [T, \infty)$. The optimal timing of relocation can be derived from maximizing $v(t)$ with respect to t.

One naturally expects that if reconstruction takes very long time (high T), foreign capital with positive discount rate θ never relocates to the host country, i.e., $t = \infty$. Furthermore,

[22] We note that under the forward-looking behavior multiple equilibria disappear. If the fixed labor input F takes a value in between F_a and F_b and the situation is like Fig. 3, foreign capital chooses point S_1 at which it earns a higher flow return than at S_2, so that S_1 is the unique stable equilibrium. Domestic firms also prefer S_1 to S_2 because they make positive profits at S_1 and zero profits at S_2. Point S_1 is better than S_2 in the Pareto sense.

discussions in Section 3.1 tell that multinationals make greater profits as the share of local inputs in multinational production, μ_m, is higher or trade costs, τ, are lower. This should imply that higher μ_m or lower τ would push up the timing of multinationals' reentering, i.e., lower t. Assuming (a) $\alpha > 1-(1-\mu)/\mu_m$ and (b) $K_f > \Theta\overline{N}^{\frac{1-\mu-\mu_m}{1-\mu}}(1-\alpha)$ as in Propositions 1 and 2, we can establish these arguments in Proposition 4 and formally prove them in Appendix 4.

Proposition 4 (Recovery from disaster). *Consider the situation where the host country is hit by a natural disaster and hosts no multinationals at time $s = 0$. Suppose that the fixed labor input at time $s < T$ is given by $F(s) = Fe^{\delta(T-s)}$ with $F(0) = Fe^{T} > F_b$ and is fully recovered to the pre-shock level $F \leq F_b$ from time $s = T$ onward. On the optimal timing t of multinational reentering, the following holds:*

(i) Multinationals never reenter the host country, i.e., $t = \infty$, if the recovery time from the disaster is too long such that $T >> \overline{T}$, where $\overline{T}$ is a bundle of parameters distinct from T.

(ii) Assuming a range of parameters that ensure interior solutions of optimal timing $t \in (0, \infty)$, multinationals reenter the host country more quickly, as the recovery time is shorter (lower T), multinationals are more dependent on local intermediates (higher μ_m) or they face lower trade costs (lower τ), i.e., $\partial t/\partial T > 0$; $\partial t/\partial \mu_m < 0$; and $\partial t/\partial \tau > 0$.

5 Conclusion

This paper has developed a theoretical framework to address the resilience of multinationals against a severe shock such as natural disasters. Our focus is on two notable aspects of multinationals, footloose-ness and input-output linkages with local suppliers. These aspects give rise to multiple equilibria, one in which multinationals help local industry develop and the other in which multinationals never enter. When a natural disaster seriously damages local firms and thus raises the price of local intermediate inputs, the equilibrium switch occurs: multinationals leave the host country and shall never return. We have then identified under what conditions multinationals are more likely to stay in the disaster-hit host country. The key parameters are the share of local intermediates in multinational production and trade costs of foreign intermediates. In particular, as multinationals rely more on local suppliers and make greater profits through low sourcing costs, a decline in the local supplying industry due to natural disasters is less likely to affect their relocation decision. This insight carries over to the case where multinationals are heterogeneous and the analysis of the timing of disaster reconstruction.

We believe that our model yields rich analytical outcomes, yet remains sufficiently simple to produce new insights into the nexus between natural disasters and multinationals. The analysis can be enriched in many ways. One way is to explicitly introduce local upstream and downstream firms and allow them to benefit from technology spillovers from multinationals. Using the extended model, one can distinguish between inter-industry (i.e., horizontal) and intra-industry (i.e., vertical) spillovers and examine their interactions with natural disasters. The degree of spillovers may decrease when greater disaster risk discourages MNEs' commitment to local procurement. We leave this and other possible extensions to future research.

Appendices

Appendix 1. Derivations

We here provide detailed derivations of cost function $C(q)$, total demand for a differentiated product q, and free entry conditions.

A1-1. Cost function

The cost-minimization problem for a typical domestic firm producing variety ω is

$$\min_{\{q_u(\omega')\},l} \int p(\omega')q_u(\omega')d\omega' + wl + wF,$$
$$\text{s.t. } \widetilde{a}q(\omega) = z\left[\left(\int q_u(\omega')^{\frac{\sigma-1}{\sigma}}d\omega'\right)^{\frac{\sigma}{\sigma-1}}\right]^{\mu} l^{1-\mu},$$

where $q_u(\omega')$ is intermediate demand for variety ω'. The symmetry of firms implies $q(\omega) = q$. The problem can be solved in two steps. First, we consider the cost-minimization problem for the differentiated inputs:

$$\min_{\{q_u(\omega')\}} \int p(\omega')q_u(\omega')d\omega',$$
$$\text{s.t.} \;\; Q_u = \left(\int q_u(\omega')^{\frac{\sigma-1}{\sigma}} d\omega'\right)^{\frac{\sigma}{\sigma-1}}.$$

The FOCs yield $q_u(\omega') = [p(\omega')/P]^{-\sigma}Q_u$. Using this, we formulate the original problem as

$$\min_{Q_u, q_u} pQ_u + wl + wF,$$
$$\text{s.t.} \;\; \widetilde{a}q = zP^{\mu}w^{1-\mu},$$

The FOCs for the above minimization problem give demand functions for both domestic and foreign intermediates:

$$Q_u = \mu z \mu^{-\mu}(1-\mu)^{-(1-\mu)}P^{\mu-1}w^{1-\mu}\widetilde{a}q,$$
$$q_u = (1-\mu)z\mu^{-\mu}(1-\mu)^{-(1-\mu)}P^{\mu}w^{-\mu}\widetilde{a}q.$$

By using these results and choosing z as $z = \mu^{\mu}(1-\mu)^{1-\mu}$, we obtain the cost function for the domestic firm in the text. The cost function for the multinational firm is obtained in a similar way.

A1-2. Total demand

We apply Shephard's lemma to the cost function given in Eq. (5) to obtain input demand by domestic firms for variety ω:

$$\begin{aligned}\frac{\partial C(q)}{\partial p(\omega')} &= \frac{\partial P^{\mu}}{\partial p(\omega')} \cdot w^{1-\mu}\widetilde{a}q \\ &= \frac{\partial}{\partial p(\omega')}\left(\int p(\omega')^{1-\sigma}d\omega\right)^{\frac{\mu}{1-\sigma}} \cdot \widetilde{a}q \\ &= \frac{\mu}{1-\sigma}(1-\sigma)p(\omega')^{-\sigma}P^{\mu-1}\widetilde{a}q \\ &= \mu p(\omega')^{-\sigma}P^{\sigma+\mu-1}\widetilde{a}q,\end{aligned}$$

noting that $w = 1$. As all domestic firms are symmetric, the intermediate demand for the variety by them becomes $N\mu p^{-\sigma}P^{\sigma+\mu-1}\widetilde{a}q$. Similarly, we derive intermediate demand by all multinationals as $N_m\mu_m p_m^{-\sigma}P^{\sigma+\mu_m-1}(\tau p_u^*)^{1-\mu_m}\widetilde{a}_m q_m$. The total demand for the variety is the sum of these input demand and final-good demand (Eq.(2)):

$$\begin{aligned}q &= \left(\frac{p}{P}\right)^{-\sigma}\frac{E}{P} + N\mu p^{-\sigma}P^{\sigma+\mu-1}w^{1-\mu}\widetilde{a}q + N_m\mu_m p^{-\sigma}P^{\sigma+\mu_m-1}(\tau p_u^*)^{1-\mu_m}\widetilde{a}_m q_m \\ &= p^{-\sigma}\left[P^{\sigma-1}E + N\mu P^{\sigma+\mu-1}\widetilde{a}q + N_m\mu_m P^{\sigma+\mu_m-1}(\tau p_u^*)^{1-\mu_m}\widetilde{a}_m q_m\right]. \end{aligned} \qquad (11)$$

which is given in the text.

A1-3. Free entry conditions

The following expressions are useful for later reference:

$$P = a^{\frac{1}{1-\mu}} N^{\frac{1}{(1-\sigma)(1-\mu)}}, \tag{A1}$$

$$p^{1-\sigma} = (aP^{\mu})^{1-\sigma} = a^{\frac{1-\sigma}{1-\mu}} N^{\frac{1}{1-\mu}}, \tag{A2}$$

$$p_m^{1-\sigma} = \left[a_m P^{\mu_m} (\tau p_u^*)^{1-\mu_m}\right]^{1-\sigma} = \left[a_m a^{\frac{\mu_m}{1-\mu}} (\tau p_u^*)^{1-\mu_m}\right]^{1-\sigma} N^{\frac{\mu_m}{1-\mu}}. \tag{A3}$$

Free entry and exit of domestic firms imply that no domestic firms enter if their excess profits are negative, $\Pi = pq - C(q) < 0$, while if $\Pi \geq 0$ there are positive entries. As typical domestic firm breaks even if

$$\begin{aligned} 0 = \Pi &= pq - C(q) \\ &= pq - P^{\mu}\widetilde{a}q - F \\ &= pq - \frac{\sigma-1}{\sigma}\frac{\sigma P^{\mu}\widetilde{a}}{\sigma-1}q - F \\ &= pq - \frac{\sigma-1}{\sigma}pq - F \\ &= pq/\sigma - F, \end{aligned}$$

where we used Eq. (6) from the third to the fourth line. The break-even level of sales of domestic firms are thus $pq = \sigma F$. They make positive excess profits if the differentiated sector uses up local labor so that no further entry into the sector is possible, that is, if $N = \overline{N} \equiv L/F[\sigma(1-\mu)+\mu]$, which will be derived later.

We multiply both sides of Eq. (11) by p to get

$$\begin{aligned} pq &= \left(\frac{p}{P}\right)^{1-\sigma} E + N\mu \left(\frac{p}{P}\right)^{1-\sigma} P^{\mu}\widetilde{a}q + N_m\mu_m \left(\frac{p}{P}\right)^{1-\sigma} P^{\mu_m}(\tau p_u^*)^{1-\mu_m}\widetilde{a}_m q_m \\ &= \frac{E}{N} + \mu\frac{\sigma-1}{\sigma}\frac{\sigma\widetilde{a}P^{\mu}}{\sigma-1}q + \mu_m\frac{N_m}{N}\frac{\sigma-1}{\sigma}\frac{\sigma\widetilde{a}_m P^{\mu_m}(\tau p_u^*)^{1-\mu_m}}{\sigma-1}q_m \\ &= \frac{E}{N} + \frac{\sigma-1}{\sigma}\mu pq + \frac{\sigma-1}{\sigma}\mu_m\frac{N_m}{N}p_m q_m, \end{aligned}$$

where we used Eq. (3) from the first to the second line and Eqs. (6) and (9) from the second to the last line. Solving this equation for pq gives

$$\begin{aligned} pq &= \frac{\sigma}{\sigma-\mu(\sigma-1)}\left[\frac{E}{N} + \frac{\mu_m(\sigma-1)}{\sigma}\frac{N_m}{N}p_m q_m\right] \\ &= \frac{\sigma}{\sigma(1-\mu)+\mu}\left[\frac{E}{N} + \frac{\mu_m(\sigma-1)}{\sigma}\frac{N_m}{N}p_m^{1-\sigma}D^*\right]. \end{aligned}$$

When there are no excess profits for domestic firms, the aggregate expenditure on differentiated goods is α share of total labor income: $E = \alpha w L = \alpha L$. Substituting the above expression, Eq. (A3) and $E = \alpha L$ into the break even level of sales yields

$$
\begin{aligned}
& pq = \sigma F, \\
& \rightarrow \frac{\sigma}{\sigma(1-\mu)+\mu}\left[\frac{\alpha L}{N} + \frac{\mu_m(\sigma-1)}{\sigma}\frac{N_m}{N}N^{\frac{\mu_m}{1-\mu}}\left\{a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right\}^{1-\sigma} D^*\right] = \sigma F, \\
& \rightarrow \alpha L + \frac{\mu_m D^*(\sigma-1)}{\sigma}\left[a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right]^{1-\sigma} N^{\frac{\mu_m}{1-\mu}} N_m = NF[\sigma(1-\mu)+\mu], \\
& \rightarrow N_m = \Theta N^{-\frac{\mu_m}{1-\mu}}\left(N - \alpha\overline{N}\right), \qquad (12) \\
& \text{where } \; \Theta \equiv \frac{\sigma F[\sigma(1-\mu)+\mu]\left[a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right]^{\sigma-1}}{\mu_m D^*(\sigma-1)}, \qquad \overline{N} \equiv \frac{L}{F[\sigma(1-\mu)+\mu]},
\end{aligned}
$$

which is given in the text.

Free entry and exit of multinational and foreign firms drive their excess profits to zero, which determines their rental rate of foreign capital:

$$
\begin{aligned}
& \Pi_m = p_m q_m - C_m(q_m) = p_m q_m - P^{\mu_m}(\tau p_u^*)^{1-\mu_m}\widetilde{a}_m q_m - r_m = 0, \\
& \rightarrow r_m = p_m q_m/\sigma = p_m^{1-\sigma} D^*/\sigma, \\
& \Pi_f = p_f q_f - C_f(q_f) = p_f q_f - p_u^* \widetilde{a}_m q_f - r_f = 0, \\
& \rightarrow r_f = p_f q_f/\sigma = p_f^{1-\sigma} D^*/\sigma.
\end{aligned}
$$

Foreign capital is indifferent between becoming a multinational and a foreign firm if the return differential is zero:

$$
\begin{aligned}
\Delta r_m \equiv r_m - r_f &= D^*(p_m^{1-\sigma} - p_f^{1-\sigma})/\sigma \\
&= D^*\left[\left(a_m P^{\mu_m}(\tau p_u^*)^{1-\mu_m}\right)^{1-\sigma} - (a_m p_u^*)^{1-\sigma}\right]/\sigma, \\
&= D^*\left[\left\{a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right\}^{1-\sigma} N^{\frac{\mu_m}{1-\mu}} - (a_m p_u^*)^{1-\sigma}\right]/\sigma \\
&= D^*(a_m p_u^*)^{1-\sigma}\left[\left\{a^{\frac{\mu_m}{1-\mu}}\tau^{1-\mu_m}(p_u^*)^{-\mu_m}\right\}^{1-\sigma} N^{\frac{\mu_m}{1-\mu}} - 1\right]/\sigma = 0. \qquad \text{(A4)}
\end{aligned}
$$

Solving this for N gives

$$
N = a^{\sigma-1}\left[\tau^{\frac{1-\mu_m}{\mu_m}}(p_u^*)^{-1}\right]^{(\sigma-1)(1-\mu)} \equiv N_0, \qquad (13)
$$

which is given in the text.

A1-4. Upper bound of the number of domestic firms

Aggregate labor demand in the differentiated sector is the product of the labor demand by individual local firms and the number of local firms, N. Applying Shephard's lemma to Eq. (5), we obtain

$$\begin{aligned}
N\frac{\partial C(q)}{\partial w} &= N\frac{\partial(P^{\mu}w^{1-\mu}\widetilde{a}q + wF)}{\partial w} \\
&= N\left[(1-\mu)P^{\mu}w^{-\mu}\widetilde{a}q + F\right] \\
&= N\left[(1-\mu)P^{\mu}\widetilde{a}q + F\right].
\end{aligned}$$

We evaluate this at the break-even level of sales, $pq = \sigma F$, to get

$$\begin{aligned}
N\left[(1-\mu)P^{\mu}\widetilde{a}q + F\right] &= N\left[(1-\mu)(\sigma-1)pq/\sigma + F\right] \\
&= N\left[(1-\mu)(\sigma-1)\sigma F/\sigma + F\right] \\
&= NF[\sigma(1-\mu)+\mu].
\end{aligned}$$

The labor demand must be smaller than the total workforce in the host country, L:

$$\begin{aligned}
&NF[\sigma(1-\mu)+\mu] \le L, \\
&\to N \le \frac{L}{F[\sigma(1-\mu)+\mu]} \equiv \overline{N},
\end{aligned}$$

which determines the upper bound of N.

Appendix 2. Impact of natural disaster

A2-1. Proof of Proposition 2

Since Proposition 2(i) is established in the text, here we prove Proposition 2(ii): $\partial(\Delta F_{min})/\partial\mu_m \ge 0$; $\partial(\Delta F_{min})/\partial\tau \le 0$. Differentiating ΔF_{min} defined in Eq. (14) with respect to μ_m yields

$$\begin{aligned}
\frac{\partial(\Delta F_{min})}{\partial\mu_m} &= \frac{\partial}{\partial\mu_m}\left[\frac{L}{N_0\{\sigma(1-\mu)+\mu\}} - F\right] \\
&= -\frac{L}{N_0^2[\sigma(1-\mu)+\mu]}\cdot\frac{\partial N_0}{\partial\mu_m} \\
&= -\frac{L}{N_0^2[\sigma(1-\mu)+\mu]}\cdot\frac{\partial}{\partial\mu_m}\left[a^{\sigma-1}\left\{\tau^{\frac{1-\mu_m}{\mu_m}}(p_u^*)^{-1}\right\}^{(\sigma-1)(1-\mu)}\right] \\
&= -\frac{L}{N_0^2[\sigma(1-\mu)+\mu]}\cdot N_0\left[-\frac{(\sigma-1)(1-\mu)}{\mu_m^2}\ln\tau\right] \\
&= \frac{L(\sigma-1)(1-\mu)\ln\tau}{\mu_m^2\tau N_0[\sigma(1-\mu)+\mu]} \ge 0,
\end{aligned}$$

where equality holds at $\tau = 1$.

Similarly, differentiating ΔF_{min} with respect to τ gives

$$\begin{aligned}
\frac{\partial(\Delta F_{min})}{\partial \tau} &= -\frac{L}{N_0^2[\sigma(1-\mu)+\mu]} \cdot \frac{\partial N_0}{\partial \tau} \\
&= -\frac{L}{N_0^2[\sigma(1-\mu)+\mu]} \cdot \frac{N_0}{\tau} \cdot \frac{(\sigma-1)(1-\mu)(1-\mu_m)}{\mu_m} \\
&= -\frac{L(\sigma-1)(1-\mu)(1-\mu_m)\ln\tau}{\mu_m N_0[\sigma(1-\mu)+\mu]} \leq 0,
\end{aligned}$$

where equality holds at $\tau = 1$. These establish Proposition 2(ii).

A2-2. Other issues

We derive the condition for $\partial(\Delta F_{min})/\partial\mu > 0$ if $F \in (F_a, F_b)$:

$$\begin{aligned}
\frac{\partial(\Delta F_{min})}{\partial \mu} &= \frac{\partial}{\partial \mu}\left[\frac{L}{N_0\{\sigma(1-\mu)+\mu\}} - F\right] \\
&= \frac{L(\sigma-1)}{N_0[\sigma(1-\mu)+\mu]^2} - \frac{L}{N_0^2[\sigma(1-\mu)+\mu]}\frac{\partial N_0}{\partial \mu} \\
&= \frac{L(\sigma-1)}{N_0[\sigma(1-\mu)+\mu]}\left[\frac{1}{\sigma(1-\mu)+\mu} + \ln\left\{\tau^{\frac{1-\mu_m}{\mu_m}}(p_u^*)^{-1}\right\}\right] \\
&= \frac{F\overline{N}(\sigma-1)}{N_0}\left[\frac{1}{\sigma(1-\mu)+\mu} + \ln\left\{\tau^{\frac{1-\mu_m}{\mu_m}}(p_u^*)^{-1}\right\}\right] \\
&> F(\sigma-1)\left[\frac{1}{\sigma(1-\mu)+\mu} + \ln\left\{\tau^{\frac{1-\mu_m}{\mu_m}}(p_u^*)^{-1}\right\}\right] \equiv RHS(\mu).
\end{aligned}$$

where from the second-to-last to the last line we used the fact that $F < F_b$, or equivalently $N_0 < \overline{N}$. A sufficient condition for $\partial(\Delta F_{min})/\partial\mu > 0$ is $RHS(\mu) \geq 0$ for $\mu \in (0, 1)$. While noting that $RHS'(\mu) > 0$ holds. we use the expression of N_0 given in Eq. (13) to rewrite $RHS(\mu)$ as

$$\begin{aligned}
RHS(\mu) &= F(\sigma-1)\left[\frac{1}{\sigma(1-\mu)+\mu} + \frac{\ln(a^{1-\sigma}N_0)}{(\sigma-1)(1-\mu)}\right] \\
&\geq RHS(0) = F(\sigma-1)\left[\frac{1}{\sigma} + \frac{\ln(a^{1-\sigma}N_0)}{\sigma-1}\right] \\
&\geq F(\sigma-1)\left[\frac{1}{\sigma} + \frac{\ln\left(a^{1-\sigma}\alpha\overline{N}\right)}{\sigma-1}\right].
\end{aligned}$$

The expression in the last line is positive if

$$\frac{1}{\sigma} + \frac{\ln\left(a^{1-\sigma}\alpha\overline{N}\right)}{\sigma - 1} \geq 0,$$
$$\rightarrow a \leq e^{\frac{1}{\sigma}}(\alpha\overline{N})^{\frac{1}{\sigma-1}}.$$

which is a sufficient condition for $\partial(\Delta F_{min})/\partial\mu > 0$.

Next we show $P \leq \tau p_u^*$ if there exists $N_0 \geq 0$ that satisfies Eq. (13) (or equivalently Eq. (A4)). Let us first look at Eq. (A4):

$$\Delta r_m = D^*(a_m p_u^*)^{1-\sigma}[g(N;\mu_m) - 1]/\sigma = 0, \tag{A4}$$
$$\text{where } \; g(N;\mu_m) \equiv \left[a^{\frac{\mu_m}{1-\mu}}\tau^{1-\mu_m}(p_u^*)^{-\mu_m}\right]^{1-\sigma} N^{\frac{\mu_m}{1-\mu}}.$$

We consider a range of parameters that ensure the existence of $N_0 \geq 0$ satisfying Eq. (A4). Because $g(N;0) = \tau^{1-\sigma} \leq 1$ and $g(N;\mu_m) > 0$, we must have $\partial g(N;\mu_m)/\partial\mu_m \geq 0$ in order for Eq. (13) to have a solution for $N = N_0 \geq 0$. This condition results in $\tau p_u^*/P \geq 1$:

$$\frac{\partial g(N;\mu_m)}{\partial\mu_m} = g(N;\mu_m) \cdot \ln\left[\tau p_u^*\left(aN^{\frac{1}{1-\sigma}}\right)^{-\frac{1}{1-\mu}}\right]^{\sigma-1} \geq 0,$$
$$\rightarrow \ln\left[\tau p_u^*\left(aN^{\frac{1}{1-\sigma}}\right)^{-\frac{1}{1-\mu}}\right]^{\sigma-1} \geq 0,$$
$$\rightarrow \tau p_u^*\left(aN^{\frac{1}{1-\sigma}}\right)^{-\frac{1}{1-\mu}} = \tau p_u^*/P \geq 1,$$

noting that the derivative of $f(x) = a^{A(x)}b^{B(x)}$ is given by $f'(x) = f(x)\ln\left[a^{A'(x)}b^{B'(x)}\right]$.

Appendix 3. Multinationals with heterogeneous productivity

A3-1. Location condition of multinationals

Using the results in Appendix A1-3, we can write the return differential of foreign capital as

$$\begin{aligned}
\Delta r_m(a_m) &= r_m(a_m) - r_f(a_m) \\
&= p_m(a_m)q_m(a_m)/\sigma - p_f(a_m)q_f(a_m)/\sigma \\
&= D^*\left[p_m(a_m)^{1-\sigma} - p_f(a_f)^{1-\sigma}\right] \\
&= D^*(a_m p_u^*)^{1-\sigma}\left[\left\{a^{\frac{\mu_m}{1-\mu}}(a_m^\gamma)^{1-\mu_m}(p_u^*)^{-\mu_m}\right\}^{1-\sigma} N^{\frac{\mu_m}{1-\mu}} - 1\right]/\sigma \\
&= D^*(a_m p_u^*)^{1-\sigma}\left[\left\{a^{\frac{\mu_m}{1-\mu}}(a_m^\gamma)^{1-\mu_m}(p_u^*)^{-\mu_m}\right\}^{1-\sigma} N^{\frac{\mu_m}{1-\mu}} - 1\right]/\sigma,
\end{aligned}$$

noting that $\tau(a_m) = a_m^\gamma$. The cut-off productivity, a_m^R, is given by the solution of $\Delta r_m(a_m^R) = 0$. Since the big square bracket term in the above expression decreases with a_m because $\gamma(1-\mu_m)(1-\sigma) < 0$, the return differential is positive (or negative) if $a_m < a_m^R$ (or $a_m > a_m^R$).

We can explicitly solve for the cut-off productivity:

$$
\begin{aligned}
&\Delta r_m(a_m^R) = 0, \\
&\to (a_m^R)^{\gamma(1-\mu_m)(1-\sigma)} \left\{ a^{\frac{\mu_m}{1-\mu}} (p_u^*)^{-\mu_m} \right\}^{1-\sigma} N^{\frac{\mu_m}{1-\mu}} - 1 > 0, \\
&\to (a_m^R)^{\gamma(1-\mu_m)(1-\sigma)} = \left\{ a^{\frac{\mu_m}{1-\mu}} (p_u^*)^{-\mu_m} \right\}^{-(1-\sigma)} N^{-\frac{\mu_m}{1-\mu}}, \\
&\to a_m^R = \left\{ a^{\frac{1}{1-\mu}} (p_u^*)^{-1} \right\}^{-\frac{\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}}.
\end{aligned}
$$

On the other hand, the mass of multinationals is expressed as a function of the cut-off productivity:

$$
\begin{aligned}
&N_m = \Pr(\widehat{a}_m \leq a_m^R) = G(a_m^R) K_f = \frac{K_f (a_m^\rho - 1)}{\overline{a}_m^\rho - 1}, \\
&\to a_m^R = [N_m(\overline{a}_m^\rho - 1)/K_f + 1]^{1/\rho}. \qquad \text{(A5)}
\end{aligned}
$$

Substituting this into the explicit solution of a_m^R gives

$$
\begin{aligned}
&[N_m(\overline{a}_m^\rho - 1)/K_f + 1]^{1/\rho} = \left\{ a^{\frac{1}{1-\mu}} (p_u^*)^{-1} \right\}^{-\frac{\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\rho\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}}, \\
&\to N_m(\overline{a}_m^\rho - 1)/K_f + 1 = \left\{ a^{\frac{1}{1-\mu}} (p_u^*)^{-1} \right\}^{-\frac{\rho\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\rho\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}}, \\
&\to N_m = \frac{K_f}{\overline{a}_m^\rho - 1} \left[\left\{ a^{\frac{1}{1-\mu}} (p_u^*)^{-1} \right\}^{-\frac{\rho\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\rho\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}} - 1 \right], \qquad \text{(A6)}
\end{aligned}
$$

which increases with N because $\rho\mu_m/[\gamma(\sigma-1)(1-\mu)(1-\mu_m)] > 0$. Fig. A1(b) draws the $\Delta r_m(a_m^R) = 0$-locus defined in Eq. (A6), where $\widetilde{N}_0$, at which $N_m = 0$, is given by

$$
\begin{aligned}
&N_m = 0, \\
&\to N = a^{\sigma-1} \left[(p_u^*)^{-1} \right]^{(\sigma-1)(1-\mu)} \equiv \widetilde{N}_0,
\end{aligned}
$$

which is assumed to be greater than one: $\widetilde{N}_0 > 1$. The arrows indicates the direction of motion of foreign capital. As in the basic model, the area where foreign capital moves to the host country (upper arrow) expands as N increases and thus local suppliers develops. Unlike the basic model, however, the locus is not a vertical line but a upward-sloping curve because the relocation incentive differs in productivity. High-productive foreign capital is ready to move to the host country with small number of suppliers, whereas for low-productive one to move, a sufficient number of local suppliers is necessary.

A3-2. Zero-profit conditions of domestic firms

The goods market clearing condition requires that the total sales must be equal to total purchase by consumers, domestic firms and multinationals:

$$
\begin{aligned}
pq &= \left(\frac{p}{P}\right)^{1-\sigma} E + N\mu \left(\frac{p}{P}\right)^{1-\sigma} P^{\mu}\widetilde{a}q + K_f\mu_m \left(\frac{p}{P}\right)^{1-\sigma} \int_1^{a_m^R} P^{\mu_m}[\tau(a_m)p_u^*]^{1-\mu_m}\widetilde{a}_m q_m(a_m)dG(a_m) \\
&= \frac{E}{N} + \mu\frac{\sigma-1}{\sigma}\frac{\sigma\widetilde{a}P^{\mu}}{\sigma-1}q + \mu_m\frac{K_f}{N}\frac{\sigma-1}{\sigma}\int_1^{a_m^R} \frac{\sigma\widetilde{a}_m P^{\mu_m}[\tau(a_m)p_u^*]^{1-\mu_m}}{\sigma-1} q_m(a_m)dG(a_m) \\
&= \frac{E}{N} + \frac{\sigma-1}{\sigma}\mu pq + \frac{\sigma-1}{\sigma}\mu_m\frac{K_f}{N}\int_1^{a_m^R} p_m(a_m)q_m(a_m)dG(a_m),
\end{aligned}
$$

noting that multinationals with $a_m \in [1, a_m^R]$ are in the host country. The integral part in the right-hand side is

$$
\begin{aligned}
\int_1^{a_m^R} p_m(a_m)q_m(a_m)dG(a_m) &= \int_1^{a_m^R} p_m(a_m)^{1-\sigma}D^* \cdot \frac{\rho a_m^{\rho-1}}{\overline{a}_m^{\rho}-1}da_m \\
&= \frac{\rho D^*}{\overline{a}_m^{\rho}-1}\int_1^{a_m^R}\left[a_m a^{\frac{\mu_m}{1-\mu}}(a_m^{\gamma}p_u^*)^{1-\mu_m}\right]^{1-\sigma} N^{\frac{\mu_m}{1-\mu}} \cdot a_m^{\rho-1}da_m \\
&= \frac{\rho D^*}{\overline{a}_m^{\rho}-1}\left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma} N^{\frac{\mu_m}{1-\mu}}\int_1^{a_m^R} a_m^{\rho-1-(\sigma-1)[1+\gamma(1-\mu_m)]}da_m \\
&= \frac{\rho D^*}{\overline{a}_m^{\rho}-1}\left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma} N^{\frac{\mu_m}{1-\mu}}\frac{(a_m^R)^{\widetilde{\rho}}-1}{\widetilde{\rho}},
\end{aligned}
$$

where $\widetilde{\rho} \equiv \rho - (\sigma-1)[1+\gamma(1-\mu_m)]$ and $p_m^{1-\sigma}$ is given by Eq. (A3).

As in Appendix A1-3, we substitute these expressions into the zero-profit condition of domestic firms, $pq = \sigma F$, to obtain

$$
\begin{aligned}
& pq = \sigma F, \\
& \to \frac{\sigma}{\sigma-\mu(\sigma-1)}\left[\frac{E}{N} + \frac{\mu_m(\sigma-1)}{\sigma}\frac{K_f}{N}\int_1^{a_m^R} p_m(a_m)q_m(a_m)dG(a_m)\right] = \sigma F, \\
& \to \frac{\sigma}{\sigma(1-\mu)+\mu}\left[\frac{\alpha L}{N} + \frac{\mu_m(\sigma-1)}{\sigma}\frac{K_f}{N}\frac{\rho D^*}{\overline{a}_m^{\rho}-1}\left\{a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right\}^{1-\sigma} N^{\frac{\mu_m}{1-\mu}}\frac{(a_m^R)^{\widetilde{\rho}}-1}{\widetilde{\rho}}\right] = \sigma F, \\
& \to K_f[(a_m^R)^{\widetilde{\rho}}-1] = \widetilde{\Theta}_0 N^{-\frac{\mu_m}{1-\mu}}(N-\alpha\overline{N}), \\
& \text{where } \widetilde{\rho} \equiv \rho - (\sigma-1)[1+\gamma(1-\mu_m)], \\
& \qquad \widetilde{\Theta}_0 \equiv \frac{\widetilde{\rho}(\overline{a}_m^{\rho}-1)\sigma F[\sigma(1-\mu)+\mu]\left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma}}{\rho\mu_m D^*(\sigma-1)}, \quad \overline{N} \equiv \frac{L}{F[\sigma(1-\mu)+\mu]},
\end{aligned}
$$

noting that the upper bound of the number of domestic firms, $\overline{N}$, is the same as that in the basic model.

Using Eq. (A5), we can rewrite the above equation as

$$K_f\left[\{N_m(\overline{a}_m^{\rho}-1)/K_f+1\}^{\widetilde{\rho}/\rho}-1\right]=\widetilde{\Theta}_0 N^{-\frac{\mu_m}{1-\mu}}(N-\alpha\overline{N}),$$
$$\to N_m=\frac{K_f}{\overline{a}_m^{\rho}-1}\left[\left\{\widetilde{\Theta}N^{-\frac{\mu_m}{1-\mu}}(N-\alpha\overline{N})+1\right\}^{\rho/\widetilde{\rho}}-1\right], \tag{A7}$$
$$\text{where}\quad \widetilde{\Theta}\equiv\widetilde{\Theta}_0/K_f=\frac{\widetilde{\rho}(\overline{a}_m^{\rho}-1)\sigma F[\sigma(1-\mu)+\mu]\left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma}}{\rho\mu_m D^* K_f(\sigma-1)},$$

which increases as we have assumed $\alpha > 1-(1-\mu)/\mu_m$. Fig. A1(b) draws the $\Pi = 0$ locus with arrows indicating the direction of motion of domestic firms.

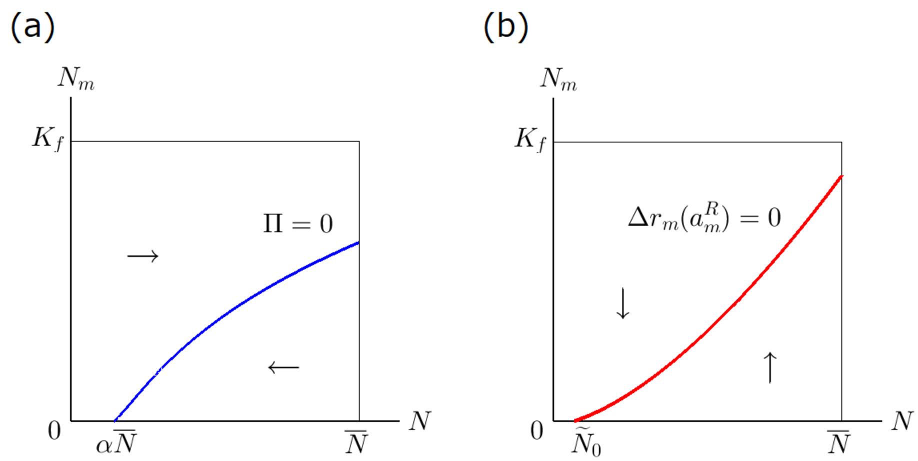

Fig. A1. Equilibrium curves under heterogeneous multinationals.

A3-3. Conditions for multiple equilibria

We can know from Figs. 6 and A1 that multiple equilibria occur if the two equilibrium curves intersect twice. The sufficient conditions for this are as follows. First, the N-intercept of the $\Pi = 0$ curve is greater than or equal to that of the $\Delta r_m(a_m^R) = 0$ curve, that is, $\alpha\overline{N} \geq \widetilde{N}_0$. Second, the $\Pi = 0$ curve is located above the $\Delta r_m(a_m^R) = 0$ curve for some $N \in [\alpha\overline{N}, \overline{N}]$. Finally, the $\Delta r_m(a_m^R) = 0$ curve is located above the $\Pi = 0$ curve at $N = \overline{N}$.

The first condition reduces to

$$\alpha\overline{N}\equiv\frac{\alpha L}{F[\sigma(1-\mu)+\mu]}\geq\widetilde{N}_0\equiv a^{\sigma-1}\left[(p_u^*)^{-1}\right]^{(\sigma-1)(1-\mu)},$$
$$\to F\leq\frac{\alpha L}{\widetilde{N}_0[\sigma(1-\mu)+\mu]}\equiv\widetilde{F}_b.$$

The second condition requires that for some $N \in [\alpha\overline{N}, \overline{N}]$, the following must hold:

$$\frac{K_f}{\overline{a}_m^\rho - 1}\left[\left\{\widetilde{\Theta}N^{-\frac{\mu_m}{1-\mu}}(N-\alpha\overline{N})+1\right\}^{\rho/\widetilde{\rho}} - 1\right] > \frac{K_f}{\overline{a}_m^\rho - 1}\left[\left\{a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right\}^{-\frac{\rho\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\rho\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}} - 1\right],$$

$$\to \left\{\widetilde{\Theta}N^{-\frac{\mu_m}{1-\mu}}(N-\alpha\overline{N})+1\right\}^{\rho/\widetilde{\rho}} > \left\{a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right\}^{-\frac{\rho\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\rho\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}},$$

$$\to \widetilde{\Theta}N^{-\frac{\mu_m}{1-\mu}}(N-\alpha\overline{N})+1 > \left\{a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right\}^{-\frac{\widetilde{\rho}\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\widetilde{\rho}\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}},$$

$$\to \widetilde{\Theta}_1 N^{-\frac{\mu_m}{1-\mu}}\left[FN - \frac{\alpha L}{\sigma(1-\mu)+\mu}\right]+1 > \left\{a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right\}^{-\frac{\widetilde{\rho}\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\widetilde{\rho}\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}},$$

$$\to F > \max\{F_1, 0\} \equiv \widetilde{F}_a,$$

$$\text{where} \quad F_1 \equiv \widetilde{\Theta}_1^{-1} N^{\frac{\mu_m}{1-\mu}-1}\left[\left\{a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right\}^{-\frac{\widetilde{\rho}\mu_m}{\gamma(1-\mu_m)}} N^{\frac{\widetilde{\rho}\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}} - 1\right] + \frac{\alpha L}{\sigma(1-\mu)+\mu},$$

and $\widetilde{\Theta}_1 \equiv \widetilde{\Theta}/F$.

The third condition implies

$$\frac{K_f}{\overline{a}_m^\rho - 1}\left[\left\{a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right\}^{-\frac{\rho\mu_m}{\gamma(1-\mu_m)}} \overline{N}^{\frac{\rho\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}} - 1\right] > \frac{K_f}{\overline{a}_m^\rho - 1}\left[\left\{\widetilde{\Theta}\overline{N}^{1-\frac{\mu_m}{1-\mu}}(1-\alpha)+1\right\}^{\rho/\widetilde{\rho}} - 1\right],$$

$$\to \left\{a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right\}^{-\frac{\rho\mu_m}{\gamma(1-\mu_m)}} \overline{N}^{\frac{\rho\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}} > \left\{\widetilde{\Theta}\overline{N}^{\frac{1-\mu-\mu_m}{1-\mu}}(1-\alpha)+1\right\}^{\rho/\widetilde{\rho}},$$

$$\to \left\{a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right\}^{-\frac{\widetilde{\rho}\mu_m}{\gamma(1-\mu_m)}} \overline{N}^{\frac{\widetilde{\rho}\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}} > K_f^{-1}\widetilde{\Theta}_0\overline{N}^{\frac{1-\mu-\mu_m}{1-\mu}}(1-\alpha)+1,$$

$$\to K_f > \left[a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right]^{\frac{\widetilde{\rho}\mu_m}{\gamma(1-\mu_m)}} \overline{N}^{-\frac{\widetilde{\rho}\mu_m}{\gamma(\sigma-1)(1-\mu)(1-\mu_m)}} \left[\widetilde{\Theta}_0\overline{N}^{\frac{1-\mu-\mu_m}{1-\mu}}(1-\alpha)+1\right] \equiv \widetilde{K}_f.$$

In sum, the multiple equilibria occurs if the fixed labor input takes an intermediate value such that $\widetilde{F}_a < F \leq \widetilde{F}_b$ and the amount of foreign capital is so large that $K_f > \widetilde{K}_f$ holds.

A3-4. Proof of Proposition 3

Since Proposition 3(i) is evident from Fig. 7 and the discussions in the text, here we prove Proposition 3(ii). Assume that (a) $\alpha > 1-(1-\mu)/\mu_m$; (b) $\widetilde{N}_0 \equiv [a(p_u^*)^{-(1-\mu)}]^{\sigma-1} > 1$; (c) $K_f > \widetilde{K}_f$; (d) $F \in (\widetilde{F}_a, \widetilde{F}_b]$; and (e) $\widetilde{\rho} \equiv \rho - (\sigma-1)[1+\gamma(1-\mu_m)]$. All assumptions are necessary for considering the possibility of equilibrium switch due to natural disasters. The first three are sort of regularity conditions. Assumption (a) guarantees the upward slope of the $\Pi = 0$ locus in the (N, N_m) plane. Assumptions (b) and (c) respectively ensures a finite value of expectation and a sufficient number of local suppliers at point S_2. If (c) did not hold, the comparative statics with respect to the exponent of N would yield meaningless results (see Eq. (A7)). Under the last two assumptions, (d) and (e), multiple equilibria arise.

Consider an increase in the fixed labor input F due to a natural disaster. As in the basic model, this shock results in (A) a leftward shift of the vertical line $N = \overline{N}$; (B) an upward shift of the $\Pi = 0$ curve upward; (C) no change in the $\Delta r_m(a_m^R) = 0$ curve. Fig. 7 illustrates these shifts of curves, where the $\Pi' = 0$ curve and the $N = \overline{N}'$ line are the corresponding curves after the shock.

It can be seen from from observations (B) and (C) that point S_1 in Fig. 7 is no longer a stable equilibrium if the upward shift of the $\Pi = 0$ curve is so large that the new $\Pi' = 0$ and the $\Delta r_m(a_m^R) = 0$ curves do not intersect at point U. From Eq. (A7), the shift of the $\Pi = 0$ curve is proportional to

$$
\begin{aligned}
0 < \frac{\partial N_m}{\partial F} &\propto \frac{\partial}{\partial F}\left[\widetilde{\Theta} N^{-\frac{\mu_m}{1-\mu}}(N - \alpha\overline{N})\right] = \frac{\partial}{\partial F}\left[\widetilde{\Theta}_1 N^{-\frac{\mu_m}{1-\mu}}\left\{FN - \frac{\alpha L}{\sigma(1-\mu)+\mu}\right\}\right] \\
&= \widetilde{\Theta}_1 N^{\frac{1-\mu-\mu_m}{1-\mu}} \\
&= \frac{\widetilde{\rho}(\overline{a}_m^{\rho} - 1)\sigma[\sigma(1-\mu)+\mu]\left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma}}{\rho\mu_m D^* K_f(\sigma-1)}.
\end{aligned}
$$

As $\partial N_m/\partial F$ is greater, point S_1 is less likely to be an stable equilibrium. The magnitude of the upward shift depends on the share of local inputs for multinational production, μ_m, entering both the numerator and the denominator of the term in the last line. Under our assumption that $\widetilde{N}_0 > 1$ or $\ln \widetilde{N}_0 > 1$, the numerator decreases with μ_m:

$$
\begin{aligned}
\frac{\partial}{\partial \mu_m}\left[\left\{a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right\}^{1-\sigma}\right] &= \left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma} \ln\left[a^{\frac{1}{1-\mu}}(p_u^*)^{-1}\right]^{1-\sigma} \\
&= (1-\mu)^{-1}\left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma} \ln\left[a(p_u^*)^{-(1-\mu)}\right]^{1-\sigma} \\
&= (1-\mu)^{-1}\left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma} \ln \widetilde{N}_0^{-1} \\
&= -(1-\mu)^{-1}\left[a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right]^{1-\sigma} \ln \widetilde{N}_0 < 0.
\end{aligned}
$$

Since the denominator unambiguously increases with μ_m, the whole term decreases with μ_m:

$$
\begin{aligned}
\frac{\partial^2 N_m}{\partial F \partial \mu_m} &\propto \frac{\partial^2}{\partial F \partial \mu_m}\left[\widetilde{\Theta} N^{-\frac{\mu_m}{1-\mu}}(N - \alpha\overline{N})\right] \\
&= \frac{\widetilde{\rho}(\overline{a}_m^{\rho}-1)\sigma[\sigma(1-\mu)+\mu]}{\rho D^* K_f(\sigma-1)}\frac{\partial}{\partial \mu_m}\left[\mu_m^{-1}\left\{a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right\}^{1-\sigma}\right] \\
&= \frac{\widetilde{\rho}(\overline{a}_m^{\rho}-1)\sigma[\sigma(1-\mu)+\mu]}{\rho D^* K_f(\sigma-1)}\left[\mu_m^{-1}\frac{\partial}{\partial \mu_m}\left\{a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right\}^{1-\sigma} - \mu_m^{-2}\left\{a^{\frac{\mu_m}{1-\mu}}(p_u^*)^{1-\mu_m}\right\}^{1-\sigma}\right] < 0.
\end{aligned}
$$

That is, the upward shift of the $\Pi = 0$ curve is smaller as μ_m is higher. This establishes Proposition 3(ii), stating that multinationals emphasizing local sourcing show the resilience to natural disasters.

Appendix 4. Reconstruction from disasters

Supposing that a natural disaster strikes at an initial time $s = 0$, the fixed labor input at time $s \geq 0$ is specified as $F(s) = Fe^{\delta(T-s)}$. The fixed input returns to the pre-shock level F after time T. At point S_1, capital return of becoming a multinational at time s ($\leq T$), denoted by $r_m(s)$, is then

$$\begin{aligned}
r_m(s) &= (D^*/\sigma)\left[a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right]^{1-\sigma}\overline{N}(s)^{\frac{\mu_m}{1-\mu}} \\
&= (D^*/\sigma)\left[a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right]^{1-\sigma}\left[\frac{L}{F(s)\{\sigma(1-\mu)+\mu\}}\right]^{\frac{\mu_m}{1-\mu}} \\
&= (D^*/\sigma)\left[a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right]^{1-\sigma}\left[\frac{L}{Fe^{\delta(T-s)}\{\sigma(1-\mu)+\mu\}}\right]^{\frac{\mu_m}{1-\mu}} \\
&= (D^*/\sigma)\left[a_m a^{\frac{\mu_m}{1-\mu}}(\tau p_u^*)^{1-\mu_m}\right]^{1-\sigma}\overline{N}^{\frac{\mu_m}{1-\mu}}e^{-\frac{\delta\mu_m(T-s)}{1-\mu}} \\
&= r_m e^{-\frac{\delta\mu_m(T-s)}{1-\mu}} \qquad \text{for } s < T,
\end{aligned}$$

which becomes the pre-shock level r_m after time T. Note that in equilibrium S_1 the number of domestic firms is given by $N = \overline{N}$.

Letting t ($\leq T$) be the time at which foreign capital moves from the foreign to the host country, the lifetime return it generates is given by

$$\begin{aligned}
v(t) &\equiv \int_0^t e^{-\theta s} r_f ds + \int_t^\infty e^{-\theta s} r_m'(s) ds \\
&= \int_0^t e^{-\theta s} r_f ds + \int_t^T e^{-\frac{\theta\delta\mu_m(T-s)}{1-\mu}} r_m ds + \int_T^\infty e^{-\theta s} r_m ds, \qquad \text{for } t \leq T,
\end{aligned}$$

where $\theta > 0$ is the discount rate. The optimal timing of entering the host country is derived from the following first-order condition:

$$\begin{aligned}
& v'(t) = e^{-\theta t} r_f - e^{-\frac{\theta\delta\mu_m(T-t)}{1-\mu}} r_m = 0, \\
& \to -\theta t + \ln r_f = -\frac{\theta\delta\mu_m(T-t)}{1-\mu} + \ln r_m, \\
& \to \frac{\theta(1-\mu+\delta\mu_m)t}{1-\mu} = \frac{\theta\delta\mu_m T}{1-\mu} + \ln\left(\frac{r_f}{r_m}\right), \\
& \to t = \begin{cases} 0 & \text{if } \ T \leq \widehat{T} \equiv \dfrac{1-\mu}{\theta\delta\mu_m}\ln\left(\dfrac{r_m}{r_f}\right) \\ \dfrac{1}{1-\mu+\delta\mu_m}\left[\delta T - \dfrac{1-\mu}{\theta}\ln\left(\dfrac{r_m}{r_f}\right)\right] \equiv \widehat{t}\ (>0) & \text{if } \ T > \widehat{T} \end{cases},
\end{aligned} \tag{A8}$$

noting that $r_m > r_f$, or equivalently $\ln(r_m/r_f) > 0$ holds at point S_1. We can immediately see from Eq. (A8) that the optimal timing weakly increases with the recovery time, i.e., $\partial t/\partial T \geq 0$. This optimal timing is indeed smaller than T:

$$T - \widehat{t} = \frac{1-\mu}{1-\mu+\delta\mu_m}\left[T + \frac{1-\mu}{\theta}\ln\left(\frac{r_m}{r_f}\right)\right] > 0.$$

The second-order condition (SOC) is

$$\begin{aligned}
v''(t) &= -\theta e^{-\theta t} r_f + \frac{\theta\delta\mu_m}{1-\mu} e^{-\frac{\theta\delta\mu_m(T-t)}{1-\mu}} r_m < 0,\\
&\to \frac{\delta\mu_m}{1-\mu}\cdot\exp\left(\theta\left[t - \frac{\delta\mu_m(T-t)}{1-\mu}\right]\right) < \frac{r_f}{r_m},\\
&\to \ln\left(\frac{\delta\mu_m}{1-\mu}\right) + \theta\left[t + \frac{\delta\mu_m(t-T)}{1-\mu}\right] < \ln\left(\frac{r_f}{r_m}\right).
\end{aligned}$$

If the SOC does not hold, the objective function $v(t)$ exhibits a convex one and foreign capital never moves to the host country, i.e., $t = \infty$. The inequality in the last line always holds if the following sufficient condition holds:

$$\begin{aligned}
&\ln\left(\frac{\delta\mu_m}{1-\mu}\right) + \theta\left[t + \frac{\delta\mu_m(t-T)}{1-\mu}\right] \leq \ln\left(\frac{\delta\mu_m}{1-\mu}\right) + \theta\left[T + \frac{\delta\mu_m(T-T)}{1-\mu}\right] < \ln\left(\frac{r_f}{r_m}\right),\\
&\to \ln\left(\frac{\delta\mu_m}{1-\mu}\right) + \theta T < \ln\left(\frac{r_f}{r_m}\right),\\
&\to T < \overline{T} \equiv \frac{1}{\theta}\ln\left(\frac{1-\mu}{\delta\mu_m}\cdot\frac{r_f}{r_m}\right),
\end{aligned}$$

where $\overline{T}$ is defined over a parameter range that ensures $\overline{T} > 0$. If T is sufficiently higher than $\overline{T}$, the SOC is not satisfied and the time of reentering never comes, i.e., $t = \infty$, which establishes Proposition 4(i).

Assuming the existence of interior solutions, that is, a parameter range that satisfies $\widehat{T} < \overline{T}$ and $T \in (\widehat{T}, \overline{T})$, we can check that the optimal timing $t = \widehat{t}$ decreases with μ_m:

$$\begin{aligned}
\frac{\partial\widehat{t}}{\partial\mu_m} &= \frac{1}{(1-\mu+\delta\mu_m)^2}\left[-\frac{1-\mu}{\theta}\frac{\partial\ln(r_m/r_f)}{\partial\mu_m}\cdot(1-\mu+\delta\mu_m) - \delta\left\{\delta T - \frac{1-\mu}{\theta}\ln\left(\frac{r_m}{r_f}\right)\right\}\right]\\
&= \frac{1}{(1-\mu+\delta\mu_m)^2}\left[-\frac{(1-\mu)(1-\mu+\delta\mu_m)}{\theta\mu_m}\frac{r_f}{r_m}\frac{r_m}{r_f}\left\{\ln\left(\frac{r_m}{r_f}\right) - \ln\tau^{1-\sigma}\right\} - \delta\left\{\delta T - \frac{1-\mu}{\theta}\ln\left(\frac{r_m}{r_f}\right)\right\}\right]\\
&= \frac{1}{(1-\mu+\delta\mu_m)^2}\left[\frac{(1-\mu)(1-\mu+\delta\mu_m)}{\theta\mu_m}\ln\tau^{1-\sigma} - \delta^2 T - (1-\mu)^2\ln\left(\frac{r_m}{r_f}\right)\right] < 0.
\end{aligned}$$

From the first to the second line, the following relations were used:

$$\begin{aligned}
\frac{r_m}{r_f} &= \left[\left\{ a^{\frac{1}{1-\mu}} (\tau p_u^*)^{-1} \right\}^{1-\sigma} \overline{N}^{\frac{1}{1-\mu}} \right]^{\mu_m} \tau^{1-\sigma} > 1, \\
\frac{\partial (r_m/r_f)}{\partial \mu_m} &= r_m \ln \left[\left\{ a^{\frac{1}{1-\mu}} (\tau p_u^*)^{-1} \right\}^{1-\sigma} \overline{N}^{\frac{1}{1-\mu}} \right], \\
&= \frac{1}{\mu_m} \frac{r_m}{r_f} \left[\ln \left(\frac{r_m}{r_f} \right) - \ln \tau^{1-\sigma} \right] > 0.
\end{aligned}$$

Similarly, it can be checked that $\partial \widehat{t} / \partial \tau < 0$. These establish Proposition 4(ii).

Data Appendix for
“The Resilience of FDI to Natural Disasters through Industrial Linkages”

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This appendix provides supplementary tables for empirical examples in Introduction.

Table A1. Description of variables

Variable	Description	Source
No. of natural disasters	Number of natural disasters that record positive financial damages.	EM-DAT
FDI (as % of GDP)	FDI net inflows (new investment inflows less disinvestment) divided by GDP.	WDI
Population growth rate (%)	Annual population growth rate.	WDI
Inflation rate (%)	Inflation as measured by the annual growth rate of the GDP deflator.	WDI
Corporate tax rate (%)	Statutory corporate tax rate.	Asen (2020)
Financial depth	Score measures of the depth of stock market and international debt securities, ranging from zero to one (FMD: Financial Market Depth).	IMF

Notes: EM-DAT: Emergency Events Database by the Centre for Research on the Epidemiology of Disasters, `https://www.emdat.be/` WDI: World Development Indicators by the World Bank, `https://datatopics.worldbank.org/world-development-indicators/` Statutory tax rates collected by Asen (2020) and the Tax Foundation, `https://taxfoundation.org/publications/corporate-tax-rates-around-the-world/` IMF: Financial Development Index Database by the International Monetary Fund,
`https://data.imf.org/?sk=F8032E80-B36C-43B1-AC26-493C5B1CD33B`

Table A2. List of countries

Developing countries #112			Developed countries #41
Angola	Hungary	Russian Federation	Argentina
Albania	Indonesia	Rwanda	Australia
Argentina	India	Saudi Arabia	Austria
Armenia	Iran, Islamic Rep.	Sudan	Belgium
Azerbaijan	Jamaica	Senegal	Brunei Darussalam
Burundi	Jordan	Solomon Islands	Canada
Benin	Kazakhstan	El Salvador	Chile
Burkina Faso	Kenya	Serbia	Czech Republic
Bangladesh	Kyrgyz Republic	Slovak Republic	Germany
Bulgaria	Cambodia	Slovenia	Denmark
Bosnia and Herzegovina	Korea, Rep.	Seychelles	Spain
Belarus	Lao PDR	Chad	Estonia
Bolivia	St. Lucia	Thailand	Finland
Brazil	Sri Lanka	Tajikistan	France
Bhutan	Lithuania	Turkmenistan	United Kingdom
Botswana	Latvia	Tonga	Greece
Chile	Morocco	Trinidad and Tobago	Croatia
China	Moldova	Tunisia	Hungary
Cameroon	Madagascar	Turkey	Iceland
Congo, Dem. Rep.	Maldives	Tanzania	Israel
Congo, Rep.	Mexico	Uganda	Italy
Colombia	Myanmar	Ukraine	Japan
Comoros	Mongolia	Uruguay	Korea, Rep.
Costa Rica	Mozambique	Uzbekistan	Lithuania
Czech Republic	Mauritania	Venezuela, RB	Latvia
Dominica	Mauritius	Vietnam	Netherlands
Dominican Republic	Malawi	Samoa	Norway
Algeria	Malaysia	Yemen, Rep.	New Zealand
Ecuador	Namibia	South Africa	Oman
Egypt, Arab Rep.	Niger	Zambia	Poland
Estonia	Nigeria		Portugal
Ethiopia	Nicaragua		Russian Federation
Fiji	Nepal		Saudi Arabia
Micronesia, Fed. Sts.	Oman		Slovak Republic
Georgia	Pakistan		Slovenia
Ghana	Peru		Sweden
Guatemala	Philippines		Seychelles
Guyana	Papua New Guinea		Trinidad and Tobago
Honduras	Poland		Uruguay
Croatia	Paraguay		United States
Haiti	Romania		Venezuela, RB

Notes: Developing countries are those belonging to low-income, lower-middle-income, or upper-middle-income groups at some point in 1996 to 2015, according to the World Bank. See: `https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html` Developed countries are those belonging to high-income group at some point in 1996 to 2015. The list does not include countries identified as tax havens ("big seven" and "dots") by Hines and Rice (1994).

Table A3. Summary statistics

	N	Mean	St. Dev.	Min	Max
Developing countries					
FDI	2,000	3.601	3.477	−2.499	21.687
No. of disasters in the prior 5 years	2,000	3.861	9.280	0	112
No. of disasters in the prior 10 years	2,000	6.833	16.603	0	199
No. of disasters in the prior 15 years	2,000	8.921	22.150	0	273
Population growth rate	2,000	1.417	1.226	−3.848	5.432
Inflation rate	2,000	44.108	631.813	−26.300	26,765.860
Corporate tax rate	2,000	29.615	8.640	0	55
Financial depth	2,000	0.118	0.159	0.000	0.837
Developed countries					
FDI	655	3.270	4.706	−5.616	36.953
No. of disasters in the prior 5 years	655	6.476	12.815	0	88
No. of disasters in the prior 10 years	655	11.812	23.391	0	165
No. of disasters in the prior 15 years	655	15.789	31.572	0	236
Population growth rate	655	0.695	0.911	−1.854	7.350
Inflation rate	655	2.609	4.860	−27.632	40.440
Corporate tax rate	655	30.446	8.240	12	58
Financial development	655	0.500	0.290	0.004	0.999

Table A4. Disaster impact on FDI: developing vs. developed countries

	Dependent variable: FDI (as % of GDP)					
	Developing countries			Developed countries		
	(1)	(2)	(3)	(4)	(5)	(6)
No. of disasters in the prior 5 years	−0.031**			−0.056		
	(0.014)			(0.052)		
No. of disasters in the prior 10 years		−0.027***			−0.020	
		(0.007)			(0.024)	
No. of disasters in the prior 15 years			−0.020***			−0.007
			(0.005)			(0.014)
Population growth rate	0.535***	0.519***	0.509**	0.576	0.579	0.607
	(0.196)	(0.197)	(0.198)	(1.060)	(1.066)	(1.071)
Inflation rate	−0.0001***	−0.0001***	−0.0001***	−0.017	−0.017	−0.017
	(0.00004)	(0.00004)	(0.00004)	(0.028)	(0.028)	(0.027)
Corporate tax rate	−0.049***	−0.047***	−0.047***	−0.093	−0.096	−0.102
	(0.018)	(0.018)	(0.018)	(0.081)	(0.081)	(0.082)
Financial depth	0.910	1.276	1.498	3.477	3.479	3.629
	(1.581)	(1.536)	(1.529)	(2.707)	(2.761)	(2.734)
Country fixed effects	✓	✓	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
Number of countries	112	112	112	41	41	41
Number of observations	2,000	2,000	2,000	655	655	655
R^2	0.513	0.515	0.515	0.426	0.424	0.423

Notes: Standard errors clustered by country are in parentheses. Developed countries are those belonging to the high-income group, while developing countries to the other income groups, according to the classification of the World Bank. We exclude tax haven countries identified by Hines and Rice (1994) and countries that never experienced natural disasters in 1976–2015. We drop the top 1% and the bottom 1% of the observations of the dependent variable as outliers.

*Significant at 10% level; **Significant at 5% level; ***Significant at 1% level.

Table A5. Disaster impact on FDI in developing countries: severe vs. non-severe disasters

	Dependent variable: FDI (as % of GDP)			
	Severe disasters		Non-severe disasters	
	(1)	(2)	(3)	(4)
No. of disasters in the prior 5 years	0.013	0.014	0.019	0.018
	(0.055)	(0.056)	(0.024)	(0.024)
No. of disasters in the prior 6 to 10 years	−0.081*		−0.053**	
	(0.049)		(0.022)	
No. of disasters in the prior 11 to 15 years	−0.095***		−0.031	
	(0.034)		(0.028)	
No. of disasters in the prior 6 to 15 years		−0.088***		−0.042***
		(0.022)		(0.013)
Population growth rate	0.488**	0.489**	0.519***	0.517***
	(0.199)	(0.199)	(0.198)	(0.198)
Inflation rate	−0.0001***	−0.0001***	−0.0001***	−0.0001***
	(0.00004)	(0.00004)	(0.00004)	(0.00004)
Corporate tax rate	−0.046***	−0.046***	−0.049***	−0.049***
	(0.018)	(0.018)	(0.018)	(0.018)
Financial development	1.196	1.182	1.622	1.652
	(1.555)	(1.566)	(1.528)	(1.518)
Country dummies	✓	✓	✓	✓
Year dummies	✓	✓	✓	✓
Number of countries	112	112	112	112
Number of observations	2,000	2,000	2,000	2,000
R^2	0.516	0.516	0.515	0.515

Notes: Standard errors clustered by country are in parentheses. A severe disaster in country i in year t is defined as one that records financial damages as a share of GDP exceeding its median for all countries that have ever experienced natural disasters in 1976–2015. A non-severe disaster in country i in year t is defined as one that is not severe. We exclude tax haven countries identified by Hines and Rice (1994) and countries that never experienced natural disasters during the sample period. We drop the top 1% and the bottom 1% of the observations of the dependent variable as outliers.

*Significant at 10% level; **Significant at 5% level; ***Significant at 1% level.

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