Export-Led Takeoff in a Schumpeterian Economy

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Abstract

This study develops an open-economy Schumpeterian growth model with endogenous takeoff to explore the effects of exports on the transition of an economy from stagnation to innovation-driven growth. We find that a higher export demand raises the level of employment, which causes a larger market size and an earlier takeoff along with a higher transitional growth rate of domestic output per capita but has no effect on long-run economic growth. These theoretical results are consistent with empirical evidence that we document using cross-country panel data in which the positive effect of exports on economic growth becomes smaller, as countries become more developed, and eventually disappears. We also calibrate the model to data in China and find that its export share increasing from 4.6% in 1978 to 36% in 2006 causes a rapid growth acceleration, but the fall in exports after 2007 causes a growth deceleration that continues until recent times.

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"Globalisation brought much of Asia out of extreme poverty." The Economist (2009)[1]

1 Introduction

In the 20th century, many Asian economies started to develop rapidly via export-led growth. It was first Japan in the early 20th century and then the so-called "tiger economies" (Hong Kong, Singapore, South Korea, and Taiwan) in the 1960's. At the end of the 1970's, China also opened up its economy and started to grow rapidly. More recently, the 21st century witnesses the rise of the "tiger cub economies" (Indonesia, Malaysia, the Philippines, Thailand, and Vietnam). How does international trade affect the endogenous transition of an economy from stagnation to economic growth? To explore this question, this study develops an open-economy Schumpeterian growth model with endogenous takeoff. In summary, we find that an increase in export demand gives rise to an earlier takeoff of the local economy and a higher transitional growth rate of domestic output per capita; however, it does not affect long-run economic growth.

The intuition of the above results can be explained as follows. An increase in export demand raises the level of employment in the local economy. The resulting larger market size of the economy either gives rise to an earlier takeoff or even triggers an immediate takeoff by activating innovation in the local economy.[2] Intuitively, the larger market size increases firm size in the short run, which improves incentives for innovation and raises the transitional growth rate of domestic output per capita. In the long run, the entry of firms causes firm size to converge to a steady-state equilibrium level that does not depend on the level of employment. As a result, export demand does not affect the steady-state equilibrium growth rate. These theoretical results are consistent with empirical evidence that we document using cross-country panel data. In our empirical analysis, we indeed find that the positive effect of exports on economic growth becomes smaller, as countries become more developed, and eventually disappears.

We also explore the quantitative implications of exports on the takeoff of an economy. We first derive a formula for the derivative of the takeoff time with respect to the export share and find that the magnitude of the effect of exports on takeoff is decreasing in the population growth rate and the degree of labor intensity in production but increasing in the level of labor and the preference parameter for leisure. Then, we calibrate the model to data in China and find that an increase in the export share by 0.1 triggers an earlier transition to innovation-driven growth by over a decade. Furthermore, the export share of the Chinese economy increasing from 4.6% in 1978 to 36% in 2006 causes a rapid growth acceleration, but the fall in exports after 2007 causes a growth deceleration that continues until recent times.

This study relates to the literature on innovation and economic growth. In this literature, Romer (1990) is the seminal study that develops the R&D-based growth model with the invention of new products. Then, another seminal study by Aghion and Howitt (1992) develops the Schumpeterian growth model that features the quality improvement of products; see also Grossman and Helpman (1991a) and Segerstrom *et al.* (1990) for other early studies. Subsequent studies combine these two dimensions of innovation to develop the Schumpeterian growth model with endogenous market structure;[3] see Peretto (1998, 1999) and Smulders and van de

[1] https://www.economist.com/asia/2009/03/25/the-export-trap

[2] Examining data in the four tiger economies plus China and also India, Ang and Madsen (2011) find that innovation plays a key role for economic growth in these Asian economies.

[3] See Laincz and Peretto (2006), Ha and Howitt (2007) and Madsen (2008, 2010) for empirical evidence that

Klundert (1995) for the variant with creative accumulation and Howitt (1999) for the variant with creative destruction.[4] Our study contributes to this literature by developing an open-economy version of the Schumpeterian model with endogenous market structure to explore the effects of international trade on the complete transition dynamics of economic growth.

This study also relates to the literature on international trade and innovation-driven growth. Early studies by Grossman and Helpman (1990) and Rivera-Batiz and Romer (1991a, b) develop two-country versions of the Romer model, whereas Grossman and Helpman (1991b) develop a small-open-economy version; see Grossman and Helpman (1991c) for a textbook treatment of this literature. All these studies belong to the first-generation R&D-based growth model in which the long-run growth rate exhibits a counterfactual scale effect.[5] Peretto (2003) develops a multi-country Schumpeterian growth model with endogenous market structure that removes the scale effect. Subsequent studies apply the open-economy Schumpeterian growth model to explore various issues, such as the cross-country effects of R&D subsidies in Impullitti (2010), the cross-country effects of changes in the resource endowment in Peretto and Valente (2011) and the interaction between comparative advantage in Ricardian trade and innovation-driven growth in Ji and Seater (2020). This study contributes to this literature by developing a small-open-economy version of the Schumpeterian growth model with endogenous market structure and endogenous takeoff to explore the effects of international trade on endogenous takeoff.

Finally, this study relates to the literature on endogenous takeoff and economic growth. The seminal study by Galor and Weil (2000) develops unified growth theory that explores the endogenous transition of an economy from stagnation to economic growth;[6] see Galor and Moav (2002), Galor and Mountford (2008), Galor *et al.* (2009) and Ashraf and Galor (2011) for subsequent studies and empirical evidence that supports the theory and Galor (2005, 2011) for a comprehensive review of unified growth theory. A recent branch of this literature examines the transition from stagnation to innovation-driven growth. Peretto (2015) develops a closed-economy Schumpeterian growth model with endogenous takeoff. Subsequent studies by Iacopetta and Peretto (2021), Chu, Fan and Wang (2020), Chu, Kou and Wang (2020), Chu, Furukawa and Wang (2022) and Chu, Peretto and Wang (2022) explore different mechanisms, such as corporate governance, status-seeking culture, intellectual property rights, rent-seeking government and agricultural revolution, that affect endogenous takeoff in the Schumpeterian economy. This study contributes to this literature by developing an open-economy version of the Peretto model to explore the effects of international trade on the transition of the economy from pre-industrial stagnation to innovation-driven growth.

The rest of this study is organized as follows. Section 2 documents some stylized facts. Section 3 develops the model. Section 4 presents our theoretical and quantitative results. Section 5 explores an extension of the model with an agricultural sector. Section 6 concludes.

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supports this class of the Schumpeterian growth model.

[4] A recent study by Garcia-Macia *et al.* (2019) shows that innovation is mostly driven by quality improvement from incumbents (i.e., creative accumulation).

[5] See Jones (1999) and Laincz and Peretto (2006) for a discussion of the scale effect.

[6] See also Hansen and Prescott (2002) and Kalemli-Ozcan (2002) for other early studies on endogenous takeoff.

2 Stylized facts

In this section, we document an empirical relationship between exports and economic growth.[7] To do this, we use the following regression specification:

$$g_{it} = \kappa_1 Export_{it} + \kappa_2 Export_{it} \times y_{it} + \kappa_3 y_{it} + \Phi_{it} + \zeta_i + \zeta_t + \epsilon_{it},$$

where g_{it} denotes the growth rate of real GDP, real GDP per capita or real GDP per worker in country i at time t. $Export_{it}$ is the ratio of exports to GDP, whereas y_{it} is the initial level of income at time t measured by the log of real GDP per capita. Our theory predicts that $\kappa_1 > 0$ and $\kappa_2 < 0$. In other words, exports have a positive relationship with economic growth, but this positive effect becomes smaller as the economy becomes more developed. Our theory also predicts that this positive effect eventually disappears and becomes insignificant as y_{it} becomes large enough.

Φ_{it} denotes the following set of control variables: the log level of population, R&D intensity (i.e., the ratio of R&D expenditures to GDP), the ratio of imports to GDP, the real interest rate, and the capital depreciation rate. The variables ζ_i and ζ_t denote country fixed effects and time fixed effects, respectively. Finally, ϵ_{it} is the error term.

Given the cyclical fluctuations in annual data that may bias our estimation, we consider ten years as a period to remove these fluctuations in the data.[8] In this case, we have a sample of up to 561 observations covering 203 countries for the period 1991-2020 after merging data from the Penn World Table and the World Bank Data. We provide the summary statistics of our data in Appendix A.

In Table 1, the dependent variable in columns (1)-(2) is the average annual growth rate of real GDP. The dependent variable in columns (3)-(4) is the average annual growth rate of real GDP per capita. The dependent variable in columns (5)-(6) is the average annual growth rate of real GDP per worker. In all columns, the regression coefficient κ_1 on exports is significantly positive, whereas the regression coefficient κ_2 on the interaction term between exports and the income level is significantly negative.

For example, in column (4), the estimated coefficient on exports is 0.3110, which is statistically significant at the 5% level, whereas the estimated coefficient on the interaction term is -0.0247, which is also statistically significant at the 5% level. These results suggest that exports have a positive relationship with economic growth. However, this positive relationship becomes weaker as the economy becomes more developed. Specifically, for a country with minimal GDP per capita, increasing exports by 1% is associated with an increase in the growth rate by 0.1584% ($0.3110 - 0.0247 \times 6.1777$), which is statistically significant at the 1% level. For a country with average GDP per capita, increasing exports by 1% is associated with an increase in the growth rate by 0.0866% ($0.3110 - 0.0247 \times 9.0844$), which is statistically significant at the 5% level. For a country with maximal GDP per capita, increasing exports by 1% is associated with an increase in the growth rate by 0.0183% ($0.3110 - 0.0247 \times 11.8517$), but it is not statistically significant with a p-value of 0.66.[9] Therefore, the positive effect of exports on economic growth becomes smaller, as the level of income rises, and eventually disappears.

[7] See Sachs and Warner (1995), Edwards (1998) and Frankel and Romer (1999) for empirical studies that also find a positive relationship between international trade and economic growth.

[8] We also consider five years as a period. In this case, most of the estimated coefficients remain significant at least at the 5% level; see Appendix A.

[9] This insignificant effect at maximal GDP per capita also applies to other columns with control variables.

Table 1: Effects of exports on economic growth

	GDP growth		per capita GDP growth		per worker GDP growth	
	(1)	(2)	(3)	(4)	(5)	(6)
$Export_{it}$	0.2059***	0.3315**	0.2168***	0.3110**	0.2000***	0.3246**
	(0.0756)	(0.1348)	(0.0696)	(0.1288)	(0.0705)	(0.1328)
$Export_{it} \times y_{it}$	-0.0201***	-0.0258**	-0.0211***	-0.0247**	-0.0211***	-0.0284**
	(0.0075)	(0.0129)	(0.0069)	(0.0123)	(0.0070)	(0.0127)
y_{it}	-0.0544***	-0.0591***	-0.0538***	-0.0580***	-0.0556***	-0.0437***
	(0.0059)	(0.0101)	(0.0054)	(0.0097)	(0.0055)	(0.0100)
Control variables		✓		✓		✓
Country fixed effects	✓	✓	✓	✓	✓	✓
Time fixed effects	✓	✓	✓	✓	✓	✓
Observations	561	190	561	190	532	188
R^2	0.6241	0.7928	0.6388	0.7967	0.6497	0.7863

*Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Standard errors in parentheses.*

3 An open-economy Schumpeterian growth model

The Schumpeterian growth model with endogenous takeoff is based on Peretto (2015). The model features both the development of new products and the quality improvement of products. The combination of these two dimensions of innovation gives rise to endogenous market structure that removes the scale effect from the Schumpeterian model. We convert the closed-economy model in Peretto (2015) into a small-open-economy version as in Grossman and Helpman (1991b). This open-economy extension preserves the tractability of the Peretto model and enables us to derive the complete transition dynamics of the economy from pre-industrial stagnation to long-run economic growth in the modern economy.

3.1 Household

In the local economy, there is a representative household, which has the following utility function:

$$U = \int_0^\infty e^{-(\rho-\lambda)t} \left[\ln c_t + \delta \ln(1 - l_t) + \psi \frac{(\iota_t)^{1-\varepsilon}}{1-\varepsilon} \right] dt,$$

where $\varepsilon \in [0, 1)$. The parameter $\rho > 0$ is the subjective discount rate, and $\psi > 0$ is a preference parameter for ι_t, which is the per capita consumption of an imported good. c_t is the per capita consumption of a domestically produced final good, which is also the numeraire. $\delta > 0$ is a preference parameter for leisure $1 - l_t$, in which l_t is the supply of labor per household member. Finally, the parameter $\lambda \in (0, \rho)$ is the growth rate of the population size $L_t = L_0 e^{\lambda t}$.

The asset-accumulation equation is

$$\dot{a}_t = (r_t - \lambda)a_t + w_t l_t - c_t - p_t \iota_t, \tag{1}$$

where a_t is the value of assets per household member, and r_t is the real interest rate in the local economy.[10] Each household member supplies l_t units of labor to earn wage w_t. Finally, p_t is the price of the imported good relative to the domestic final good.

Dynamic optimization yields the familiar path of domestic consumption given by

$$\frac{\dot{c}_t}{c_t} = r_t - \rho. \tag{2}$$

The relative demand for consumption is

$$p_t = \frac{\psi c_t}{(\iota_t)^{\varepsilon}}, \tag{3}$$

and the supply of labor is

$$l_t = 1 - \frac{\delta c_t}{w_t}. \tag{4}$$

3.2 Domestic final good

Final good Y_t is produced by competitive domestic firms. The production function is

$$Y_t = \int_0^{N_t} X_t^{\theta}(i)[Z_t^{\alpha}(i)Z_t^{1-\alpha}L_{y,t}/N_t^{1-\sigma}]^{1-\theta}di, \tag{5}$$

where $\{\theta, \alpha, \sigma\} \in (0,1)$. There is a variety of N_t differentiated intermediate goods at time t. The quantity of each differentiated intermediate good $i \in [0, N_t]$ is denoted by $X_t(i)$, whose quality level is denoted by $Z_t(i)$. The average quality across intermediate goods is $Z_t \equiv \frac{1}{N_t}\int_0^{N_t} Z_t(i)di$, and the parameter α determines the degree $1-\alpha$ of technology spillovers. Production labor is denoted as $L_{y,t}$, and the specification $L_{y,t}/N_t^{1-\sigma}$ captures a congestion effect $1-\sigma$ of variety that removes the scale effect for $\sigma < 1$.

Profit maximization yields the conditional demand functions for $\{L_{y,t}, X_t(i)\}$:

$$L_{y,t} = (1-\theta)Y_t/w_t, \tag{6}$$

$$X_t(i) = \left[\frac{\theta}{P_t(i)}\right]^{1/(1-\theta)} Z_t^{\alpha}(i)Z_t^{1-\alpha}L_{y,t}/N_t^{1-\sigma}, \tag{7}$$

where $P_t(i)$ denotes the price of $X_t(i)$. Competitive firms pay $(1-\theta)Y_t = w_t L_{y,t}$ for production labor and $\theta Y_t = \int_0^{N_t} P_t(i)X_t(i)di$ for intermediate goods.

[10] We assume that the domestic financial market is not integrated to the global financial market; see Section 4.4 for a discussion of this assumption.

3.3 Intermediate goods and in-house R&D

Each differentiated intermediate good i is produced by a monopolistic firm, which uses a linear one-to-one production function. Specifically, the monopolistic firm employs $X_t(i)$ units of domestic final good to produce $X_t(i)$ units of intermediate good i. However, it also needs to incur $\phi Z_t^{\alpha}(i) Z_t^{1-\alpha}$ units of domestic final good as a fixed operating cost in which $\phi > 0$ is an operating cost parameter. To improve the quality $Z_t(i)$ of intermediate good i, the firm also invests $R_t(i)$ units of domestic final good, and the in-house R&D process is

$$\dot{Z}_t(i) = R_t(i). \tag{8}$$

Then, the profit flow (before R&D) of the firm at time t is

$$\Pi_t(i) = P_t(i)X_t(i) - X_t(i) - \phi Z_t^{\alpha}(i) Z_t^{1-\alpha}, \tag{9}$$

where $P_t(i)X_t(i)$ is the revenue, $X_t(i)$ is the production cost, and $\phi Z_t^{\alpha}(i) Z_t^{1-\alpha}$ is the operation cost. Given $\{\Pi_t(i), R_t(i)\}$, the value of the monopolistic firm is

$$V_t(i) = \int_t^{\infty} \exp\left(-\int_t^s r_u du\right) [\Pi_s(i) - R_s(i)]\, ds. \tag{10}$$

Maximizing $V_t(i)$ subject to (7)-(9), we specify the current-value Hamiltonian as

$$H_t(i) = \Pi_t(i) - R_t(i) + \eta_t(i)\dot{Z}_t(i), \tag{11}$$

where $\eta_t(i)$ is the co-state variable on (8). We relegate this optimization problem to Appendix B in which we derive the monopolistic price as $P_t(i) = \min\{\mu, 1/\theta\} = \mu$, where $\mu \in (1, 1/\theta)$ is the unit production cost of competitive firms that can imitate the production of $X_t(i)$ with the same quality $Z_t(i)$ as the monopolistic firm. Therefore, Bertrand competition implies that the monopolistic firm must set its price to μ that is below the unconstrained profit-maximizing price $1/\theta$.

Following previous studies, we consider a symmetric equilibrium in which $Z_t(i) = Z_t$ and $X_t(i) = X_t$ for $i \in [0, N_t]$.[11] Substituting $P_t(i) = \mu$ in (7) yields the quality-adjusted firm size as

$$\frac{X_t}{Z_t} = \left(\frac{\theta}{\mu}\right)^{1/(1-\theta)} \frac{L_{y,t}}{N_t^{1-\sigma}} = \left(\frac{\theta}{\mu}\right)^{1/(1-\theta)} \frac{l_t L_t}{N_t^{1-\sigma}}, \tag{12}$$

where we have used the resource constraint on labor $L_{y,t} = l_t L_t$ in which $l_t L_t$ is the total supply of labor. We will show that the following transformed state variable captures the dynamics of the economy:

$$x_t \equiv \left(\frac{\theta}{\mu}\right)^{1/(1-\theta)} \frac{L_t}{N_t^{1-\sigma}}. \tag{13}$$

Lemma 1 shows that the rate of return on quality-improving R&D is increasing in the quality-adjusted firm size $x_t l_t$.

[11] Symmetry also implies $\Pi_t(i) = \Pi_t$, $R_t(i) = R_t$ and $V_t(i) = V_t$.

Lemma 1 *The rate of return to in-house R&D is*

$$r_t^q = \alpha \frac{\Pi_t}{Z_t} = \alpha \left[(\mu - 1) x_t l_t - \phi \right]. \tag{14}$$

Proof. See Appendix B. ■

3.4 Entrants

To ensure the symmetric equilibrium at any time t, we follow previous studies to assume that entrants have access to aggregate technology Z_t. Entering the market with a new intermediate good requires an entry cost of βX_t units of domestic final good, where $\beta > 0$ is an entry-cost parameter. The asset-pricing equation that determines the rate of return on assets is

$$r_t = \frac{\Pi_t - R_t}{V_t} + \frac{\dot{V}_t}{V_t}. \tag{15}$$

When there is entry, free entry implies that

$$V_t = \beta X_t. \tag{16}$$

We substitute (8), (9), (12), (13), (16) and $P_t(i) = \mu$ into (15) to derive the rate of return on entry as

$$r_t^e = \frac{1}{\beta} \left(\mu - 1 - \frac{\phi + z_t}{x_t l_t} \right) + \frac{\dot{l}_t}{l_t} + \frac{\dot{x}_t}{x_t} + z_t, \tag{17}$$

where $z_t \equiv \dot{Z}_t / Z_t$ is the quality growth rate.

3.5 International trade

We consider a small open economy by assuming that export demand from abroad is exogenous to the domestic economy, instead of the relative price p_t being exogenous, because we want to explore the effects of changes in export demand. Specifically, χY_t units of final good are exported abroad, where $\chi > 0$ is an exogenous export demand parameter. Then, the local economy uses the export revenue to pay for imported goods, and the balanced-trade condition is

$$p_t \iota_t L_t = \chi Y_t \Rightarrow \psi(\iota_t)^{1-\varepsilon} = \chi \frac{y_t}{c_t}, \tag{18}$$

where $\varepsilon \in [0, 1)$ and $y_t \equiv Y_t / L_t$. In (18), p_t is determined by (3), and import consumption ι_t is the balancing item that adjusts endogenously to ensure balanced trade.[12]

[12] On the other hand, if p_t is exogenous, then both ι_t and χ_t would be endogenous.

3.6 Equilibrium

The equilibrium is a time path of allocations $\{a_t, \iota_t, c_t, Y_t, L_{y,t}, l_t, X_t(i), R_t(i)\}$ and a time path of prices $\{r_t, w_t, p_t, P_t(i), V_t(i)\}$ such that the following conditions are satisfied:

- the household chooses $\{\iota_t, c_t, l_t\}$ to maximize utility taking $\{p_t, r_t, w_t\}$ as given;
- competitive firms choose $\{L_{y,t}, X_t(i)\}$ to produce Y_t and maximize profit taking $\{w_t, P_t(i)\}$ as given;
- a monopolistic firm produces $X_t(i)$ and chooses $\{P_t(i), R_t(i)\}$ to maximize $V_t(i)$ taking r_t as given;
- entrants make entry decisions taking V_t as given;
- the value of monopolistic firms is equal to the total value of household assets such that $N_t V_t = a_t L_t$;
- the labor market clears such that $l_t L_t = L_{y,t}$;
- the balanced-trade condition holds such that $p_t \iota_t L_t = \chi Y_t$; and
- the domestic final-good market clears.

3.7 Aggregation

Substituting (7) and $P_t(i) = \mu$ into (5) and imposing symmetry yield the aggregate production function of domestic output:

$$Y_t = \left(\frac{\theta}{\mu}\right)^{\theta/(1-\theta)} N_t^{\sigma} Z_t L_{y,t} = \left(\frac{\theta}{\mu}\right)^{\theta/(1-\theta)} N_t^{\sigma} Z_t L_t l_t, \tag{19}$$

which uses $L_{y,t} = l_t L_t$. Therefore, the growth rate of domestic output per capita $y_t \equiv Y_t/L_t$ is

$$g_t \equiv \frac{\dot{y}_t}{y_t} = \sigma n_t + z_t + \frac{\dot{l}_t}{l_t}, \tag{20}$$

where $n_t \equiv \dot{N}_t/N_t$ is the variety growth rate and $z_t \equiv \dot{Z}_t/Z_t$ is the quality growth rate.

3.8 Dynamics

Recall that the state variable x_t is defined in (13). Then, its law of motion is given by

$$\frac{\dot{x}_t}{x_t} = \lambda - (1-\sigma)n_t, \tag{21}$$

where the variety growth rate n_t in equilibrium is either equal to zero or given by an autonomous and increasing function in x_t. As we will show, the dynamics of the economy is determined by the dynamics of x_t, which is globally stable if the following parameter condition holds:

$$\beta\phi > \frac{1}{\alpha}\left[\mu - 1 - \beta\left(\rho + \frac{\sigma\lambda}{1-\sigma}\right)\right] > \mu - 1. \tag{22}$$

In this case, given an initial value x_0, the state variable x_t gradually increases towards its steady-state value x^*. The economy begins in a pre-industrial era in which both the variety growth rate n_t and the quality growth rate z_t are zero because firm size $x_t l_t$ is not large enough to activate innovation. As firm size becomes large enough, the economy enters the first phase of the industrial era in which monopolistic firms begin to develop new products (i.e., $n_t > 0$).[13] Then, as firm size continues to grow, the economy enters the second phase of the industrial era in which monopolistic firms begin to improve the quality of products (i.e., $z_t > 0$) in addition to developing new products. In the long run, the economy converges to the balanced growth path with steady-state growth when x_t converges to its steady-state value x^*.

Substituting $L_{y,t} = l_t L_t$ and (6) into (4) yields the level of labor as

$$l_t = \left(1 + \frac{\delta}{1-\theta}\frac{c_t}{y_t}\right)^{-1}, \tag{23}$$

which is decreasing in c_t/y_t. Therefore, we need to derive the consumption-output ratio in order to determine the equilibrium level of labor l_t. As in previous studies such as Chu, Furukawa and Wang (2022) and Chu, Peretto and Wang (2022), we assume that in the pre-industrial era, monopolistic firms do not yet operate and only start operating when innovation is activated.[14] During this time, intermediate goods are produced by competitive firms with constant returns to scale subject to the unit production cost μ, and this sector generates zero profit. Therefore, in the pre-industrial era, the resource constraint on domestic final good is

$$(1-\chi)Y_t = c_t L_t + \mu N_t X_t, \tag{24}$$

and the consumption-output ratio is simply

$$\frac{c_t}{y_t} = \frac{w_t l_t - p_t \iota_t}{y_t} = 1 - \theta - \chi > 0, \tag{25}$$

which can also be obtained by substituting $\theta Y_t = N_t P_t X_t = \mu N_t X_t$ into (24).

As the economy enters the industrial era, monopolistic firms begin operation and innovation is activated. Therefore, in both phases of the industrial era, intermediate goods are produced by monopolistic firms, and the resource constraint on domestic final good is

$$(1-\chi)Y_t = c_t L_t + N_t(X_t + \phi Z_t + R_t) + \dot{N}_t \beta X_t, \tag{26}$$

where $R_t = 0$ ($R_t > 0$) in the first (second) phase of the industrial era.

[13] We consider the realistic case in which new products are developed before their quality improves.

[14] In Appendix C, we solve the model without this assumption to show that the dynamics becomes less realistic.

Lemma 2 *When the entry condition in (16) holds, the consumption-output ratio jumps to*

$$\frac{c_t}{y_t} = \frac{(\rho - \lambda)\beta\theta}{\mu} + 1 - \theta - \chi > 0. \tag{27}$$

Proof. See Appendix B. ■

4 Export-led takeoff

In this section, we explore how an expansion in export demand χ affects the transition of the economy from the pre-industrial era without innovation to the industrial era with innovation. After providing analytical results, we calibrate the model to data to perform a quantitative analysis in Section 4.4.

4.1 The pre-industrial era

In the pre-industrial era, firm size $x_t l_t$ is not large enough to activate innovation. Therefore, the variety growth rate n_t is zero. In this case, the dynamics of x_t is given by

$$\frac{\dot{x}_t}{x_t} = \lambda - (1 - \sigma) n_t = \lambda > 0, \tag{28}$$

which shows that x_t increases over time. Eventually, firm size becomes sufficiently large to activate innovation. However, during the pre-industrial era, the growth rate of domestic output per capita is zero:

$$g_t = \sigma n_t + z_t + \frac{\dot{l}_t}{l_t} = 0 \tag{29}$$

because $n_t = z_t = \dot{l}_t / l_t = 0$. Substituting (25) into (23) yields the equilibrium level of labor,

$$l_t = l = \left[1 + \frac{\delta(1 - \theta - \chi)}{1 - \theta}\right]^{-1}, \tag{30}$$

which is stationary in the pre-industrial era.

4.2 The first phase of the industrial era

In the first phase of the industrial era, the variety growth rate n_t becomes positive. In this case, we can combine (2) and (17) by setting $r_t = r_t^e$ to derive

$$\frac{\dot{c}_t}{c_t} = \frac{1}{\beta}\left(\mu - 1 - \frac{\phi}{x_t l_t}\right) + \frac{\dot{x}_t}{x_t} - \rho, \tag{31}$$

which also uses $z_t = \dot{l}_t / l_t = 0$. Then, we can use $\dot{c}_t / c_t = \dot{y}_t / y_t$ from the stationary consumption-output ratio in Lemma 2 and $g = \sigma n_t$ from (20) to derive

$$n_t = \frac{1}{\beta} \left(\mu - 1 - \frac{\phi}{x_t l_t} \right) + \lambda - \rho, \tag{32}$$

which also uses (21) for $\dot{x}_t / x_t$. In (32), the variety growth rate n_t is positive if and only if

$$x_t l_t > \frac{\phi}{\mu - 1 - \beta(\rho - \lambda)}, \tag{33}$$

where l_t is determined by (23) and (27) as

$$l_t = l^* = \left\{ 1 + \frac{\delta}{1 - \theta} \left[\frac{(\rho - \lambda)\beta\theta}{\mu} + 1 - \theta - \chi \right] \right\}^{-1}, \tag{34}$$

which is also stationary in the industrial era.

We substitute (34) into (33) to re-express the inequality as

$$x_t > x_N(\underset{-}{\chi}) \equiv \frac{\phi}{\mu - 1 - \beta(\rho - \lambda)} \left\{ 1 + \frac{\delta}{1 - \theta} \left[\frac{(\rho - \lambda)\beta\theta}{\mu} + 1 - \theta - \chi \right] \right\}, \tag{35}$$

where the threshold x_N is decreasing in export demand χ. Therefore, an expansion in export demand reduces the threshold x_N and gives rise to an earlier activation or even an immediate activation of innovation by increasing the level of employment l^* and firm size $x_t l^*$ in the local economy. Proposition 1 summarizes this result.

Proposition 1 *A larger export demand χ leads to an earlier transition of the economy from pre-industrial stagnation to innovation-driven growth and a higher transitional growth rate g_t in the first phase of the industrial era.*

Proof. Recall from (28) that x_t increases at the exogenous rate λ in the pre-industrial era. Then, use (35) to show that the threshold x_N (for the activation of $n_t > 0$) is decreasing in χ. Finally, use (32) to show that $g = \sigma n_t$ is rising in $l_t = l^*$, which is increasing in χ in (34). ■

In the first phase of the industrial era, the state variable x_t has reached the threshold x_N. At this point, the variety growth rate n_t becomes positive, and the dynamics of x_t becomes

$$\frac{\dot{x}_t}{x_t} = \lambda - (1 - \sigma) n(x_t) > 0, \tag{36}$$

where $n(x_t)$ is given by (32) and increasing in x_t. The state variable x_t keeps rising in the first phase of the industrial era because n_t is below its steady-state value $n^* = \lambda/(1 - \sigma)$ during this phase.

4.3 The second phase of the industrial era

Eventually, the economy enters the second phase of the industrial era, during which quality improvement is also activated (i.e., $z_t > 0$) in addition to variety growth (i.e., $n_t > 0$). In this case, we can combine (2) and (14) by setting $r_t = r_t^q$ to derive

$$\frac{\dot{y}_t}{y_t} = \frac{\dot{c}_t}{c_t} = \alpha \left[(\mu - 1) x_t l^* (\underset{+}{\chi}) - \phi \right] - \rho, \tag{37}$$

where the first equality uses the stationary consumption-output ratio from Lemma 2. Equation (37) shows that for a given x_t, the growth rate g_t of domestic output per capita is once again increasing in export demand χ via the level of employment l^* and firm size $x_t l^*$. Then, we can use $g_t = \sigma n_t + z_t$ from (20) to derive the quality growth rate as

$$z_t = \alpha \left[(\mu - 1) x_t l^* - \phi \right] - \rho - \sigma n_t, \tag{38}$$

where n_t is still an endogenous variable.

To complete the derivations for $\{n_t, z_t\}$, we combine (2) and (17) by setting $r_t = r_t^e$ to derive

$$\frac{\dot{c}_t}{c_t} = \frac{1}{\beta} \left(\mu - 1 - \frac{\phi + z_t}{x_t l^*} \right) + \frac{\dot{x}_t}{x_t} + z_t - \rho, \tag{39}$$

where we have used $\dot{l}_t / l_t = 0$. Then, we can use $\dot{c}_t / c_t = \dot{y}_t / y_t$ from Lemma 2 and $g_t = \sigma n_t + z_t$ from (20) to derive

$$n_t = \frac{1}{\beta} \left(\mu - 1 - \frac{\phi + z_t}{x_t l^*} \right) + \lambda - \rho, \tag{40}$$

which also uses (21) for $\dot{x}_t / x_t$. Substituting (40) into (38) yields $z_t = z(x_t)$, which is positive if and only if $x_t > x_Z$ given by

$$x_Z(\underset{-}{\chi}) \equiv \underset{x}{\arg\text{solve}} \left\{ \left[(\mu - 1) x l^*(\chi) - \phi \right] \left[\alpha - \frac{\sigma}{\beta x l^*(\chi)} \right] = (1 - \sigma)\rho + \sigma\lambda \right\} > x_N. \tag{41}$$

Similarly, substituting (38) into (40) yields $n_t = n(x_t)$, which can be combined with (21) to derive the *linearized* dynamics of x_t as[15]

$$\dot{x}_t = \frac{1 - \sigma}{\beta} \left\{ \left[(1 - \alpha)\phi - \left(\rho + \frac{\sigma\lambda}{1 - \sigma} \right) \right] \frac{1}{l^*} - \left[(1 - \alpha)(\mu - 1) - \beta \left(\rho + \frac{\sigma\lambda}{1 - \sigma} \right) \right] x_t \right\} \gtrless 0. \tag{42}$$

In the second phase of the industrial era, the state variable x_t keeps rising until n_t reaches its steady-state value $n^* = \lambda / (1 - \sigma)$, at which point the state variable x_t also reaches its steady-state value x^*. Lemma 3 derives the steady-state values of x_t and g_t.

Lemma 3 *The steady-state equilibrium values of x_t and g_t are given by*

$$x^* = \frac{1}{l^*} \frac{(1 - \alpha)\phi - \left[\rho + \sigma\lambda / (1 - \sigma) \right]}{(1 - \alpha)(\mu - 1) - \beta \left[\rho + \sigma\lambda / (1 - \sigma) \right]} > x_Z, \tag{43}$$

$$g^* = \alpha \left[(\mu - 1) \frac{(1 - \alpha)\phi - \left[\rho + \sigma\lambda / (1 - \sigma) \right]}{(1 - \alpha)(\mu - 1) - \beta \left[\rho + \sigma\lambda / (1 - \sigma) \right]} - \phi \right] - \rho > 0. \tag{44}$$

Proof. See Appendix B. ■

[15] See the proof of Lemma 3 in Appendix B.

Lemma 3 shows that the steady-state equilibrium growth rate g^* is independent of employment l^* and export demand χ due to the scale-invariant property of the Schumpeterian growth model with endogenous market structure. Specifically, although long-run economic growth depends on firm size $x^* l^*$, it is independent of export demand χ because a larger l^* implies a smaller x^* by increasing the number of firms N_t. Proposition 2 summarizes all the results in this section.

Proposition 2 *A larger export demand χ leads to a higher transitional growth rate g_t in the second phase of the industrial era but does not affect the steady-state growth rate g^*.*

Proof. Use (37) to show that for a given x_t, $g \equiv \dot{y}_t/y_t$ is increasing in $l_t = l^*$, which in turn is increasing in χ in (34). Then, use (44) to show that g^* is independent of l^* and χ. ■

4.4 Quantitative analysis

In this section, we explore the quantitative implications of exports on the takeoff of an economy. Given the dynamics of $x_t = x_0 e^{\lambda t}$ in the pre-industrial era, the time it takes x_t to reach x_N from x_0 is given by

$$T_N = \frac{1}{\lambda} \ln\left(\frac{x_N}{x_0}\right),$$

where x_N is given in (35). Differentiating T_N with respect to χ and using l^* in (34) yield

$$\frac{\partial T_N}{\partial \chi} = \frac{1}{\lambda}\frac{\partial \ln x_N}{\partial \chi} = -\frac{1}{\lambda}\frac{\delta l^*}{1-\theta},$$

which is negative because a larger export χ leads to an earlier takeoff (i.e., a decrease in the takeoff time T_N). The magnitude of this effect is decreasing in the population growth rate λ and the degree of labor intensity $1-\theta$ in production but increasing in the equilibrium level of labor l^* and the leisure preference parameter δ. The population growth rate matters because it determines how fast x_t grows towards x_N, whereas $\delta l^*/(1-\theta)$ matters because it determines the effect of export χ on employment l^* and firm size $x_t l^*$.

We now calibrate these parameters to data in the Chinese economy. China is a suitable example for our quantitative illustration because its takeoff has been largely export-led.[16] Also, its financial market is not integrated to the global financial market making our assumption of a locally determined interest rate r_t valid, and Ang and Madsen (2011) provide empirical evidence that innovation plays a key role for economic growth in China. Furthermore, before China joined the World Trade Organization in 2001, the size of its economy (US$1.21 trillion in 2000) was smaller than that of the UK (US$1.66 trillion in 2000),[17] which is often viewed as a small open economy. It wasn't until 2006 when the size of the Chinese economy caught up with the UK economy.

[16] See Wan, Lu and Chen (2007) and Yao (2014) for a discussion of Chinese growth and international trade.

[17] The comparison here is based on the market exchange rate as we are comparing the market size of two economies for international trade, rather than domestic purchasing power.

China started opening up its economy at the end of the 1970's. In 1978, its export share of GDP was 4.6%. Then, it rose to roughly 20% in 2000 and reached a peak of 36% in 2006 before falling below 20% in recent times.[18] The average population growth rate in China from 1980 to 2020 is 0.9%,[19] and the labor share $1-\theta$ of output in China is about 0.5,[20] which is lower than a typical Western economy. Furthermore, we set the share of time devoted to employment l^* to 0.4, which is higher than a typical Western economy, due to the longer working hours in China. As for the leisure preference parameter δ, it is inversely related to the equilibrium level of labor l^*. From (23), $l_t \approx 1/(1+\delta)$ if $c/y \approx 1-\theta$, which are both roughly 0.5 in China. So, setting $\delta = 1.5$, which corresponds to $l^* \approx 1/(1+\delta) = 0.40$, is a reasonable back-of-the-envelope value. Then, we have

$$\frac{\partial T_N}{\partial \chi} = -\frac{1}{\lambda}\frac{\delta l^*}{1-\theta} \approx 133,$$

which implies that an increase in the export share χ by 0.1 triggers an earlier transition to innovation-driven growth in China by 13.3 years.

In the rest of this section, we calibrate the entire model to the Chinese economy to perform a more complete quantitative analysis. The model features the following set of parameters: $\{\lambda, \theta, \rho, \alpha, \sigma, \mu, \beta, \phi, \delta, \chi\}$.[21] As before, we set the population growth rate λ to 0.9% and the labor share $1-\theta$ of output to 0.5. We set the discount rate ρ to a conventional value of 0.03. We follow Iacopetta *et al.* (2019) to set the degree of technology spillovers $1-\alpha$ to 0.833 and the social return of variety σ to 0.25. We set the markup ratio μ to 1.3 according to the empirical estimates in Lu and Yu (2015), Fan *et al.* (2018) and Wen (2022). Then, we calibrate $\{\beta, \phi, \delta\}$ by matching the following moments of the Chinese economy: 49.5% for the consumption share,[22] 1% for the long-run average TFP growth rate,[23] and 0.40 for the share of time devoted to work. Finally, the export share in China was 4.6% in 1978. Table 2 summarizes the parameter values.

Table 2: Calibrated parameter values

λ	θ	ρ	α	σ	μ	β	ϕ	δ	χ_{1978}
0.009	0.500	0.030	0.167	0.250	1.300	5.076	0.177	1.515	0.046

Figure 1 plots the path of the export share in China and shows that it rises from 4.6% in 1978 to 36.0% in 2006 before falling to 18.5% in 2020. Using this data, we compute a time path of χ and model the changes in χ as a sequence of unanticipated and permanent changes (i.e., MIT shocks). Given this calibrated path of χ, Figure 2 presents the simulated path of the technology growth rate $\sigma n_t + z_t$ and shows that it matches the HP-filter trend of the TFP growth rate in China reasonably well. Specifically, the technology growth rate gradually increased and was below 1% before China joined the WTO. After that, it accelerated sharply to above 2.5% in 2006, and then it kept falling as in the data.[24] Figure 3 presents again the simulated path of the technology growth rate, along with a simulated path of the growth rate without changes

[18] Data source: World Bank Data.

[19] Data source: World Bank Data.

[20] See Bai, Hsieh and Qian (2006).

[21] The import preference parameter ψ affects the equilibrium level of import ι but not the rest of the economy.

[22] Data source: CEIC Data.

[23] Data source: Federal Reserve Bank of St. Louis.

[24] In the last two years of the data, there were the China-US trade war and the COVID-19 pandemic, which are likely responsible for the strongly negative TFP growth.

in the export share (i.e., χ remains at its initial value of 0.046) and a simulated path of the growth rate in which the export share χ hypothetically remains at its peak value of 0.36 after 2006. This figure shows that the rapid rise in the export share since 1978 (and especially since joining the WTO) has caused a rapid growth acceleration in the Chinese economy, but the fall in exports since 2007 has also caused a growth deceleration that continues until recent times.

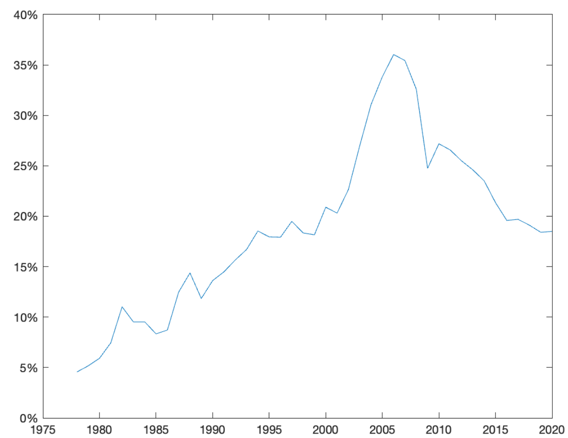

Figure 1: Export share in China

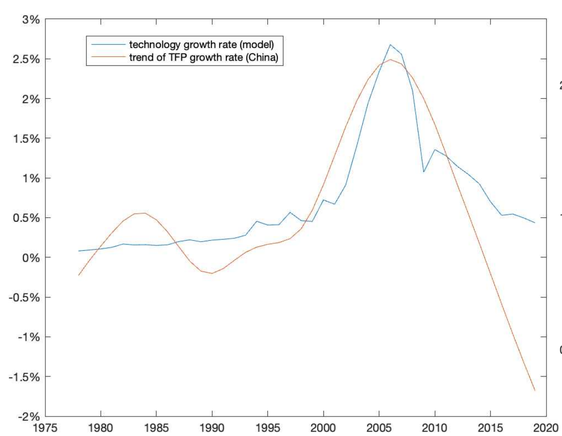

Figure 2: Simulation and data

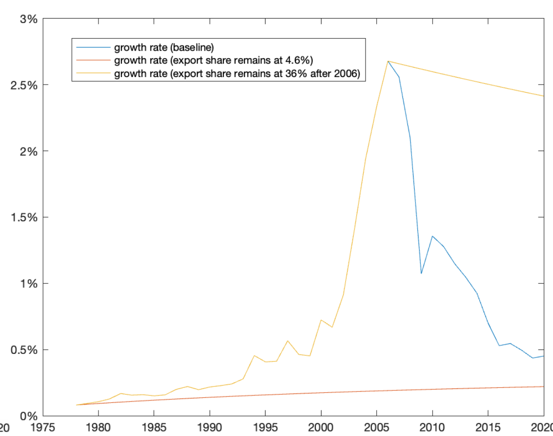

Figure 3: Simulation and counterfactual

5 Extension with an agricultural sector

Like any typical macroeconomic model, our baseline model features an aggregate final good Y_t in the macroeconomy. A model with a more realistic structure of the economy would feature multiple final goods, such as an industrial final good and an agricultural final good, and the allocation of labor between these sectors. In this section, we explore an extension of our model with an agricultural sector to explore the robustness of our results.[25]

[25] The extension is essentially an open-economy version of the model in Chu, Peretto and Wang (2022).

Specifically, we modify the utility function of the household as follows:

$$U = \int_0^\infty e^{-(\rho-\lambda)t} \left[\ln c_t + \delta \ln q_t + \psi \frac{(\iota_t)^{1-\varepsilon}}{1-\varepsilon} \right] dt, \tag{45}$$

where $\delta > 0$ is now a preference parameter on the per capita consumption of an agricultural good q_t.[26] In this case, the asset-accumulation equation becomes[27]

$$\dot{a}_t = (r_t - \lambda)a_t + w_t - c_t - p_t\iota_t - p_{q,t}q_t, \tag{46}$$

where $p_{q,t}$ is the price of the agricultural good. Then, (4) is replaced by the following optimality condition for agricultural consumption per capita:

$$q_t = \frac{\delta c_t}{p_{q,t}}. \tag{47}$$

As for the agricultural sector, we follow Lagakos and Waugh (2013) to model it as a competitive sector with the following linear technology:

$$Q_t = AL_{q,t}, \tag{48}$$

where Q_t is the aggregate output of agricultural good and the parameter $A > 0$ determines the productivity of agricultural labor $L_{q,t}$. Profit maximization yields

$$w_t = p_{q,t}A, \tag{49}$$

which equates the wage rate to the value of the marginal product of agricultural labor.

The rest of the model is the same as before, except for the resource constraint on labor:

$$L_{q,t} + L_{y,t} = L_t. \tag{50}$$

As a result, we also need to modify the quality-adjusted firm size as follows:

$$\frac{X_t}{Z_t} = \left(\frac{\theta}{\mu}\right)^{1/(1-\theta)} \frac{L_{y,t}}{N_t^{1-\sigma}} = x_t l_{y,t}, \tag{51}$$

which uses the definition of x_t in (13) and also the newly defined industrial labor share $l_{y,t} \equiv L_{y,t}/L_t$. Then, we simply replace labor supply l_t by industrial labor share $l_{y,t}$ in all the other equations. Combining (6) and (47)-(50) yields the modified version of (23) as

$$l_{y,t} = \left(1 + \frac{\delta}{1-\theta}\frac{c_t}{y_t}\right)^{-1}, \tag{52}$$

where the industrial consumption-output ratio is determined as before by (25) in the pre-industrial era and (27) in the industrial era. Therefore, one can simply replace l_t by $l_{y,t}$ in (33) and (34) to derive the following condition for the activation of innovation:

$$x_t > x_N(\underset{-}{\chi}) \equiv \frac{\phi}{\mu - 1 - \beta(\rho-\lambda)} \left\{1 + \frac{\delta}{1-\theta}\left[\frac{(\rho-\lambda)\beta\theta}{\mu} + 1 - \theta - \chi\right]\right\}, \tag{53}$$

[26] Our results are robust to a subsistence parameter φ in $\delta \ln(q_t - \varphi)$ as in Chu, Peretto and Wang (2022).

[27] It is useful to note that we now assume perfectly inelastic labor supply (i.e., $l = 1$) for simplicity.

which is identical to (35).

Although the aggregate structure and the takeoff of the industrial economy is the same as in our baseline model, the underlying mechanism for the takeoff in this extended model is different. In this extension, a higher export demand χ for industrial goods causes a reallocation of labor from the agricultural sector to the industrial sector, which then has the same implications of a larger market size in the industrial sector and an earlier activation of innovation. Therefore, despite the different microeconomic mechanisms, the macroeconomic trigger of the takeoff in both models is the expansion in industrial production labor $L_{y,t}$. The only difference is that the increase in $L_{y,t}$ is from a higher employment l_t (recall that $L_{y,t} = l_t L_t$) due to a reallocation of labor from leisure to production in the baseline model versus a reallocation of labor from agriculture to industrial production $l_{y,t}$ (recall that $L_{y,t} = l_{y,t} L_t$) in the extended model.

The above analysis is based on the assumption that the agricultural good is not exported abroad. Allowing the agricultural good to be exported would not change our results, so long as the expansion in the export demand for industrial goods is not accompanied by a higher export demand for the agricultural good. In this case, one can re-derive (52) as

$$l_{y,t}(\underset{-}{\chi_q}) = \left(1 + \frac{\delta}{1-\theta}\frac{c_t/y_t}{1-\chi_q}\right)^{-1}, \tag{54}$$

where χ_q is the share of Q_t exported and c_t/y_t is given by (25) and (27) in the two eras. Equation (54) shows that an expansion in the export demand χ_q for the agricultural good (holding constant the export demand χ for industrial goods) would lead to a reallocation of labor from the industrial sector to the agricultural sector, which then has the opposite implications of a smaller market size in the industrial sector and a delayed activation of innovation.

6 Conclusion

In this study, we have developed a small-open-economy Schumpeterian growth model to explore the effects of exports on endogenous takeoff and economic growth. We find that a higher export demand leads to a larger market size and an earlier takeoff of the economy but does not affect economic growth in the long run due to the scale-invariant property of the Schumpeterian growth model with endogenous market structure. Using cross-country panel data, we find supportive evidence for a positive effect of exports on economic growth; furthermore, this positive effect becomes smaller, as the level of income rises, and eventually disappears as our theory predicts. Despite this neutral effect of exports on long-run economic growth, we find a quantitatively significant effect of exports on the endogenous takeoff of the Chinese economy by calibrating the model to data in China. This finding suggests that the opening up of the Chinese economy since the end of the 1970's has been crucial for the transition of the Chinese economy to innovation-driven growth; however, the fall in exports since 2007 has also caused a deceleration of technology growth that continues until recent times. Finally, we conclude this section with a caveat that this study has focused on export-led growth as one of the mechanisms for achieving economic development. It is useful to emphasize that we are not ruling out the importance of other mechanisms, such as mass education, political institutions, and investment in capital and infrastructure, but simply consider their effects as independent from the effects of exports on economic growth.

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Appendix A: Data and robustness

Table A1: Summary statistics

Variable	Observations	Mean	Min	Max	Sd
Growth of real GDP	561	0.0330	-0.0839	0.1848	0.0272
Growth of real GDP per capita	561	0.0178	-0.0986	0.1380	0.0255
Growth of real GDP per worker	532	0.0167	-0.0889	0.1491	0.0260
Export share of GDP	561	0.3950	0.0440	2.0673	0.2745
Log real GDP per capita	561	9.0844	6.1777	11.8517	1.1696
Log population (in millions)	404	2.0548	-3.2348	7.2486	1.8811
R&D intensity	362	0.0086	0.0001	0.0437	0.0088
Import share of GDP	561	0.4411	0.0490	1.9634	0.2546
Depreciation rate	401	0.0424	0.0127	0.0982	0.0124
Real interest rate	339	0.0644	-0.3270	0.4103	0.0755

Data source: Penn World Table for the population size and the depreciation rate. World Bank for others.

Table A2: Effects of exports on economic growth (5 years per period)

	GDP growth		per capita GDP growth		per worker GDP growth	
	(1)	(2)	(3)	(4)	(5)	(6)
$Export_{it}$	0.1630**	0.1555*	0.1877***	0.1950**	0.1563**	0.1584*
	(0.0658)	(0.0862)	(0.0624)	(0.0807)	(0.0645)	(0.0833)
$Export_{it} \times y_{it}$	-0.0150**	-0.0150*	-0.0176***	-0.0197**	-0.0172***	-0.0193**
	(0.0066)	(0.0086)	(0.0063)	(0.0080)	(0.0065)	(0.0083)
y_{it}	-0.0483***	-0.0371***	-0.0494***	-0.0373***	-0.0558***	-0.0368***
	(0.0058)	(0.0074)	(0.0055)	(0.0069)	(0.0056)	(0.0071)
Control variables		✓		✓		✓
Country fixed effects	✓	✓	✓	✓	✓	✓
Time fixed effects	✓	✓	✓	✓	✓	✓
Observations	1,128	445	1,128	445	1,072	445
R^2	0.4111	0.6313	0.4249	0.6146	0.4185	0.5965

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. *Standard errors in parentheses.*

Appendix B: Proofs

Proof of Lemma 1. We use the Hamiltonian to solve the firm's dynamic optimization. The current-value Hamiltonian of firm i is given by

$$H_t(i) = \Pi_t(i) - R_t(i) + \eta_t(i)\dot{Z}_t(i) + \xi_t(i)[\mu - P_t(i)], \tag{B1}$$

where $\eta_t(i)$ is the costate variable on $\dot{Z}_t(i)$ and $\xi_t(i)$ is the multiplier on $P_t(i) \leq \mu$. We substitute (7)-(9) into (B1) and derive

$$\frac{\partial H_t(i)}{\partial P_t(i)} = 0 \Rightarrow \frac{\partial \Pi_t(i)}{\partial P_t(i)} = \xi_t(i), \tag{B2}$$

$$\frac{\partial H_t(i)}{\partial R(i)} = 0 \Rightarrow \eta_t(i) = 1, \tag{B3}$$

$$\frac{\partial H_t(i)}{\partial Z_t(i)} = \alpha \left\{ [P_t(i) - 1]\left[\frac{\theta}{P_t(i)}\right]^{1/(1-\theta)} \frac{L_{y,t}}{N^{1-\sigma}} - \phi \right\} \frac{Z_t^{1-\alpha}}{Z_t^{1-\alpha}(i)} = r_t\eta_t(i) - \dot{\eta}_t(i), \tag{B4}$$

where $Z_t(i)$ is a state variable. If $P_t(i) < \mu$, then $\xi_t(i) = 0$. In this case, $\partial\Pi_t(i)/\partial P_t(i) = 0$ yields $P_t(i) = 1/\theta$. If the constraint on $P_t(i)$ is binding, then $\xi_t(i) > 0$. In this case, we have $P_t(i) = \mu$. Then, the assumption $\mu < 1/\theta$ implies $P_t(i) = \mu$. Substituting (B3), (13) and $P_t(i) = \mu$ into (B4) and imposing symmetry yield (14). ■

Proof of Lemma 2. We use the entry condition $V_t = \beta X_t$ to derive

$$a_t = \frac{V_t N_t}{L_t} = \frac{\beta X_t N_t}{L_t} = \frac{\beta\theta}{\mu} y_t, \tag{B5}$$

which also uses $\theta Y_t = \mu X_t N_t$. Differentiating (B5) with respect to t yields

$$\frac{\beta\theta}{\mu}\dot{y}_t = \dot{a}_t = (r_t - \lambda)a_t + w_t l_t - c_t - p_t\iota_t = (r_t - \lambda)a_t + (1 - \theta - \chi)y_t - c_t, \tag{B6}$$

which uses (1) and the last equality uses (6) and (18). Then, we use (2) and (B5) to rearrange (B6) as

$$\frac{\dot{c}_t}{c_t} - \frac{\dot{y}_t}{y_t} = \frac{\mu}{\beta\theta}\frac{c_t}{y_t} - \left[\frac{\mu(1-\theta-\chi)}{\beta\theta} + \rho - \lambda\right], \tag{B7}$$

which implies that the consumption-output ratio jumps to the steady-state value in (27) whenever the entry condition in (16) holds. ■

Proof of Lemma 3. Substituting (38) into (40) to obtain $n_t = n(x_t)$, we then substitute it into (21) to derive the *non-linear* dynamics of x_t as

$$\dot{x}_t = \frac{1-\sigma}{\beta - \sigma/(x_t l^*)}\left\{\left[(1-\alpha)\phi - \left(\rho + \frac{\sigma\lambda}{1-\sigma}\right)\right]\frac{1}{l^*} - \left[(1-\alpha)(\mu - 1) - \beta\left(\rho + \frac{\sigma\lambda}{1-\sigma}\right)\right]x_t\right\}, \tag{B8}$$

where $x_t l^* > \alpha x_Z l^* > \sigma/\beta$ is ensured by (41). Setting $\dot{x}_t = 0$ in (B8) yields x^* in (43). Finally, substituting (43) into (37) yields g^* in (44). ■

Appendix C: Monopolistic firms in the pre-industrial era

In this appendix, we consider an alternative assumption in the model in which monopolistic firms operate even in the pre-industrial era. In this case, we need to assume that the initial value of x_t is sufficiently large (despite being lower than x_N). Specifically,

$$x_0 > \frac{\phi}{(\mu - 1)l_0}, \tag{C1}$$

where l_0 is determined below in (C7). Equation (C1) is equivalent to $\Pi_0 > 0$. Therefore, it is possible for monopolistic profits to be positive in the pre-industrial era before the takeoff occurs. When $n_t = 0$, the entry condition in (16) does not hold. However, the asset-pricing equation in (15) still holds and becomes

$$r_t = \frac{\Pi_t}{V_t} + \frac{\dot{V}_t}{V_t}, \tag{C2}$$

where $R_t = z_t = 0$. We use (B5) and $n_t = 0$ to derive $\dot{a}_t/a_t = \dot{V}_t/V_t - \lambda$ and then substitute this equation into (1) to obtain

$$\frac{\dot{V}_t}{V_t} - \lambda = \frac{\dot{a}_t}{a_t} = r_t - \lambda + \frac{w_t l_t - p_t \iota_t - c_t}{a_t}. \tag{C3}$$

Substituting (C2) into (C3) yields

$$c_t = \frac{\Pi_t}{V_t} a_t + w_t l_t - p_t \iota_t = \frac{N_t}{L_t} \Pi_t + (1 - \theta - \chi)\, y_t, \tag{C4}$$

where we have used (B5), $p_t \iota_t = \chi y_t$ and $w_t l_t = (1 - \theta)\, y_t$. Then, substituting (9) and $P_t = \mu$ into (C4) yields

$$c_t = \frac{N_t X_t (\mu - 1 - \phi Z_t / X_t)}{L_t} + (1 - \theta - \chi)\, y_t = \frac{\theta}{\mu}\left(\mu - 1 - \frac{\phi}{x_t l_t}\right) y_t + (1 - \theta - \chi)\, y_t, \tag{C5}$$

which uses $\theta Y_t = \mu N_t X_t$ and (12)-(13). Then, the consumption-output ratio from (C5) is

$$\frac{c_t}{y_t} = \frac{\theta}{\mu}\left(\mu - 1 - \frac{\phi}{x_t l_t}\right) + 1 - \theta - \chi, \tag{C6}$$

which would increase from (25) to (27) if firm size $x_t l_t$ were to start from $\phi/(\mu - 1)$ and increases towards $\phi/[\mu - 1 - \beta(\rho - \lambda)]$. Finally, we substitute (C6) into (23) and manipulate the resulting equation to obtain the equilibrium firm size as follows:

$$x_t l_t = \frac{x_t + \frac{\delta\phi}{\mu}\frac{\theta}{1-\theta}}{1 + \delta\left(1 + \frac{\theta}{1-\theta}\frac{\mu-1}{\mu} - \frac{\chi}{1-\theta}\right)}, \tag{C7}$$

which is increasing in export demand χ for a given x_t.

Given that the dynamics of x_t is still given by (28) in the pre-industrial era, firm size $x_t l_t$ gradually increases towards the threshold in (33) to trigger the takeoff as before. The only difference is that as x_t increases over time, l_t in (C7) gradually decreases towards l^* in (34) (instead of jumping from l in (30) to l^* at the time of the takeoff). This additional dynamics of l_t in the pre-industrial era gives rise to negative growth in domestic output per capita before the takeoff, which is not as realistic as the dynamics in the baseline model.