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Cross-Border Technology Investments in Recession

Juliana Yu Sun and Huanhuan Zheng*

Abstract

Utilizing industry-level foreign direct investment (FDI) from 72 source markets to 122 destination markets between 2003 to 2018, we evaluate how cross-border technology investments respond to economic recessions. We find that FDI embedded with intensive research and development (R&D) drops when the destination market is in a recession and the source market is in a normal state, and recovers to the pre-recession levels when both destination and source markets are in recession. However, there is little evidence that recessions affect cross-border investments in other aspects of technology measured by the penetration of robots, intellectual property products, and information and communications technology (ICT). The response of R&D-intensive FDI to recessions is particularly pronounced in deep and long recessions, during the propagation stage of recessions, and in destination markets with relatively weak institutional protection of intellectual property and rule of law, loose FDI regulation, and high financial development. Our findings are limited to advanced markets: there is no evidence that R&D-intensive FDI from or to emerging markets responds to either destination or source market recessions.

Keywords: Technology, R&D, Recession, FDI, Multinational Corporations

JEL: F21, F23, F44, E32

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1 Introduction

Investing in technology is potentially rewarding but not without risk, especially during economic recessions. Historically, many technology leaders and unicorns such as Apple, Microsoft, and Zoom emerged, even thrived in economic downturns. However, technology investments require considerable amounts of funds, which are difficult to sustain in recessions when cash flows are scarce. Multinational corporations (MNCs) that represent the most competitive firms are the major investors in technology (UNCTAD 2005; Helpman 2006). To diversify risk and optimize global networks, MNCs have increasingly utilized foreign direct investments (FDI) to develop, disseminate, and apply technology (Narula and Zanfei 2005; Branstetter, Glennon, and Jensen 2019). Despite growing globalization of technology and rising concerns over macroeconomic shocks, little is known about how technology investments embedded in FDI respond to economic recessions. This paper explores how MNCs navigate macroeconomic risk and opportunities associated with business cycles through FDI embedded with various technology intensity.

We define technology in terms of the production function, following the convention of growth theory. In particular, we identify industry-level production technology using intensities and qualitative attributes of various factors in the production function following Rajan and Zingales (1998) and Samaniego (2010). Higher level of technology is associated with greater productivity. We refer to FDI in industry with relatively high (low) technology level as technology-intensive FDI (technology-light FDI), and use cross-border technology investments a general term for FDI with different magnitude of technology embeddedness. To explore the response of cross-border technology investments to economic recessions, we compare the difference in FDI between technology-intensive and technology-light industries in recessions with that in normal states. Our key measure of technology level is the intensity of research and development (R&D).[1] Our empirical analysis reveals that R&D-intensive FDI decline significantly more than R&D-light FDI during recessions in destination markets. However, there is no similar evidence when source markets are in recessions. Interestingly, when source market recessions occur simultaneously with destination market recessions, R&D-intensive FDI increase to an extent that offsets the negative effects of destination recessions. A possible explanation is that exhausted investment opportunities motivate MNCs to concentrate resources on R&D, so as

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[1] Examples of R&D-intensive FDI includes (i) Huawei Technology, a Chinese MNE, set up a R&D office in Bristol, UK, in 2014; and (ii) GE Healthcare invested M$1000 to set up an R&D center in Bangalore, India, in 2009. Ideally, we would like to have the data on R&D spending in FDI at industry level. But due to lack of data, especially for broad coverage of industry technological indicators in FDI, we look into FDI in technology intensive and light industries instead.

to strengthen their competitiveness in the next economic boom. These findings are robust for FDI between advanced markets (AM) but do not apply to FDI from or into emerging markets (EM).[2]

We further dig into the duration and magnitude of recessions and explore how different types of recession affect R&D-intensive FDI. We find that R&D-intensive FDI drops more substantially when the destination market recession dips deeper and lasts longer. Moreover, when the destination recession is deep, R&D-intensive FDI rises above pre-recession levels if the source market switches from a normal state to a recession. Furthermore, the dynamics of R&D-intensive FDI in different stages of business cycles are not driven by banking crises that constrain credit.

Finally, we document evidence that institutional quality, regulation and finance could also affect how R&D-intensive FDI respond to recessions. In particular, R&D-intensive FDI drops more during recessions in destination markets with weaker institutions, looser FDI regulation, and higher financial development. Moreover, in destination markets with looser regulation and higher financial development, we find that R&D-intensive FDI is restored to pre-recession levels when the source market is also in a recession.

Understanding how MNCs allocate cross-border technology investments in response to recessions is important for at least three reasons. First, it informs policymakers how to utilize cross-border technology investments to mitigate macroeconomic risks: cross-border technology investments in recessions enhance technology spillovers and economic productivity, which pave way for economic recovery. Second, it provides a foundation to study how MNCs may survive and thrive from recessions through cross-border technology investments: many technology leaders and unicorns emerge and thrive during recessions. Third, growing globalization of technology and rising concerns over macroeconomic shocks have been studied separately, we bridge the gap between these two strands of literature by exploring how technology investments embedded in FDI respond to economic recessions. This paper is closely related to the literature on the cyclicality of technology investments and creative destruction.

Cyclicality of Technology Investments R&D investments tend to be procyclical. Anzoategui et al. (2019) find that R&D declined sharply during the Great Recession, which contributes to the subsequent decline in productivity and slow recovery back to the precrisis trend in the US. Geroski and

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[2] AM and EM are defined according to IMF classification. The list of markets in each categories in our sample is presented in Appendix Table A2.

Walters (1995), Aghion et al. (2012), and Fabrizio and Tsolmon (2014) document similar evidence of procyclical R&D investments in the UK, France, and the US respectively. These studies focus on a single market in exploring the cyclicality of technological investments. In recent decades, R&D activities have become increasingly globalized (Narula and Zanfei 2005; Branstetter, Glennon, and Jensen 2019), despite home-country bias (Belderbos, Leten, and Suzuki 2013), partially due to rising competition (Berry 2019).[3] MNCs that engage in cross-border investments are among the most competent (Helpman 2006). Indeed, they are also the dominant players in technology investments throughout the world (UNCTAD 2005), which makes it particularly interesting to explore how MNCs respond to recessions.

We contribute to this strand of literature by establishing a linkage between MNCs' international allocation of R&D investments and macroeconomic shocks. Unlike their domestic peers, MNCs can utilize their global networks to optimize resources and investments during times of macroeconomic shock. Our finding that MNCs cut R&D-intensive FDI during destination market recessions is consistent with existing literature on the procyclicality of R&D investments. We add to the literature by showing that the magnitude and duration of recessions as well as institution could reshape the pattern of R&D-intensive FDI in recessions.

Creative destruction A recession shakes up the economy, challenging the incumbents and rewarding the innovators (Schumpeter 1942). Creative destruction stimulates investment in technology, which fosters long-term productivity growth (Caballero and Hammour 1994; Aghion and Saint-Paul 1998; Canton and Uhlig 1999). Investing in technology during a recession generates high impacts and value (Steenkamp and Fang 2011; Amore 2015), which increases the likelihood not only of surviving a recession but of coming out of it in a stronger position (Gulati, Nohria, and Wohlgezogen 2010). However, resturctuing in recessions could be costly and inefficient due to job losses, resource misallocation, and financial distress (Anderson et al. 1994; Ramey and Watson 1997; Caballero and Hammour 2005).

We contribute to the debate in the literature by documenting new evidence of creative destruction in the context of cross-border technology investments. We show that conditional on destination markets being in deep recessions, R&D-intensive FDI increases when the source market switches from

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[3] We refer readers to Papanastassiou, Pearce, and Zanfei (2020) for a comprehensive literature survey on how and why MNCs allocate R&D and innovation activities globally

a normal state to a recession. This is consistent with the anecdotal evidence that many of today's leading MNCs such as Apple and Microsoft that increase stakes in technology during recessions have not only survived but also thrive.

The rest of this paper is organized as follows. We describe the data and methodology in Section 2, and present the empirical results that document causal effects of recessions on cross-border technology investments in Section 3, and conclude with key findings and their policy implications in Section 4.

2 Data and Methodology

2.1 Data

Foreign Direct Investment The data on cross-border greenfield investment projects are from fDi Markets of Financial Times. fDi Markets collects data primarily from publicly available sources such as newswires, supplemented with private market reports. Each observation is cross-referenced against multiple sources, with primary focus on direct company sources. The dataset reports the name and location of the investor, the destination, sector, and size of the investment project, as well as the number of jobs created for a wide range of countries around the world. We map the variable "Subsector" in this dataset with 3-digit ISIC codes revision 2 so as to merge with the industry-level measures of technology. All FDI in this paper is greenfield FDI.

To understand the response of FDI to business cycles across different industries characterized with heterogeneous technology intensity, we aggregate investments by the destination and source markets in each year for each industry. We restrict the sample to the manufacturing sector with ISIC codes ranging from 311 to 390 in line with the data availability of industry-level technology measures. As core technological innovation and application occurs most intensively in the manufacturing sector, FDI in the manufacturing sector meets our purpose of understanding cross-border technology investment. Even though monthly data on FDI is available, we aggregate it to annual frequency because FDI does not occur frequently between any pair of markets in a given industry.

The final sample covers FDI flows from 72 source markets to 122 destination markets over 28 distinct manufacturing industries from 2003 to 2018. Although a large proportion of FDIs reported by this dataset are estimated, the quality of the greenfield FDI in dollar amount is endorsed by various issues of UNCTAD's World Investment Report (see for example UNCTAD (2019)) along with much academic research, such as Duanmu (2014) and Aizenman, Jinjarak, and Zheng (2018), among many others. Because the size of FDI varies significantly across industries in the manufacturing sector, it is not practical to rely on the count of the FDI project, in the manner of Castellani, Jimenez, and Zanfei (2013) and Castellani and Lavoratori (2020), which focus exclusively on FDI in R&D activities. After all, a small project in manufacturing clothes is not comparable with a big project in manufacturing equipment. However, we do explore how the number of FDI projects respond to recessions in the robustness checks.

Technology Measures Although firms' relative levels of exposure to technology change frequently, the average technological intensity in each industry is rather similar over time and across countries (Samaniego 2010; Ilyina and Samaniego 2011). This provides relatively exogenous industrial variations in technology, which enables us to identify whether recessions could affect technology FDI. It also allows us to utilize all FDI information in the manufacturing sector to exploit the roles of technology without sample bias. After all, not all FDIs in technology intensive industries are related to the generation or application of technology, and even FDI in low-technology industries may involve R&D or other aspects of technology.

The core industry-level measure of technology is *R&D intensity*: the ratio of R&D expenditure to total capital expenditure. As R&D intensity is stable over time within the same sector and the rank of sectors in terms of R&D intensity is consistent across countries (Ilyina and Samaniego 2011), we follow Samaniego and Sun (2015) in using R&D intensity for each of the 28 manufacturing industries, based on US firm-level information averaged over 1970-1999. In particular, R&D intensity is computed for each publicly traded US firm from the Compustat dataset in each year, and then averaged by industry over 1970-1999 to calculate the industry-level R&D intensity.[4]

MNCs have established a large number of R&D laboratories in offshore locations, especially in advanced markets, to access science and technology talents, customize products, and support offshore markets (e.g., Florida 1997; Papanastassiou, Pearce, and Zanfei 2020). Even though we do not have direct measure of FDI in R&D activities across countries by industry, the variation in R&D intensity across industries in offshore markets are largely similar with the variations in foreign R&D activi-

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[4] We acknowledge that it would be ideal to calculate industry-level R&D intensity for each country and over time, which is left for future research due to limited availability for firm-level data across such a large number of economies.

ties. For example, Florida (1997) finds that the biotechnology and pharmaceutical sector obsorbs the largest portion of foreign R&D investments in the US, which is also the highest R&D intensive industry in our measure (industry 352 other chemical). Other foreign R&D-intensive industries include electronics, chemical and automotive, which are also R&D-intensive industries in our list (industry 385, 382, 383, 384 and 351). Moreover, based on the study of foreign investments in the US from UK firms, Griffith, Harrison, and Van Reenen (2006) show that industries that obsorb most FDI are chemical, electrical machinery, and other equipments, which are R&D-intensive industries as in our data.

Technological progress is driven primarily by R&D activities. However, broader measures of technology can also take the form of applying existing technology or improving total factor productivity (TFP). We use alternative measures that reflect other aspects of technology in the robustness checks. The first measure is the industry-level share of robots, calculated as the number of robots used in an industry as a share of the total robots used in the whole manufacturing sector. The data is from the International Federation of Robotics (IFR) 2019 reports, which covers the stock of industrial robots in operation from 2004 to 2018. The industry classification reported by IFR is different from ISIC revision 2. Some industries are disaggregated, while others are not. We first obtain the sum of the disaggregated industries to the ISIC level, and then for each sector, compute the median level of robot shares, calculated as the number of robots used in an industry as a share of the total robots used in the manufacturing sector. For the more aggregated industries in IFR, we sum the FDI accordingly to match its classifications. We use the industry-level robot share in the US averaged over the period from 2004 to 2018 as the indicator for the depth of automation, again assuming this represents standard industry characteristics and is constant across all countries.

The second measure of technology application is information and communication technology (ICT). ICT intensity in each sector is calculated as the ratio of capital expenditure on ICT equipment to total assets. The third measure of technology is the intensity of intellectual property products, calculated as the ratio of capital expenditure on equipment related to intellectual property to total assets. Data on both ICT and intellectual property products are taken from EU KLEMS and are averaged over the period 2008-2015. Because the capital input table EU KLEMS uses more aggregate classification with only 13 manufacturing industries, we map our FDI data to these broader industries when exploring these two aspects of technology.

We also follow Ilyina and Samaniego (2011), Samaniego and Sun (2015), and Samaniego and Sun (2020) in defining technology as a measure related to the total factor productivity growth. Technological characteristics are then captured by the features of capital, inputs, and labor, which can be summarized as follows:

1. *Investment-specific technical change* measures the rate of decline in the price of capital goods relative to the price of consumption and services. This is obtained from the BEA industry-level capital flow tables. This indicator reflects the extent to which technology embodied in capital goods becomes obsolete (Greenwood, Hercowitz, and Huffman 1997).

2. *Investment lumpiness* is defined as the average number of investment spikes per firm during a decade in any given industry, obtained from Compustat. A spike is defined as an annual capital expenditure exceeding 30% of the firm's stock of fixed assets (Doms and Dunne 1998). Samaniego (2010) suggests that investment lumpiness may indicate that a significant portion of a firm's capital cannot be transferred (alienated) without destroying its value, and hence, capital that tends to be adjusted in "lumps" is less suitable as collateral.

3. *Depreciation* is the industry rate of capital depreciation, computed with the BEA industry-level capital flow tables. Industries that use capital with high rates of depreciation might have more difficulty raising external funds during recessions, since rapidly depreciating capital is less adequate as collateral.

4. *Asset fixity* is the ratio of fixed assets to total assets, obtained from Compustat. According to Hart and Moore (1994), non-fixed assets are intangible and thus may be less contractible or transferable, leading to a sensitivity to credit constraints.

5. *Intermediate intensity* is measured by the difference between gross output and value added, divided by gross output, using UNIDO INDSTAT3. Industries that use intermediate inputs more intensively may be particularly sensitive to international trade conditions since most intermediate goods are traded internationally.

6. *Input specificity* is the relationship-specificity indicator, measured by the proportion of inputs that are not sold on an organized exchange or reference-priced in a trade publication, and therefore reflects the extent to which this good is dependent on a specific relationship. The data is from Nunn (2007).

7. *Labor intensity* is total wages and salaries divided by the total value added, using UNIDO INDSTAT3. This measures the overall importance of labor in production.

8. *Skilled labor* measures the intensity of human capital using the average wage bill, i.e., the ratio of wages over total number of employees, taken from UNIDO INDSTAT3.

9. *TFP growth* is the growth of the technology component from the Cobb-Douglas production function. This measures the efficiency of utilizing capital and labor. Manufacturing industry TFP growth data are computed with the NBER-CES Manufacturing Industry Database and use Domar weights to aggregate this TFP growth from the SIC classification to the ISIC revision 2.

Unlike firm-specific exposure to technology, the industry-level technology intensity is rather stable over time and across countries (Samaniego 2010; Ilyina and Samaniego 2011), which provides relatively exogenous variations. This enables us to better identify the impacts of recessions on cross-border R&D activities, as we can compare FDI difference between R&D-intensive and R&D-light industries in recessions with that occurring in normal times. It also helps us to avoid sample bias and preserve different dimensions of technology. After all, firms and industries that have not directly engaged in R&D activities are still exposed to technology in one way or another. [5]

Recessions We follow Braun and Larrain (2005) in defining recessions as the periods leading from peak to trough. Using the Hodrick-Prescott filter, we identify the trough as the year when the logarithmic annual real GDP, obtained from World Development Indicators (WDI), falls below the trend by at least one standard deviation of the cyclical component of GDP.[6] The peak is identified as the nearest year that precedes the trough and features a detrended GDP that is higher than that of its previous and succeeding years. The dummy variable $R_{d,t}$ ($R_{s,t}$) equates to 1 if the destination (source) market is in a recession at period t, and 0 otherwise.[7] Note that such an identification of economic recessions is

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[5] We further compute the R&D intensity measure using all available years in Compustat from 1955 to 2022. The average R&D intensity over decades from 1970-2020 are strongly correlated with each other as shown in Table A5. We also compute R&D intensity for different countries using KLEMS capital accounts dataset for 1995-2019. There are 13 manufacturing industries in KLEMS, which are more aggreagated than our baseline industry indicators. We show in Table A6 that the industry-level R&D intensity among countries are highly correlated.

[6] The value of λ is 6.25, as recommended for annual data by Ravn and Uhlig (2002).

[7] The NBER definition of the contraction is similar to ours, except that it is defined using monthly data and that it excludes the peak, presumably under the assumption that the conditions that lead to the contraction do not coincide with the peak. We are using annual data out of necessity, so that in general the shock that leads to the contraction will coincide with the *year* in which the peak occurs. The alternative of dropping the year in which the peak occurs in general does not change our results concerning the interaction of contractions with technology, as discussed later.

ex post: MNCs may not be immediately aware of the advent of a recession. [8]

We follow Samaniego and Sun (2015) in dividing the recession into (i) shock (the first year of a recession); and (ii) propagation (the years following a shock in a given recession). In addition, the magnitude and duration of a recession may shape cross-border technology investment. We further define *deep* recessions as episodes of recession in which the magnitude of trough, measured by the absolute value of the lowest detrended GDP during a recession, is at the largest 50th percentile of all recessions. All other instances are classified as moderate recessions. Furthermore, we classify recessions that last for more than 3 years, the longest 50th percentile of the recession duration, as *long* recessions and the rest as short recessions. To differentiate recessions from banking crises, we also classify the recession episodes according to whether they are accompanied by any banking crises, as indicated by the Systemic Banking Crises Database of Laeven and Valencia (2012).

Macroeconomic Data Macroeconomic characteristics could affect the MNCs' decisions regarding technology investments. Proprietary technology transfers associated with FDI are highly dependent on institutions. We measure intellectual property protection with the property rights enforcement index developed by the Property Rights Alliance (2008). In a society where rule of law (ROL) is strong, the rules of society, the quality of contract enforcement, property rights and laws enhance the protection of the proprietary technology. We obtain ROL from Worldwide Governance Indicators (WGI).

To understand how FDI regulation affects MNCs' investment decisions, we utilize the FDI restrictiveness index from the OECD, which measures foreign equity limitations, screening or approval mechanisms, restrictions on the employment of foreigners, and operational restrictions. An alternative regulation measure is minimum capital as percentage of income per capita to start a business, from the World Bank's Doing Business data. This is an indicator of entry cost and reflects the restrictiveness of entry regulations in the destination market.

Moreover, technology investments are sensitive to financial development (Rajan and Zingales 1998; Ilyina and Samaniego 2011), which determines funding availability. We follow King and Levine (1993) in measuring the financial development by the credit-to-GDP ratio as well as the stock-market-capitalization-to-GDP ratio from WDI.

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[8] MNCs may forecast business cycles *ex ante* and then act accordingly. However the variations in their forecasts are substantial, which prevents us from identifying the effects of these forecasted recessions on FDI. We thus focus on the actual recessions as in Braun and Larrain (2005) and many others.

It takes a long time to change these measures of market-level characteristics substantially. Given the relative stability of country rank along these variables, we average intellectual property protection over the available period from 2007–2013 and the other measures from $2003-2018$. Based on the average measures, we classify the markets into two groups according to whether their measures are higher than the whole sample's median value.

2.2 Methodology

Samaniego (2010) and Ilyina and Samaniego (2011) show that the average technology intensity in each industry is rather similar over time and across countries, which provides relatively exogenous variations in technology intensity across industries. Following the convention in macroeconomic and trade literature, we adopt static industry-level technology measures calculated based on the US firms for all countries (Samaniego 2010; Ilyina and Samaniego 2011; Rajan and Zingales 1998; Nunn 2007).[9] We can therefore evaluate how FDI with different technology embeddedness or cross-border technology investments respond to recessions in destination and source markets by comparing the differential FDI between technology-intensive and technology-light industries in recessions with that in normal times. When exploiting the R&D aspect of technology, our baseline model is:

$$\begin{aligned} log(1+FDI_{ds,i,t}) = \beta_d \times R_{d,t} \times R\&D_i + \beta_s \times R_{s,t} \times R\&D_i \\ + \beta_{ds} \times R_{d,t} \times R_{s,t} \times R\&D_i + \delta_{ds,t} + \delta_{ds,i} + \delta_{i,t} + \varepsilon_{ds,i,t} \end{aligned} \tag{1}$$

The variable $FDI_{ds,i,t}$ is the bilateral greenfield FDI per million USD to destination market d from source market s in industry i at period t. Following the convention in innovation literature, we take the log of 1 plus $FDI_{ds,t}$ as the dependent variable to deal with zeros in the sample (see for example Aghion et al. 2012). The dummy variable $R_{d,t}$ ($R_{s,t}$) equals 1 when the destination (source) market is in recession at period t and 0 otherwise. To simplify presentation, we abbreviate the subscript on time in the subsequent context and refer to all non-recession periods as normal times, following Samaniego and Sun (2015). R&D intensity, $R\&D_i$, our key measure of technology, is the ratio of R&D expenditure to total capital expenditure in industry i.

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[9] Resources are relatively undistorted in the U.S. market compared to other economies, so that the measures computed using the U.S. data reflect the "true" technology. The benefit to use the U.S measure is that we can avoid potential endogenous issue. Because the country-specific R&D intensity measure may be affected by country institutions, market friction and misallocation of resources, FDI can determine country-specific R&D intensity measures, and thus lead to endogenous problems.

The list of fixed effects absorbs a comprehensive range of confounding factors. The destination-source-time fixed effects, $\delta_{ds,t}$, absorb the time-varying interaction between destination and source markets that affect bilateral FDI, such as international relations, trade linkages, and changes in comparative advantage in growth potential. Moreover, $\delta_{ds,t}$ captures the effects of push and pull factors that drive and attract FDI to destination d;[10] the dynamic motivations of cross-border investment by source market s; the dynamic asset-exploiting, asset-seeking and asset-augmenting strategies (see Papanastassiou, Pearce, and Zanfei 2020, for a survey on related literature); the time-varying global factors such as risk appetite and liquidity; and the evolving external conditions such as the average economic growth and business environment in other markets. The destination-source-industry fixed effects, $\delta_{ds,i}$, digests the industry-level variations in bilateral FDI. Industrial structure differs across markets, while a destination market may attract investment in some industries more than the others, i.e. due to easy access to inputs or economies of scale, a source market may concentrate upon a particular industry to best utilize its comparative advantage. These variations which may affect FDI are controlled by $\delta_{ds,i}$. The share of FDI in manufacturing sector declines from 50% in 2003 to 40% in 2019, or around 0.6% per year on average. There are ebbs and flows in different industries within the manufacturing setor. The industry-time fixed effects, $\delta_{i,t}$, takes care of these industrial cycles and dynamics in each industry. Finally $\varepsilon_{ds,i,t}$ is the error term.

If $R\&D_i$ is a dummy variable that equates to 1 for R&D intensive industries, it is clear that Eq.(1) compares the FDI difference between R&D intensive and R&D light industries in recessions with that in normal times. The coefficient β_d thus represents the effect of the destination market's recession on R&D-intensive FDI, conditional on the source market being in a normal state. Similarly, the coefficient β_s reflects the effect of the source market recession on R&D-intensive FDI, conditional on the destination market being in a normal state. The coefficient of the triple interaction term β_{ds} records the additional correlation of destination (source) market recession on R&D-intensive FDI when both markets fall into recession, relative to the scenario when only the destination (source) market is in a recession. In other words, the correlation of a destination recession on R&D-intensive FDI conditional on the source market being in a recession is recorded by the sum of β_d and β_{ds}. Similarly, the effect of a source market recession on R&D-intensive FDI, conditional on the destination market being in a recession, is captured by the sum of β_s and β_{ds}. The sum of β_d, β_s and β_{ds} captures the response of

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[10] Push factors refer to external forces that drive FDI to destination markets such as global liquidity, source market monetary policy, etc. Pull factors are destination market-specific factors such as economic growth, market size, and liberalization that attract FDI to the destination.

R&D-intensive FDI to simultaneous recessions in destination and source markets.

When $R\&D_i$ is a continuous variable with a higher value corresponding to greater R&D intensity, the interpretation of coefficients in Eq.(1) is similar. A negative and statistically significant estimated coefficient of β_d (β_s) suggests R&D-intensive FDI falls during a destination (source) market recession. The difference is that the magnitude of the coefficients now measures the elasticity of FDI to every unit of technology intensity rather than the growth rate of FDI. Similar specifications are adopted by Rajan and Zingales (1998), Ilyina and Samaniego (2011), and Samaniego and Sun (2015) to evaluate the impact of recessions and financial development on economic growth.

FDI to AM and EM differs significantly in motivation and distribution across sectors. For example, FDI tends to target technology, knowledge, and market size in AM; but is attracted to cheap labor and high growth potential in EM. Similarly, FDI from AM and EM is driven by different forces. To enhance the comparability between the R&D intensive and R&D light FDI, we group the destination and source markets by AM and EM and evaluate them separately.

Other than the R&D of technology, we are also interested in the application of technology as well as other characteristics related to TFP. To evaluate how investments in other dimensions of technology respond to recessions, we replace $R\&D_i$ in Eq.(1) with alternative measures of technology including (i) the degree of automation measured by the number of robots used in each industry as a share of the total robots used in the whole manufacturing sector; (ii) ICT, calculated by the ratio of expenditure on ICT equipment to total assets; (iii) intellectual property products (IPP), measured by the ratio of expenditure on software and other equipment related to intellectual property products to all assets in each industry; and (iv) different measures of technological characteristics related to TFP as detailed in the data section.

3 Empirical Analysis

In this section, we first present the baseline results on how R&D-intensive FDI responds to recessions in destination and source markets. We then evaluate whether such responses to recessions by R&D-intensive FDI can be generalized to cross-border investments in other aspects of technology. Next, we perform heterogeneity analysis to understand how recession patterns, institution, regulation, and finance shape the dynamics of cross-border technology investments during recessions. Finally, we check the robustness of the baseline results.

[Insert Table 1 here]

3.1 Baseline Results

We explore the patterns of cross-border technology investments during recessions by estimating Eq.(1), which compares the difference between R&D-intensive and R&D-light FDI in and out of recessions. The results are presented in Table 1. We first focus on FDI between AMs, differentiating their responses to recessions in destination (source) markets conditional on the other markets being in recessions and normalcy separately, and then extend the discussion to FDI related to EMs.

Recessions in destination markets only Recessions are accompanied by weak demand, which reduces the rewards of R&D and discourages investment in R&D intensive industries (Barlevy 2007; Fabrizio and Tsolmon 2014). When only destination markets are in recession, MNCs have the flexibility and experience to shift R&D investments from the market that is in recession to others that are normal, to better gain from international business cycles, thus further reducing R&D investment in destination markets during recessions. In line with these argument, Column 1 shows that the coefficient of $R_d \times R\&D$ is $-.165$ and statistically significant at the 5% level. It means that when destination markets are in recession and source markets are in a normal state, R&D-intensive FDI from AM to AM drops by 16.5% for every unit increase in R&D intensity. Appendix Table A3 shows that the most and least R&D intensive industries in our sample are Other Chemicals (ISIC code 352, R&D = 1.95) and Apparel (ISIC code 322, R&D = 0.02), respectively. The coefficient of $R_d \times R\&D$ in column 1 implies that during a recession in the destination market and normalcy in the source market, FDI to Other Chemicals declines by 32% ($= -.165 \times (1.95 - 0.02)$) more than that to Apparel.

Recessions in source markets only Unlike their local peers that are credit constrained due to the recessions in source markets, MNCs may utilize revenues generated from markets that are booming to sustain R&D investment in the target destinations, thus muting the effects of source market recessions. In line with this prediction, we find no evidence that FDI from AM to AM responds to source market recessions when the destination market is in a normal state – the coefficient of $R_s \times R\&D$ is not statistically significant.

Recessions in both destination and source markets Given the synchronization of business cycles across the world (Kose, Prasad, and Terrones 2003; Kose, Otrok, and Prasad 2012), profit opportunities are likely to be rare everywhere when source and destination markets are in recession simultaneously. This was particularly the case during the 2007 global financial crisis (GFC) when the majority of AMs were in recession. A shortage of profit opportunities worldwide may motivate MNCs to concentrate resources on R&D of technology so as to enhance their competitiveness in the next economic boom period. If this is the case, simultaneous recessions in destination and source markets may stimulate cross-border R&D investment. Our analysis shows that the coefficient of the triple interaction term $R_d \times R_s \times R\&D$ in column 1 is 0.208 and statistically significant at the 5% level. It suggests that, compared to the scenario when either destination or source market is in recession, R&D-intensive FDI increases when both destination and source markets are in recession.

To better interpret the estimation result on the triple interaction term, we consider two scenarios. In the first scenario, only the source market is in recession, such that $R_s = 1$ and $R_d = 0$. The coefficient of $R_s \times R\&D$ indicates that the effect of a source market recession on R&D-intensive FDI in this scenario is -0.067, which is not statistically significant. In the second scenario, both destination and source markets are in recession, such that $R_s = 1$ and $R_d = 1$. The effect of a source market recession on R&D-intensive FDI in such a scenario is 0.141, which is calculated as the sum of the coefficients of $R_s \times R\&D$ (-0.067×0.154) and $R_d \times R_s \times R\&D$ (0.208×0.154). The difference in the magnitude of R&D-intensive FDI change between the second and first scenario is 0.208, which is statistically significant at the 5% level. It means that for every unit increase in R&D intensity, R&D-intensive FDI increases by an additional 20.8% in response to a source market recession, when the destination market switches from a normal state to a recession. More specifically, when a destination market goes into recession, in response to the source market recession, FDI to the most R&D intensive industry (Other Chemical) increases by an additional 40.1% $(= 20.8\% * (1.95 - 0.02))$ more than that to the least R&D intensive industry (Apparel). Using a similar argument, we can show that when the source market transitions from a normal state to a recession, for every unit increment in R&D intensity, R&D-intensive FDI increases by an additional 20.8% in response to the destination market recessions.

FDI dynamics conditional on simultaneous recessions We now turn to analyze cross-border R&D investment dynamics, conditional on simultaneous recessions in both destination and source markets.

The total effect of a destination market recession on R&D-intensive FDI, conditional on the source market being in recession, is 0.043,[11] which is economically trivial and statistically insignificant. It indicates that although R&D-intensive FDI falls during a destination market recession, it recovers to pre-recession levels when the source market also falls into recession. The effect of a source market recession on R&D-intensive FDI conditional on the destination market being in recession is 0.141,[12] which is not statistically significant either. Recalling that the coefficient of $R_s \times R\&D$ is also not statistically significant, our results suggest that R&D-intensive FDI does not respond to source market recessions, regardless of the business cycles in the destination markets. The total response of R&D-intensive FDI to simultaneous recessions in destination and source markets is 0.024,[13] which is economically small and statistically insignificant. This implies that R&D-intensive FDI remains resilient when both source and destination markets are in recession.

To summarize, R&D-intensive FDI from AM to AM drops during a destination market recession only when the source market is in a normal state, and recovers to pre-recession levels when the source market is also in a recession.

Cross-border technology investments related to EM Columns 2 to 4 of Table 1 report estimation results for FDI from AM to EM, EM to AM, and EM to EM, respectively. For investments that involve EM, there is no evidence that R&D-intensive FDI responds to the destination and/or source market recessions. The R&D-intensive FDI dynamics during recessions discussed above concentrate on AM, which is consistent with the stylized fact that FDI among AM focuses primarily on R&D intensive activities (Antràs and Yeaple 2014). However, the finding that R&D-intensive FDI to EM is acyclical contradicts the findings of Barlevy (2007) and Fabrizio and Tsolmon (2014), each of which focus on the US market. Such a deviation from the literature can be explained by the dominance of vertical FDI in EM (Roy and Viaene 1998), which is produced in EM, i.e. to utilize cheap labor or materials, and is sold to international markets. There are greater uncertainties in EM than AM (Gavin and Hausmann 1998), which motivates MNCs to diversify production in several EM to mitigate risk (Aizenman 2003). Such arrangements may mute R&D-intensive FDI's response to EM recessions. Moreover, R&D-intensive FDI from EM does not respond to recessions because (i) EM may invest

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[11] It is calculated as the sum of the coefficients of $R_d \times R\&D$ (-0.165) and $R_d \times R_s \times R\&D$ (0.208) as in column 1 of Table 1.

[12] It is calculated as the sum of the coefficients of $R_s \times R\&D$ (-0.067) and $R_d \times R_s \times R\&D$ (0.208) as in column 1 of Table 1.

[13] It is calculated as the sum of the coefficients of the three interaction terms.

for strategic purposes instead of profits, i.e. acquiring some specific resources, and (ii) EM are relatively inexperienced in cross-border investments and may not be able to respond quickly to rising uncertainties in recessions.

The heterogeneous responses of R&D-intensive FDI to recessions in AM and EM mitigate concerns over reverse causality. FDI is more central to economic growth in EM than AM. If our result is driven by FDI reducing the likelihood of recessions in destination markets, the coefficient of $R_d \times R\&D$ should be more negative for EM than for AM. However, we find an insignificant response of R&D-intensive FDI to EM recessions, which mitigates concerns over reverse causality. If more FDI leads to a higher likelihood of recessions in destination markets, our results can only be strengthened after addressing reverse causality. From here onward, we focus on R&D-intensive FDI from AM to AM only, which is more general and representative, to explore the response of this particular dynamic to recessions.[14]

3.2 Alternative Measures of Technology

Thus far, technology has been measured by R&D intensity. Higher R&D intensity is associated with greater technological improvement in the future. Broad definitions of technology cover not only the R&D of new technology, but also application of existing technology, as well as factors that can improve total factor productivity (TFP). We check whether the findings in the above section are unique to R&D or robust to alternative specifications of technology in this subsection.

[Insert Table 2 here]

We first look at the application of existing technology. Robots and ICT have been increasingly used in the manufacturing sector to automate routine work. Following Acemoglu and Restrepo (2019), we measure the degree of automation by the number of robots used in each industry as a share of the total robots used in the whole manufacturing sector. The intensity of applying ICT in each industry is calculated by the ratio of expenditure on ICT equipment to total assets. We also look at the the intensity of applying IPP in each industry, which is measured by the ratio of expenditure on software and other equipment related to intellectual property products to all assets. Greater value of robot share, ICT intensity, and IPP intensity corresponds to more intensive technology application.

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[14] There are some developing countries which are defined neither as AMs nor EMs, and therefore they are not included in the regressions.

Replacing *R&D* in Eq.(1) with each of these three measures of technology separately, we re-run the estimation and present the results in columns 1 to 3 of Table 2. There is no evidence that recessions in either destination or source markets affect FDI to industries with more intensive application of existing technology, such as robots, ICT, or IPP.[15] These results reveal that cross-border investments in applying existing technology are different to those in R&D of new technology, in terms of their response to recessions.

We further broaden our definition of technology to encompass measures that could improve the total factor productivity (TFP), following Ilyina and Samaniego (2011). Growth in TFP could be driven by an improvement in capital, inputs, and labor. From the perspective of capital, we use (i) investment-specific technical change, which reflects the extent that technology embodied in capital goods becomes obsolete; (ii) investment lumpiness, the frequency of big investments; (iii) depreciation, the industry rate of physical and economic depreciation; and (iv) asset fixity, the ratio of fixed assets to total assets. In terms of inputs, we look at intermediate intensity, the ratio of intermediate inputs over gross output; and input specificity, which measures the proportion of inputs that are not sold on an organized exchange nor reference-priced in a trade publication (Nunn 2007). As for labor, we use labor intensity, the total wages and salaries divided by the total value added; and skilled labor, which measures the intensity of human capital. We also include the industry-level TFP growth indicator from Samaniego and Sun (2020). A more detailed description of these measures and their constructions can be found in Ilyina and Samaniego (2011) and Appendix Table A1.

The results in columns 4 to 12 of Table 2 show that FDI to industries with higher investment-specific technical change, input specificity, and human capital intensity, falls significantly during destination recessions. However, there is no evidence that cross-border investments in other technological characteristics respond to recessions in either destination or source markets.

Throughout the various measures of technological characteristics, we find no evidence of additional effects of simultaneous recessions in destination and source markets on cross-border investments in alternative aspects of technology. This suggests that the recovery of cross-border technology investments during simultaneous recessions is unique to R&D activities. Unlike other technology measures, R&D activities that take a long time to harvest face high risk and require large amounts

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[15] We also check an alternative indicator of R&D intensity which is measured as R&D expenditure over total sales ratio, from Ngai and Samaniego (2011). The results are similar to our baseline and available upon request. However, because this measure is affected by markups in an environment with imperfect competition by construction, we need to use it with caution and do not treat it as a pure technological measure.

of investment during the development process, and are extremely sensitive to aggregate economic fluctuations. From here onward, we focus on the R&D aspect of technology to further explore its response to recessions.

3.3 Heterogeneity Analysis

So far, we have documented that R&D-intensive FDI from AM to AM falls during destination market recessions, but recovers to pre-recession levels when source markets also fall into recession. Such a pattern is unique to R&D but not in other aspects of technology. In this section, we further explore how the dynamics of R&D-intensive FDI vary with the patterns of recessions, institutions, regulations, and finance in destination markets.

3.3.1 Different Types of Recession

Depth of Recessions Deep recessions hit the economy harder than moderate ones. The deeper the recession, the larger the number of firms that will suffer from credit constraints, the smaller the rents of R&D, and the lower the R&D investments will be (Barlevy 2007; Aghion et al. 2012). To test whether the response of R&D-intensive FDI varies with the depth of recessions, we evaluate the effects of deep and moderate recessions on cross-border technology investments separately. We classify deep recessions as those with magnitudes of trough above the 50th percentile of all recessions in AM, and all others are considered to be moderate recessions.[16] Table A4 list all deep and moderate recessions during 2003-2018.

We re-estimate Eq.(1) by replacing R_d with R_{d_a}, with alternative definitions of recession specified in the first row (deep and moderate), while keeping the control group (observations during normal times) unchanged. The results are presented in Table 3. The dummy variable R_{d_a} in column 1 (2) equates to 1 during deep (moderate) recessions in destination markets and 0 during normal times.[17] Columns 1 and 2 summarize the effects of deep and moderate recessions on R&D-intensive FDI separately.

[Insert Table 3 here]

The coefficient of $R_{d_a} \times R\&D$ is -0.138 and -0.232 in columns 1 and 2 respectively, but is only

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[16] We compare the magnitudes of recessions in our full sample during 1960 to 2018.

[17] R_{d_a} has no value during episodes of moderate recession in destination markets.

statistically significant at the 10% level in column 2 during moderate recessions. It suggests that, conditional on source markets being in a normal state, the drop in R&D-intensive FDI in response to destination recessions concentrates on episodes of moderate rather than deep recession.[18] The coefficient of the triple interaction term is 0.327 and is statistically significant at the 5% level in deep recessions (column 1) but no similar evidence is documented for moderate recessions (column 2). Thus, the baseline result that R&D-intensive FDI rebounds when the source market falls into a recession is mainly driven by deep recessions.

The total effect of the source market recessions on R&D-intensive FDI, conditional on the destination market being in a deep recession, calculated as the sum of the coefficients of $R_s \times R\&D$ and $R_{d_a} \times R_s \times R\&D$, is 0.263 and is statistically significant at the 5% level. This suggests that a source market recession enhances R&D-intensive FDI only when the destination market is in a deep recession. The result is consistent with the philosophical argument of Schumpeter (1942) and the theoretical prediction of Caballero and Hammour (1994), Aghion and Saint-Paul (1998), and Canton and Uhlig (1999) that recessions provide a good opportunity to invest in technology. Our result complements the existing literature by showing that creative destruction exists under certain restricted conditions such as deep recessions.

Duration of Recessions Some recessions last longer than the others and exert more profound influences on the economy. It is more difficult for firms to finance investments when facing a long-term rather than a temporary recession. Long-term recessions exhaust existing resources accumulated during periods of economic expansion, making it hard to raise funds both internally and externally. To test whether the duration of recessions shapes R&D investment in recessions, we differentiate between long and short recessions. We classify recession episodes that last longer than 3 years (the 50th percentile value in the duration of all recession episodes in AM) as long recessions, and the rest as short recessions. Please see column 3 and 4 in Table A4.[19]

We re-define the dummy variable R_{d_a} as 1 during a long (short) recession in the destination market and 0 during a normal state, and then estimate Eq.(1) by replacing R_d with R_{d_a}. The results for the

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[18] The difference in the coefficient of $R_{d_a} \times R\&D$ between columns 1 and 2 is 0.094 and is not statistically significant. Note that because the coefficient of $R_{d_a} \times R\&D$ is more negative for moderate recessions in destination markets (column 2) than for deep recessions (column 1), even if the difference in the coefficients between columns 1 and 2 is not statistically significant.

[19] Please note that we compare recessions during 1960-2018, although the table only lists period between 2003 and 2018. Some countries have 2003 in the long recession category because the recession started from 2000 or earlier.

response of R&D-intensive FDI to long and short recessions are presented in columns 3 and 4 of Table 3. The coefficient of $R_{d_a} \times R\&D$ is -0.187 and is statistically significant at the 5% level in long recessions (column 3). We find no such evidence in short recessions (column 4). This suggests that our baseline result that R&D-intensive FDI falls during destination market recessions is mainly driven by long recessions.

Comparing the coefficients of $R_{d_a} \times R_s \times R\&D$ in columns 3 and 4, we find little difference between long and short recessions in terms of their additional effects on R&D-intensive FDI when the source markets fall into recession. Thus, long recessions in destination markets reduce R&D-intensive FDI, but this is not the key reason why R&D-intensive FDI rebounds during simultaneous recessions in both destination and source markets.

Stages of Recession While some investments bear the brunt of recessions, others feel the pain only in the later stages, once the recession fully manifests itself. Economic growth slows down further as the initial shock is propagated. Typically, only at the propagation stage of the recession does it become clear that the economy is in fact in recession. We follow Samaniego and Sun (2015) in splitting a recession into two stages: (i) shock, the first period of a recession; and (ii) propagation, the recession periods after the shock. We then estimate Eq.(1) for the shock and propagation stages of recessions separately and report the results in columns 5 and 6 of Table 3.

The coefficient of $R_{d_a} \times R\&D$ is -0.215 and 0.154 in the shock and propagation stages of recessions in destination markets (see columns 5 and 6), which are statistically significant at the 10% level. The difference in the coefficients $R_{d_a} \times R\&D$ between columns 5 and 6 is not statistically significant. Thus, conditional on source markets being in normal states,the drops in R&D-intensive FDI do not concentrate on the propagation stage.

The coefficient of the triple interaction term is 0.360 and is statistically significant in the propagation stage (see column 6) but economically trivial and statistically insignificant in the shock stage (see column 5). This suggests that when the source market falls into a recession the additional increment of R&D-intensive FDI during the destination recession concentrates on the propagation stage. The difference in the coefficient $R_{d_a} \times R_s \times R\&D$ between the propagation (column 6) and shock (column 5) stages of recessions is positive and statistically significant at the 5% level, conditional on source markets being in recessions. The sum of $R_{d_a} \times R\&D$ and $R_{d_a} \times R_s \times R\&D$ in column 6 is 0.324, which is positive and statistically significant at the 5% level. This indicates that source market recessions promote R&D-intensive FDI during the propagation stage of destination market recessions, which provides new evidence in support of the principle of creative destruction.

Concurrence with Banking Crises Some recessions are accompanied by a banking crisis, which further tightens the credit constraints, especially when banks hoard liquidity to protect themselves from unexpected shocks. Hardy and Sever (2020) document evidence that financial crises, in particular banking crises, reduce the number of patents in industries with more credit constraints. To see whether our baseline results on cross-border technology investments are driven by banking crises, we group the destination recessions into two categories: one with and one without banking crises. The estimation results are reported in columns 7 and 8 of Table 3. The coefficient of $R_{d_a} \times R\&D$ in column 8 is -0.177 and is statistically significant at the 5% level, which suggests that even in the absence of banking crises R&D-intensive FDI still falls in response to destination recessions. The coefficient of the triple interaction term is positive and significant when concurrent with banking crisis. Since our sample in this subsection is limited to AM that experienced banking crises concentrated into 2008 and 2009, it is not surprising that the triple coefficient is statistically significant in column 7 when recessions coincide with banking crises in destination markets.

Concurrence with 2007 Great Recession Our sample period includes the 2007 Great Recession, which was accompanied with a large and permanent decline in the share of manufacturing employment. One might be concerned that this could cause endogeneity issues since it could affect the attractiveness of the manufacturing sector for foreign investors. To mitigate this concern, we exclude this episode of Great Recession (years 2007 and 2008) from our sample. Columns 9 of Table 3 shows that our key results remain robust after exculding the Great Recession: R&D-intensive FDI drops when only during destination market is in recession and rebounds when both destination and source markets are in recession. This rules out the possibility that our findings are driven by the Great Recession or sudden decline in the share of manufacturing sector.

3.3.2 Institutions, Regulation, and Finance

Institutions Weak intellectual property protection reduces rents for innovators, which is expected to encourage R&D investments. Weak rule of law (ROL) fails to enforce contracts or punish infringements, which encourages imitation and reduces the interval during which innovators can reap profits from their innovation. Thus cross-border technology investments are expected to drop mainly in destination markets with weak institutions. We divide destination markets into two subgroups- strong and weak intellectual property protection- depending on whether their intellectual property protection (or ROL) is above or below the median value found across all AM. Estimating Eq.(1) for each subsample, we present the results in columns 1 - 4 of Table 4.

[Insert Table 4 here]

We find that the coefficient of $R_{d_a} \times R\&D$ is statistically significant at 5% level in columns 2 and 4, but not in columns 1 and 3. This suggests that R&D-intensive FDI drops during destination market recessions only for the subsample with weak institutions.[20] This is consistent with Fabrizio and Tsolmon (2014), who find that weak intellectual property protection and ROL discourages R&D investment. Thus, conditional on source markets being in normal states, cross-border R&D investment falls during recessions mainly in destination markets with weak institutions.

In terms of the coefficient of the triple interaction term, there is no evidence that this differs between cases of strong and weak intellectual property protection (see columns 1 and 2), or strong and weak ROL (see columns 3 and 4). These results suggest that institutional quality has little additional effect on cross-border R&D investment when both destination and source markets are in recession.

Regulation Loose regulation in destination markets gives MNCs the flexibility to downgrade R&D investments during recessions, but may also attract cross-border investments due to the low cost of entering a market. We measure regulations using the FDI restrictiveness index and the cost of market entry respectively. To understand the roles of FDI regulations in shaping cross-border R&D investment during recessions, we divide destination markets into two subsamples- tight and loose regulation- depending on whether their average FDI restrictiveness index or cost of market entry is above or below the median value of all AM in the sample. The estimation results for each subsample, based on each measure of regulation, are reported in columns 5-8 of Table 4.

The coefficients of $R_{d_a} \times R\&D$ are similar between the tight-regulation subsample (columns 5) and the loose-regulation subsample (column 6). Therefore, we conclude that the response of R&D-intensive FDI to recessions is not concentrated within destination markets with loose regulation. How-

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[20] The coefficient of $R_{d_a} \times R\&D$ is more negative in the weak-institution subsample (column 2) than in the strong-institution subsample (column 1) and the difference is statistically significant at the 10% level, which suggests that R&D-intensive FDI drops more profoundly in response to destination market recessions when intellectual property protection is relatively weak. Similar evidence is found when measuring institutions with ROL.

ever, when regulation on market entry is employed, we find the coefficient of $R_{d_a} \times R\&D$ becomes statistically significant at the 1% level in the loose-regulation subsample (column 8) but remains statistically insignificant in the tight-regulation subsample (column 7).[21]

The coefficient of $R_{d_a} \times R_s \times R\&D$ is statistically significant at the 1% level in both column 6 and 8 , which represent the loose-regulation subsamples. In column 6 for the subsample with loose FDI restriction, the sum of the coefficients of $R_s \times R\&D$ and $R_{d_a} \times R_s \times R\&D$ is 0.28, which is positive and statistically significant at the 5% level. Similar evidence is found in column 8 when measuring the regulation alongside the cost of market entry. It suggests that, conditional on destination markets being in recession, source market recessions boost more R&D-intensive FDI in less regulated destination markets. There is no such evidence in the tight-regulation subsamples (see columns 5 and 7). We argue that loose regulation reduces the cost of investment; which attracts cost-sensitive MNCs that try to concentrate resources on R&D investment during simultaneous recessions in destination and source markets so as to maximize their competitiveness in the next round of economic boom.

Financial Development Higher financial developments enjoy better access to capital in boom periods but also suffer a larger capital contraction when the market busts. All else held the same, recessions more aggressively reduce funding availability in markets with higher financial development. Higher financial development thus exerts greater influence on R&D-intensive FDI that depends highly on financial access for long-run growth (Ilyina and Samaniego 2011). To test whether financial developments increase the sensitivity of R&D-intensive FDI to destination recessions, we divide destination markets into two subsamples according to whether their financial development indicators are above or below the median value of the sample. We measure financial development with (i) credit-to-GDP ratio, and (ii) stock market capitalization as a ratio of GDP. The estimation results based on both indicators are fairly similar, as shown in columns 9-12 of Table 4.

The coefficient of $R_{d_a} \times R\&D$ is -0.272 and is statistically significant at the 1% level in the subsample with high financial development (column 9) but economically trivial and statistically insignificant in the subsample with low financial development (column 10).[22] Similar evidence is found when we measure financial development with stock market capitalization as a ratio of GDP. When only des-

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[21] The coefficients of $R_{d_a} \times R\&D$ prove to be more negative in the loose-regulation subsample (column 8) than in the tight-regulation subsample (column 7) and the difference is statistically significant at the 5% level.

[22] The difference in the coefficient of $R_{d_a} \times R\&D$ between high financial-development subsample (column 9) and low financial-development subsample (column 10) is negative and statistically significant at the 5% level. Similar evidence is found when we measure financial development with stock market capitalization as a ratio of GDP.

tination markets are in recession, R&D-intensive FDI drops during recessions mainly in destination markets with high financial development.

The coefficient of $R_{d_a} \times R_s \times R\&D$ is 0.332 and is statistically significant at the 1% level in the subsample with high financial development (columns 9) but not in the subsample with low financial development (columns 8). The sum of $R_{d_a} \times R\&D$ and $R_{d_a} \times R_s \times R\&D$ in column 9 is close to 0 and statistically insignificant, which means that, conditional on source markets being in recession, cross-border technology investments barely change during recessions in destination markets with high financial development. We document similar evidence when measuring financial development with stock market capitalization as a ratio of GDP (see columns 10 and 11). This suggests that the subsamples with high financial development (columns 9 and 11) are driving the key result that R&D-intensive FDI falls during destination market recessions and rebounds when source markets enter recessions.

3.4 Further analysis and Robustness Checks

3.4.1 The Role of MNC Size

According to Helpman, Melitz, and Yeaple (2004), only the most productive firms participate in FDI, and among those, the most productive firms do most of the FDI. Some destination markets may attract relatively large MNCs disproportionately, leading to diverse response of R&D-intensive FDI to recessions. We explore whether our baseline results are driven by MNC size. Note that large MNCs typically engage in more FDI, we first classify MNCs into two groups according to the median value of their total FDI during our sample. For each source-destination market pair, we then calculate industry-level bilateral FDI from relatively large and relatively small MNCs, and evaluate their responses to recessions separately. The estimation results in Table 5 indicate that large MNCs are driving our baseline results. We find that R&D-intensive FDI from large MNCs but not those from small MNCs drop significantly during destination market recessions. This is intuitive as larger MNCs have greater global network and are more capable of shifting their investments to other markets without recessions. We also find that only R&D-intensive FDI from large MNCs increases in response to simultaneous recessions in source and destination markets, possibly because they are more capable of utilizing the revenues generated from markets that are booming to sustain technology investments in the ideal destinations.

[Insert Table 5 here]

3.4.2 The Role of Gravity

Gravity is a key driver of not only trade but also FDI (Anderson 2011). Our results could be biased if the relationships in FDI are more stable in neighboring countries, or countries in the same trade agreements. We split our sample into two groups according to whether source and destination markets have common borders (Contiguity=1), common offical or primary language (ComLanguage=1), sibling relationship (Sibling=1), or bilateral investment treaty (BIT=1). The estimation results based on the splitted subsamples are reported in Table 6. It appears that our baseline results are mainly driven by source-destination market pairs without common borders, common language, sibling relationship, or BIT. In particular, the coefficients of $R_d \times$R&D are negative while those of $R_d \times R_s \times$R&D are positive and significant in columns 1, 3, 5 and 7 of Table 6 for the subsamples with Contiguity=0, ComLanguage=0, Sibling=0, and BIT=1, but not for the rest (see columns 2, 4, 6 and 8 of Table 6).[23] This suggests that FDI between source and destination markets sharing closer ties is relatively stable and less responsive to recessions.[24]

[Insert Table 6 here]

3.4.3 Alternative Measures of FDI

So far our analysis has been based on the dollar amount of bilateral FDI in any given industry. To check the robustness of our baseline results, we replace FDI in Eq.(1) with alternative measures that include (i) the average project size; (ii) the number of investment projects; (iii) the number of jobs created; and (iv) FDI normalized by destination market GDP. Similar to industry-level FDI used in the main context, all of these measures are aggregated by destination and source markets for each industry in each period. The estimation results are reported in columns 1 to 4 of Table 7. Column 1 shows that the average project size of R&D-intensive FDI drops significantly at the 5% level during destination market recessions and source market normalcy. However the number of R&D-intensive FDI projects does not seem to respond to destination recessions. This suggests that the baseline result that R&D-intensive FDI drops during destination market recessions is mainly driven by the intensive

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[23] The coefficients of $R_d \times R_s \times$R&D are only significant at the 10% level possibly due to the small sample in which simultaneous recessions in source and destination markets are scarce.

[24] All gravity variables are taken from CEPII archive 2021: http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=8

margin (size of project) rather than the extensive margin (number of projects).

Column 3 shows that the number of jobs created by R&D-intensive FDI drops during destination market recessions and rebounds when source markets switch from a normal state to recession. This pattern is consistent with the value of R&D-intensive FDI in the baseline results. In column 4, where the GDP-normalized FDI is the dependent variable, the coefficient of $R_d \times R\&D$ is negative (-0.097) but no longer statistically significant. This suggests that the drop in R&D-intensive FDI documented in the baseline results is proportional to the decline in destination GDP. The coefficients of the triple interaction term remain positive and statistically significant in column 4, which suggests that R&D-intensive FDI as a ratio of GDP increases when both destination and source markets are in recession. However, GDP is used to identify recession. Normalizing FDI by GDP is potentially endogenous, so we should be cautious in how we interpret this.

[Insert Table 7 here]

3.4.4 Alternative Estimation Techniques

Estimating the log linear model such as Eq.(1) with ordinary least square (OLS) is a common practice in the literature. Yet one may remain concerned about the problem of zeros in the dependent variable and the presence of heteroskedasticity, which lead to bias estimation in the coefficients of interest. To address these two issues, we use the Poisson pseudo maximum likelihood estimator (PPML) estimation technique from Silva and Tenreyro (2006) to conduct our analysis again. The estimation result based on PPML is reported in column 1 of Table 8. Consistent with the baseline result based on OLS, the coefficient of $R_d \times$R&D is -0.464 and is statistically significant at the 1% level, while that of $R_d \times R_s \times$R&D is 0.442 and is statistically significant at the 5% level. This delivers the same message that R&D-intensive FDI drops during destination market recessions, and recovers to pre-recession levels when source markets switch from a normal state to recession. We also apply Tobit estimation to deal with the issue of zeros. The Tobit estimation results using log(FDI) and log(1+FDI) as the dependent variables, presented in columns 2 and 3 of Table 8 respectively, yield similar findings to the baseline results based on OLS. Thus, our baseline results are robust when checked against alternative estimation techniques.

[Insert Table 8 here]

4 Conclusion

This paper studies how cross-border technology investments respond to recessions in destination and/or source markets, utilizing the relatively exogeneous industrial variations in technological intensity. Comparing R&D-intensive FDI with R&D light FDI in recessions relative to normal states, we document evidence that R&D-intensive FDI falls during destination market recessions and recovers to pre-recession levels if source markets also fall into recession. These findings are limited to FDI from AM to AM. There is no evidence that R&D-intensive FDI responds to EM recessions. Delving into other aspects of technology, such as the application of robots, ICT, and intellectual property products and TFP related measures, we find limited evidence that cross-border investments in alternative dimensions of technology respond to recessions.

Focusing on the R&D aspect of technology, we further show that our baseline results are mainly driven by cross-border R&D investments in deep and long recessions in destination markets, especially during their propagation stages. In particular, when source markets are in recession, we show that R&D-intensive FDI rises to exceed its pre-recession level in response to deep recessions in destination markets and during the propagation stage of recessions. These findings add new evidence of Schumpeterian creative destruction in the context of cross-border R&D investment.

Moreover, we find that the decline in R&D-intensive FDI during destination recessions and source market normalcy concentrates in destination markets with relatively weak institutions in relation to intellectual property protection and rule of law, loose FDI regulations, and high financial development. However, when both destination and source markets are in recession, R&D-intensive FDI rises profoundly in destination markets with loose regulation and high financial development. It appears that simultaneous recessions exhaust investment opportunities for MNCs, which motivates them to concentrate resources on R&D activities in destinations with business-friendly environments and loose constraints on credit and regulation so as to improve their future competitiveness.

Cross-border technology investments during recessions enhances technology spillovers and economic productivity, which pave the way for economic recovery. Our findings on the hybrid effects of economic recessions on cross-border technology investments have important implications for state-dependent investment decisions and policymaking. First, MNCs may allocate technology investments worldwide to navigate macroeconomic risks and explore opportunities when only some economies are in recession. Second, MNCs engage in creative destruction in the case of a global recession, which enhance long-term economic growth. Third, policymakers in destination markets undergoing recessions may preserve cross-border technology investments from economies that are doing well through tightening regulations on market entry. Fourth, in the case of a global recession, policymakers may instead loosen regulations and improve financial development to attract cross-border technology investments.

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Table 1: Technology FDI in recessions.
The dependent variable is $log(1+FDI_{ds,i,t})$, where $FDI_{ds,i,t}$ is the foreign direct investment (FDI) to destination market d from source market s in industry i at period t. The recession dummy variable R_d (R_s) equates to 1 during the destination (source) market recession and 0 otherwise. *R&D* is the industry-level R&D intensity, calculated as the ratio of R&D expenditure to total capital expenditure. Columns 1 to 4 report the estimation results based on FDI from advanced markets (AM) to AM, AM to emerging markets (EM), EM to AM, and EM to EM, respectively. Source-destination-industry, source-destination-year, and industry-year fixed effects are included in all regressions. Heterogeneity robust standard error clustered by source-destination-industry is reported in the parenthesis. ***, ** and * denotes significance at levels 1%, 5%, and 10%, respectively.

	(1) AM to AM	(2) AM to EM	(3) EM to AM	(4) EM to EM
$R_d \times$R&D	-0.165**	-0.034	-0.037	-0.141
	(0.072)	(0.093)	(0.222)	(0.235)
$R_s \times$R&D	-0.067	0.007	-0.042	0.102
	(0.060)	(0.061)	(0.202)	(0.338)
$R_d \times R_s \times$R&D	0.208**	0.043	-0.217	-0.019
	(0.103)	(0.125)	(0.433)	(0.540)
Constant	3.054***	3.538***	2.653***	3.474***
	(0.008)	(0.008)	(0.022)	(0.017)
Observations	18,970	13,745	1,911	1,684
R-squared	0.452	0.473	0.573	0.543

Table 2: Alternative measures of technology.

The dependent variable is $log(1+FDI_{ds,i,t})$, where $FDI_{ds,i,t}$ is the foreign direct investment (FDI) to destination d from source s in industry i at period t. The recession dummy variable R_d (R_s) equates to 1 during the destination (source) market recessions and 0 otherwise. X_i is the industry-level measure of technology specified in the same row. Detailed description of each technological measure is given in Appendix Table A1. Only FDI among advanced markets is included. Source-destination-industry, source-destination-year, and industry-year fixed effects are included in all regressions. Heterogeneity robust standard error clustered by source-destination-industry is reported in the parenthesis. ***, ** and * denotes significance at levels 1%, 5% and 10%, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Existing Technology			Capital				Input		Labor		TFP
X_i	Robot	ICT	IPP	Investment-specific Technical Change	Investment Lumpiness	Depreciation	Asset Fixity	Intermediate Intensity	Input Specificity	Labor Intensity	Skill Labor	TFP Growth
$R_d \times X_i$	-0.285	-3.982	-0.878	-0.026**	-0.052*	-0.011*	-0.244	-0.161	-0.114**	-0.219	-0.045**	-0.093*
	(0.233)	(3.226)	(0.759)	(0.013)	(0.028)	(0.006)	(0.173)	(0.101)	(0.057)	(0.134)	(0.022)	(0.052)
$R_s \times X_i$	0.180	0.805	0.357	0.001	-0.004	0.002	0.101	0.058	0.011	0.047	0.006	0.016
	(0.233)	(2.932)	(0.691)	(0.011)	(0.023)	(0.005)	(0.149)	(0.087)	(0.050)	(0.114)	(0.020)	(0.045)
$R_d \times R_s \times X_i$	0.139	2.723	0.894	0.014	0.050	0.005	-0.074	0.011	0.046	0.027	0.024	0.033
	(0.384)	(5.040)	(1.182)	(0.042)	(0.042)	(0.009)	(0.257)	(0.153)	(0.087)	(0.204)	(0.034)	(0.079)

Table 3: Heterogeneity across different types of recession.
The dependent variable is $log(1+FDI_{ds,i,t})$, where $FDI_{ds,i,t}$ is the foreign direct investment (FDI) to destination d from source s in industry i at period t. The dummy variable R_{d_a} takes the value of 1 during the particular type of recession specified in the top rows. The dummy variable R_s equates to 1 during the source market recessions and 0 otherwise. *R&D* is the industry-level R&D intensity, calculated as the ratio of R&D expenditure to the total capital expenditure. The sample includes FDI between advanced markets only. Source-destination-industry, source-destination-year, and industry-year fixed effects are included in all regressions. Heterogeneity robust standard error clustered by source-destination-industry is reported in the parenthesis. ***, ** and * denotes significance at levels 1%, 5% and 10%, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Depth of Recession		Duration of Recession		Stages of Recession		Concurrence with Banking Crisis		Exclude Great Recession
R_{d_a}	Deep	Moderate	Long	Short	Shock	Propagation	Yes	No	
$R_{d_a}\times$R&D	-0.138	-0.232*	-0.187**	0.009	-0.215*	-0.154*	-0.127	-0.177**	-0.171**
	(0.085)	(0.120)	(0.080)	(0.192)	(0.125)	(0.083)	(0.115)	(0.079)	(0.083)
$R_s\times$R&D	-0.064	-0.069	-0.044	-0.094	-0.070	-0.036	-0.056	-0.046	-0.082
	(0.076)	(0.114)	(0.072)	(0.128)	(0.087)	(0.082)	(0.063)	(0.062)	(0.072)
$R_{d_a}\times R_s\times$R&D	0.327**	0.196	0.202*	0.216	0.050	0.360***	0.312**	0.156	0.332**
	(0.148)	(0.152)	(0.116)	(0.349)	(0.162)	(0.128)	(0.141)	(0.119)	(0.143)
Observations	16,345	15,882	17,640	13,914	14,876	16,957	16,992	17,205	16,381
R-squared	0.466	0.469	0.460	0.483	0.477	0.464	0.461	0.462	0.465

Table 4: Heterogeneity across institutions, regulation, and financial development.
The dependent variable is $log(1+FDI_{ds,i,t})$, where $FDI_{ds,i,t}$ is the foreign direct investment (FDI) to destination d from source s in industry i in period t. The recession dummy variable R_d (R_s) equates to 1 during the destination (source) market recession and 0 otherwise. *R&D* is the industry-level R&D intensity, calculated as the ratio of R&D expenditure to total capital expenditure. The sample is divided into two subgroups depending on whether the destination market's average institutional quality, regulation strictness, and financial development is above the sample median. The sample includes FDI between advanced markets only. Source-destination-industry, source-destination-year, and industry-year fixed effects are included in all regressions. Heterogeneity robust standard error clustered by source-destination-industry is reported in the parenthesis. ***, ** and * denotes significance level at 1%, 5% and 10%, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Institution				Regulation				Financial Development			
	Intellectual Property Protection		Rule of Law		FDI Restrictiveness		Market Entry		Credit/GDP		Market Capitalization/GDP	
	Strong	Weak	Strong	Weak	Tight	Loose	Tight	Loose	High	Low	High	Low
R_d×R&D	0.002	-0.236**	0.028	-0.223**	-0.139	-0.159*	0.015	-0.320***	-0.272***	0.016	-0.374***	0.062
	(0.090)	(0.095)	(0.092)	(0.094)	(0.108)	(0.084)	(0.088)	(0.107)	(0.090)	(0.092)	(0.104)	(0.087)
R_s×R&D	-0.157**	0.127	-0.127*	0.079	-0.037	-0.061	-0.016	-0.138*	-0.108	-0.008	-0.186**	0.072
	(0.068)	(0.103)	(0.072)	(0.095)	(0.085)	(0.080)	(0.097)	(0.073)	(0.082)	(0.082)	(0.073)	(0.092)
$R_d \times R_s$×R&D	0.204*	0.281*	0.189	0.268*	0.066	0.343**	0.001	0.433***	0.332**	0.050	0.473***	-0.074
	(0.121)	(0.168)	(0.127)	(0.153)	(0.136)	(0.135)	(0.165)	(0.123)	(0.130)	(0.144)	(0.129)	(0.145)

Table 5: FDI from small versus large MNCs.

This table summarize how cross-border technology investments from relatively large and small MNCs respond to recessions. The recession dummy variable R_d (R_s) equates to 1 during the destination (source) market recession and 0 otherwise. R&D is the industry-specific R&D intensity, measured by the average R&D expenditure as a ratio of the total capital spending. Source-destination-industry, source-destination-year, and industry-year fixed effects are included in all regressions. Heterogeneity robust standard error clustered by source-destination-industry is reported in the parenthesis. ***, ** and * denotes significance level at 1%, 5% and 10%, respectively.

	(1) Large MNCs	(2) Small MNCs
$R_d \times$R&D	-0.184**	-0.043
	(0.076)	(0.088)
$R_s \times$R&D	-0.073	0.048
	(0.069)	(0.063)
$R_d \times R_s \times$R&D	0.195*	-0.059
	(0.116)	(0.109)
Observations	15,849	4,651

Table 6: The role of gravity.

This table summarizes how the response of cross-border technology investments to recessions vary with different gravity terms. The dependent variable is $log(1+FDI_{ds,i,t})$, where $FDI_{ds,i,t}$ is the foreign direct investment (FDI) to destination d from source s in industry i in period t. The sample is splitted into two according to whether source and destination markets have common borders (Contiguity=1), common official or primary language (ComLanguage=1), sibling relationship (Sibling=1), and bilateral investment treaty (BIT=1). The recession dummy variable R_d (R_s) equals 1 during the destination (source) market recession and 0 otherwise. R&D is the industry-specific R&D intensity, measured by the average R&D expenditure as a ratio of total capital spending. Only FDI between advanced markets is included. Source-destination-industry, source-destination-year, and industry-year fixed effects are included in all regressions. Heterogeneity robust standard error clustered by source-destination-industry is reported in the parenthesis. ***, ** and * denotes significance level at 1%, 5% and 10%, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Contiguity=0	Contiguity=1	ComLanguage=0	ComLanguage=1	Sibling=0	Sibling=1	BIT=0	BIT=1
$R_d \times$R&D	-0.169**	-0.090	-0.215***	0.207	-0.183**	0.189	-0.205**	0.052
	(0.078)	(0.199)	(0.073)	(0.173)	(0.072)	(0.342)	(0.095)	(0.165)
$R_s \times$R&D	-0.059	-0.143	-0.086	0.056	-0.082	0.080	-0.106	0.040
	(0.067)	(0.138)	(0.066)	(0.137)	(0.061)	(0.269)	(0.079)	(0.155)
$R_d \times R_s \times$R&D	0.186*	0.287	0.205*	0.123	0.199*	0.341	0.251*	-0.123
	(0.112)	(0.285)	(0.115)	(0.209)	(0.106)	(0.397)	(0.137)	(0.269)
Observations	15,280	3,649	15,403	3,512	18,132	743	15,029	4,131

Table 7: Alternative measures of FDI.
The recession dummy variable R_d (R_s) equates to 1 during the destination (source) market recession and 0 otherwise. R&D is the industry-specific R&D intensity, measured by the average R&D expenditure as a ratio of the total capital spending. The dependent variables in columns 1 to 4 are respectively (1) project size, measured by the log of 1 plus the average project size; (2) project number, the log of 1 plus the total number of FDI projects; (3) job number, the log of 1 plus the total number of jobs created by FDI; and (4) FDI/GDP, the log of 1 plus FDI normalized by destination market GDP. Only FDI between advanced markets is included. Source-destination-industry, source-destination-year, and industry-year fixed effects are included in all regressions. Heterogeneity robust standard error clustered by source-destination-industry is reported in the parenthesis. ***, ** and * denotes significance level at 1%, 5% and 10%, respectively.

	(1) Project Size	(2) Project Number	(3) Job Number	(4) FDI/GDP
R_d×R&D	-0.119**	-0.032	-0.145**	-0.097
	(0.058)	(0.020)	(0.068)	(0.075)
R_s×R&D	-0.040	-0.021	-0.046	-0.064
	(0.052)	(0.016)	(0.053)	(0.061)
$R_d \times R_s$×R&D	0.142*	0.045	0.214**	0.216**
	(0.086)	(0.029)	(0.093)	(0.107)
Observations	18,970	18,970	18,970	18,970
R-squared	0.416	0.559	0.490	0.872

Table 8: Alternative estimation techniques
The recession dummy variable R_d (R_s) equates to 1 during the destination (source) market recession and 0 otherwise. R&D is the industry-specific R&D intensity, measured by the average R&D expenditure as a ratio of total capital spending. The estimation technique in column 1 is the Poisson pseudo maximum likelihood estimator (PPML), while that in columns 2 and 3 is the Tobit estimator. The dependent variables in columns 1 to 3 are FDI, log (1+FDI), and log (FDI) respectively. Only FDI between advanced markets is included. Source-destination-industry, source-destination-year, and industry-year fixed effects are included in all regressions. Heterogeneity robust standard error clustered by source-destination-industry is reported in the parenthesis. ***, ** and * denotes significance level at 1%, 5% and 10%, respectively.

	(1)	(2)	(3)
Estimator	PPML	Tobit	
Dependent variable	FDI	log (1+FDI)	log (FDI)
R_d×R&D	-0.464***	-0.335 ***	-0.389 ***
	(0.157)	(0.057)	(0.067)
R_s×R&D	-0.193	-0.191 ***	-0.216***
	(0.130)	(0.052)	(0.061)
$R_d \times R_s$×R&D	0.442**	0.432 ***	0.465***
	(0.185)	(0.087)	(0.103)
Observations	20,332	20,332	20,312

Appendix Table A1: Variable Definitions

Name	Definition	Source
$FDI_{ds,i,t}$	FDI from source s to destination d in industry i at period t	fDi Markets
R&D intensity	The ratio of R&D expenditure to total capital expenditure	Compustat
R_d	Dummy variable that equates to 1 during destination market recession	WDI, author calculation
R_s	Dummy variable equates to 1 during source market recession	WDI, author calculation
IPP	Intellectual property protection rights enforcement index	Property Rights Alliance
ROL	Rules of society, the quality of contract enforcement, property rights and laws	WGI
FDI restrictiveness index	Foreign equity limitations, screening or approval mechanisms, restrictions on the employment of foreigners and operational restrictions	OECD
Foreign entry	Entry costs paid as a share of income per capita	Doing Business
Financial Development	1. Credit-to-GDP ratio 2. Stock market capitalization as a ratio of GDP	WDI
Robot	The number of robots used in a sector divided by the total robots in the manufacturing industry	IFR
ICT	the ratio of capital expenditure on ICT equipment to total assets	EU KLEMS
Intellectual property products	the ratio of expenditure on intellectual property equipment to total assets	EU KLEMS
Investment-specific technical change	The rate of decline in the price of capital goods relative to the price of consumption and services	BEA
Investment lumpiness	Average number of investment spikes in any given industry	Compustat
Depreciation	The industry rate of capital depreciation	BEA
Asset fixity	The ratio of fixed assets to total assets	Compustat
Intermediate intensity	The difference between gross output and value added divided by gross output	UNIDO
Input specificity	The proportion of inputs that are not sold on an organized exchange or reference-priced in a trade publication	Nunn (2007)
Labor intensity	Total wages and salaries divided by the total value added	UNIDO
Skilled labor	Average wage bill, i.e., the ratio of wages over total number of employees	UNIDO
TFP growth	Growth in the technology component of Cobb-Douglas production function.	NBER, author calculation
Contiguity	A dummy that equals 1 if source and destination markets share common borders	CEPII
ComLanguage	A dummy that equals 1 if source and destination markets share common offical or primary language	CEPII
Sibling	A dummy that equals 1 if source and destination markets are currently in sibling relationship	CEPII
BIT	A dummy that equals 1 if source and destination markets have established bilateral investment treaty	CEPII

Appendix Table A2: List of Destination and Source Markets

Source Markets				Destination Markets			
Advance Markets		Emerging Markets		Advance Markets		Emerging Markets	
ISO	N	ISO	N	ISO	N	ISO	N
AUS	542	ARG	35	AUS	708	ARG	386
AUT	1,030	BGD	5	AUT	340	BGD	75
BEL	716	BGR	13	BEL	688	BGR	396
CAN	1,087	BRA	289	CAN	768	BRA	1,214
CHE	2,013	CHL	64	CHE	334	CHL	238
CHL	64	CHN	1,769	CHL	238	CHN	2,979
CZE	136	COL	26	CZE	621	COL	326
DEU	4,244	HUN	63	DEU	2,239	HUN	716
DNK	954	IDN	33	DNK	289	IDN	598
ESP	1,532	IND	1,064	ESP	1,137	IND	1,871
EST	46	MEX	217	EST	133	MEX	1,204
FIN	936	MYS	295	FIN	307	MYS	741
FRA	2,678	PAK	12	FRA	1,564	PAK	112
GBR	2,598	PER	6	GBR	1,897	PER	157
GRC	131	PHL	34	GRC	62	PHL	368
HUN	63	POL	185	HUN	716	POL	1,263
IRL	355	RUS	476	IRL	293	ROU	831
ISL	13	THA	220	ISL	5	RUS	1,565
ISR	242	TUR	412	ISR	89	THA	851
ITA	1,781	UKR	75	ITA	521	TUR	677
JPN	3,705	VEN	13	JPN	553	UKR	317
KOR	1,193	ZAF	168	KOR	528	VEN	35
LTU	45			LTU	231	ZAF	455
LUX	307			LUX	30		
LVA	9			LVA	106		
MEX	217			MEX	1,204		
NLD	1,593			NLD	659		
NOR	442			NOR	96		
NZL	124			NZL	135		
POL	185			POL	1,263		
PRT	154			PRT	202		
SVN	81			SVK	457		
SWE	1,430			SVN	68		
TUR	412			SWE	294		
USA	6,144			TUR	677		
				USA	3,400		

Appendix Table A3: Measures of technological characteristics

Industry	ISIC code	R&D	Robots (%)	ICT (%)	Investment-specific Technical Change	Investment lumpiness	Depreciation	Asset fixity	Intermediate intensity	Input specificity	Labor Intensity	Skilled labor	TFP Growth
Apparel	322	0.020	0.05	2.46	4.369	1.998	6.437	0.134	0.493	0.975	0.447	1.084	0.991
Wood products	331	0.032	0.05	1.53	3.926	1.720	9.525	0.305	0.596	0.670	0.467	1.624	0.996
Beverages	313	0.039	4.39	1.23	3.975	1.290	7.090	0.372	0.549	0.949	0.248	2.378	1.008
Petroleum refineries	353	0.057		0.91	3.923	0.763	6.776	0.591	0.833	0.759	0.173	3.450	0.984
Iron and steel	371	0.066	2.12	1.34	3.442	0.951	6.578	0.427	0.578	0.816	0.477	2.691	1.012
Food products	311	0.073	4.39	1.23	3.948	1.195	7.090	0.373	0.658	0.557	0.281	1.780	1.002
Paper and products	341	0.083	0.11	1.53	3.250	0.902	8.632	0.472	0.551	0.885	0.363	2.406	0.999
Other non-met. Min. prod.	369	0.095		1.25	4.754	0.990	8.234	0.480	0.478	0.963	0.385	2.072	0.992
Printing and publishing	342	0.100		1.53	4.410	1.670	9.745	0.261	0.350	0.995	0.407	1.969	0.978
Non-ferrous metals	372	0.101	2.12	1.34	3.431	1.245	5.393	0.364	0.681	0.460	0.424	2.373	1.008
Glass and products	362	0.115		1.25	4.379	1.755	7.554	0.400	0.409	0.967	0.399	2.189	1.011
Textiles	321	0.144	0.05	2.46	3.914	1.232	7.665	0.345	0.586	0.820	0.458	1.463	1.002
Fabricated metal products	381	0.147	6.04	1.34	3.421	1.365	7.043	0.274	0.488	0.945	0.455	2.025	1.004
Footwear	324	0.153		2.46	4.056	2.239	8.325	0.160	0.483	0.934	0.446	1.156	0.997
Furniture, except metal	332	0.155	0.05	1.53	4.045	1.381	8.312	0.280	0.484	0.910	0.488	1.555	1.005
Plastic products	356	0.171	8.30	1.25	3.204	1.557	10.072	0.374	0.494	0.985	0.402	1.808	1.005
Misc. pet. and coal products	354	0.186		0.91	3.996	1.042	6.776	0.372	0.648	0.895	0.300	2.395	0.982
Rubber products	355	0.187	6.05	1.25	3.144	1.098	10.072	0.322	0.482	0.923	0.423	2.139	1.015
Leather	323	0.198		2.46	4.008	1.927	9.266	0.135	0.550	0.848	0.444	1.439	1.006
Tobacco	314	0.222		1.23	3.975	0.815	5.248	0.189	0.357	0.483	0.117	2.648	0.980
Industrial chemicals	351	0.269		0.85	4.595	1.340	9.646	0.381	0.558	0.884	0.241	2.921	1.009
Other manufactured prod.	390	0.302	3.18	1.67	2.996	2.006	10.070	0.186	0.460	0.863	0.414	1.640	0.997
Transport equipment	384	0.316	49.67	1.04	3.847	1.614	10.559	0.264	0.598	0.985	0.440	2.815	1.003
Pottery, china, earthenware	361	0.503		1.25	4.603	1.292	8.234	0.400	0.311	0.946	0.475	1.733	0.999
Machinery, electric	383	0.814	18.70	2.42	4.313	2.704	9.381	0.208	0.443	0.960	0.407	2.268	1.044
Machinery, except electrical	382	0.933	1.15	1.96	5.149	2.694	8.832	0.195	0.479	0.975	0.433	2.389	1.031
Prof. & sci. equip.	385	1.194	0.13	1.68	4.456	2.790	9.210	0.181	0.344	0.981	0.382	2.550	0.997
Other chemicals	352	1.951	0.07	0.85	4.683	2.130	6.888	0.207	0.393	0.946	0.218	2.568	1.003

Appendix Table A4: Deep and long recessions

Country	Deep recession	Moderate recession	Long recession	Short recession
AUT	2003,2009, 2010	2008	2003	2008-2010
BEL	2003,2009	2007,2008	2003	2007-2009
CAN	2009	2007,2008		2007-2009
CHE	2003,2009	2008	2003	2008-2009
CHL	2009	2007,2008		2007-2009
DEU	2004,2005,2009	2008		2004-2005, 2008-2009
DNK	2003 ,2009	2007, 2008	2003	2007-2009
ESP	2012,2013	2011, 2014	2011-2014	
EST	2009,2010	2007,2008	2007-2010	
FIN	2009	2008		2008-2009
FRA	2003, 2009	2007, 2008	2003	2007-2009
GBR	2009	2007, 2008		2007-2009
GRC	2005, 2011, 2012 ,2013	2004, 2008,2009,2010	2008-2013	2004-2005
HUN	2009,2010, 2012	2008, 2011	2008-2012	
IRL	2003, 2009-2013	2007, 2008, 2014	2003, 2007-2014	
ISL	2003, 2019, 2010	2008	2003	2008-2010
ISR	2003		2003	
ITA	2009, 2012, 2013	2007, 2008, 2011		2007-2009, 2011-2013
JPN	2009	2007, 2008		2007-2009
KOR	2009	2007, 2008		2007-2009
LTU	2009, 2010	2008		2008-2010
LUX	2009	2007, 2008		2007-2009
LVA	2009, 2010	2007, 2008	2007-2010	
MEX	2003,2009	2007, 2008	2003	2007-2009
NLD	2003-2005, 2009	2008	2003-2005	2008-2009
NOR	2003, 2009-2011	2007, 2008	2003	2007-2010
PRT	2012, 2013	2010, 2011		2010-2013
SVK	2009	2008	2008-2009	
SVN	2009, 2012, 2013	2008, 2011		2008-2009, 2011-2013
SWE	2003, 2009,	2007, 2008	2003	2007-2009
TUR	2003,2009,2010	2007, 2008	2003, 2007-2010	
USA	2009	2007, 2008		2007-2009

Appendix Table A5: Correlation of R&D intensity over time.
This table reports the Pearson's correlation coefficients of industry-level R&D intensity based on US firms in different decades. ** denotes significance level at 5%.

	R&D in 1970s	R&D in 1980s	R&D in 1990s	R&D in 2000s
R&D in 1980s	0.9567**			
R&D in 1990s	0.9481**	0.976**		
R&D in 2000s	0.8775**	0.893**	0.8850**	
R&D in 2010s	0.7909**	0.8243**	0.8290**	0.8770**

Appendix Table A6: Correlation between R&D intensity across countries in KLEMS.
The table reports the Pearson's correlation coefficients of industry-level R&D intensity among different countries. ** denotes significance level at 5%.

	AUT	CZE	DNK	FIN	FRA	GBR	HUN	ITA	JPN	LVA	NLD	PRT	SVK	SWE
CZE	0.694**													
DNK	0.792**	0.615**												
FIN	0.865**	0.693**	0.883**											
FRA	0.809**	0.857**	0.697**	0.766**										
GBR	0.835**	0.857**	0.830**	0.863**	0.879**									
HUN	0.596**	0.902**	0.651**	0.771**	0.826**	0.854**								
ITA	0.894**	0.766**	0.717**	0.835**	0.820**	0.861* *	0.691**							
JPN	0.853**	0.590**	0.878**	0.745**	0.749**	0.805**	0.471	0.776**						
LVA	0.726**	0.589**	0.814**	0.849**	0.771**	0.747**	0.775**	0.638* *	0.585**					
NLD	0.904**	0.676* *	0.828**	0.894**	0.844**	0.877**	0.681**	0.832**	0.837* *	0.762**				
PRT	0.518**	0.803**	0.695**	0.731**	0.734**	0.758**	0.946**	0.573**	0.421	0.836**	0.585**			
SVK	0.597**	0.573**	0.682**	0.453	0.572**	0.573**	0.407	0.365	0.731**	0.473	0.488**	0.450		
SWE	0.969**	0.772**	0.8432**	0.826**	0.765**	0.886**	0.881**	0.864**	0.922**	0.719**	0.866**	0.820**	0.684**	
USA	0.735**	0.615**	0.834**	0.716**	0.750**	0.794**	0.678**	0.684**	0.944**	0.559**	0.722**	0.621**	0.707**	0.814**