Macroeconomic Dynamics (2024), **28**, pp. 1122–1149
doi:10.1017/S1365100523000408

ARTICLE

Temporary prosperity or sustainable development: the long-run impact of developing pollution-intensive industries†

Hongyu Nian[1], Zhiwei Xu[2], and Haitao Yin[1]

[1]Antai College of Economics and Management, Shanghai Jiao Tong University, Shanghai, China
[2]School of Economics, Fudan University, Shanghai, China
Corresponding author: Haitao Yin; Email: htyin@sjtu.edu.cn

Abstract

This paper proposes a dynamic model to capture the interaction among the environment, human capital accumulation, and economic growth. We emphasize the mechanism that pollution stock depresses human capital accumulation, which has received increasing support from empirical studies. The model predicts that the development of pollution-intensive industries can help an economy gear up a short-run prosperity, but it impairs the capability for long-run economic growth, trapping the economy at a low development level. The cost for a dirty economy to switch is expensive and even infeasible if the environmental degradation is irreversible. Policy interventions, such as tax on pollution and subsidy on human capital, can help alleviate but cannot eradicate the economic stagnation.

Keywords: Environmental pollution; Economic growth; Human capital accumulation; Environmental Kuznets Curve

1. Introduction

The relationship between economic growth and environmental pollution is one of the most concerning topics among environmental economists. Many of the debates centered on the proposition of the Environmental Kuznets Curve (EKC), which was formulated by Grossman and Krueger (1991) and Panayotou et al. (1993). The EKC argues that there is an inverted U-shape between economic growth and environmental pollution: pollution first increases as the economy flourishes and then decreases after a turning point as the economy grows. The EKC posits a notion that economic growth can naturally lead to a comeback of clean environment. As Beckerman (1992) argues, "there is clear evidence that, although economic growth usually leads to environmental degradation in the early stages of the process, in the end the best and probably the only way to attain a decent environment in most countries is to become rich." (P. 491).

Following this tenet, in practice, may be harmful. Stern (2017) concerns that "the EKC literature might encourage policymakers to incorrectly de-emphasize environmental policy and pursue growth as a solution instead." (P. 24). It supports a strategy of "pollute first, remediate later," with a belief that a region could achieve economic growth by sacrificing the environment, and once people become wealthy, they will have stronger willingness, larger financial capacity, and better technologies for environmental protection, from which a clean environment will naturally ensue. For instance, the two cities in China, Wenchuan and Beichuan, which collapsed into rubble in the 2008 earthquake, decided to rebirth as ecological cities but eventually turned instead

---

†Financial supports from the National Natural Science Foundation of China (No.72022011; 71974124; 72221001), Foundation on Modern Finance Research at Shanghai Jiao Tong University are greatly appreciated.

to pollution-intensive industries, in an effort for economic recovery. However, it is questionable whether this development model could eventually lead to a comeback of clean environment and simultaneously sustainable economic growth.

Theoretically, the EKC argument has two implicit assumptions. First, it assumes a unidirectional relationship from economic growth to pollution and implicitly ignores the reverse impact of pollution on economic growth. As Stern (2004) writes, "the EKC model,. . ., assumes that there is no feedback from environmental damage to economic production as income is assumed to be an exogenous variable." (P. 1426). However, a large body of literature shows that environmental degradation negatively affects working productivity (e.g., Zivin and Neidell, 2012; Chang et al. 2016; Fu et al., 2021). In particular, several lines of literature show that human capital are evidently impaired by pollution. Cavalcanti et al. (2023) show that air pollution significantly reduces human capital's creativity, and the negative effects are more salient among human capital who works on high-quality innovations. Another branch of literature shows that pollution decreases human's cognitive development, such as school performance and education years (e.g., Currie et al. 2009; Ebenstein et al. 2016; Bharadwaj et al. 2017; Zivin et al. 2020). The development of pollution-intensive industries creates an environment unsuitable for people to advance their own and children's education. Moreover, human capital is less likely to resident in polluting areas than labor. Hart (2020) shows that high-skilled workers have stronger preference over environmental amenities. The flexible job choices and income enable them to migrate more freely than low-skilled labor. In addition, while human capital basically works indoor, Archsmith et al. (2018) show that the variation in outdoor pollution exerts negative effects on the indoor activities as well. Taking the feedback effects of pollution on human capital into account, the model shows that the development of pollution-intensive industries impairs a region's capability for long-run economic growth, although it helps gear up a short-run prosperity. Second, the EKC assumes that environmental damage is reversible at a reasonable cost. This might be true for some types of pollution but not for many others, such as soil contamination, desertification, and loss of biodiversity (Arrow et al. 1995), the remediation of which is prohibitively expensive. The ongoing concern over climate change is one example, and the long-standing brownfield dilemma for urban redevelopment in the USA is another example (High, 2017).

When pollution is very difficult to remediate and the feedback impact of pollution on economic growth is significant, it is likely that a region that initially relies on dirty technology would be trapped in a low development level instead of following the EKC pattern. This study is to theorize the feedback mechanism and constrained pollution reversibility into an endogenous growth model. We start with an endogenous growth model to describe a clean economy, in which human capital accumulation serves as the engine for growth. We then extend the model to capture a dirty economy, in which pollution emitted by manufacturing sector is considered as a stock variable and exerts external costs on knowledge-producing activity by reducing the efficiency of education and research sector. As a result, the dirty economy loses its growth engine because the stock of pollution crowds out labor allocation to the education and research sector and reduces the efficiency of human capital accumulation. Provided with an exogenous choice between a clean versus a dirty technology, the model shows how social welfare, physical capital, human capital, pollution, and abatement are endogenously determined in equilibrium and dynamically evolve over the short and the long run.

We find that the dirty economy experiences temporary prosperity by sacrificing the environment in the early stage but stagnates at a low-level equilibrium in the long run, whereas the clean economy is capable of sustainable growth. Even in a social optimal system that can fully internalize externalities, the dirty economy still ends up with a growth trap because of the pollution-induced losses of human capital accumulation. Within this framework, we also discuss the cost that a region will have to pay if it later decides to "remediate and switch" to a clean path of development. The pain for this switch depends not only on the search friction and financial friction in the reallocation of used capital and labor (Dong et al., 2020; Dong, 2022) but also on the friction of transitioning resources (capital, labor, and human capital) across occupations (Kambourov and Manovskii, 2009)—from polluting industries into clean industries, as well as on the reversibility of environmental degradation. At last, we discuss policies including pollution tax and human capital subsidies. We observe a trade-off between the short-run and the long-run development in the choice of tax and subsidy rates. A higher taxation rate leads to less pollution and slows down the economy in the short run, but it contributes to a higher development level in the long run. This is close in spirit to the study by He et al. (2021) who highlight the positive relationship between taxation and the future accumulation of health capital. The difference between us exits in divergent mechanisms: He et al. (2021) suggest that high taxation on income leads to more leisure time and thus enhances human's health and utility, while we emphasize the effects of taxation on curbing pollution, which reduces the harm on the efficiency of human capital accumulation and thus the long-run growth.

This paper contributes to three streams of literature. The first is built upon the vast literature on the EKC hypothesis, with an attempt to enhance our understanding with regard to the interaction between economic growth and environmental degradation. After Grossman and Krueger (1991) and Panayotou et al. (1993), significant efforts have been made to provide a theoretical underpinning for the EKC pattern (Stokey, 1998; Andreoni and Levinson, 2001; Smulders, 2006; Brock and Taylor, 2010; Figueroa and Pasten, 2015; Hart, 2020). They argue that the scale effect dominates when people are poor, whereas the technique effect dominates when people become rich. Then, the increasing willingness to pay (WTP) for clean environment makes the implementation of expensive clean technology feasible. However, far too little attention has been paid to the feedback mechanism—pollution stock negatively affects human capital accumulation by weakening human's health and the efficiency in the education and research sector. A theoretical work that highlights this mechanism in an endogenous growth model is undertaken by Bosi and Ragot (2013). A large and growing body of literature has shown empirical evidence on this feedback mechanism, but the theoretical discussions on this topic is far from sufficient.

The EKC hypothesis also inspires many economists to empirically examine the relationship between economic growth and pollution. Different measurements of environmental degradation are used, and different countries and regions are investigated (e.g., Ahmad et al. 2016; Esteve and Tamarit, 2012; Fodha and Zaghdoud, 2010; Jalil and Mahmud, 2009; Holtz-Eakin and Selden, 1995). The best takeaway from this vast empirical literature seems to be a doubt of the existence of a simple and predictable relationship between pollution and income (Copeland and Taylor, 2004; Stern, 2004; Stern, 2017). These empirical endeavors are generally based on reduced-form regressions. The empirical setup is consistent with the EKC and implicitly assumes that pollution is a function of economic growth, without a feedback reversely from pollution to economic growth. In reality, however, the economy always interacts with the environment in a complex and dynamic manner, which cannot be precisely described by a static reduced-form model. As a modest effort to fill this gap, this paper provides a structural model to explore the dynamic interaction between the environment and the economic growth.

Second, this paper contributes to the understanding of the interactions among the environment, human capital, and economic growth in a macroeconomic framework. Our model is based on the endogenous growth theory pioneered by Lucas (1988), Romer (1986, 1990), and Rebelo (1991), in which knowledge and human capital accumulation serve as drivers of growth. The endogenous growth model has been exploited extensively in discussing environment and growth issues (Ligthart and van der Ploeg, 1994; Bovenberg and Smulders, 1995; Byrne, 1997; Stokey, 1998; Goulder and Mathai, 2000). Different from previous studies, in this paper, pollution is a stock variable and exerts external costs on education and research sector. As such, we made the feedback mechanism clear in our model—pollution negatively affects long-run economic growth though the damages on human capital accumulation, a step forward from earlier dynamic models (Brock and Taylor, 2010; Criado et al., 2011; Bosi and Ragot, 2013; Lopez and Yoon, 2014). In this paper, we present a different pattern in which the dirty economy experiences temporary prosperity in the early stage but gradually loses its engine for growth and stagnates at a low-level equilibrium because of inadequate human capital accumulation.

Third, our model characterizes another element that is often ignored by the EKC literature, that is, the irreversibility of environmental degradation. Stokey (1998) theoretically explores the cumulative effects of past pollution, but she assumes that environmental damage is self-correcting and has no effect on production activities, by which the EKC curve ensures. Nevertheless, the reversibility varies with the type of pollution. Some types of pollution, such as sulfur dioxide (SO_2) in the air and COD in the water, might be naturally removed, but some are prohibitively expensive to remove, such as soil contamination, climate change, and loss of biodiversity, many of which would become a permanent constraint for long-run development.

Last but not least, we compare the dirty and clean paths of development in a decentralized system with those in a social optimal system as benchmark. An important departure from previous work is that we emphasize both the short-run and the long-run dynamics. Previous studies place more emphasis on the long-run equilibrium, for example, balance growth rate or steady state (Gradus and Smulders, 1993; Bovenberg and Smulders, 1995; Byrne, 1997), except that Klarl (2016) places more weight on the transition dynamics relative to the equilibrium behavior in policy design. In this paper, we also particularly discuss more on the short-run transition dynamics because it links to officials' incentives for career promotions, a reason why the dirty technology is often initially chosen.

The rest of the paper proceeds as follows. Section 2 presents the model. Section 3 calibrates the structural parameters. Section 4 simulates the model and conducts a quantitative analysis on the transition dynamics and equilibria. Section 5 discusses policy interventions. Section 6 provides a further discussion. Section 7 concludes the paper.

2. Model

This section presents a dynamic model to highlight that an economy loses its engine for long-run economic growth through the mechanism of pollution-induced inefficiency of human capital accumulation. Here, human capital represents educated or trained employees or knowledge itself. We extend a standard endogenous growth model in the following manners: pollution from manufacturing sector accumulates over time; and it exerts external costs on knowledge-producing activities by reducing the productivity of the education and research sector.

2.1. Decentralized dirty economy

Time is infinite and discrete, indexed by $t = 0, 1, \cdots$. The economy is inhabited by a continuum of households, who consume goods, supply labor, and accumulate physical capital and human capital; a continuum of firms that produce consumption goods and emit pollution; and a continuum of education and research institutions that produce human capital. All the markets are competitive.

2.1.1. Household

A representative household consists of a continuum of agents, each of whom can be employed either in the manufacturing sector or the education and research sector. Total labor provided by the household is given by $L = l_{yt} + l_{ht}$, where l_{yt} and l_{ht} stand for the labor allocated to manufacturing sector and education and research sector, respectively. The household accumulates both physical capital k_t and human capital h_t .

Income can be used on a one-to-one basis for consumption c_t and physical capital accumulation; it can also be used on human capital accumulation, which is priced at p_{ht}, measured by consumption goods. In the polluting economy, pollution x_t causes disutility to the household. By choosing consumption, capital, and human capital, the household maximizes its expected present value of utility over an infinite horizon:

$$\max_{\{c_t,k_{t+1},h_{t+1}\}} \sum_{t=0}^{\infty} \rho^t \left(\frac{c_t^{1-\sigma}-1}{1-\sigma} - \frac{Dx_t^{\gamma}}{\gamma} \right),$$

subjects to the budget constraint:

$$c_t + k_{t+1} - (1-\delta_k)\,k_t + p_{ht}\left[h_{t+1} - (1-\delta_h)\,h_t\right] = r_t k_t + w_{yt}(l_{yt}+l_{ht}) + w_{ht}h_t + \pi_{yt} + \pi_{ht} + T_t, \tag{1}$$

where $\rho \in (0,1)$ is the discount rate for the future, $\sigma > 0$ is the relative risk aversion parameter, $D > 0$ is an exogenous parameter that describes the magnitude of the disutility, and $\gamma > 1$ is the elasticity parameter in the disutility function of pollution. The left-hand side of equation (1) represents household's spending on consumption and investments in physical capital and human capital, and the right-hand side represents household's disposable income; w_{yt}, w_{ht}, and r_t represent labor wage, human capital wage, and capital rent, respectively. Total income also includes firm profits π_{yt}, institutional profits π_{ht}, and a lump-sum rebate T from tax on industrial pollution. Denoting λ_t as the Lagrangian multipliers of the budget constraint, the optimal conditions for $\{c_t, k_{t+1}, h_{t+1}\}$ are given by:

$$c_t^{-\sigma} = \lambda_t, \tag{2}$$

$$\lambda_t = \rho\lambda_{t+1}\left(r_{t+1} + 1 - \delta_k\right), \tag{3}$$

$$p_{ht}\lambda_t = \rho\lambda_{t+1}\left[w_{ht+1} + p_{ht+1}\left(1-\delta_h\right)\right]. \tag{4}$$

Equation (2) is the optimal condition for consumption. Equations (3) and (4) are Euler equations for the optimal intertemporal decisions on physical capital and human capital, respectively.

2.1.2. Firm

In each period, output y_t is produced by combining physical capital, human capital, and labor. The production function takes the Cobb–Douglas form, $y_t = A_d k_t^{\alpha} h_t^{1-\alpha} {l_{yt}}^{1-\alpha}\left(1-z_t\right)$, and $0 < \alpha < 1$. A_d is the technical parameter in the dirty economy and remains time-invariant. $z_t \in [0,1]$ denotes the level of pollution abatement. A lower value of z_t yields more outputs but more pollution. $z_t = 0$ corresponds to the potential output in the most polluting way. The production function exhibits neoclassical properties: positive and diminishing marginal products of each input and satisfies the Inada conditions.

In reality, environmental pollution accumulates over time and has cumulative effects on future economic activities. To capture this fact, we assume that pollution x_t is a stock variable, $x_{t+1} = (1-\eta)\,x_t + (1-z_t)^{\beta-1}\,y_t$, where η denotes the nature's self-correcting capacity (Stokey, 1998) and $\beta > 1$. The second term $(1-z_t)^{\beta-1}\,y_t$ reflects the newly emitted pollution which increases with the output and decreases with the abatement z_t. The government controls pollution by taxing firms' newly emitted pollution at the rate of ϕ. We assume $\phi \in [0,+\infty)$, implying that the government can stop production if the society's WTP for the environment runs to infinity.

Since there is a continuum of firms in the manufacturing sector, in the decentralized economy, each firm is small and does not take pollution externalities into account when making production decisions. In each period, a representative firm chooses k_t, l_{yt}, h_t, and z_t to maximize its profit:

$$\pi_{yt} = \max_{\{k_t,l_{yt},h_t,z_t\}} A_d k_t^{\alpha} h_t^{1-\alpha} {l_{yt}}^{1-\alpha}\left(1-z_t\right) - r_t k_t - w_{yt}l_{yt} - w_{ht}h_t - \phi A_d {k_t}^{\alpha} {l_{yt}}^{1-\alpha} {h_t}^{1-\alpha}\left(1-z_t\right)^{\beta}.$$

The optimal conditions with respect to k_t, l_{yt}, h_t, and z_t are given by:

$$r_t = \alpha A_d k_t^{\alpha-1}\left(h_t l_{yt}\right)^{1-\alpha}\left(1-z_t\right)\left[1-\phi\left(1-z_t\right)^{\beta-1}\right], \tag{5}$$

$$w_{yt} = (1-\alpha)\, A_d k_t^{\alpha} h_t^{1-\alpha} {l_{yt}}^{-\alpha} (1-z_t) \left[1 - \phi\, (1-z_t)^{\beta-1}\right], \tag{6}$$

$$w_{ht} = (1-\alpha) A_d k_t^{\alpha} h_t^{-\alpha} {l_{yt}}^{1-\alpha} (1-z_t) \left[1 - \phi\, (1-z_t)^{\beta-1}\right], \tag{7}$$

$$\phi\beta = (1-z_t)^{1-\beta}. \tag{8}$$

In this setting, the firm's problem does not involve intertemporal elements, and hence it maximizes static profit in each specific period. Equations (5), (6), and (7) show that, for each input, its market price equals its marginal product. Taking the pollution tax rate as given, the firm chooses an optimal pollution abatement level according to condition (8).

2.1.3. Education and research sector

The education and research institution hires labor to cultivate human capital and produces knowledge. The process of human capital accumulation is given by:

$$\Delta h_{i,t+1} = B l_{i,ht}\, (1+x_t)^{-\xi}\, h_t, \tag{9}$$

where $\xi \geq 1$ measures the extent to which pollution decreases the efficiency of human capital accumulation in light of the empirically plausible evidence. B denotes the technical parameter and remains time-invariant, and $l_{i,ht}$ denotes the amount of labor working in each education and research institution i.[1] $\Delta h_{i,t+1} = h_{i,t+1} - (1-\delta_h)\, h_{i,t}$ is the amount of human capital produced in period t. δ_h is the depreciation rate of the stock of human capital. The newly produced human capital in the clean economy is $\Delta h_{i,t+1} = B l_{i,ht} h_t$.[2]

An individual institution chooses the optimal level of l_{ht} to maximize profit:

$$\pi_{i,ht} = \max_{\{l_{ht}\}} p_{ht} B\, (1+x_t)^{-\xi}\, l_{i,ht} h_t - w_{yt} l_{i,ht}.$$

The optimal condition for $l_{i,ht}$ is given by:

$$p_{ht} B\, (1+x_t)^{-\xi}\, h_t = w_{yt}. \tag{10}$$

The allocation of labor is determined by the non-arbitrage condition: working in the manufacturing sector and the education and research sector earns the same wage w_{yt}. The existence of pollution, however, discourages labor from working in the education and research sector because it decreases the marginal productivity of this sector. As a result, compared to the clean economy, a smaller proportion of labor will be devoted to the education and research sector; and human capital accumulation is relatively inadequate. This is more of a phenomenon as pollution accumulates and finally traps the economy in a slump where growth loses its internal engine–human capital accumulation.

In equation (9), there are three mechanisms playing important roles. The first mechanism is driven by learning by doing effects. As Romer (1986) proposed, the productivity improvement of human capital accumulation comes from the accumulation itself. More specifically, an education and research institution can simultaneously produce human capital and learn how to produce more efficiently. The second mechanism is driven by spillover effects. As each institution i expands $h_{i,t}$, h_t rises accordingly and results in spillover effect that raises the productivity of the entire sector (Lucas, 1988). Nevertheless, since an individual institution is too small to consider its own contribution to the aggregate, in the decentralized economy, it takes h_t as given and fails to internalize the spillover effects. The third mechanism is driven by pollution externalities, because of which both learning by doing and spillover effects are largely muted over time, ruling out the possibility of endogenous economic growth.

2.1.4. Decentralized equilibrium

Throughout the paper, we define the balanced growth path (BGP) as a situation in which all the variables grow at a positive constant rate. If the growth rate is zero, we define it as steady state. Equations (1)–(10) define the full dynamics of the decentralized dirty economy. A decentralized general equilibrium consists of the steady-state consumption c^*, capital k^*, human capital h^*, output y^*, labor allocations $\left\{l_h^*, l_y^*\right\}$, pollution x^*, abatement z^*, and interest rate r^* such that: (*i*) taking prices as given, allocations solve the maximization problem of each agent; and (*ii*) the prices clear the markets for capital, human capital, labor, and final goods. Appendix A provides the description of the steady states.

2.1.5. Social optimal equilibrium

To offer insights for policy interventions, we discuss a social optimal equilibrium that the dirty economy can achieve. All the notations remain the same. A social planner maximizes social benefit:

$$\max_{\{c_t, l_{ht}, k_{t+1}, h_{t+1}, x_{t+1}\}} \sum_{t=0}^{\infty} \rho^t \left(\frac{c_t^{1-\sigma} - 1}{1-\sigma} - \frac{D{x_t}^{\gamma}}{\gamma} \right),$$

subjects to the budget constraint:

$$c_t + k_{t+1} - (1-\delta_k)\, k_t = A_d k_t^{\alpha} h_t^{1-\alpha} (1 - l_{ht})^{1-\alpha} (1 - z_t), \tag{11}$$

the law of motion of human capital accumulation:

$$h_{t+1} = B l_{ht} (1 + x_t)^{-\xi} h_t + (1 - \delta_h)\, h_t, \tag{12}$$

and the law of motion of pollution accumulation:

$$x_{t+1} = (1-\eta)\, x_t + A_d {k_t}^{\alpha} \left(L - l_{ht}\right)^{1-\alpha} {h_t}^{1-\alpha} (1 - z_t)^{\beta}. \tag{13}$$

Different from the agents in the decentralized economy, social planner can fully take the externalities of pollution from the manufacturing sector, as well as the spillover effects from the education and research sector into consideration. In particular, firms are required to abate pollution at the cost of production until the external costs on education and research sector are completely internalized. A social optimal equilibrium consists of the steady states of consumption c^*, capital k^*, human capital h^*, output y^*, labor allocations $\left\{l_h^*, l_y^*\right\}$, pollution x^*, and abatement z^*, such that allocations solve the social optimization problem. Appendix B provides the description of the steady states.

2.2. Decentralized clean economy

The clean economy is a special case of the dirty economy, in which pollution and its corresponding influences do not exit. Any divergence between the clean economy and the dirty economy can be interpreted as a consequence of pollution. For simplicity, we briefly present the general equilibrium put the description of agents' problems in appendices.

2.2.1. Decentralized equilibrium

As we remove the law of motion of pollution accumulation, the externality of pollution no longer exists. The decentralized general equilibrium of a clean economy consists of the BGPs of consumption c_t, capital k_t, human capital h_t, output y_t, and labor allocations $\left\{l_h^*, l_y^*\right\}$, such that (*i*) taking the prices as given, the allocations solve the optimization problem of each agent; and (*ii*)

Table 1. A summary of the four types of economic development paths

	Social optimal economy	Decentralized economy
Clean path	First-best economic growth path. No pollution externality. Two mechanisms: (i) learning by doing and (ii) spillover effects in education and research sector.	As a positive externality, spillover effect fails to be internalized into individual decisions.
Dirty path	Pollution acts as a negative externality that damages mechanism (i) and (ii).	Pollution acts as a negative externality that damages mechanism (i) and (ii) neither pollution externality nor spillover effect is internalized.

the prices clear the markets for capital, human capital, labor, and final goods. The dynamic system is defined in Appendix C.

2.2.2. Social optimal equilibrium

In the social optimal clean economy, the first-best economic equilibrium is achieved with spillover effect internalized. This social optimal general equilibrium consists of the BGP of consumption c_t, capital k_t, human capital h_t, output y_t, and labor allocations $\left\{l_h^*, l_y^*\right\}$, such that the allocations solve the social optimization problem. The dynamic system is defined in Appendix D. In addition, since the clean economy exhibits endogenous growth properties and does not converge to steady states. We elaborate on how the clean economy finds an optimal way toward its BGP from an arbitrary starting point in Appendix E. In equilibrium, since labor allocations $\{l_{ht}, l_{yt}\}$, c-k ratio $\frac{c_t}{k_t}$, and k-h ratio $\frac{k_t}{h_t}$ remain stable on the BGP, we can rearrange the model and construct a new dynamic system, through which, as long as the labor allocation, c-k ratio, and k-h ratio converge to their own steady states, the clean economy can reach its own BGP.

2.3. A summary of the model

In order to present a clear comparison, we summarize the characteristics of above four types of economic growth models in Table 1.

The key insights are as follows. The social optimal clean economy achieves the first-best economic growth because the externalities are completely taken into account. The endogenous growth comes from the mechanisms of learning by doing (contributing to its own efficiency) and the internalized spillover effect (contributing to the efficiency of the entire education and research sector), which relaxes the constraint of diminishing returns to capital. The decentralized clean economy is also capable of endogenous growth, but to a smaller extent, because the spillover effect in the education and research sector is ignored in individual decisions. However, the social optimal dirty economy loses its engine for sustainable growth in that pollution from manufacturing sector exerts negative externalities on the productivity of the education and research sector. As a result, a larger proportion of labor will be allocated to manufacturing sector, which further weakens the learning by doing and spillover effects in the education and research sector. The decentralized dirty economy traps at a lower equilibrium than the social optimal dirty economy because individual agents neither internalize the pollution externalities from manufacturing sector nor the spillover effects from the education and research sector. Therefore, the economy loses its engine for endogenous growth, which implies that pollution is likely to rule out sustainable growth through the human capital channels.

Table 2. Parameter calibration

Panel A. Following literature and assumption		
α	Capital share	0.5
δ_k	Capital depreciation rate	0.05
δ_h	Human capital depreciation rate	0.05
ρ	Discounting factor	0.96
σ	Inverse intertemporal substitution elasticity in CES	0.9
B	Technical parameter in human capital accumulation	0.2
L	Total labor (standardized to 1)	1
D	Parameter in disutility function (standardized to 1)	1
ϕ	Pollution tax rate (based on an assumption)	1.5
η	Natural purification rate (based on an assumption)	0.5
Panel B. Estimates from data		
A_c	TFP in clean economy (ASIF 1998–2013)	3.25
A_d	TFP in dirty economy (ASIF 1998–2013)	3.32
Panel C. Fits data moments		
β	Parameter in pollution generation function (ESR 1998–2012)	1.98
ξ	Parameter in human capital accumulation	1.45
γ	Parameter in disutility function	1.98

3. Parameter calibration

We calibrate the model parameters based on China's economy. The calibration is summarized in Table 2.

3.1. *Parameters in Human Capital Accumulation {ξ, B}*

The critical parameter ξ represents the extent to which pollution diminishes human capital accumulation. The process of human capital accumulation can be rewritten as $\frac{\Delta h_{t+1}}{h_t} = B(1+x_t)^{-\xi} l_{ht}$, where Δh_{t+1} represents the newly produced human capital and $\frac{\Delta h_{t+1}}{h_t}$ represents the average human capital productivity in the education and research sector. The parameter ξ is essentially an elasticity of the efficiency of human capital accumulation $B(1+x_t)^{-\xi}$ on pollution.

In the empirical analysis, we adopt a linear econometric model to investigate the effects of pollution on human capital productivity. The specification is given by:

$$\ln HumanCap_{it} = \beta_0 + \beta_1 \ln Pollution_{it} + \beta_2 W_{it} + \mu_i + \phi_t + \sigma_{it}, \tag{14}$$

where i and t denote firm and year, respectively; $HumanCap_{it}$ represents human capital's productivity, corresponding to the term $B(1+x_t)^{-\xi}$ in our theory. We measure the human capital as employees who are engaged in knowledge-producing activities. X_{it} represents air pollution measured by $PM_{2.5}$. β_1 is of our interest, and it represents how pollution affects human capital productivity. Error term (ε_{it}) absorbs the unobservable factors varying with year and firm-level characteristics. Firm fixed effect (μ_i) is used to control for time-invariant firm-level characteristics. Year fixed effects (ϕ_t) are included to control for macro shocks like national policies that affect human capital's productivity. W_{it} denotes a vector of firm-level and meteorological control variables, including firm age and total assets, hours of sunlight, wind speed, and precipitation.

The dataset includes several sources: firm-level human capital and innovation information, county-level air pollution indicator $PM_{2.5}$, and county-level thermal inversion. The firm-level human capital data come from the *Surveys of Science and Technology Activities of Industrial Firms* (SSTA) database. The SSTA is conducted by China's National Bureau of Statistics (NBS). Based on the SSTA database, human capital productivity is measured by total innovation per unit of human capital. Here, innovation is regarded as the outcome of human capital.[3] The publicly available data $PM_{2.5}$ and thermal inversion are monitored by the Earth Observing System (EOS) of the National Aeronautics and Space Administration (NASA). We aggregate their annual average value from the grid to the county level.

The exposure to $PM_{2.5}$ could be endogenous in different ways, such as unobserved social and political factors varying with time across regions. To address the potential endogeneity of pollution, we exploit a two-stage least squares (2SLS) approach by which we first use thermal inversion to instrument pollution ($PM_{2.5}$) and replace the independent variable in equation (14) with instrumented $PM_{2.5}$. Thermal inversion as a meteorological phenomenon is correlated with $PM_{2.5}$ but uncorrelated with production activities. It occurs when the temperature at the upper atmospheric layer is higher than that of the lower layer, which prevents dissipating $PM_{2.5}$ locally near the ground. The specification of first-stage estimation is defined as:

$$\ln X_{it} = \alpha_0 + \alpha_1 \ln V_{it} + \alpha_2 W_{it} + \tau_i + \theta_t + \epsilon_{it}, \tag{15}$$

where V_{it} denotes thermal inversion at firm i's location in year t, respectively.

Table 3 reports the 2SLS results from the linear specifications in equations (14) and (15). Column (1) suggests that thermal inversion is a reliable predictor for $PM_{2.5}$. Column (2) shows that a 1% increase of $PM_{2.5}$ significantly reduces human capital productivity by 0.149 innovation per capita. In calibration, we set the value of $\xi = 1.45$ by matching the simulated moments with the empirical facts in Table 3. Since choosing different measures of pollution (such as the mean or aggregate $PM_{2.5}$, PM_{10}) and thermal inversion (such as the frequency or the level at different atmospheric layers) might drive the estimate either upward or downward, we attempt to figure out how the economic pattern varies with ξ. Furthermore, we conduct a sensitivity analysis on parameter ξ. As shown in Figure F1, a larger value of ξ diminishes human capital accumulation to a larger extent. In the short run, the economic path is a bit higher than the baseline because the equilibrium condition of labor wage leads to a large proportion of labor flowing to final goods production. However, in the long run, less human capital accumulation leads to a significantly lower economic equilibrium than the baseline.

We now discuss the calibration of parameter B. In our model, h_t represents the aggregate human capital in the education and research sector. It contributes to the productivity of each individual institution. B is the technical parameter representing the scale of spillover effects of h_t. It also contains the learning-by-doing effects of $h_{i,t}$: an individual institution can simultaneously produce human capital and learn how to produce efficiently. Nevertheless, we do not have access to reliable information about the technical parameter that represents both the spillover effects and learning-by-doing effects in the education and research sector in the background of China. In literature, Chyi et al. (2012) use data from 92 Hsinchu Science Park (HSP) firms listed publicly in Taiwanese stock markets during 2000–2004 and find that the level of knowledge spillovers to sales ranging from 0.166 to 0.525. While this estimation cannot precisely reflect the parameter value of B in our model, it provides a reasonable reference for the magnitude of spillover effects. Thus, we set the parameter value of B to 0.2, which is within the range of the findings by Chyi et al. (2012). The model predicts that a larger value of B will increase the productivity of the education and research sector; more labor will flow to this sector to produce human capital until labor wage equals that in the manufacturing sector. As a result, the long-run equilibrium will be higher because of the higher level of human capital accumulation.

Table 3. Short-run effects of air pollution on human capital productivity (2SLS)

First stage	
Dependent variable	$PM_{2.5}$
	(1)
Thermal inversion	0.168^{***}
	(0.005)
Second stage	
Dependent variable	Human capital productivity
	(2)
$PM_{2.5}$	-0.149^{***}
	(0.065)
Firm fixed effects	Yes
Year fixed effects	Yes
Firm controls	Yes
Weather controls	Yes
KP F-statistic	452.1
Sample size	74,664

Notes: Human capital productivity is measured by total innovations divided by human capital stock. Firm controls include firm age and firm total assets, and weather controls include precipitation, temperature, and hours of sunlight. Standard errors are reported in parentheses. $***$ denotes significance at the 1% level.

3.2. *Parameters in Pollution Function: {η, β}*

As described in the manuscript, the natural purification rate η is set to be 0.5. The natural purification rate represents that pollution dissipates or is naturally purified in a certain percentage. Since it depends on various meteorological factors, we do not have sufficient information to calibrate it. For robustness, we further assign different values to η and check how it affects the simulated patterns.

We then calibrate β to fit the facts that firm's pollution emission intensity is 15.98 kg per 10,000 CNY, defined as $\frac{\Delta x_{t+1}}{A_d {k_t}^{\alpha}(L-l_{ht})^{1-\alpha} {h_t}^{1-\alpha}(1-z_t)}$, which is constructed based on *Environmental Survey and Reporting Database* (ESR) from 1998 to 2012. It yields $\beta = 1.98$. We use chemical oxygen demand (COD) as a pollution indicator because it is well recorded and commonly targeted by environmental policies. In the revision, as a robustness check, we use sulfur dioxide (SO_2) as an air pollutant indicator to do the calibration. It yields very similar values for η (0.5) and β (1.91). Furthermore, we conduct a sensitivity analysis so that we can see how the parameterization on parameter η affects the value of parameter β and then how the two parameters affect the simulated pattern. Figure F.2 shows that, given a set of varying β and η, the predictions of the model are generally unchanged.

3.3. *Parameters in Disutility: {D, γ}*

In the environmental literature, $\frac{\Delta c}{\Delta x} \equiv -\frac{\partial U(c,x)/\partial x}{\partial U(c,x)/\partial c}$ represents the household's WTP for the environment. Our model follows the conventional theoretical literature to assume a convex disutility function. Ito and Zhang (2020) find that a household is willing to pay \$1.34 annually to remove 1 $\mathrm{mg/m^3}$ of air pollution (PM_{10}). In calibration, parameter D is standardized to 1 and γ is calibrated to fit the facts that the WTP is \$1.34 at steady states. Specifically, the marginal disutility is $\frac{\partial U(c,x)}{\partial x} = 0.68$ and the marginal utility is $\frac{\partial U(c,x)}{\partial c} = 0.24$ at steady states. We assume that the exchange rate between the US dollars and CNY is 7.1, and each household has 3.3 family members as sampled in the *China Family Panel Studies Database* (CFPS). The simulated moments fit well and yield WTP = \$1.32 at the steady states.

3.4. Parameters in Production Function: $\{A_c, A_d\}$

We use the firm-level Annual Survey of Industrial Firms (ASIF) database from 1998 to 2007 to construct industrial firms' total factor productivities (TFPs). A_c and A_d represents the productivity of the manufacturing sector in the clean and dirty economies, respectively. The ASIF database is conducted and maintained by China's NBS, which covers all state-owned enterprises and all private enterprises with annual sales above 5 million RMB. The total output value included in ASIF accounts for approximately 90% of the total industrial output value of China, covering more than 40 two-digit-code industries. We clean and process the data following the procedure provided by Brandt et al. (2012): calculating real capital stock by using the perpetual inventory method, deflating the value of inputs, outputs, and wages by four-digit industrial code output deflators and input deflators, and correcting the misrecorded firm information. Even though many approaches can be used to calculate TFP, we choose the commonly used semiparametric algorithms suggested by Levinsohn and Petrin (2003), which accounts for the simultaneity and selection biases in estimating the capital and labor coefficients by using intermediates as the proxy for unobservable shocks. According to the official definition by China's Environmental Protection Agency (MEP), firms in ASIF can be categorized into polluting industries and nonpolluting industries. We set $A_c = 3.25$ and $A_d = 3.32$ in light of the average TFP of polluting industries and nonpolluting industries, respectively.

The remaining set of parameters $\{\alpha, \delta_k, \delta_h, \rho, \sigma, L\}$ is calibrated following the mainstream macroeconomic literature. In China's economy, labor's share of value added is 0.55 according to the NBS. Following Hsieh and Klenow (2009) and Brandt et al. (2012), we set parameter $\alpha = 0.5$. The discount factor is set to $\rho = 0.96$ to generate a steady-state real interest rate of 0.04. We set the capital depreciation rate and human capital depreciation rate to $\delta_h = 0.05$ and $\delta_h = 0.05$, respectively. The parameter in the utility function is set to $\sigma = 0.9$, implying that the intertemporal substitution elasticity in the CES function is 1.11. Total labor L in the economy is standardized to 1.

4. Transition dynamics: short-run and long-run development

In this section, we simulate the transition dynamics of the four types of economic development paths: decentralized dirty economy, social optimal dirty economy, decentralized clean economy, and social optimal clean economy. From the perspective of policy, the whole society concerns about the long-run equilibrium, whereas government officials might place more weight on the short-run dynamics for career promotions. Taking the realistic situation into account, we assume that the dirty economy starts with a higher development level than the clean economy, because the introduction of polluting industries can attract more investors and capitals in the early stage, and it can avoid costly clean production lines and pollution abatement investment, which is a bonus at the expense of environmental quality and natural resources.

In Figure 1, we first focus on the social optimal system and compare the transitional dynamics between the dirty and the clean economies. The model predicts that the dirty path performs better in terms of output and investment in the short run. First, it relies on the assumption that the

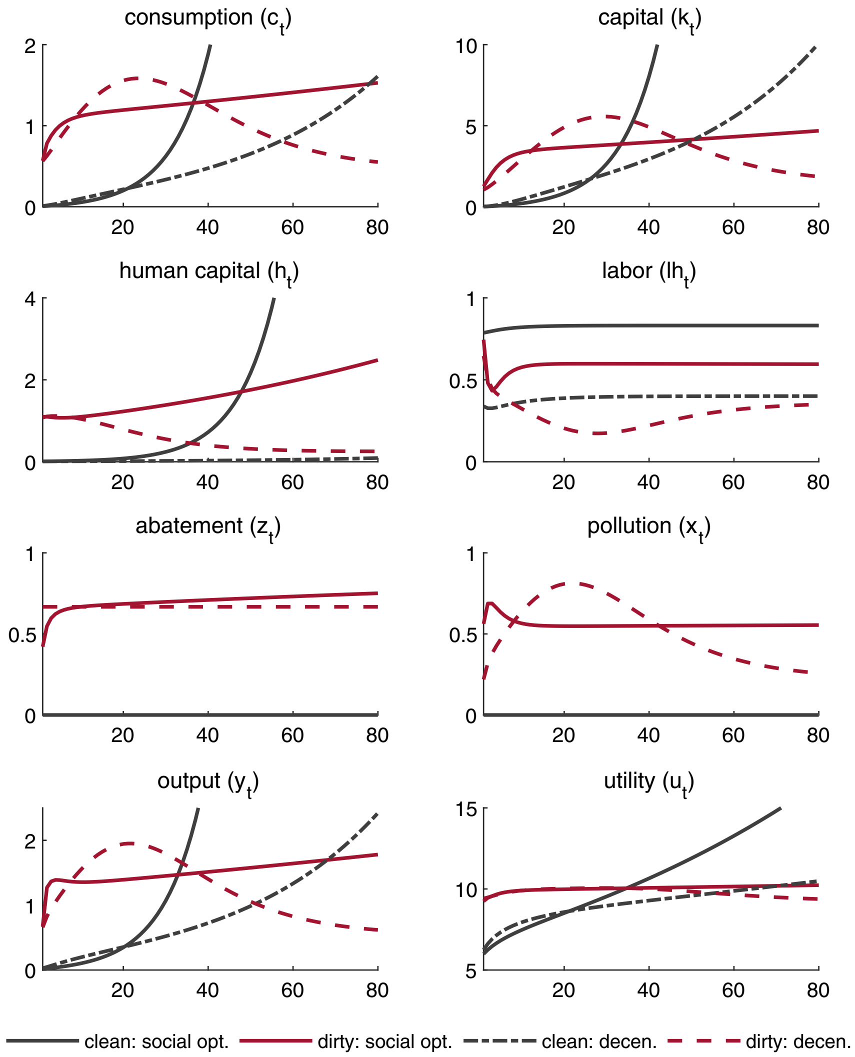

Figure 1. Transition dynamics of four types of economic growth paths.

Notes: The simulation of the four economic paths is based on the calibrated parameters presented in Table 2. In period 0, the dirty economy starts with capital $k_0 = 1$ and human capital $h_0 = 1$; the clean economy starts with capital $k_0 = 0.1$ and human capital $h_0 = 0.1$.

development of a pollution-intensive industry can attract more capital and human capital in the early stage of development, and the productivity parameter is higher in the polluting industries. The calibrated simulation has taken this assumption into account. While setting the initial value affects the catch-up dynamics, it does not change the model predictions. Second, since pollution decreases the productivity in the education and research sector, and the marginal productivity of labor is higher in the manufacturing sector of the dirty economy, a larger proportion of labor will be endogenously allocated to the manufacturing sector, and it thus contributes a higher level of outputs over the short run. The cost of the short-run prosperity is that human capital accumulation is not sufficient to overrule the diminishing returns to capital, which eventually brings the economy to a zero-growth steady state. Comparatively, in the social optimal clean economy, even though output, consumption, and capital grow slowly in the beginning, they are capable of sustainable growth in the long run because human capital accumulation relaxes the constraint of diminishing returns to capital.

We then focus on the differences between the decentralized and the social optimal dirty economies. In Figure 1, the social optimal dirty economy performs better than the decentralized dirty economy over the long run. This is because the negative externalities of industrial pollution on human capital accumulation is not fully considered in the decentralized scenario. The education and research sector cares about pollution but has no control over it. From a social point of view, firms produce too much pollution in the decentralized dirty economy.[4] Moreover, an individual education and research institution neglects the fact that an increase in its own human capital stock can contribute to the productivity of the entire sector. From a social point of view, each institution makes inadequate investments into human capital accumulation in the decentralized economy. As a result, the two types of externalities weaken the working productivity in the education and research sector. Comparatively, the social optimal dirty economy is able to the eliminate these externalities by mandating pollution abatement in the manufacturing sector and internalize the spillover effects in the education and research sector. Over the long run, therefore, the decentralized dirty economy falls below the social optimal dirty economy.

5. Policy analysis: switch, taxation, and subsidies

We have so far studied the development paths of dirty and clean economies in different scenarios. This section analyzes how policy interventions change the evolutionary path of a dirty economy. Two types of policy intervention are of interest. First, a successor that takes over a dirty economy and intends to shift the economy to a clean path of development. Second, a policymaker uses tax or subsidy policies to mitigate the adverse effects of pollution on human capital accumulation. This analysis might be of interest to a central government that wants to constrain the local governments' shortsighted behavior or a local government that attempts to pursue a balance between short-term economic prosperity and environmental protection.

5.1. Switch from a dirty path to a clean path

As shown in Figure 1, the dirty economy is overtaken by the clean economy and finally traps at a low level of development. We assume that a local government can steer its dirty path toward a clean path and save itself from stagnation. Suppose that, on the dirty path, the government decides to switch when the economy starts to stagnate. In addition, we assume that pollution stock from the dirty economy can be gradually and completely removed at an annual purification rate of 0.5.

However, in fact, the transition friction is nontrivial. With regard to market and financial factors, Dong et al., (2022) show that both search friction and financial friction hinder the reallocation of used capital. Also, Dong (2022) proposes that financial friction reduces the matching efficiency in the labor market, especially over business cycles. This implies that capital and labor that have been used in dirty industries can rarely be perfectly employed by clean industries. In addition, the transitioning from dirty resources to clean resources adds another layer of difficulty to the switch. Kambourov and Manovskii (2009) find that an employee loses his or her human capital and experiences an 18% drop in wage after the displacement in occupation. For instance, an expert who masters at dirty technology may find difficulties in adapting to a new job in the clean industry. And a dirty production line is almost useless in a clean economy, and it is usually sold at the price of scrap metal. Moreover, the dirty economy also needs to pay a large amount of money for clean technologies and production lines that can support its switch to a clean path, which would further tightens its borrowing constraint and increase the financial friction. Adding up the above costs, we assume that the dirty economy has to sacrifice what it has obtained and

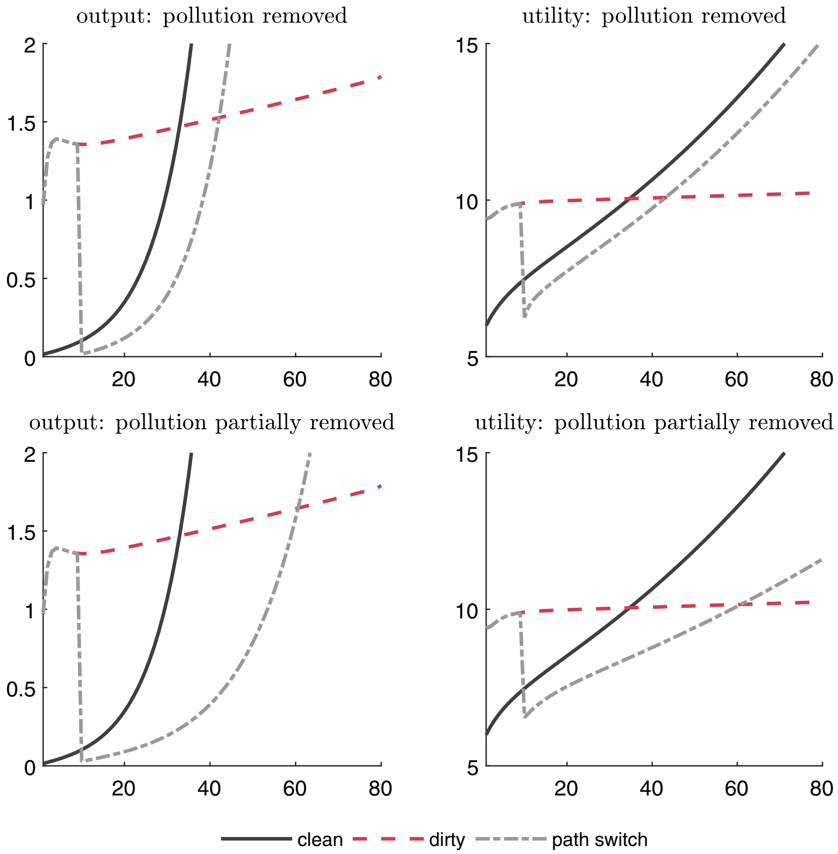

Figure 2. The switch to a clean path with pollution removed.
Notes: The simulation of the three economic paths is based on the calibrated parameters presented in Table 2. The first line corresponds to the case where the pollution is completely removed. The second line corresponds to the case where the pollution is partially removed. For the latter scenario, we assume that 40% of the pollution stock will remain permanently.

switches to the path with a lower economic level compared with the same period of the clean economy.

In Figure 2, the gray lines in the first row show the dynamics and the size of recession during the transition. The economy experiences a dramatic drop and then gradually head toward a transitioned clean path. Another legacy that we should consider is that some types of pollution cannot be completely removed, or the environment is unable to recover from serious damage. We assume that 40% of the pollution stock will remain permanently. As shown in the second row, the existence of permanent pollution makes the growth rate of the transitioned path lower than the case with pollution being completely removed because the long-lasting environmental degradation will permanently reduce the efficiency of human capital accumulation.

Figure 2 suggests that switching from a dirty path to a clean path suffers a long period of economic depression. This corresponds to the reason why, in reality, local officials are reluctant to make a structural transition, especially when economic growth links to their career promotion. Even though the central government has incentives to make the transition, the transitioned economy will always lag behind the clean economy. Worse than that, if the environmental damage

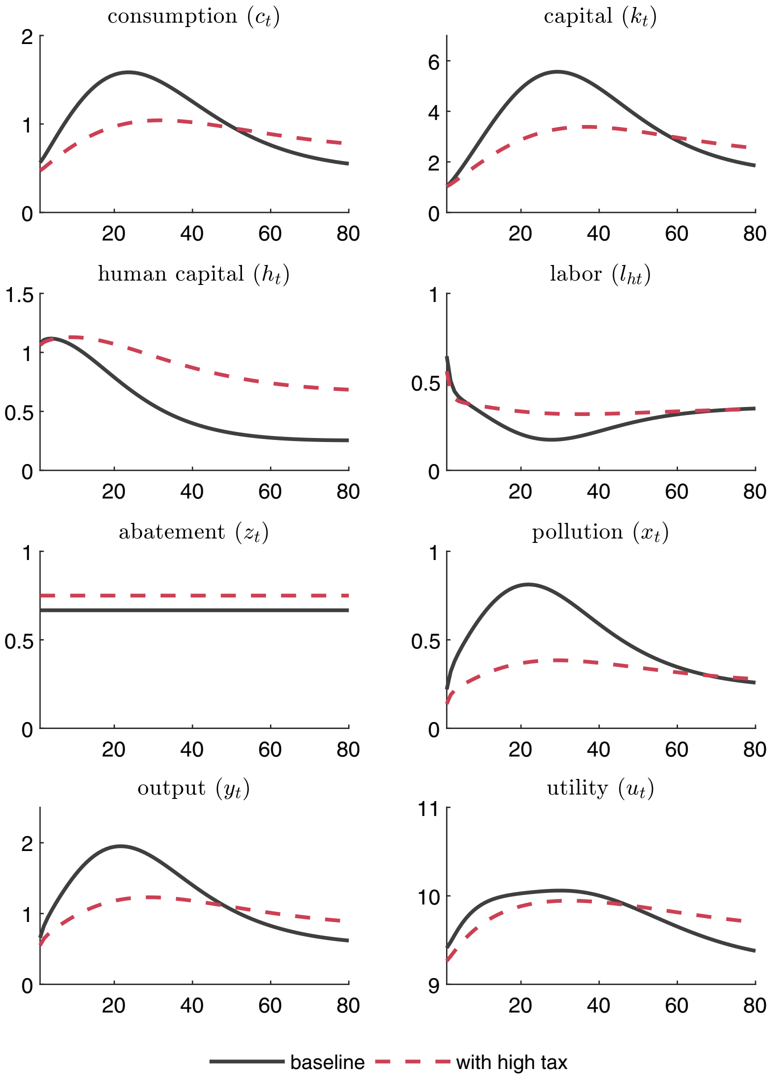

Figure 3. Tax on manufacturing sector.

Notes: The simulation of the two different economic paths is based on the calibrated parameters presented in Table 2. In period 0, the dirty economies start with capital $k_0 = 1$ and human capital $h_0 = 1$..

cannot be completely removed, the transitioned economy will grow even more slowly than the clean economy.

5.2. Taxation on pollution

The social planner in a dirty economy improves social welfare by fully internalizing two types of externalities: pollution externalities and spillover effects of knowledge. In this section, we discuss how the government addresses the externalities using tax and subsidy policies.

We start with the case of addressing pollution externalities by tax policy. In theory, abatement can be set at a level that exactly internalizes the social costs of pollution, which requires the government to implement a tax rate to induce a social optimal abatement level. However, this is unlikely

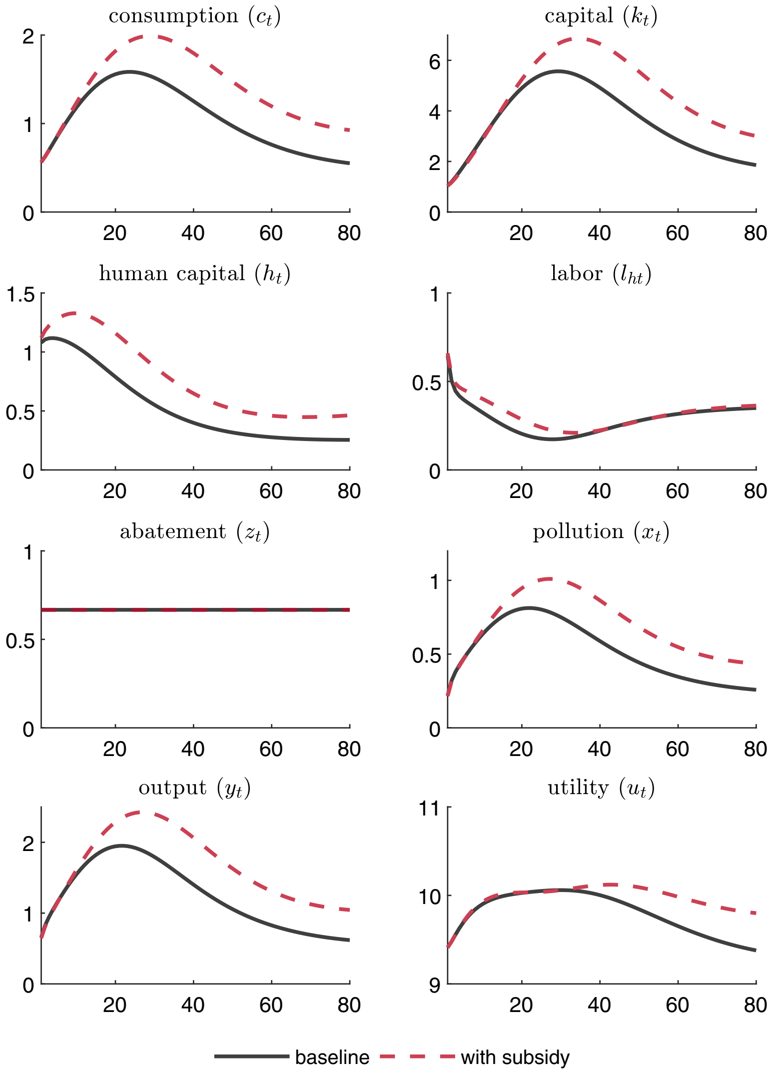

Figure 4. Subsidy on education and research sector.
Notes: The simulation of the two different economic paths is based on the calibrated parameters presented in Table 2. In period 0, the dirty economies start with capital $k_0 = 1$ human capital $h_0 = 1$.

to happen in the real world because it is politically expensive and almost impossible for a government to predict time-varying external cost of pollution (Hart, 2020; Pigou, 1932). For the realistic reasons, we suppose that the government chooses to implement an exogenous tax on pollution generated by manufacturing sector. Figure 3 compares the baseline tax rate $\phi = 1.5$, depicted by the black solid line, with a higher taxation rate $\phi = 2$, depicted by the red dashed line. It indicates that the government faces a trade-off between the short-run and the long-run development in the choices of tax rates. While a higher taxation rate reduces pollution and slows down the economy in the short run, it contributes to a higher equilibrium in the long run, because it reduces the harm on the efficiency of human capital accumulation—the engine for long-run growth.

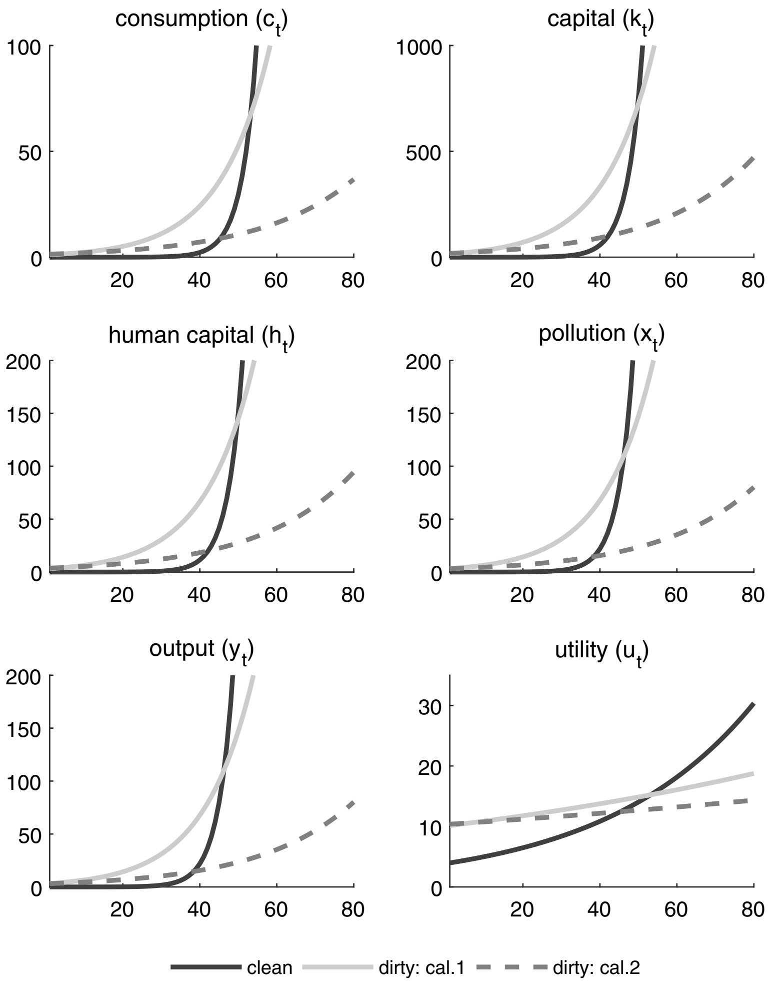

Figure 5. Transition dynamics of clean and dirty economic growth paths.

Notes: "Clean" represents a clean economy with zero pollution. "Cal.1" represents a dirty economy with $\xi = 0.781$ which is calibrated to fit the fact that the economic growth rate is 0.069. "Cal.2" represents a dirty economy with $\xi = 0.835$ for comparison.

5.3. Subsidy on education and research

To address the spillover effects of knowledge, the subsidy on the education and research sector is helpful to raise the private return of human capital and thereby narrow the gap between private and social benefits. We assume that the government subsidizes ψw_{ht} for each unit of human capital. The total wage of human capital is given by $(1 + \psi)\, w_{ht} h_t$. To avoid other distortions, we assume the subsidy is financed by a lump-sum taxation $T = \psi w_{ht} h_t$ from the household.

The subsidy essentially changes the relative returns of capital and human capital as well as the household's total income. Specifically, the intertemporal decisions on physical capital and human capital yield a non-arbitrage condition between physical capital and human capital, $r_{t+1} + 1 - \delta_k = \frac{p_{ht+1}(1-\delta_h)+w_{ht+1}}{p_{ht}}$. The subsidy on w_{ht} implies that the household will invest more in human capital than physical capital and consumption. In Figure 4, we present the transition dynamics with subsidy rate $\psi = 0.3$. The subsidy induces a reduction of labor in the manufacturing sector, which is expected to depress the real economy. Nevertheless, a larger proportion of labor allocated to the education and research sector expands human capital stock, which can accelerate economic growth. The two channels work in opposite directions. Figure 4 shows that, with a subsidy on human capital, the short-term economic performance remains almost the same as those in the baseline model. In contrast, the long-run economic performance saliently dominates that in the baseline model. It implies that while the subsidy on human capital can hardly boost the short-run economy, it can lead to an economic boom in the long run.

6. A further discussion

There are alternative ways to model the interaction among the environment, production, and human capital that can make the long-run economic growth sustainable. In reality, this notion is observably true that the economies keep growing even if they adopt a polluting development path. In theory, it is also feasible to model a polluting but sustainable economy as it depends on how outputs generate pollution and to what extent pollution diminishes human capital accumulation.

As a further discussion, we conduct an exercise by modifying certain model assumptions such that, instead of causing economic stagnation, environmental pollution slows down economic growth over the long run. The quantitative results indicate that the economic sustainability in the model depends on whether human capital accumulation will be exhausted by environmental pollution in the long run.

In particular, we allow sustainable long-run growth for the dirty economy by choosing a relatively small value of the parameter ξ. The simulated transition dynamics are presented in Figure 5. The dirty economy, represented by the gray solid line, starts with higher capital and human capital. Still, it grows noticeably slower than the clean economy, represented by the black solid line. For the comparison, we plot a dotted gray line representing a dirty economy with parameter $\xi = 0.835$. It shows that this economy grows slower than the economy with calibrated parameter $\xi = 0.781$. If we assign a larger value to ξ, the dirty economy will stop growing and even decline, implying that sustainability will not occur unless $\Delta h_{t+1}/h_t$ remains positive in the long run. The above exercise indicates that the model with a dirty economy associated with positive long-run growth has a similar prediction that the polluting development path leads to a short-run boom and a long-run slow or stagnated growth. The description of the model is put in Appendix G.

7. Conclusion

The relationship between economic growth and environmental pollution has been a central concern of environmental economists. Our paper revisits this important topic and propose a dynamic structural model to capture the interaction between economic growth, human capital accumulation, and environmental pollution. We relax two strong assumptions of the EKC: first, there exists no feedback mechanism through which pollution impairs long-run economic growth; second, pollution is reversible as income grows.

We demonstrate that if pollution stock exerts negative effects on human capital accumulation over time, the dirty economy will experience a short-run boom but finally stagnate at a low development level, not following an EKC pattern. We further illustrate that the cost for a dirty economy to switch is expensive and sometimes infeasible if the environmental damage is irreversible. Policy interventions, such as pollution tax or human capital subsidies, help alleviate but will never be able to eradicate this issue.

Local governments may find the EKC argument appealing because temporary economic prosperity is attractive to politicians with tenure constraints. They may also believe that developing regions are too poor to green and therefore follow the “pollute first, remediate later” strategy. However, our theory demonstrates that this strategy lacks wisdom in that it ignores the feedback mechanism of pollution on the long-run economic activities.

Notes

1 In the parts above, individual subscripts have been omitted to simplify notation. Here, since we need to distinguish the human capital produced by individual institution and the aggregate level of human capital, *i* is added to the subscript to denote a representative individual institution.

2 Pollution might also directly affect manufacturing's productivity. In theory, we can incorporate this channel into manufacturing production function, such as $y_t = A_d \mu(x_t) k_t^{\alpha} h_t^{1-\alpha} {l_{yt}}^{1-\alpha} (1 - z_t)$, in which $\mu(x_t)$ represents the adverse effects of pollution on manufacturing's productivity. We find that this channel does not change the predictions of our model. The results are available upon request.

3 The literature shows that environmental pollution significantly reduces people's health, concentration, as well as cognitive development (e.g., Chen et al. 2013; Power et al. 2015; Heft-Neal et al. 2018; Jans et al. 2018). On this intensive margin, environmental pollution might not reduce the scale of human capital but might substantially decrease their creativity on knowledge. In this way, these invisible adverse effects of pollution are more likely to be observed in the outcome of knowledge produced by human capital.

4 The pollution level depends on production and pollution abatement. The social optimal and the decentralized economies start with the same production level but with different pollution abatement efforts. In the decentralized scenario, an exogenous pollution tax rate determines a firm's abatement. While in the social optimal scenario, the abatement varies with the negative externalities of pollution on human capital accumulation and household utilities.

References

Ahmad, A., Y. Zhao, M. Shahbaz, S. Bano, Z. Zhang, S. Wang and Y. Liu (2016) Carbon emissions, energy consumption and economic growth: An aggregate and disaggregate analysis of the Indian economy. *Energy Policy* 96, 131–143.

Andreoni, J. and A. Levinson (2001) The simple analytics of the environmental Kuznets curve. *Journal of Public Economics* 80(2), 269–286.

Archsmith, J., A. Heyes and S. Saberian (2018) Air quality and error quantity: Pollution and performance in a high-skilled, quality-focused occupation. *Journal of the Association of Environmental and Resource Economists* 5(4), 827–863.

Arrow, K., B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C. S. Holling, B.-O. Jansson, S. Levin, K.-G. Mäler, C. Perrings, D. Pimentel (1995) Economic growth, carrying capacity, and the environment. *Ecological Economics* 15(2), 91–95.

Beckerman, W. (1992) Economic growth and the environment: Whose growth? Whose environment? *World Development* 20(4), 481–496.

Bharadwaj, P., M. Gibson, J. G. Zivin and C. Neilson (2017) Gray matters: Fetal pollution exposure and human capital formation. *Journal of the Association of Environmental and Resource Economists* 4(2), 505–542.

Bosi, S. and L. Ragot (2013) On the optimal control of pollution in a human capital growth model. *Mathematical Economics Letters* 1(1), 9–15.

Bovenberg, A. L. and S. Smulders (1995) Environmental quality and pollution-augmenting technological change in a two-sector endogenous growth model. *Journal of Public Economics* 57(3), 369–391.

Brandt, L., J. Van Biesebroeck and Y. Zhang (2012) Creative accounting or creative destruction? Firm-level productivity growth in Chinese manufacturing. *Journal of Development Economics* 97(2), 339–351.

Brock, W. A. and M. S. Taylor (2010) The green Solow model. *Journal of Economic Growth* 15(2), 127–153.

Byrne, M. M. (1997) Is growth a dirty word? Pollution, abatement and endogenous growth. *Journal of Development Economics* 54(2), 261–284.

Cavalcanti, T., K. Mohaddes, H. Nian and H. Yin (2023) Air pollution and firm-level human capital, knowledge and innovation. CAMA Working Paper.

Chang, T., J. G. Zivin, T. Gross and M. Neidell (2016) Particulate pollution and the productivity of pear packers. *American Economic Journal: Economic Policy* 8(3), 141–169.

Chen, Y., A. Ebenstein, M. Greenstone and H. Li (2013) Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *Proceedings of the National Academy of Sciences* 110(32), 12936–12941.

Chyi, Y.-L., Y.-M. Lai and W.-H. Liu (2012) Knowledge spillovers and firm performance in the high-technology industrial cluster. *Research Policy* 41(3), 556–564.

Copeland, B. R. and M. S. Taylor (2004) Trade, growth, and the environment. *Journal of Economic Literature* 42(1), 7–71.

Criado, C. O., S. Valente, T. Stengos (2011) Growth and pollution convergence: Theory and evidence. *Journal of Environmental Economics and Management* 62(2), 199–214.

Currie, J., E. A. Hanushek, E. M. Kahn, M. Neidell and S. G. Rivkin (2009) Does pollution increase school absences? *The Review of Economics and Statistics* 91(4), 682–694.

Dong, F. (2022) Aggregate implications of financial frictions for unemployment. *Review of Economic Dynamics* 48, 45–71.

Dong, F., P. Wang and Y. Wen (2020) A search-based neoclassical model of capital reallocation. *European Economic Review* 128, 103515.

Ebenstein, A., V. Lavy and S. Roth (2016) The long-run economic consequences of high-stakes examinations: Evidence from transitory variation in pollution. *American Economic Journal: Applied Economics* 8(4), 36–65.

Esteve, V. and C. Tamarit (2012) Is there an environmental Kuznets curve for Spain? Fresh evidence from old data. *Economic Modelling* 29(6), 2696–2703.

Figueroa, E. and R. Pasten (2015) Beyond additive preferences: Economic behavior and the income pollution path. *Resource and Energy Economics* 41, 91–102.

Fodha, M. and O. Zaghdoud (2010) Economic growth and pollutant emissions in Tunisia: An empirical analysis of the environmental Kuznets curve. *Energy Policy* 38(2), 1150–1156.

Fu, S., V. B. Viard and P. Zhang (2021) Air pollution and manufacturing firm productivity: Nationwide estimates for China. *The Economic Journal* 131(640), 3241–3273.

Goulder, L. H. and K. Mathai (2000) Optimal CO2 abatement in the presence of induced technological change. *Journal of Environmental Economics and Management* 39(1), 1–38.

Gradus, R. and S. Smulders (1993) The trade-off between environmental care and long-term growth pollution in three prototype growth models. *Journal of Economics* 58(1), 25–51.

Grossman, G. M. and A. B. Krueger (1991). Environmental impacts of a North American free trade agreement. NBER Working Paper.

Hart, R. (2020) Growth, pollution, policy! *European Economic Review* 126, 103455.

He, H., K. X. D. Huang and L. Ning (2021) Why do Americans spend so much more on health care than Europeans? *International Economic Review* 62(4), 1363–1399.

Heft-Neal, S., J. Burney, E. Bendavid and M. Burke (2018) Robust relationship between air quality and infant mortality in Africa. *Nature* 559(7713), 254–258.

High, S. (2017) Brownfield public history. In *The Oxford Handbook of Public History*, p. 423. Oxford: Oxford University Press.

Holtz-Eakin, D. and T. M. Selden (1995) Stoking the fires? CO2 emissions and economic growth. *Journal of Public Economics* 57(1), 85–101.

Hsieh, C.-T. and P. J. Klenow (2009) Misallocation and manufacturing TFP in China and India. *Quarterly Journal of Economics* 124(4), 1403–1448.

Ito, K. and S. Zhang (2020) Willingness to pay for clean air: Evidence from air purifier markets in China. *Journal of Political Economy* 128(5), 1627–1672.

Jalil, A. and S. F. Mahmud (2009) Environment Kuznets curve for CO2 emissions: A cointegration analysis for China. *Energy Policy* 37(12), 5167–5172.

Jans, J., P. Johansson and J. P. Nilsson (2018) Economic status, air quality, and child health: Evidence from inversion episodes. *Journal of Health Economics* 61, 220–232.

Kambourov, G. and I. Manovskii (2009) Occupational specificity of human capital. *International Economic Review* 50(1), 63–115.

Klarl, T. (2016) Pollution externalities, endogenous health and the speed of convergence in an endogenous growth model. *Journal of Macroeconomics* 50, 98–113.

Levinsohn, J. and A. Petrin (2003) Estimating production functions using inputs to control for unobservables. *The Review of Economic Studies* 70(2), 317–341.

Ligthart, J. E. and F. van der Ploeg (1994) Pollution, the cost of public funds and endogenous growth. *Economics Letters* 46(4), 339–349.

Lopez, R. E. and S. W. Yoon (2014) "Sustainable" economic growth: The ominous potency of structural change. *International Review of Environmental and Resource Economics* 7(2), 179–203.

Lucas, R. E. (1988) On the mechanics of economic development. *Journal of Monetary Economics* 22(1), 3–42.

Panayotou, T., et al. (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development. Technical Report, International Labour Organization.

Pigou, A. C. (1932) The effect of reparations on the ratio of international interchange. *The Economic Journal* 42(168), 532–543.

Power, M. C., M.-A. Kioumourtzoglou, J. E. Hart, O. I. Okereke, F. Laden and M. G. Weisskopf (2015) The relation between past exposure to fine particulate air pollution and prevalent anxiety: Observational cohort study. *BMJ* 350, h1111.

Rebelo, S. (1991) Long-run policy analysis and long-run growth. *Journal of Political Economy* 99(3), 500–521.

Romer, P. M. (1986) Increasing returns and long-run growth. *Journal of Political Economy* 94(5), 1002–1037.

Romer, P. M. (1990) Endogenous technological change. *Journal of Political Economy* 98(5, Part 2), S71–S102.

Smulders, S. (2006) Growth and environment: On U-curves without U-turns. In: *Economic Modelling of Climate Change*, pp. 9–23. Cheltenham: Edward Elgar.

Stern, D. I. (2017) The environmental Kuznets curve after 25 years. *Journal of Bioeconomics* 19(1), 7–28.

Stern, D. I. (2004) The rise and fall of the environmental Kuznets curve. *World Development* 32(8), 1419–1439.

Stokey, N. L. (1998) Are there limits to growth? *International Economic Review* 39(1), 1–31.

Zivin, J. G. and M. Neidell (2012) The impact of pollution on worker productivity. *American Economic Review* 102(7), 3652–3673.

Zivin, J. G., T. Liu, Y. Song, Q. Tang and P. Zhang (2020) The unintended impacts of agricultural fires: Human capital in China. *Journal of Development Economics* 147, 102560.

APPENDIX A: THE DECENTRALIZED EQUILIBRIUM OF A DIRTY ECONOMY

This section describes the steady states of a decentralized dirty economy based on the model dynamic systems, which are given by equations (1)–(10):

$$z^* = 1 - (\phi\beta)^{\frac{1}{1-\beta}}, \tag{A1}$$

$$r^* = \frac{1}{\rho} - 1 + \delta_k, \tag{A2}$$

$$l_h^* = \frac{\delta_h L}{\frac{1}{\rho} - 1 + 2\delta_h}, \tag{A3}$$

$$l_y^* = L - l_h^*, \tag{A4}$$

$$x^* = \left(\frac{Bl_h^*}{\delta_h}\right)^{\frac{1}{\xi}} - 1, \tag{A5}$$

$$k^* = \frac{\eta x^* \alpha \left((1-z^*)^{1-\beta} - \phi\right)}{r^*}, \tag{A6}$$

$$h^* = \left[\frac{r^*}{\left((1-z^*) - \phi\,(1-z^*)^{\beta}\right)\alpha A_d}\right]^{\frac{1}{1-\alpha}} \frac{k^*}{l_y^*}, \tag{A7}$$

$$y^* = Ak_t^{*\alpha} h_t^{*1-\alpha} l_{yt}^{*1-\alpha}\left(1-z^*\right), \tag{A8}$$

$$c^* = y^* - \delta_k k^*. \tag{A9}$$

APPENDIX B: THE SOCIAL OPTIMAL EQUILIBRIUM OF A DIRTY ECONOMY

This section describes a social optimal dirty economy. A social planner maximizes the social benefit:

$$\max_{\{c_t, l_{ht}, k_{t+1}, h_{t+1}, x_{t+1}\}} \sum_{t=0}^{\infty} \rho^t \left(\frac{c_t^{1-\sigma} - 1}{1-\sigma} - \frac{D{x_t}^{\gamma}}{\gamma}\right)$$

which subjects to the budget constraint:

$$c_t + k_{t+1} - (1-\delta_k)\,k_t = A_d k_t^{\alpha} h_t^{1-\alpha} {l_{yt}}^{1-\alpha}\,(1-z_t), \tag{B1}$$

the law of motion of human capital accumulation:

$$h_{t+1} = Bl_{ht}(1+x_t)^{-\xi}\,h_t + (1-\delta_h)\,h_t, \tag{B2}$$

and the law of motion of pollution accumulation:

$$x_{t+1} = A_d {k_t}^{\alpha}\left(L - l_{ht}\right)^{1-\alpha} {h_t}^{1-\alpha}\,(1-z_t)^{\beta} + (1-\eta)\,x_t. \tag{B3}$$

Denoting λ_t, p_t, and q_t as the Lagrangian multipliers of the last three constraints correspondingly, the optimal conditions for c_t, z_t, l_{ht}, k_{t+1}, h_{t+1}, and x_{t+1} are given by:

$$c_t^{-\sigma} = \lambda_t, \tag{B4}$$

$$\lambda_t = q_t \beta (1 - z_t)^{\beta - 1}, \tag{B5}$$

$$\begin{aligned} p_t B (1 + x_t)^{-\xi} h_t = {} & \lambda_t A_d (1 - \alpha)\, k_t^{\alpha} \left(L - l_{ht}\right)^{-\alpha} {h_t}^{1-\alpha} (1 - z_t) \\ & - q_t A_d \,(1 - \alpha)\, k_t^{\alpha} \left(L - l_{ht}\right)^{-\alpha} {h_t}^{1-\alpha} (1 - z_t)^{\beta}, \end{aligned} \tag{B6}$$

$$\begin{aligned} \frac{1}{\rho} \lambda_t = {} & \lambda_{t+1} \left[A_d \alpha k_{t+1}^{\alpha - 1} \left[L - l_{ht+1}\right]^{1-\alpha} {h_{t+1}}^{1-\alpha} \left[1 - z_{t+1}\right] + 1 - \delta_k \right] \\ & - q_{t+1} A_d \alpha k_{t+1}^{\alpha - 1} \left(L - l_{ht+1}\right)^{1-\alpha} {h_{t+1}}^{1-\alpha} (1 - z_t)^{\beta}, \end{aligned} \tag{B7}$$

$$\begin{aligned} \frac{1}{\rho} p_t = {} & \lambda_{t+1} A_d (1 - \alpha)\, k_{t+1}^{\alpha} \left(L - l_{ht+1}\right)^{1-\alpha} {h_{t+1}}^{-\alpha} (1 - z_{t+1}) \\ & - q_{t+1} A_d (1 - \alpha)\, k_{t+1}^{\alpha} \left(L - l_{ht+1}\right)^{1-\alpha} {h_{t+1}}^{-\alpha} (1 - z_{t+1})^{\beta} \\ & + p_{t+1} \left[B l_{ht+1} \left[1 + x_t\right]^{-\xi} + 1 - \delta_h \right], \end{aligned} \tag{B8}$$

$$\frac{1}{\rho} q_t = D x_{t+1}^{\gamma - 1} + p_{t+1} B \xi \,(1 + x_t)^{-\xi - 1}\, l_{ht+1} h_{t+1} + q_{t+1} \,(1 - \eta). \tag{B9}$$

Equations (B1)–(B9) define the dynamic system of a social optimal dirty economy. The steady states are given by:

$$x^* = \left(\frac{BL}{\frac{1}{\rho} - 1 + \delta_h} \right)^{\frac{1}{\xi}} - 1,$$

$$l_h^* = \frac{\delta_h L}{\frac{1}{\rho} - 1 + \delta_h},$$

$$k^* = \frac{\frac{\beta - 1}{\beta} \alpha \eta x^* \left(1 - z^*\right)^{1-\beta}}{\frac{1}{\rho} - 1 + \delta_k},$$

$$z^* = 1 - \left[\eta x^* \left(1 - \frac{\frac{\beta - 1}{\beta} \alpha \delta_k}{\frac{1}{\rho} - 1 + \delta_k} \right) \right]^{\frac{\sigma}{(1-\beta)(1-\sigma)}} \left(q^* \beta\right)^{\frac{1}{(1-\beta)(1-\sigma)}},$$

$$y^* = A_d k^{\alpha *} h^{* 1-\alpha} {l_y}^{* 1-\alpha} \left(1 - z^*\right),$$

$$h^* = \left(\eta x^*\right)^{\frac{1}{1-\alpha}} k^{* - \frac{\alpha}{1-\alpha}} \left(L - l_h^*\right)^{-1} \left(1 - z^*\right)^{\frac{-\beta}{1-\alpha}} {A_d}^{-\frac{1}{1-\alpha}},$$

$$c^* = y^* - \delta_k k^*.$$

APPENDIX C: THE DECENTRALIZED EQUILIBRIUM OF A CLEAN ECONOMY

This section describes a decentralized dirty economy.

C.1. HOUSEHOLD

The household's maximization problem is given by:

$$\max_{\{c_t,k_{t+1},h_{t+1}\}} \sum_{t=0}^{\infty} \rho^t \frac{c_t^{1-\sigma}-1}{1-\sigma},$$

subject to the budget constraint:

$$c_t + k_{t+1} - (1-\delta_k)\, k_t + p_{ht}\left[h_{t+1} - [1-\delta_h]\, h_t\right] = r_t k_t + w_{yt}(l_{yt}+l_{ht}) + w_{ht}h_t + \pi_{yt} + \pi_{ht}. \tag{C1}$$

The optimal conditions for c_t, k_{t+1}, and h_{t+1} are given by:

$$c_t^{-\sigma} = \lambda_t, \tag{C2}$$

$$\lambda_t = \rho\lambda_{t+1}\left(r_{t+1} + 1 - \delta_k\right), \tag{C3}$$

$$p_{ht}\lambda_t = \rho\lambda_{t+1}\left[p_{ht+1}\left[1-\delta_h\right] + w_{ht+1}\right]. \tag{C4}$$

The household's optimal problem no longer suffers pollution disutility in the clean scenario.

C.2. FIRMS

A representative firm's maximization problem is given by:

$$\max_{\{k_t,l_{yt},h_t\}} \pi_{yt} = A_c k_t^{\alpha} h_t^{1-\alpha} {l_{yt}}^{1-\alpha} - r_t k_t - w_{yt} l_{yt} - w_{ht} h_t.$$

The optimal conditions for k_t, l_{yt}, and h_t are given by:

$$r_t = A_c \alpha k_t^{\alpha-1} h_t^{1-\alpha} {l_{yt}}^{1-\alpha}, \tag{C5}$$

$$w_{yt} = A_c\left(1-\alpha\right) k_t^{\alpha} h_t^{1-\alpha} {l_{yt}}^{-\alpha}, \tag{C6}$$

$$w_{ht} = A_c\left(1-\alpha\right) k_t^{\alpha} h_t^{-\alpha} {l_{yt}}^{1-\alpha}. \tag{C7}$$

C.3. EDUCATION AND RESEARCH

An individual institution's maximization problem is given by:

$$\pi_{i,ht} = \max_{\{l_{i,ht}\}} p_{ht} B l_{i,ht} h_t - w_{yt} l_{i,ht}.$$

The optimal condition with respect to l_{ht} is given by:

$$p_{ht} B h_t = w_{yt}. \tag{C8}$$

Equations (C1)–(C8) define the full dynamic of the decentralized clean economy, which yields the BGP: $\frac{y_{t+1}}{y_t} = \frac{c_{t+1}}{c_t} = \frac{k_{t+1}}{k_t} = \frac{h_{t+1}}{h_t} = BL - r^* - 2\delta_h + \delta_k + 1$. In equilibrium, labor allocations between the manufacturing and education and research sectors are given by $l_{yt}^* = \frac{r^*+\delta_h-\delta_k}{B}$ and $l_{ht}^* = L - l_{yt}^*$.

APPENDIX D: THE SOCIAL OPTIMAL EQUILIBRIUM OF A CLEAN ECONOMY

This section describes a social optimal clean economy. The social planner's maximization problem is given by:

$$\max_{\{c_t,k_{t+1},h_{t+1}\}} \sum_{t=0}^{\infty} \rho^t \frac{c_t^{1-\sigma}-1}{1-\sigma},$$

which subjects to the budget constraint:

$$c_t + k_{t+1} - (1-\delta_k)\, k_t = A_c k_t^{\alpha} h_t^{1-\alpha} l_{yt}{}^{1-\alpha}, \tag{D1}$$

and the law of motion of human capital accumulation:

$$h_{t+1} = B l_{ht} h_t + (1-\delta_h)\, h_t. \tag{D2}$$

The optimal conditions with respect to c_t, l_{ht}, k_{t+1}, and h_{t+1} are given by:

$$c_t^{-\sigma} = \lambda_t, \tag{D3}$$

$$p_t B h_t = (1-\alpha)\, \lambda_t A_c k_t^{\alpha} h_t^{1-\alpha} \left(L - l_{ht}\right)^{-\alpha}, \tag{D4}$$

$$\lambda_t = \rho \lambda_{t+1} \alpha A k_{t+1}^{\alpha-1} h_{t+1}^{1-\alpha} \left(L - l_{ht+1}\right)^{1-\alpha} + 1 - \delta_k, \tag{D5}$$

$$p_t = \rho \lambda_{t+1} (1-\alpha)\, A_c k_{t+1}^{\alpha} h_{t+1}^{-\alpha} \left(L - l_{ht+1}\right)^{1-\alpha} + \rho p_{t+1} \left(B l_{ht+1} + 1 - \delta_h\right). \tag{D6}$$

Equations (D1)–(D6) define the full dynamic of the decentralized clean economy, which yields the BGP: $\frac{y_{t+1}}{y_t} = \frac{c_{t+1}}{c_t} = \frac{k_{t+1}}{k_t} = \frac{h_{t+1}}{h_t} = \left[\rho\left(BL + 1 - \delta_h\right)\right]^{\frac{1}{\sigma}}$.

APPENDIX E: TRANSITION DYNAMICS OF A CLEAN ECONOMY

In the equilibrium of a clean economy, the labor allocations $\left\{l_{ht}, l_{yt}\right\}$, *c*-*k* ratio $\frac{c_t}{k_t}$, and *k*-*h* ratio $\frac{k_t}{h_t}$ remain stable on the BGP. We rearrange the model and construct a new dynamic system through which, as long as the labor allocation, *c*-*k* ratio, and *k*-*h* ratio converge to their own steady states, the clean economy will reach its BGP.

The reconstructed dynamic of the decentralized clean economy from equations (C1)–(C8) is given by:

$$\frac{c_t}{k_t} + \frac{k_{t+1}}{k_t} - (1-\delta_k) = A_c \left(\frac{k_t}{h_t}\right)^{\alpha-1} l_{yt}^{1-\alpha}, \tag{E1}$$

$$\frac{h_{t+1}}{h_t} = B(1+x_t)^{-\xi}\, l_{ht} + 1 - \delta_h, \tag{E2}$$

$$\left(\frac{c_{t+1}}{c_t}\right)^{\sigma} = \left(\frac{\lambda_{t+1}}{\lambda_t}\right)^{-1}, \tag{E3}$$

$$\left(\frac{\lambda_{t+1}}{\lambda_t}\right)^{-1} = \rho\left(r_{t+1} + 1 - \delta_k\right), \tag{E4}$$

$$\frac{\frac{c_t}{k_t}}{\frac{c_{t+1}}{k_{t+1}}} = \left(\frac{c_{t+1}}{c_t}\right)^{-1} \frac{k_{t+1}}{k_t}, \tag{E5}$$

$$r_t = \alpha A_c \left(\frac{k_t}{h_t}\right)^{\alpha-1} l_{yt}^{1-\alpha}, \tag{E6}$$

$$p_{ht}B\left(1+x_t\right)^{-\xi}=\left(1-\alpha\right)A_c\left(\frac{k_t}{h_t}\right)^{\alpha}l_{yt}^{-\alpha}. \tag{E7}$$

Equations (E1)–(E7) define a new dynamic system through which the decentralized clean economy finds its transition dynamic and BGP given an arbitrary starting point.

In the social optimal clean economy, similarly, we rearrange the dynamic represented by equations (D1)–(D6) as:

$$\frac{k_{t+1}}{k_t}=A_c\left(\frac{k_t}{h_t}\right)^{\alpha-1}\left(L-l_{ht}\right)^{1-\alpha}+1-\delta_k-\frac{c_t}{k_t}, \tag{E8}$$

$$\frac{k_{t+1}}{k_t}=B(1+x_t)^{-\xi}\,l_{ht}+1-\delta_h, \tag{E9}$$

$$\left(\frac{c_{t+1}}{c_t}\right)^{\sigma}=\rho\left[\alpha A_c\left(\frac{k_{t+1}}{h_{t+1}}\right)^{\alpha-1}\left(L-l_{ht+1}\right)^{1-\alpha}+1-\delta_k\right], \tag{E10}$$

$$\rho\left[B\left(1+x_t\right)^{-\xi}L+1-\delta_h\right]=\left(\frac{c_{t+1}}{c_t}\right)^{\sigma}\left(\frac{k_t}{h_t}\right)^{\alpha}\left(\frac{k_{t+1}}{h_{t+1}}\right)^{-\alpha}\left(\frac{L-l_{ht+1}}{L-l_{ht}}\right)^{\alpha}, \tag{E11}$$

$$\frac{c_t/k_t}{c_{t+1}/k_{t+1}}=\left(\frac{c_{t+1}}{c_t}\right)^{-1}\frac{k_{t+1}}{k_t}, \tag{E12}$$

$$x_{t+1}=\left(1-\eta\right)x_t. \tag{E13}$$

Equations (E8)–(E13) define a new dynamic system through which the social optimal clean economy finds its transition dynamic and BGP given an arbitrary starting point.

APPENDIX F: SENSITIVITY ANALYSIS ON PARAMETERS

This section presents sensitive analysis on parameters $\{\xi, \beta\}$, which are closely related to the key mechanism that how pollution generates and affects the economic dynamics.

Parameter ξ corresponds to the negative effects of pollution on human capital accumulation. In Section 3, it is empirically calibrated by how air pollution ($PM_{2.5}$) affects the productivity of human capital, using the two-stage least square method with thermal inversion as an instrumental variable. Figure F1 presents the sensitivity analysis of parameter ξ. A larger value of ξ diminishes human capital accumulation to a larger extent. In the short run, the economic path is a bit higher than the baseline because the equilibrium condition of labor wage leads to a large proportion of labor flowing to final goods production. However, in the long run, less human capital accumulation leads to a significantly lower economic equilibrium than the baseline. Within a certain range of ξ, the economic dynamics change systematically and the predictions of the model still hold.

Furthermore, we conduct a sensitivity analysis on how the parameterization on parameter η affects the value of parameter β and then how the two parameters affect the simulated pattern. We assign different values to parameter η and compute the corresponding values of parameter β. Figure F2 shows that a lower η leads to a higher β, implying that pollution accumulates faster and the productivity of education and research sector is reduced much more, and thus more labor will flow to the manufacturing sector. While it promotes the short-run economy, the long-run economic equilibrium is relatively lower because it leads to a lower level of human capital accumulation. As a result, given a set of varying β and η, the predictions of the model are generally unchanged.

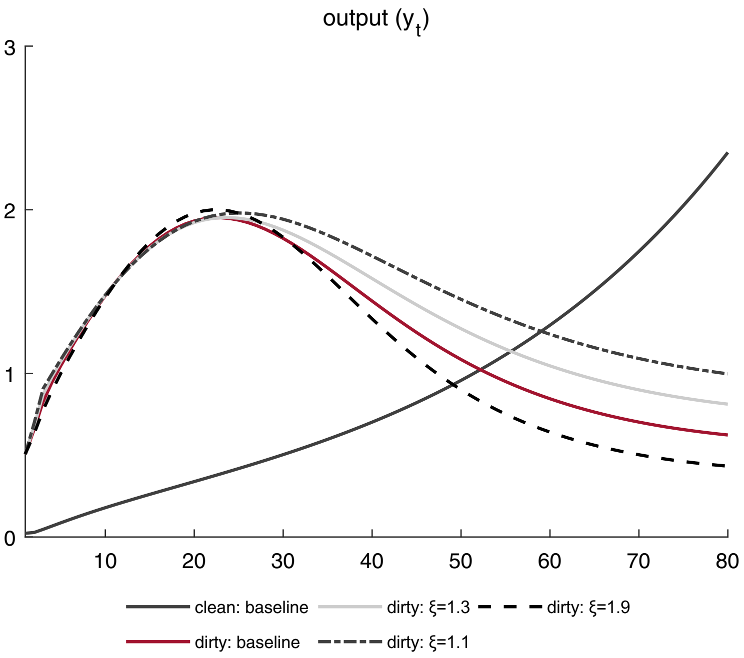

Figure F1. Sensitivity analysis on parameter ξ.
Notes: The simulation is based on decentralized economy scenario. The black and the red solid lines describe the baseline decentralized clean and dirty economies, respectively, as presented in Figure 1.

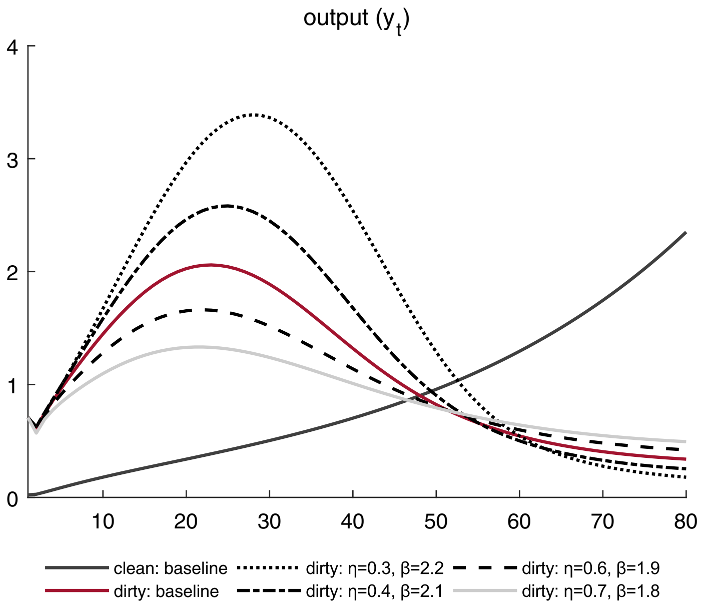

Figure F2. Sensitivity analysis on parameter β.
Notes: The simulation is based on decentralized economy scenario. The black and the red solid lines describe the baseline decentralized clean and dirty economies, respectively, as presented in Figure 1.

APPENDIX G: A POLLUTING AND SUSTAINABLE ECONOMY

In this model, a social planner maximizes social benefit:

$$\max_{\{c_t,s_t,k_{t+1},h_{t+1}\}} \sum_{t=0}^{\infty} \rho^t \left(\frac{c_t^{1-\sigma}-1}{1-\sigma} \right), \tag{G1}$$

which subjects to the budget constraint:

$$c_t + k_{t+1} - (1-\delta_k)\, k_t = A k_t^{\alpha} h_t^{1-\alpha} {L_t}^{1-\alpha} \, (1-s_t)\,, \tag{G2}$$

and the law of motion of human capital accumulation:

$$h_{t+1} = B y_t s_t - \xi x_t + (1-\delta_h) h_t. \tag{G3}$$

The notations remain the same as the manuscript. The production function is given by $y_t = A k_t^{\alpha} h_t^{1-\alpha} {L_t}^{1-\alpha}$. Production is used for consumption, physical capital accumulation, and human capital accumulation. s_t denotes the share of production allocated to human capital accumulation. We assume that pollution function $x_t = y_t$. In the process of human capital accumulation, a proportion of the allocated production $y_t s_t$ pays for pollution-caused medical care, preventive protection, and work inefficiency (such as work absenteeism, loss of concentration, and less skilled employees a result of environmental pollution), which is assumed to be proportional to environmental pollution.

The general equilibrium comprises the BGP of consumption c_t, capital k_t, human capital h_t, pollution x_t, and output y_t, and production allocation share s_t. The main parameters are consistent with the manuscript, except that $\xi = 0.781$ due to the different setup. To calibrate parameter ξ, we use environmental pollution ($PM_{2.5}$) between 2000 and 2012 to compute the average county-year level growth rate of pollution (0.032), which implies that $\xi = 0.835$. The $PM_{2.5}$ value is obtained from *National Aeronautics and Space Administration* (NASA) and aggregated from grid level to county-year level. We choose the period prior to 2012 because the China's *Action Plan of Air Pollution Prevention and Control* was implemented in 2013. As a robustness check, the model implies that $\xi = 0.781$ if we assume that the growth rate of pollution equals to 0.06 which is closer to China's average real GDP growth rate between 2000 and 2012.

Cite this article: Nian H, Xu Z and Yin H (2024). “Temporary prosperity or sustainable development: the long-run impact of developing pollution-intensive industries.” *Macroeconomic Dynamics* **28**, 1122–1149. https://doi.org/10.1017/S1365100523000408