China's Pursuit of Environmentally Sustainable Development:: Harnessing the New Engine of Technological Innovation

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Summary

Whether China continues its business-as-usual investment-driven, environment-polluting growth pattern or adopts an investment and innovation-driven, environmentally sustainable development holds important implications for both national and global environmental governance. Building on a Ramsey-Cass-Koopmans growth model that features endogenous technological change induced by R&D and knowledge stock accumulation, this paper presents an exposition, both analytically and numerically, of the mechanism underlining China's economic transition from an investment-driven, pollution-intensive to an investment and innovation-driven, environmentally sustainable growth path. We show that if R&D technological innovation is incorporated into China's growth mechanism, then at some tipping point in time when marginal welfare gain of R&D for knowledge accumulation becomes equalized with that of investment for physical asset deployment, China's economy will launch capital investment and R&D simultaneously and make a transition to a sustainable growth path along which consumption, capital investment, and R&D have a balanced share of 5: 4: 1, consumption, capital stock, and knowledge stock all grow at a rate of 4.9%, and environmental quality improves at a rate of 2.5%. In contrast, if R&D technological innovation is not harnessed as a new growth engine, then China's economy will follow its business-as-usual investment-driven growth path along which standalone accumulation of dirty physical capital stock will lead to an more than 200-fold increase in environmental pollution.

Keywords: Endogenous Technological Change, Sustainable Development, Economic Growth Model, China's Economic Transition

JEL Classification: Q55, Q58, Q43, Q48, O13, O31, O33, O44, F18

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Abstract: Whether China continues its business-as-usual investment-driven, environment-polluting growth pattern or adopts an investment and innovation-driven, environmentally sustainable development holds important implications for both national and global environmental governance. Building on a Ramsey-Cass-Koopmans growth model that features endogenous technological change induced by R&D and knowledge stock accumulation, this paper presents an exposition, both analytically and numerically, of the mechanism underlining China's economic transition from an investment-driven, pollution-intensive to an investment and innovation-driven, environmentally sustainable growth path. We show that if R&D technological innovation is incorporated into China's growth mechanism, then at some tipping point in time when marginal welfare gain of R&D for knowledge accumulation becomes equalized with that of investment for physical asset deployment, China's economy will launch capital investment and R&D simultaneously and make a transition to a sustainable growth path along which consumption, capital investment, and R&D have a balanced share of 5: 4: 1, consumption, capital stock, and knowledge stock all grow at a rate of 4.9%, and environmental quality improves at a rate of 2.5%. In contrast, if R&D technological innovation is not harnessed as a new growth engine, then China's economy will follow its business-as-usual investment-driven growth path along which standalone accumulation of dirty physical capital stock will lead to an more than 200-fold increase in environmental pollution.

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1. Introduction

In the last 1970s, with the motto of "economic development is the only hard truth", Deng Xiaoping, the architect of the Chinese economic reform and opening up policy, sought to strengthen his leadership by improving the nation's economic prosperity. With that motto placed high upon development strategies, China's successive leaders consistently kept fixed capital investment as the fundamental engine of growth to enable the achievement of industrialization and urbanization mission.[1] Over the past three decades, this investment-driven growth pattern has ignited the astonishing power of China's economic development with an impressive record of double-digit fast growth, shaping a profound transformation from a rural agricultural-based to an urban industrial-focused society (Perkins, 1988; Chow, 1993, 2007a; Zhu, 2012).

However, it is through this search for rapid economic growth by massive investment in fixed capital that China adopted another motto – growth at all costs. China is now no longer the third world country that Deng lived in, but a global manufacturing powerhouse that has turned a blind eye towards its environmental damages at high economic and social costs (World Bank, 1997; Liu and Diamond; 2005; Chow, 2010; Avaraham et al., 2015). This is particularly manifested by the massive deployment of dirty physical capital assets with lower technological sophistication in capital-intensive manufacturing sectors such as chemicals, mineral and energy, iron and steel, cements, machinery, equipment, and apparatus (Bai et al., 2006; NBS, 2014; Fisher-Vanden et al., 2015).[2] While these capital-intensive, low-tech industries continue to survive and boom in recent several decades as major pro-growth machines, the dirty by-products generated by production in these industries have caused severe environmental pollutions and hazards that incur substantial disutility and losses in social welfares (World Bank, 2007; Watts, 2008).[3] To address the daunting environmental challenge and meet social demands for a new and green growth future, there is a growing consensus among China's central policymakers that Chinese economy does need an overhaul, and in particular the current investment-driven, environment-polluting growth needs to be restructured and replaced by an environmentally sustainable development pattern (Fisher-Vanden et al.,

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[1] To meet the demand by industrialization and urbanization, these large-scale fixed asset investments include construction, infrastructure, housing, manufacturing, factory, facilities, machine and equipment installation, etc. For example, for China's year 2013 physical capital investment structure, investment in construction, manufacturing and installation of equipment and instruments, and others account for 66.9%, 20.4% and 12.7%, respectively (Song et al., 2011; NBS, 2014; World Bank. 2014).

[2] This tend to echo the "factor endowment hypothesis"', i.e., environmental pollutants are positively related to capital intensity, with a higher level of pollution emissions in capital-abundant countries (Antweiler, Copeland, & Taylor, 2000; Cole & Elliott, 2003; Frankel, 2003).

[3] China's environmental crisis includes, but not limited to, air pollution, land degradation, resource depletion, and water quality deterioration. The annual environmental costs have been estimated to be 3 to 10 percent of China's GDP, mainly due to the increased health costs and mortality associated with environmental hazards (World Bank, 2007).

2004, 2007; Zhang, 2007a,b, 2010a,b;).

This is vividly demonstrated by the theory of "new normal" elaborated by Chinese President Xi in his rethinking China's growth story with a new framework, and the full picture of Chinese economy's "new normal" sketched out by the central leadership has emerged with several notable features, among which the economy is increasingly driven by innovation instead of investment, and the economic structure is constantly improved and upgraded (World Bank, 2013). In this context, to pursue a green growth prospect, China is stepping up efforts to build the theme of R&D technological innovation in its growth story beyond the role of manufacturing powerhouse (OECD, 2008; 2010).[4] As the existing investment-driven growth model finds it difficult to maintain China's further sustainable development, R&D-related technological innovation emerges from the surface as a new engine of growth to foster economic restructuring and transition to a sustainable growth prospect. Accordingly, it is important to have a deep understanding of the interdependence and interaction among capital investment, R&D innovation, economic growth, and environmental impacts. This research is thus motivated to provide our insightful results at the right time for policymakers to understand the economic mechanism that underlines China's potential transition from an investment-driven, environment-polluting to an environmentally sustainable growth pattern.

To achieve this goal, this paper presents a detailed exposition, both analytically and numerically, of the mechanism underlining China's economic transition based on a Ramsey-Cass-Koopmans growth model incorporating endogenous technological change induced by R&D and knowledge accumulation. From a methodological perspective, our study contributes to model extensions of previous theoretical papers analyzing the relationship among environmental quality, pollution abatement, and economic growth within the context of sustainable development debates, e.g., Keeler et al. (1972), Forster (1973), D'Arge and Kogiku, (1973), Gruver (1976), Tahvonen and Kuuluvainen (1993), Selden and Song (1994, 1995), Mohtadi (1996), Smulders and Gradus (1996), Stokey (1998), Jones and Manuelli (2001), Brock and Taylor (2004), and Bartz and Kelly (2008).[5] In particular, with an explicit representation of the mechanism of endogenous technological change, our analysis is closely related to the literature on endogenous growth and the environment such as Smulders (1999), Bovenberg and Smulders (1994, 1995), Byrne (1997),

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[4] For example, China has followed the U.S. and Japan to become the world's third largest country in R&D expenditure in 2012. R&D investment grew notably by 15-20% per year over the past decade, and R&D intensity has doubled as a share of GDP, reaching 2% in 2012. To achieve the ultimate goal of building an innovation-oriented society, China has set an ambitious plan of R&D innovation, and this is reflected by the government's budget of spending 2.5% of GDP on R&D by 2020, which translates into a tripling of R&D investment over the next decade to an amount of US$300 billion (MOST, 2006a, b).

[5] Empirical studies examining the relationship between economic growth and environmental pollution include Copeland and Taylor (2003), and Grossman and Krueger (1995), and survey articles include Dasputa et al. (2002), Dinda (2004), and Smulders et al. (2014).

Grimaud (1999), Reis (2001), Cassou and Hamilton (2004), Grimaud and Rouge (2005), Brock and Taylor (2010).[6] But the difference is that our approach of modelling endogenous technological change is based on accumulation of knowledge stock induced by R&D, while representations of technological progress in the previous studies are based on the inputs of skilled workers/human capital (Byrne, 1997; Grimaud, 1999; Cassou and Hamilton, 2004; Grimaud and Rouge, 2005), inputs of physical capital and pollution (Bovenberg and Smulders, 1994, 1995; Brock and Taylor, 2010), or an autonomous rate of technological progress (Reis, 2001; Cunha-e-sá and Reis, 2007). In this respect, our representation of endogenous technological change for environmental preservation is building on the "stock of knowledge" approach introduced by Goulder and Schneider (1999) and Popp (2004) in energy/climate economics and policy analysis.[7] The key difference is that most of the existing studies focus on incorporating knowledge stock into CGE/IAM modelling for quantitative assessment of policy impacts, but our research is motivated to apply the "stock of knowledge" approach to investigate the economic mechanism of China's transition to sustainable growth. In particular, the growth dynamics in our model will deal with optimal control over an infinite horizon with two stock variables (both physical capital and knowledge stocks), with the boundary conditions explicitly considered to characterize the tipping point of economic transition.

Our main findings are summarized as follows. If the technological innovation induced by R&D and knowledge stock accumulation is incorporated into China's growth mechanism, then at some tipping point in time when marginal welfare gains of R&D become equalized with that of capital investment, China's economy will launch investment in physical capital and knowledge stock simultaneously and make a transition to a sustainable growth trajectory along which consumption, capital investment, and R&D have a balanced share of 5: 4: 1, consumption, capital stock, and knowledge stock grows at a rate of 4.9%, and environmental quality improves at a rate of 2.5%. In contrast, if the R&D-induced technological innovation is not incorporated as a new growth engine, then China's economy will evolve along its business-as-usual investment-driven growth path and reach a steady state without further growth momentum, and standalone accumulation of dirty physical capital will lead to a declining environmental quality.

The rest of this paper is structured as follows. Section 2 provides the modelling framework as well as the characterization of the socially optimal growth path. Section 3 presents an analytical exposition of China's potential transition from an investment-driven to a sustainable growth path. Section 4 shows the

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6 The general theories of endogenous economic growth are articulated in the seminal works of Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992).

7 Several subsequent studies have adopted the "stock of knowledge" method to examine the effect of technological change in energy/climate economics and policy studies, for example, Nordhaus (2002), Sue Wing (2006), Bosetti et al. (2011, 2013), Otto et al. (2008, 2011), Fisher-Vanden and Sue Wing (2008), and Jin (2012, 2015a,b).

numerical simulation results to illustrate China's potential economic transition. Section 5 concludes.

2. The modelling framework

The model will consider China's economic growth in an infinite-horizon, continuous-time dynamic setting, and characterize the socially optimal pattern of economic growth, as our study is motivated to explore the mechanism of China's economic transition from a central planner's perspective. Hence our model will focus on the optimal behavior of the social planner wishing to maximize the utility of the representative household subject to aggregate resource constraints in the economy.

2.1 Preferences, production, and environmental impacts

The socially optimal pattern of China's economic growth admits a representative household with measure normalized to unity, which has the following instantaneous utility function,

$$U(C(t),Q(t)) = \sigma_C \cdot InC(t) + \sigma_Q \cdot InQ(t) \quad , \tag{1}$$

where the utility depends on both material goods consumption C and environmental quality Q. The logarithmic preference is additively separable, strictly increasing, concave, and twice differentiable for all C and Q in their interior domains, and satisfies the Inada conditions. Exogenous parameter σ_C, σ_Q measures the extent to which the household values material goods consumption and environmental amenity, respectively.

The supply side of the economy admits a representative firm which produces unique final goods using direct inputs of physical capital stock. Moreover, environmental quality has an externality effect on final goods production, in the sense that clean environment will provide a favorable condition for operation and maintenance of capital assets and thus raises capital productivity and the output of final goods, *vice verse*, dirty environmental condition will accelerate capital depreciation (through eroding and blunting machines and equipments) and thus lower capital productivity and the output of final goods. Accordingly, the production function takes the form as

$$Y(t) = \overline{F}(A, K(t), Q(t)) = A \cdot K(t)^{\alpha} \cdot Q(t)^{\gamma} , \tag{2}$$

where Y is the outputs of final goods, K the stock of physical capital, A the capital productivity, and

Q the flow of environmental quality.[8] $0 < a, \gamma < 1$ is the elasticity of Y with respect to K and Q. Moreover, consider that China's environmental deterioration is due primarily to massive deployments of dirty physical capital in capital-intensive low-tech manufacturing sectors like chemicals, mineral products, iron and steel, cements, machinery, and equipment. We thus argue that accumulation of the dirty physical capital stock has negative impacts on environmental quality. In contrast, knowledge accumulated in R&D or knowledge-intensive high-tech sectors such as information, service and tertiary sectors is characterized by creating economic values in a environmental-friendly way. We hence suppose that accumulation of clean knowledge stock by R&D has positive impacts on the environment. By distinguishing environmental characteristics of these two types of assets, we specify the environmental quality function as

$$Q(t) = Q(K(t), H(t)) = K(t)^{-\kappa} \cdot H(t)^{\lambda}, \tag{3}$$

where environmental quality Q is negatively related to deployment of physical capital stock K, and positively related to accumulation of knowledge stock H. $\kappa, \lambda > 0$ denote the elasticity (absolute level) of environmental quality with respect to dirty physical capital stock and clean knowledge stock.

It is notable that accumulation of the clean knowledge stock, through the channel of environmental quality, will eventually create a beneficial effect on both the household's utility and final goods production, while accumulation of dirty capital stock has a negative effect. Substituting (3) into (2), the production function takes an alternative form as

$$Y(t) = F(A, K(t), H(t)) = A \cdot K(t)^{a - \gamma \cdot \kappa} \cdot H(t)^{\gamma \cdot \lambda} = A \cdot K(t)^{\overline{a}} \cdot H(t)^{\overline{\beta}}, \tag{4}$$

where $\overline{a} = a - \gamma \cdot \kappa$ is the elasticity of Y with respect to K when the negative environmental effect of accumulating dirty physical capital is explicitly considered. In other words, on the one hand, the input of capital into production has a direct positive effect to boost outputs, but on the other hand, by-products of operating dirty physical capital will generate environmental pollutions that harm output production in an indirect way. So the output elasticity of capital a will be adjusted by the negative environmental effect as measured by the factor $\gamma \cdot \kappa$. In contrast, accumulation of clean knowledge stock will favor final goods

[8] The environmental quality is treated as a flow variable as it is closely related to the flow of polluting emissions. When polluting emissions are by-products of goods production, a key question arise: whether the environmental quality or pollution constitutes a stock or a flow. It appears that environmental quality should be treated as a stock variable to capture its dynamic profile. However, incorporating environmental quality as a stock variable will substantially complicate the analysis, because our growth model already incorporate two stock variables (capital stock, and knowledge stock). As Kolstad and Krautkraemer (1993) put it: it is difficult to analytically characterize the features of a model with three state variables without restrictive assumptions about the functional forms of important relationships. For this purpose, our simplifying device is to treat environmental quality as a flow variable.

production via the channel of environmental quality that helps raise capital productivity, which is measured by the factor $\gamma \cdot \lambda$.

Using the standard perpetual inventory method, we describe the laws of motion for the two types of stock variables as follows,

$$\dot{K}(t) = I(t) \qquad \dot{H}(t) = R(t) \qquad , \tag{5}$$

where the stock of physical capital K is augmented by the flow of investment I, and accumulation of the knowledge stock is determined by R&D flows R. To simplify the notations, we omit the depreciation rate of physical capital and knowledge stock. Aggregate resource constraints at each point in time is given by

$$Y(t) = C(t) + I(t) + R(t) \tag{6}$$

2.2 Social planner problem and characterization

Given the above-described household preference and production technology, the socially optimal growth problem is equivalent to characterizing the time paths of consumption C, R&D R, physical capital stock K, and knowledge stock H that maximizes the discounted present utility of the household,

$$\max_{[C(t),R(t),K(t),H(t)]_{t=0}^{\infty}} \int_0^{\infty} \exp(-\rho t) \cdot (\sigma_C \cdot InC(t) + \sigma_Q \cdot InQ(t)) \cdot dt \tag{7}$$

subject to

$$\dot{K}(t) = A \cdot K(t)^{\bar{a}} H(t)^{\bar{\beta}} - C(t) - R(t) \qquad , \tag{8}$$

$$\dot{H}(t) = R(t), \tag{9}$$

where ρ is the discount factor for discounting intertemporal utility streams. (8)-(9) describe the law of motion for physical capital and knowledge stocks given their initial levels K_0, H_0. Note that, part of the final goods outputs are allocated to R&D which endogenously determines knowledge stock accumulation.

To capture the socially optimal pattern of economic growth, we solve the above-described social planner problem by setting up the Hamiltonian (we drop the time subscript for notational simplicity),

$$\hat{\mathrm{H}}(C,R,K,H,q_K,q_H) = U(C,Q(K,H)) + q_K \cdot (F(K,H) - C - R) + q_H \cdot R, \tag{10}$$

where C, R correspond to control variables, K, H state variables, and q_K, q_H current-value costate variables. Characterization of the socially optimal growth can be obtained by deriving the first-order necessary conditions (an interior solution is assumed),

$$C: \quad U_C(C,Q(K,H)) = q_K, \tag{11}$$

$$R: \quad q_H = q_K, \tag{12}$$

$$K: \quad \rho \cdot q_K = \dot{q}_K + U_Q(C,Q(K,H)) \cdot Q_K(K,H) + q_K \cdot F_K(K,H) \ , \tag{13}$$

$$H: \quad \rho \cdot q_H = \dot{q}_H + U_Q(C,Q(K,H)) \cdot Q_H(K,H) + q_K \cdot F_H(K,H) \ , \tag{14}$$

$$q_K: \quad \dot{K} = F(K,H) - C - R \ , \tag{15}$$

$$q_H: \quad \dot{H} = R \ , \tag{16}$$

and the transversality conditions,

$$\lim_{t\to\infty} \exp(-\rho \cdot t) \cdot q_K \cdot K = 0, \quad \lim_{t\to\infty} \exp(-\rho \cdot t) \cdot q_H \cdot H = 0.$$

Intuitively, (11)-(12) are static optimality conditions for the two control variables - consumption and R&D, where the marginal benefit (the left-hand side) is equal to the marginal cost (the right-hand side). (13)-(14) are dynamic no-arbitrage conditions for the two stock variables – physical capital and knowledge stock, where q_K, q_H denote the shadow price of physical capital and knowledge stock, respectively. The left-hand side denotes the marginal cost of holding the stock due to time discounting. The right-hand side is the marginal benefit of holding the stock, including an increase in the shadow price of stock assets $\dot{q}_K, \dot{q}_H$ and instantaneous welfare gains derived from using the stock assets. (15)-(16) corresponds to the law of motion for physical capital and knowledge stock, respectively.

In particular, the marginal welfare gain from accumulating each type of stock takes effect through the channels of both material goods consumption and environmental amenity. The welfare effect through the channel of goods consumption is positive for both types of stocks, i.e., $U_C \cdot F_K > 0$ for physical capital and $U_C \cdot F_H > 0$ for knowledge, while the welfare effect through the channel of environmental quality is positive for clean knowledge stock $U_Q \cdot Q_H > 0$ but negative for dirty physical capital stock $U_Q \cdot Q_K < 0$.

3. Analytical results

3.1 Investment-driven, environment-polluting growth

Based on the above-described model, this section will present an economic mechanism underlining China's investment-driven, environment-polluting growth pattern in the initial development phase. Intuitively, the environmental unsustainability of the investment-driven growth pattern is due primarily to an unbalanced portfolio of resource allocation between capital investment and R&D, with an overwhelming amount of resources allocated toward capital investment rather than R&D. As a result, without the build-up of clean knowledge stock, standalone accumulation of dirty physical capital leads to deterioration of environmental quality with an outcome of environmental unsustainability.

To present this intuition in a rigorous way, we consider the Hamiltion-Jacobi-Bellman (HJB) equation (13) characterizing the dynamic optimality condition for physical capital investment,

$$\begin{aligned} \rho \cdot q_K &= \dot{q}_K + U_Q(C,Q) \cdot Q_K(K,H) + U_C(C,Q) \cdot F_K(K,H) \\ &= \dot{q}_K + \left[\underbrace{-\frac{\sigma_Q}{Q} \cdot \kappa \cdot K^{-\kappa-1} \cdot H^{\lambda}}_{(1)} + \underbrace{\frac{\sigma_C}{C} \cdot A \cdot \bar{a} \cdot \left[\frac{K}{H}\right]^{\bar{a}-1}}_{(2)} \right] \end{aligned}, \tag{17}$$

where the functional forms of the model specified in Section 2.1 have been substituted to derive the explicit form of the HJB equation.[9] At the initial stage of development, China is characterized by a pre-industrial underdeveloped economy with a sufficiently high level of environmental quality Q. Given this pristine environmental condition, the marginal welfare effect of environmental pollution as a result of investment in dirty capital stock (term (1)) will be sufficiently low and can be safely ignored. Term (2) corresponds to marginal welfare effects of capital investment via the channel of material goods consumption. As the level of consumption C is fairly low at the very start of development, the household tends to receive a higher level of marginal utility gains from goods consumption. Meanwhile, at the start of China's growth the lower ratio of capital relative to knowledge stock K/H implies a higher level of marginal productivity of capital. We thus expect that marginal welfare effects associated with the term (2) will be sufficiently large.

Similarly, consider the HJB equation (14) that characterizes the dynamic optimality condition for knowledge stock accumulation,

$$\begin{aligned} \rho \cdot q_H &= \dot{q}_H + U_Q(C,Q) \cdot Q_H(K,H) + U_C(C,Q) \cdot F_H(K,H) \\ &= \dot{q}_H + \left[\underbrace{\frac{\sigma_Q}{Q} \cdot \lambda \cdot K^{-\kappa} \cdot H^{\lambda-1}}_{(1)} + \underbrace{\frac{\sigma_C}{C} \cdot A \cdot \bar{\beta} \cdot \left[\frac{K}{H}\right]^{1-\bar{\beta}}}_{(2)} \right] \end{aligned}. \tag{18}$$

The pristine environmental condition implies that the marginal welfare effect of knowledge accumulation via the channel of environmental preservation (term (1)) will be sufficiently low at the initial development

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[9] We rewrite (17) as $\rho q_K - \dot{q}_K = D_K$, where D_K is the instantaneous payoff flows from capital investment. Integration yields the shadow price of capital stock $q_K(t) = \int_t^{\infty} \exp(-\rho(s-t)) \cdot D_K(s) \cdot ds$. The shadow price measures the increments to the market value from investing an extra unit of capital, $q_K = V'(K)$, where $V(K)$ denotes the market value of the capital stock of K.

phase, and the marginal welfare effect via the channel of goods consumption (term (2)) will dominate the net effect. At the initial growth phase, while the lower level of consumption creates a higher level of marginal welfare gains from goods consumption, the lower level of capital-knowledge ratio K/H leads to a lower level of marginal productivity of knowledge stock. We thus expect that the marginal welfare effect associated with the term (2) may be low.

From (17)-(18) we get that the dynamic benefit (as indicated by the shadow price) of capital investment will be much higher than that of knowledge accumulation at China's initial development phase. As a result, the central planner only has an incentive to invest in capital stock for pursuing higher dynamic benefits, leaving aside the opportunity of R&D for knowledge accumulation. For this reason, the interior solution as characterized by (12) should be a boundary solution taking a complementary slackness form,

$$-q_K + q_H \leq 0, \quad R \geq 0, \quad (-q_K + q_H)\cdot R = 0\,. \tag{19}$$

Intuitively, at the initial growth periods, as the dynamic benefit of capital investment is larger than that of R&D $q_K > q_H$, economic resources are fully allocated towards capital investment without any spending in R&D $R = 0$. As a result, China's initial growth is characterized by massive investment in capital stock, leaving aside R&D for knowledge stock accumulation. Without spending in R&D, the stock of knowledge remains unchanged at its initial level H_0, shaping China's investment-driven growth pattern during the initial development phase. We thus establish the following proposition to summarize this result.

Proposition 1 *In the above-described model of China's economic growth, at the initial phase of economic growth the dynamic benefit of investment for capital build-up is larger than that of R&D for knowledge stock accumulation, the social planner thus only has an incentive to allocate resources to capital investment rather than R&D, shaping the investment-driven growth pattern. In specific, given that there is no resource allocated to R&D spending and the stock of knowledge remains unchanged at the initial level* H_0, *this investment-driven growth path is characterized by a consumption-capital pair that evolves according to the following system of differential equations,*

$$\dot{C} = -\kappa\cdot\frac{\sigma_Q}{\sigma_C}\cdot\frac{C^2}{K} + \bar{a}\cdot A\cdot\left[\frac{H_0}{K}\right]^{1-\bar{a}}\cdot C - \rho\cdot C \quad , \tag{20}$$

$$\dot{K} = A\cdot {H_0}^{1-\bar{a}}\cdot K^{\bar{a}} - C \quad . \tag{21}$$

Furthermore, this investment-driven growth path has a saddle-path stability around the steady state, i.e., starting from an initial consumption-capital pair (C_0, K_0), *consumption and capital stock will evolve according to the dynamic equations (20)-(21) and converge to the steady state* (C_{SS}, K_{SS}) *given by,*

$$C_{SS} = [(\bar{a} - \sigma_Q\cdot{\sigma_C}^{-1}\cdot\kappa)\cdot\rho^{-1}]^{\frac{\bar{a}}{1-\bar{a}}}\cdot A^{\frac{1}{1-\bar{a}}}\cdot H_0\,, \tag{22}$$

$$K_{SS} = [(\overline{a} - \sigma_Q \cdot \sigma_C^{-1} \cdot \kappa) \cdot \rho^{-1}]^{\frac{1}{1-\overline{a}}} \cdot A^{\frac{1}{1-\overline{a}}} \cdot H_0 . \tag{23}$$

Proof. See Appendix A. ■

Given an initial stock of physical capital stock K_0, there is an initial level of consumption C_0 that is uniquely determined in the stable manifold. Then starting with this initial capital-consumption pair (K_0, C_0), the economy will evolve along the investment-driven growth path characterized by (20)-(21) and converges to the steady state (K_{SS}, C_{SS}) given by (22)-(23). With regard to the environmental impacts associated with this growth path, it is notable that growth along this investment-driven path will lead to an environment-polluting unsustainable outcome in the long run. In specific, following the investment-driven growth path, the stock of dirty capital will be augmented to the steady state level K_{SS} and the stock of clean knowledge remains unchanged at a level of H_0. As a result, the environmental quality will decline monotonically and finally reaches the lowest level, $Q_{SS} = K_{SS}^{-\kappa} \cdot H_0^{\lambda}$. To avoid this environmentally unsustainable outcome, China's economy needs to consider making a transition to a sustainable growth prospect, to which we turn below.

3.2 Transition to environmentally sustainable growth

The last section has examined China's investment-driven, pollution-intensive growth pattern at the initial phase of economic development, and this section will consider China's transition to an environmentally sustainable prospect by creating the new growth engine of technological innovation beyond the existing driver of capital investment. As compared to the investment-driven growth model where resources are fully allocated toward accumulation of dirty capital, growth along the sustainable path features the dual drivers of capital investment and R&D innovation, with accumulations in both dirty physical capital and clean knowledge stocks simultaneously. The accumulated stock of clean knowledge assets thus plays an important role to offset the environment-polluting effect of dirty capital stock, creating an outcome of environmental sustainability

In particular, the simultaneous build-up of both capital and knowledge stocks requires establishing the equalization of marginal welfare gains between capital investment and R&D at some point in time, which is characterized by the following no-arbitrage condition,

$$U_Q(C,Q) \cdot Q_K(K,H) + U_C(C,Q) \cdot F_K(K,H) = U_Q(C,Q) \cdot Q_H(K,H) + U_C(C,Q) \cdot F_H(K,H) \quad , \tag{24}$$

where both physical capital investment and R&D for knowledge stock accumulation yields the same level of marginal welfare gains. In the LHS, capital investment causes welfare losses through environmental pollution $U_Q \cdot Q_K < 0$ but welfare gains through goods consumption $U_C \cdot F_K > 0$. In the RHS, R&D and knowledge accumulation leads to welfare gains through the channels of both environmental quality improvements $U_Q \cdot Q_H > 0$ and goods consumption increases $U_C \cdot F_H > 0$. Based on (24), we have the following proposition to characterize the sustainable growth path.

Proposition 2 *In the above-described model of China's economic growth, consumption and capital stock first evolve along the investment-driven growth path according to (20)-(11) in the initial phase of development, then at some tipping point in time* $t = \bar{t}$*, the marginal welfare gain of R&D for knowledge accumulation will be equalized with that of capital investment, i.e.,*

$$-\frac{\sigma_Q \cdot \kappa}{K(\bar{t})} + \frac{\sigma_C}{C(\bar{t})} \cdot A \cdot \bar{a} \cdot \left[\frac{K(\bar{t})}{H_0}\right]^{\bar{a}-1} = \frac{\sigma_Q \cdot \lambda}{H_0} + \frac{\sigma_C}{C(\bar{t})} \cdot A \cdot (1-\bar{a}) \cdot \left[\frac{K(\bar{t})}{H_0}\right]^{\bar{a}} ,$$

where H_0 *is the initial stock of knowledge along the investment-driven growth path,* $C(\bar{t}), K(\bar{t})$ *is the level of consumption and physical capital stock at the R&D tipping point in time* $\bar{t}$*, respectively. From then on* $t \in [\bar{t}, \infty)$ *the economy will evolve along an investment & innovation-driven growth path by launching capital investment and R&D innovation simultaneously. In specific, for the allocation in this growth path* $[C(t), K(t), H(t)]_{t \in [\bar{t}, \infty)}$*, define* $c(t) \equiv C(t)/K(t)$ *as the consumption-capital ratio, and* $k(t) \equiv K(t)/H(t)$ *as the capital-knowledge ratio at time* $t \in [\bar{t}, \infty)$*, then the investment and innovation-driven growth path can be characterized by the following static optimality condition,*

$$c(t) = \frac{A \cdot \sigma_C \cdot [\bar{a} - (1-\bar{a}) \cdot k(t)]}{\sigma_Q \cdot [\kappa \cdot k(t)^{1-\bar{a}} + \lambda \cdot k(t)^{2-\bar{a}}]} , \tag{25}$$

and dynamic optimality conditions,

$$\frac{\dot{c}(t)}{c(t)} = \frac{\dot{C}(t)}{C(t)} - \frac{\dot{K}(t)}{K(t)} = \frac{[\bar{a} \cdot \lambda + (1-\bar{a}) \cdot \kappa] \cdot A \cdot k(t)^{\bar{a}}}{\kappa + \lambda \cdot k(t)} - \rho - g_K(t) , \tag{26}$$

$$\frac{\dot{k}(t)}{k(t)} = \frac{\dot{K}(t)}{K(t)} - \frac{\dot{H}(t)}{H(t)} = (1+k(t)) \cdot g_K(t) - \frac{A \cdot \{[\sigma_Q \cdot \lambda + \sigma_C \cdot (1-\bar{a})] \cdot k(t)^{\bar{a}+1} + (\sigma_Q \cdot \kappa - \sigma_C \cdot \bar{a}) \cdot k(t)^{\bar{a}}\}}{\sigma_Q \cdot [\kappa + \lambda \cdot k(t)]} , \tag{27}$$

where (26)–(27) determine the growth rate of consumption-capital and capital-knowledge ratio, respectively, and $g_K(t) \equiv \dot{K}(t)/K(t)$ *is the growth rate of physical capital stock at time* $t \in [\bar{t}, \infty)$.

Proof. See Appendix B. ■

As Proposition 2 characterizes, the investment and innovation-driven growth pattern corresponds to a path along which the economy launches capital investment and knowledge accumulation simultaneously after the R&D tipping point is reached at time $t = \bar{t}$. Furthermore, growth along this path over the periods $t \in [\bar{t}, \infty)$ will involve two phases: an unbalanced growth phase $t \in [\bar{t}, t^*)$, and a balanced sustainable growth phase $t \in [t^*, \infty)$ where t^* is some point in time when the growth path becomes balanced. In particular, we define sustainable growth as the balanced phase of the investment and innovation-driven growth path, which is characterized by 1) both consumption-capital and capital-knowledge ratios remain constant at some level $c(t) = c^*, k(t) = k^*$, and 2) consumption, capital stock, and knowledge stock all grow at a constant rate $g_C(t) = g_K(t) = g_H(t) = g^*$, where the superscript asterisk (*) corresponds to the balanced levels. We hence establish the following proposition to characterize the sustainable growth pattern.

Proposition 3 *In the above-described model of China's economic growth, the social planner will launch both capital investment and knowledge accumulation simultaneously at the R&D tipping point in time* $t = \overline{t}$, *and from then on* $t \in [\overline{t}, \infty)$ *the economy will evolve along an investment and innovation-driven growth path. Furthermore, as the economy evolves along this path, it will make a transition to sustainable growth at some point in time* $t = t^*$. *From then on* $t \in [t^*, \infty)$, *following this sustainable growth path both capital-knowledge and consumption-capital ratios remain constant at some level* $k(t) = k^*, c(t) = c^*$, *and given the exogenous parameters* $[\sigma_C, \sigma_C, \rho, \kappa, \lambda, \overline{a}, A]$, *this capital-knowledge ratio* k^* *is endogenously determined by,*

$$[\sigma_C + \sigma_Q \cdot (\lambda - \kappa)] \cdot [\overline{a} - (1 - \overline{a}) \cdot k^*] \cdot A \cdot k^{*\overline{a}} = \sigma_Q \cdot \rho \cdot [\kappa + (\kappa + \lambda) \cdot k^* + \lambda \cdot k^{*2}] \ . \tag{28}$$

Given k^* *the consumption-capital ratio* c^* *is determined by,*

$$c^* = \frac{A \cdot \sigma_C \cdot [\overline{a} - (1 - \overline{a}) \cdot k^*]}{\sigma_Q \cdot (\kappa \cdot k^{*1-\overline{a}} + \lambda \cdot k^{*2-\overline{a}})} \quad , \tag{29}$$

consumption, capital stock, and knowledge stock grows at a constant rate $g_C(t) = g_K(t) = g_H(t) = g^*$,

$$g^* = \frac{[\overline{a} \cdot \lambda + (1 - \overline{a}) \cdot \kappa] \cdot A \cdot k^{*\overline{a}}}{\kappa + \lambda \cdot k^*} - \rho \quad , \tag{30}$$

and environmental quality improves at a rate of $g_Q^* = (\lambda - \kappa) \cdot g^*$.

Proof. Imposing the stationary conditions $\dot{c}(t) = 0, \dot{k}(t) = 0$ on (26)-(27) derives a two-equation system with two unknown variables k^* and $g_K{}^*$. Substituting out $g_K{}^*$ gets (28) that determines the balanced level of capital-knowledge ratio k^*. Given k^*, (25) pins down the balanced level of consumption-capital ratio c^*, and the balanced growth rate g^* is determined by (26). ■

The following proposition summarizes the mechanism of incorporating R&D-related technological innovation into China's growth dynamics for achieving the goal of environmental sustainability.

Proposition 4 *In the above-described model of China's economic growth, if the social planner incorporates R&D innovation into the growth dynamics, then at some tipping point in time when the marginal welfare gain of R&D knowledge accumulation becomes equalized with that of capital investment, the economy will launch an investment* *and innovation-driven growth pattern and make a transition to sustainable growth with environmental sustainability. In contrast, if the social planner does not incorporate R&D technological innovation as a new growth driver, then the economy will evolve along the investment-driven growth path and then converge to the steady state with a monotonic decline in the environmental quality.*

Proof. The preceding discussion establishes all the claims in this proposition. ■

This proposition provides the following intuitions. By incorporating the mechanism of R&D-related innovation into economic growth, the social planner will value the marginal welfare gain of R&D when it becomes equalized with that of capital investment, and then allocate resource to knowledge accumulation and create the new growth engine of technological innovation. By doing that, the economy will launch an investment and innovation-driven growth pattern and make a transition to sustainable growth that enables environmental quality improvement. In contrast, if the social planner pays no attention to the role of R&D innovation in growth dynamics, then the economy will miss the opportunity of obtaining higher marginal welfare gains from knowledge accumulation beyond traditional investment in physical capital. Following the business-as-usual investment-driven growth model, standalone accumulation of dirty physical capital will thus lead to environmental quality deterioration.

4. Numerical results

Investigation in previous sections is rooted in analytical exposition, and this section will provide numerical simulations by calibrating and estimating the above-specified structural model to China's empirical data for realistic relevance. China's economic transition from the investment-driven, pollution-intensive to an investment and innovation-driven, environmentally sustainable growth path will be derived by simulating the economic models with the aid of the computer programme MATLAB, while model parameters, which are not obtained from earlier literature, will be estimated with the aid of the econometric programme STATA.

Based on similar studies in earlier growth literature we impose the values of parameters associated with the demand side of China's economy, i.e., $\sigma_C = 0.9, \sigma_Q = 0.1$ for the household's preference towards goods consumption and environmental quality, and $\rho = 0.05$ for the time discount rate. Moreover, based on the available data on China's GDP, fixed capital investment, R&D, and environmental pollution, we use econometric methods to estimate parameters associated with the supply side (for the details of the model parameters estimation, see Appendix C). In explicit, the elasticity of production output with respect to capital stock and environment quality is estimated to be $a = 0.9$, and $\gamma = 0.2$, respectively. The elasticity of environmental quality with respect to knowledge and capital stock is estimated to be $\lambda = 0.8$, $\kappa = 0.3$, respectively. We hence obtain the elasticity of production output with respect to capital and knowledge stock when their resulting environmental effects are factored into, $\overline{a} = a - \gamma \cdot \kappa = 0.84$, $\overline{\beta} = \gamma \cdot \lambda = 0.16$, which satisfy the neoclassical condition $\overline{a} + \overline{\beta} = a + \gamma \cdot (\lambda - \kappa) = 1$. Based on these estimated exogenous parameter and China's statistical data, we then numerically solve the model and simulate China's investment-driven growth path and the potential transition to an environmentally sustainable growth prospect, to which we now turn.

4.1 Investment-driven, environment-polluting growth

In the first step, we will numerically simulate China's investment-driven growth path at the initial stage of development. Based on China's statistical data on fixed capital investment and R&D in the late 1970s, the initial values of capital and knowledge stock are estimated to be CNY 262 and 180 billion, respectively, i.e., $K(0) = 262, H(0) = 180$. From (17)-(18) we estimate the marginal welfare gain of fixed capital investment as compared to R&D for knowledge stock accumulation,[10]

$$\frac{D_K(0)}{D_H(0)} = \frac{\overline{a} \cdot [K(0)/H(0)]^{\overline{a}-1}}{\overline{\beta} \cdot [K(0)/H(0)]^{1-\overline{\beta}}} = \frac{0.84}{0.16} \cdot \left[\frac{262}{180}\right]^{-1} = 3.6 \quad .$$

It is shown that at the initial period of China's growth, the marginal welfare gain from capital investment is higher than that of knowledge stock accumulation. Accordingly, the social planner only has an incentive to allocate resources to capital investment rather than R&D, thus creating an investment-driven growth path.

Suppose that the R&D tipping point is reached at time $\overline{t}$, prior to that time China's economy evolves along an investment-driven growth path over the periods $t \in [0, \overline{t}]$. From (20)-(21) we can numerically characterize the investment-driven growth path during the initial growth periods $t \in [0, \overline{t}]$,

$$\dot{C} = -\kappa \frac{\sigma_Q}{\sigma_C} \frac{C^2}{K} + \overline{a} A \left[\frac{H_0}{K}\right]^{1-\overline{a}} C - \rho C = -0.3 \cdot \frac{0.1}{0.9} \cdot \frac{C(t)^2}{K(t)} + 0.84 \cdot 0.15 \cdot \left[\frac{180}{K(t)}\right]^{0.16} \cdot C(t) - 0.05 \cdot C(t) \quad , \tag{31}$$

$$\dot{K}(t) = A \cdot H_0^{1-\overline{a}} \cdot K^{\overline{a}} - C = 0.15 \cdot 180^{0.16} \cdot K(t)^{0.84} - C(t) \, . \tag{32}$$

where the exogenous parameters $(\sigma_C, \sigma_Q, \rho, \kappa, \lambda, \overline{a}, \overline{\beta})$ take their corresponding estimated values as detailed above, and the initial stock of knowledge is $H(0) = H_0 = 180$. The phase diagram associated with the dynamical system (31)-(32) is plotted in Fig. 1, and the Jacobian matrix of this dynamical system at

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[10] Recall that, from the very beginning, China is characterized as an agricultural-based pre-industrial economy with pristine environmental quality, the welfare effect via the channel of environmental quality is thus sufficiently low, and the welfare effect via the channel of goods consumption dominates the net effect.

the steady state yields two eigenvalues, one positive $\xi_1 = 0.06$, and one negative $\xi_2 = -0.01$, implying that the dynamic system has an one-dimensional stable manifold. As Fig. 1 shows, given the initial level of capital stock $K_0 = 262$, the stable manifold will endogenously determine the initial level of consumption $C_0 = 19$. Then starting from this initial condition of consumption-capital pair $[C_0, K_0] = [19, 262]$, China's economy will evolve along the investment-driven growth path (indicated by the red line in Fig. 1) and tend towards the steady state $[C_{SS}, K_{SS}] = [2795, 45094]$. With regard to the environmental impacts of this growth mode, the red line in Fig. 2 shows that standalone accumulation of dirty capital stock along the investment-driven growth path leads to monotonic declines in environmental quality index, from the initial level $Q_0 = 337$ to the long-run steady state level $Q_{SS} = 1.56$, which is equivalent to more than 200-fold increases in pollution.

4.2 Transition to environmentally sustainable growth

We continue to numerically simulate China's potential transition to an environmentally sustainable growth path. Consider that, China's consumption and capital stock will evolve along the investment-driven path over the initial growth periods, then at the R&D tipping point in time $t = \bar{t}$, the marginal welfare gains of knowledge accumulation will be equalized with that of capital investment,

$$\begin{aligned} &-\frac{\sigma_Q \cdot \kappa}{K(\bar{t})} + A \cdot \bar{a} \cdot \frac{\sigma_C}{C(\bar{t})} \cdot \left[\frac{K(\bar{t})}{H_0}\right]^{\bar{a}-1} = \frac{\sigma_Q \cdot \lambda}{H_0} + A \cdot (1-\bar{a}) \cdot \frac{\sigma_C}{C(\bar{t})} \cdot \left[\frac{K(\bar{t})}{H_0}\right]^{\bar{a}} \\ \Rightarrow\ &-\frac{0.1 \times 0.3}{K(\bar{t})} + \frac{0.15 \times 0.84 \times 0.9}{C(\bar{t})} \cdot \left[\frac{K(\bar{t})}{180}\right]^{-0.16} = \frac{0.1 \times 0.8}{180} + \frac{0.15 \times 0.16 \times 0.9}{C(\bar{t})} \cdot \left[\frac{K(\bar{t})}{180}\right]^{0.84} \end{aligned}, \tag{33}$$

where $H_0 = 180$ is the preexisting level of knowledge stock along the investment-driven growth path before R&D is launched at time $\bar{t}$, $C(\bar{t}), K(\bar{t})$ is consumption and capital stock at the R&D tipping time point $\bar{t}$, respectively. From solving the stable saddle-path of the dynamical equations (31)-(32) and the no-arbitrage condition (33), we obtain the consumption-capital pair at the R&D tipping point $[C(\bar{t}), K(\bar{t})] = [154, 2286]$.

Once both capital investment and knowledge accumulation create the same level of marginal welfare gains at the R&D tipping time $\bar{t}$, from then on $t \in [\bar{t}, \infty)$ China's economy will launch an investment and innovation-driven growth model where both capital and knowledge stocks are augmented simultaneously, starting from the initial levels $C(\bar{t}) = 154, K(\bar{t}) = 2286, H(\bar{t}) = H_0 = 180$. For the equilibrium allocation along this investment & innovation-driven growth path $[C(t), K(t), H(t)]_{t \in [\bar{t}, \infty)}$, define $c(t) \equiv C(t) / K(t)$ as the consumption-capital ratio, and $k(t) \equiv K(t) / H(t)$ as the capital-knowledge ratio at time $t \in [\bar{t}, \infty)$. Plugging the exogenous parameters into (25)-(27), the investment and innovation-driven growth path can be numerically characterized by the following system of equations,

$$c(t)=\frac{A\cdot\sigma_C\cdot[\bar{a}-(1-\bar{a})\cdot k(t)]}{\sigma_Q\cdot[\kappa\cdot k(t)^{1-\bar{a}}+\lambda\cdot k(t)^{2-\bar{a}}]}=\frac{0.15\cdot 0.9\cdot(0.84-0.16\cdot k(t))}{0.1\cdot[0.3\cdot k(t)^{0.16}+0.8\cdot k(t)^{1.16}]}\quad, \tag{34}$$

$$\frac{\dot{c}(t)}{c(t)}=\frac{[\bar{a}\cdot\lambda+(1-\bar{a})\cdot\kappa]\cdot A\cdot k(t)^{\bar{a}}}{\kappa+\lambda\cdot k(t)}-\rho-g_K(t)=\frac{[0.84\cdot 0.8+0.16\cdot 0.3]\cdot 0.15\cdot k(t)^{0.84}}{0.3+0.8\cdot k(t)}-0.05-g_K(t)\quad, \tag{35}$$

$$\begin{aligned}\frac{\dot{k}(t)}{k(t)}&=(1+k(t))\cdot g_K(t)-\frac{A\cdot\{[\sigma_Q\cdot\lambda+\sigma_C\cdot(1-\bar{a})]\cdot k(t)^{\bar{a}+1}+(\sigma_Q\cdot\kappa-\sigma_C\cdot\bar{a})\cdot k(t)^{\bar{a}}\}}{\sigma_Q\cdot[\kappa+\lambda\cdot k(t)]}\\&=(1+k(t))\cdot g_K(t)-\frac{0.15\cdot[(0.1\cdot 0.8+0.9\cdot 0.16)\cdot k(t)^{1.84}+(0.1\cdot 0.3-0.9\cdot 0.84)\cdot k(t)^{0.84}]}{0.1\cdot[0.3+0.8\cdot k(t)]}\quad,\end{aligned} \tag{36}$$

We further obtain the corresponding dynamic equivalence of (34) that relates the growth rate of consumption-capital ratio to that of capital-knowledge ratio,

$$\frac{\dot{c}(t)}{c(t)}=\frac{\Delta_1(k(t))}{\Delta_2(k(t))}\cdot\frac{\dot{k}(t)}{k(t)}, \tag{37}$$

where

$$\Delta_1(k(t))=\lambda\cdot(1-\bar{a})^2\cdot k(t)^2-\bar{a}\cdot[(1-\bar{a})\cdot\kappa+(2-\bar{a})\cdot\lambda]\cdot k(t)-\bar{a}\cdot(1-\bar{a})\cdot\kappa=0.021\cdot k(t)^2-0.820\cdot k(t)-0.041$$
$$\Delta_2(k(t))=-\lambda\cdot(1-\bar{a})\cdot k(t)^2+[\bar{a}\cdot\lambda-(1-\bar{a})\cdot\kappa]\cdot k(t)+\bar{a}\cdot\kappa=-0.128\cdot k(t)^2+0.624\cdot k(t)+0.252\,.$$

Solving the system of three equations (35)-(37) can fully pin down the three endogenous variables $\dot{c}/c$, $\dot{k}/k$, and g_K, in particular the growth rate of the capital-knowledge ratio takes an explicit form as

$$\begin{aligned}\frac{\dot{k}(t)}{k(t)}&=\Delta_2(k(t))\cdot\left[\frac{[\sigma_C+\sigma_Q\cdot(\lambda-\kappa)]\cdot[\bar{a}-(1-\bar{a})\cdot k(t)]\cdot A\cdot k(t)^{\bar{a}}-\sigma_Q\cdot\rho\cdot[\kappa+(\kappa+\lambda)\cdot k(t)+\lambda\cdot k(t)^2]}{\sigma_Q\cdot(\kappa+\lambda\cdot k(t))\cdot[(1+k(t))\cdot\Delta_1(k(t))+\Delta_2(k(t))]}\right]\\&=\Delta_2(k(t))\cdot\left[\frac{(0.9+0.1\cdot 0.5)\cdot[0.84-0.16\cdot k(t)]\cdot 0.15\cdot k^{0.84}-0.1\cdot 0.05\cdot[0.3+1.1\cdot k(t)+0.8\cdot k(t)^2]}{0.1\cdot(0.3+0.8\cdot k(t))\cdot[(1+k(t))\cdot\Delta_1(k(t))+\Delta_2(k(t))]}\right]\end{aligned}\quad, \tag{38}$$

Given the initial condition for the investment and innovation-driven growth path over the period $t\in[\bar{t},\infty)$, $k(\bar{t})=K(\bar{t})/H(\bar{t})=2286/180=12.7$, we use (38) to solve for the time path of capital-knowledge ratio $[k(t)]_{t\in[\bar{t},\infty]}$. Given $[k(t)]_{t\in[\bar{t},\infty]}$, we use (34) to compute the time path of consumption-capital ratio $[c(t)]_{t\in[\bar{t},\infty]}$ and (36) to simulate the time path of capital stock growth rate $[g_K(t)]_{t\in[\bar{t},\infty]}$.

After the R&D tipping point $t=\bar{t}$ is reached, China's social planner will launch capital investment and knowledge accumulation simultaneously, which enables the economy to grow along an investment and innovation-driven growth pattern as characterized by (34)-(36). Suppose that at some point in time $t=t^*$, China's economy will make a transition to a balanced phase of this investment and innovation-driven growth path, i.e., a sustainable growth path. From then on $t \in [t^*, \infty)$ both consumption-capital and capital-knowledge ratios will remain constant at some level $c(t) = c^*, k(t) = k^*$, and consumption, capital stock, and knowledge stock will grow at a constant rate $g_C(t) = g_K(t) = g_H(t) = g^*$. For numerical characterizations of this sustainable growth, from (38) we compute the capital-knowledge ratio k^*,

$$0.95 \cdot (0.84 - 0.16 \cdot k(t)) \cdot 0.15 \cdot k^{0.84} - 0.005 \cdot [0.3 + 1.1 \cdot k(t) + 0.8 \cdot k(t)^2] \;\Rightarrow\; k^* = 4.04. \quad (39)$$

Given $k^* = 4.04$, we use (34) to obtain the consumption-capital ratio c^*,

$$c^* = \frac{A \cdot \sigma_C \cdot [\bar{a} - (1 - \bar{a}) \cdot k^*]}{\sigma_Q \cdot (\kappa \cdot k^{*1-\bar{a}} + \lambda \cdot k^{*2-\bar{a}})} = \frac{0.15 \times 0.9 \times (0.84 - 0.16 \cdot k^*)}{0.1 \times [0.3 \cdot k^{*0.16} + 0.8 \cdot k^{*1.16}]} = 0.059 \quad , \quad (40)$$

and from (30) we obtain the growth rate of consumption, capital stock, and knowledge stock

$$g^* = \frac{[\bar{a} \cdot \lambda + (1 - \bar{a}) \cdot \kappa] \cdot A \cdot k^{*\bar{a}}}{\kappa + \lambda \cdot k^*} - \rho = \frac{(0.84 \cdot 0.8 + 0.16 \cdot 0.3) \cdot 0.15 \cdot k^{*0.84}}{0.3 + 0.8 \cdot k^*} - 0.05 = 0.049 \quad , \quad (41)$$

and the rate of environmental quality improvement $g_Q^* = (\lambda - \kappa) \cdot g^* = 0.5 \cdot g^* = 0.025$. Therefore, China's sustainable growth pattern can be characterized by constant capital-knowledge and consumption-capital ratios $k^* = 4.04$, $c^* = 0.059$. Following this sustainable growth path, consumption, physical capital stock, and knowledge stock all grow at a rate of 4.9%, and environmental quality improves at a rate of 2.5%.

Furthermore, we argue that the transition phase is transient and takes short time periods to reach the sustainable growth path, i.e., the economy will immediately evolve from investment-driven to sustainable growth pattern once the marginal welfare gain of knowledge accumulation becomes equalized with that of capital investment at the R&D tipping point. To show this result, we examine the saddle-path stability of China's transitional dynamics around the sustainable growth equilibrium based on (38)

$$\frac{\dot{k}}{k} = \frac{N(k)}{D(k)} \cdot \Delta_2(k) \quad ,$$

where we define the notations $N(k) = 0.95 \cdot (0.84 - 0.16 \cdot k) \cdot 0.15 \cdot k^{0.84} - 0.005 \cdot [0.3 + 1.1 \cdot k + 0.8 \cdot k^2]$, $D(k) = 0.1 \cdot (0.3 + 0.8 \cdot k) \cdot [(1 + k) \cdot \Delta_1(k) + \Delta_2(k)]$. Taking differentiation with respect to k obtains

$$\frac{d\dot{k} / k}{dk} = \frac{N'(k) \cdot \Delta_2(k) \cdot D(k) + N(k) \cdot \Delta_2'(k) \cdot D(k) - N(k) \cdot \Delta_2(k) \cdot D'(k)}{D(k)^2} \quad ,$$

and evaluated at the sustainable level of capital-knowledge ratio $k^* = 4.04$, we have $N(k^*) = 0$ (recall (39)), and

$$\left.\frac{d\dot{k}/k}{dk}\right|_{k=k^*} = \frac{N'(k^*)\cdot\Delta_2(k^*)}{D(k^*)} = 0.0124>0$$

where the positive sign implies that there is no transitional dynamics around the sustainable growth path and the economy will immediately evolve from the investment-driven into sustainable growth around the R&D tipping time point. This is consistent with our simulation results as shown in Fig. 3: starting from the initial levels of capital-knowledge and consumption-capital ratio $[k(0), c(0)] = [1.46,\ \ 0.073]$, China's economy evolves along the investment-driven growth path. Once it reaches the R&D tipping time point $\overline{t}$, the capital-knowledge and consumption-capital ratio will rapidly shift from $[k(\overline{t}), c(\overline{t})] = [12.7,\ \ 0.068]$ to a balanced level $[k^*, c^*] = [4.04,\ \ 0.059]$ corresponding to the sustainable growth path equilibrium.

To sum up, the above-derived simulation results draw important implications for China's potential economic transition. As Fig. 4 illustrates, following the investment-driven growth path China's economy can grow but will eventually stagnate at the steady state without further growth. As an alternative, by making a transition to a sustainable growth pattern China's economy can grow unremittingly without stagnation. In particular, this sustainable growth pattern is characterized by two features: (1) a constant capital-knowledge and consumption-capital ratio $k^* = 4.04$, $c^* = 0.059$, and (2) consumption, physical capital stock, and knowledge stock will grow simultaneously at a rate of 4.9%, and environmental quality improves at a rate of 2.5%. Moreover, given that capital investment flows augment the stock of capital at a rate of 4.9%, $\dot{K}^* / K^* = 0.049$, we thus obtain the relationship between capital investment and capital stock, $I^* \equiv \dot{K}^* = 0.049K^*$. As compared to the levels of consumption $C^* = 0.059K^*$, we obtain the ratio between consumption and investment $C^* : I^* = 0.059{:}0.049$. Given $k^* = K^* / H^* = 4.04$ and $\dot{H}^* / H^* = 0.049$, we obtain the level of R&D for knowledge accumulation $R^* \equiv \dot{H}^* = 0.049H^* = 0.049 \cdot 0.248K^* = 0.012K^*$. Accordingly, to achieve economic growth along a sustainable path, China's social planner should allocate resources to the three components of final use (consumption, capital investment, and R&D) according to a balanced share $C^* : I^* : R^* = 0.059{:}0.049 : 0.012 = 5{:}\ 4{:}\ 1$.

5. Conclusion

As the existing investment-driven, environment-polluting growth pattern finds it difficult to maintain China's further sustainable development, R&D-related innovation emerges from the surface as a new engine of growth to foster transition to an environmentally sustainable growth prospect. In this context, it is important to have a deep understanding of the interaction among capital investment, R&D innovation, economic growth, and environmental impacts. Based on the Ramsey-Cass-Koopmans growth model that features endogenous technological change induced by R&D and knowledge stock accumulation, this study provides our analytical and numerical results that help understand the mechanism underlining China's economic transition from an environment-polluting to environmentally sustainable growth pattern.

Our main findings are summarized as follows. At the initial period of China's economic growth, the marginal welfare gain from capital investment is more than three-fold larger than that of knowledge stock accumulation. As a result, the social planner only has an incentive to allocate resources to physical capital investment rather than R&D, thus creating an investment-driven growth path. Along this growth path, the stock of knowledge remain unchanged at the initial low level CNY 180 billion, and the consumption and capital stock will evolve from the initial level CNY 19 and 262 billion towards the steady state level CNY 2795 and 45094 billion. As the environmental consequence, standalone accumulation of dirty capital stock leads to monotonic declines in environmental quality index from the initial level $Q_0 = 337$ to the steady state level $Q_{SS} = 1.56$, which is equivalent to more than 200-fold increases in pollution.

To avoid the undesirable environmental outcome, China's social planner should consider creating the new growth engine of technological innovation beyond the existing driver of capital investment, and thus fosters economic transition to an environmentally sustainable prospect. To do that, resources should be allocated toward both capital investment and R&D innovation, with accumulations in both dirty physical capital and clean knowledge stocks simultaneously. The accumulated stock of clean knowledge assets thus plays an important role to offset environment-polluting effects of dirty capital stock, creating an outcome of environmental sustainability. In particular, if technological innovation induced by R&D and knowledge stock accumulation is incorporated into China's growth dynamics, then at some tipping point in time when marginal welfare gain of R&D becomes equalized with that of capital investment, China's economy will launch investment in physical capital and knowledge stock simultaneously and make a rapid transition to a sustainable growth path along which consumption, capital investment, and R&D have a balanced share of 5: 4: 1, capital-knowledge and consumption-capital ratios remain constant at a level of 4.04 and 0.059, and consumption, capital stock, and knowledge stock all grow at a rate of 4.9%, and environmental quality improves at a rate of 2.5%.

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Appendix A. Proof of Proposition 1

We use the following procedure to derive (20),

$$\frac{\dot{C}}{C} = -\frac{\dot{U}_C}{U_C} = -\frac{\dot{q}_K}{q_K} = \frac{U_Q \cdot Q_K}{U_C} + F_K - \rho \quad \Rightarrow \quad \dot{C} = -\frac{\sigma_Q}{\sigma_C} \cdot \kappa \cdot \frac{C^2}{K} + \bar{a} \cdot A \cdot \left[\frac{H_0}{K}\right]^{1-\bar{a}} \cdot C - \rho \cdot C,$$

where the first equality comes from the logarithmic utility, the second and third follow from the optimality conditions (11)-(13). (21) is the direct variant of aggregate resource constraints when there is no spending in R&D and the knowledge stock thus remains the initial level H_0. Imposing the steady state conditions $\dot{C} = 0, \dot{K} = 0$ on (20)-(21) derives the steady-state level of consumption and physical capital stock as given by (22)-(23). To establish the saddle-path stability around the steady state, we derive the partial derivatives of the differential equations (20)-(21) evaluated at the steady state (C_{SS}, K_{SS}),

$$\left.\frac{\partial \dot{C}}{\partial C}\right|_{K_{SS},C_{SS}} = \bar{a}\cdot A\cdot\left[\frac{H_0}{K_{SS}}\right]^{1-\bar{a}} - 2\frac{\sigma_Q}{\sigma_C}\cdot\kappa\cdot\frac{C_{SS}}{K_{SS}} - \rho = -\frac{\sigma_Q}{\sigma_C}\cdot\kappa\cdot\frac{\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa}$$

$$\left.\frac{\partial \dot{C}}{\partial K}\right|_{K_{SS},C_{SS}} = \frac{C_{SS}}{K_{SS}}\cdot\left[A\cdot(\bar{a}^2-\bar{a})\cdot\left[\frac{H_0}{K_{SS}}\right]^{1-\bar{a}} + \frac{\sigma_Q}{\sigma_C}\cdot\kappa\cdot\frac{C_{SS}}{K_{SS}}\right] = \frac{\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa}\cdot\left[\frac{\bar{a}^2\cdot\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa}-\rho\right]$$

$$\left.\frac{\partial \dot{K}}{\partial C}\right|_{K_{SS},C_{SS}} = -1$$

$$\left.\frac{\partial \dot{K}}{\partial K}\right|_{K_{SS},C_{SS}} = \bar{a}\cdot A\cdot\left[\frac{H_0}{K_{SS}}\right]^{1-\bar{a}} = \frac{\bar{a}\cdot\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa}$$

where (22)-(23) are used to simplify the notion and obtain the Jacobian matrix of the dynamical equation systems (20)-(21) at the steady state,

$$\begin{bmatrix} \left.\frac{\partial \dot{C}}{\partial C}\right|_{K_{SS},C_{SS}} & \left.\frac{\partial \dot{C}}{\partial K}\right|_{K_{SS},C_{SS}} \\ \left.\frac{\partial \dot{K}}{\partial C}\right|_{K_{SS},C_{SS}} & \left.\frac{\partial \dot{K}}{\partial K}\right|_{K_{SS},C_{SS}} \end{bmatrix} = \begin{bmatrix} -\frac{\sigma_Q}{\sigma_C}\cdot\kappa\cdot\frac{\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa} & \frac{\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa}\cdot\left[\frac{\bar{a}^2\cdot\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa}-\rho\right] \\ -1 & \frac{\bar{a}\cdot\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa} \end{bmatrix}.$$

The eigenvalues are given by the value of ξ that solves the following quadratic form:

$$\det\begin{vmatrix} -\frac{\sigma_Q}{\sigma_C}\cdot\kappa\cdot\frac{\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa} & \frac{\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa}\cdot\left[\frac{\bar{a}^2\cdot\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa}-\rho\right] \\ -1 & \frac{\bar{a}\cdot\rho}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa} \end{vmatrix} = -\frac{\rho^2\cdot(1-\bar{a})}{\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa} - \rho\cdot\xi + \xi^2.$$

Provided that $\bar{a}-\sigma_Q\cdot\sigma_C{}^{-1}\cdot\kappa > 0$, there are two real eigenvalues, one negative and one positive. This condition thus establishes the saddle-path stability. ■

Appendix B. Proof of Proposition 2

To derive (25), we plug the functional forms of the model into (24) and use $c \equiv C/K$ and $k \equiv K/H$ to simplify this expression and rearranging yields (25). For the proof of (26), we derive the growth rate of consumption as,

$$\frac{\dot{C}}{C} = -\frac{\dot{U}_C}{U_C} = -\frac{\dot{q}_K}{q_K} = \frac{U_Q\cdot Q_K}{U_C} + F_K - \rho = \frac{[\bar{a}\cdot\lambda + (1-\bar{a})\cdot\kappa]\cdot A\cdot k^{\bar{a}}}{\kappa+\lambda\cdot k} - \rho,$$

where the first equality comes from the logarithmic utility function, the second and third follow from the optimality conditions (11)-(13), and the final equality gives the explicit expression. From the equation above we can obtain (26). For the proof of (27), from the resource constraint $AK^{\bar{\alpha}}H^{\bar{\beta}} - C - \dot{K} - \dot{H} = 0$, we get the growth rate of knowledge stock,

$$g_H \equiv \frac{\dot{H}}{H} = \frac{AK^{\bar{\alpha}}H^{\bar{\beta}} - C - \dot{K}}{H} = Ak^{\bar{\alpha}} - ck - g_K k = \frac{A[(\sigma_Q\lambda + \sigma_C(1-\bar{\alpha}))k^{1+\bar{\alpha}} + (\sigma_Q\kappa - \sigma_C\bar{\alpha})k^{\bar{\alpha}}]}{\sigma_Q(\kappa + \lambda k)} - g_K k$$

where we substitute (25) for c and obtain (27). ■

Appendix C. Estimation of Model Parameters

The exogenous model parameters are estimated in the following steps. First, we impose the monotonic exponential transformations on the utility function (1) and obtain the corresponding Cobb-Douglas form of the utility function $\bar{U}(C(t), Q(t)) = C(t)^{\sigma_C} Q(t)^{\sigma_Q}$, where σ_C, σ_Q can be estimated by the cost share of spending on consuming material goods and environment-related goods and services in the household's total consumption expenditure. Based on the time-series (1978-2013) household consumption expenditure data documented in the *China Statistical Yearbook 2014* (NBS, 2014), we use consumption data items related to health care and other services as the proxy of spending on environment-related goods and services, and all other data items to represent spending on generic material goods consumption. Calculation derives that the cost share of consuming environment-related goods and material goods in China's household's total spending is about 10% and 90%, respectively. The exogenous parameters related to the preference are thus estimated to be $\sigma_C = 0.9, \sigma_Q = 0.1$.

Second, from the *China Statistical Yearbook 2014* (NBS, 2014) we collect the time series (1978-2013) data of nominal GDP and fixed assets investment, and then use GDP price index and the price index for fixed capital formation to convert nominal values into real terms. With the data on fixed capital investment (a flow variable) in hand, we estimate the stock of capital using the standard perpetual inventory approach.

$$\dot{K}_{1978} = I_{1979} - \delta_K \cdot K_{1978} \quad \Rightarrow \quad g_K \cdot K_{1978} = I_{1979} - \delta_K \cdot K_{1978} \quad \Rightarrow \quad K_{1978} = \frac{I_{1979}}{g_K + \delta_K} = \frac{81.2}{15\% + 16\%} = 262$$

where we initialize the stock of capital in year 1978 as the ratio of fixed asset investment in 1979 (CNY 81.2 billion) to the sum of the average growth rate of capital investment in 1978–1983 and the depreciation rate of physical capital. The average growth rate of capital investment is calculated to be $g_K = 15\%$ and the depreciation rate of physical capital stock $\delta_K = 16\%$.[11] Based on the initial stock of physical capital in year

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[11] The depreciation rate is 8 percent for investment in structures and buildings and 24 percent for

1978 and the available data on fixed asset investment in the subsequent years 1979-2013, we can obtain the time series data on the stock of physical capital over the period 1978-2013.

Third, based on *China Statistical Yearbook on Science and Technology 2014* (NBS and MOST, 2014), data on China's R&D spending is only available over 1990-2013, and there is no detailed data documentation for 1978-1989. But the yearbook mentions that China's R&D intensity as a share of GDP remains relatively low at a level of about 0.5% of GDP prior to 1990, so we estimate the level of R&D spending in each year over 1978-1989 by multiplying the available GDP data with a R&D intensity of 0.5%. Once the time-series (1978-2013) data on R&D spending flows is prepared, we follow the perpetual inventory approach to estimate the stock of knowledge,

$$\dot{H}_{1978} = R_{1979} - \delta_H \cdot H_{1978} \quad \Rightarrow \quad g_H \cdot H_{1978} = R_{1979} - \delta_H \cdot H_{1978} \quad \Rightarrow \quad H_{1978} = \frac{R_{1979}}{g_H + \delta_H} = \frac{18}{0.1+0} = 180$$

where we initialize the knowledge stock in 1978 as the ratio of R&D spending in 1979 (CNY 18 billion) to the sum of the average growth rate of R&D spending in 1978–1983 and the depreciation rate of knowledge assets. We calculate the average growth rate of R&D to be $g_H = 10\%$ and suppose a zero depreciation rate for knowledge stock. Based on the initial stock of knowledge in 1978 and the available data on R&D spending in the subsequent years 1979-2013, we can obtain the time series data of the stock of knowledge over the period 1978-2013.

Fourth, from *China Statistical Yearbook on Environment 2014* (NBS and MEP, 2014), we collect data of waste gas discharge (including sulfur dioxide, and smoke & dust) from industrial emissions as a proxy of environmental pollution that is inversely related to environmental quality. Data of the waste gas discharge is only available over the period 1985-2013, and we estimate the period 1978-1984 data using linear growth methods based on 1985-2013 average growth rate of emissions.

Based on the above-derived data on GDP, physical capital stock, and environmental pollution, we estimate the exogenous parameters associated with the production function

$$Y(t) = A \cdot K(t)^{a} \cdot P(t)^{-\gamma} \quad \Leftrightarrow \quad \frac{\dot{Y}(t)}{Y(t)} = a \cdot \frac{\dot{K}(t)}{K(t)} - \gamma \cdot \frac{\dot{P}(t)}{P(t)} \quad ,$$

where the growth rate of each variable is discretized on an annual basis using the time-series data.

investment in machinery and equipment, so we use the average value as the depreciation rate for physical capital stock. We arrive at these estimates of depreciation rates from estimates by Chinese researchers (for example, Huang, Ren, and Liu, 2002; Wang and Wu, 2003) of the useful lives of structures and buildings (thirty-eight years) and machinery and equipment (twelve years).

$$\frac{Y(t+1)-Y(t)}{Y(t)}=a\cdot\frac{K(t+1)-K(t)}{K(t)}-\gamma\cdot\frac{P(t+1)-P(t)}{P(t)}\quad .$$

The results of OLS estimation are shown in Tab. 1, and the estimated values of the elasticity of production with respect to capital stock and environmental pollution are about $\hat{a}=0.9$ and $\hat{\gamma}=0.2$, respectively. Moreover, based on the time-series data on GDP $Y(t)$, capital stock $K(t)$, pollution flows $P(t)$, and the estimated parameters $\hat{a},\hat{\gamma}$, we calculate the productivity parameter at each time point over the period using $\hat{A}=Y(t)/(K(t)^{\hat{a}}\cdot P(t)^{-\hat{\gamma}})$. Taking the average, the productivity parameter is equal to $\hat{A}=0.15$. Furthermore, based on the time-series data on pollution flows $P(t)$, capital stock $K(t)$, knowledge stock $H(t)$, we estimate the exogenous parameters associated with the environmental quality function

$$\frac{\dot{P}(t)}{P(t)}=\kappa\cdot\frac{\dot{K}(t)}{K(t)}-\lambda\cdot\frac{\dot{H}(t)}{H(t)}$$

where the growth rate of each variable is discretized on an annual basis using the time-series data.

$$\frac{P(t+1)-P(t)}{P(t)}=\kappa\cdot\frac{K(t+1)-K(t)}{K(t)}-\lambda\cdot\frac{H(t+1)-H(t)}{H(t)}$$

The results of OLS estimation are shown in Tab. 2, and the estimated values of the elasticity of environmental quality with respect to physical stock and knowledge stock is about $\hat{\kappa}=0.3$ and $\hat{\lambda}=0.8$.

Table 1 OLS estimation of parameters in the production function

	(1978-2013)	(1980-2013)	(1985-2013)	(1988-2013)	(1989-2013)	(1990-2013)	(1993-2013)	(1995-2013)
VARIABLES	gy	gy	gy	gy	gy	gy	gy	gy
gk	0.916***	0.913***	0.906***	0.875***	0.881***	0.877***	0.894***	0.799***
	(0.0924)	(0.0960)	(0.0992)	(0.0970)	(0.102)	(0.104)	(0.103)	(0.0778)
gp	-0.234*	-0.233*	-0.233*	-0.243*	-0.247*	-0.245*	-0.230*	-0.209*
	(0.0716)	(0.0725)	(0.0726)	(0.0725)	(0.0755)	(0.0765)	(0.0719)	(0.0609)
Observations	35	33	28	25	24	23	20	18
R-squared	0.611	0.600	0.588	0.576	0.568	0.560	0.769	0.831

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note: gy, gk, gp denote the annual growth rate of GDP, physical capital stock, and environmental pollution, respectively.

Table 2 OLS estimation of parameters in the environmental quality function

	(1978-2013)	(1979-2013)	(1980-2013)	(1981-2013)	(1982-2013)	(1985-2013)	(1989-2013)	(1990-2013)
VARIABLES	gp	gp	gp	gp	gp	gp	gp	gp
gk	-0.304*	-0.338*	-0.351*	-0.357*	-0.360*	-0.290*	-0.319*	-0.306*
	(0.201)	(0.223)	(0.230)	(0.232)	(0.233)	(0.217)	(0.257)	(0.252)
gh	0.764***	0.795***	0.806***	0.810***	0.811***	0.745***	0.773***	0.768***
	(0.239)	(0.255)	(0.259)	(0.260)	(0.260)	(0.244)	(0.265)	(0.260)
Observations	35	34	33	32	31	28	24	23
R-squared	0.633	0.628	0.623	0.617	0.611	0.624	0.624	0.629

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Note: gk, gh, gp denote the annual growth rate of physical capital stock, knowledge stock, and environmental pollution, respectively.

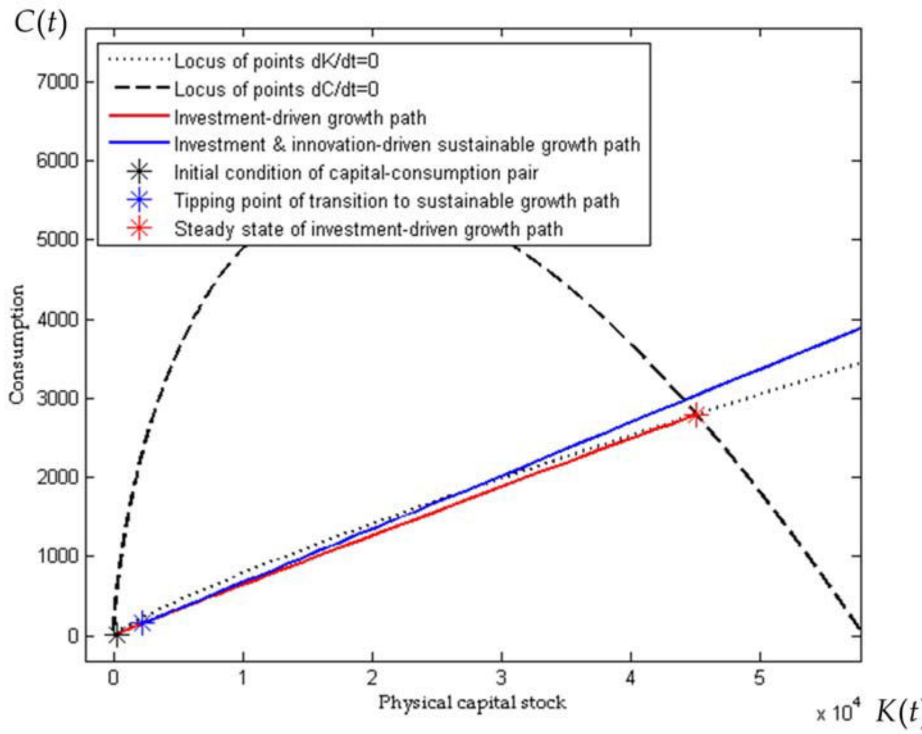

Figure 1. China's economic dynamics along the investment-driven growth path and the transition to a sustainable growth path. The red line corresponds to the stable manifold: starting with the initial consumption-capital pair (the black star), China's economy will evolve along the investment-driven growth path (the red line), and tend towards the steady state (the red star). Alternatively, if R&D-induced technological innovation is incorporated into the growth mechanism, then at the tipping point in time (the blue star) when marginal welfare gains of R&D becomes equalized with that of capital investment, China's economy will launch a transition to a sustainable growth path (the blue line) along which consumption, capital stock, and knowledge stock can continuously grow without stagnation at the steady state.

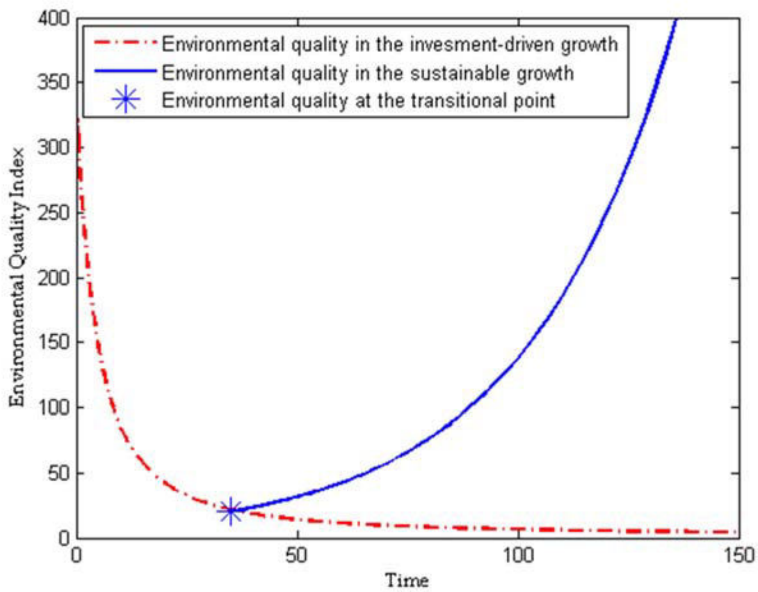

Figure 2. Time paths of environmental quality index in both investment-driven and sustainable growth paths. Along the investment-driven growth path, standalone accumulation of environment-polluting capital stock leads to monotonic decreases in environmental quality (the red line). If R&D-induced technological innovation is incorporated into the growth mechanism, then at the transitional point in time (the blue star) when R&D is launched for accumulating the clean knowledge stock, China's economy will make a transition to a sustainable growth path along which environmental quality improves at a rate of 2.5% (the blue line).

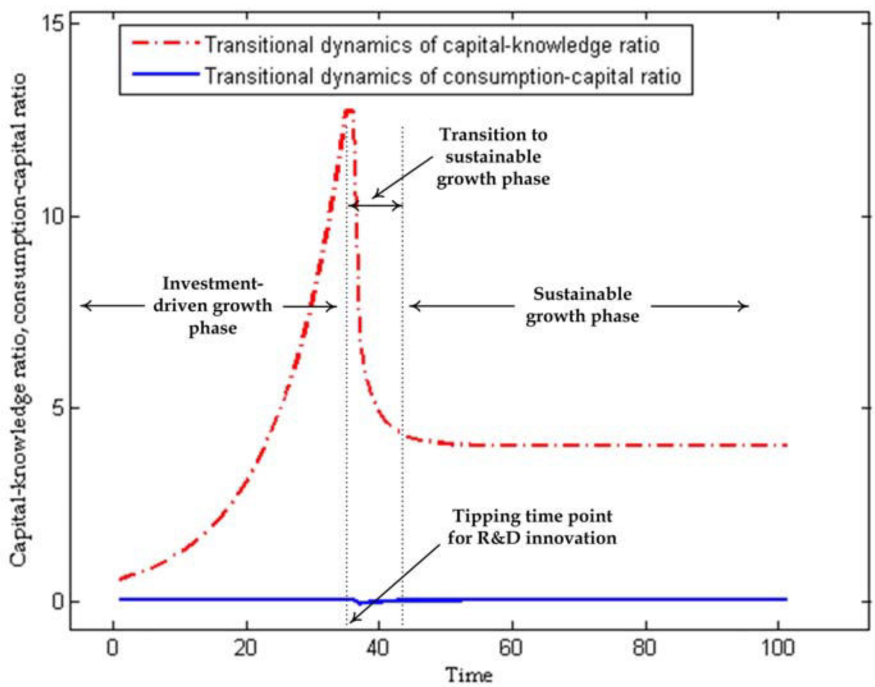

Figure 3. Time paths of capital-knowledge and consumption-capital ratios for China's economic transition from the investment-driven to sustainable growth phases. With massive standalone accumulation of capital stock along the investment-driven growth path, China's economic growth will firstly experience a rise in capital-knowledge ratio and a decline in consumption-capital ratio. When the economy evolves and reaches at the tipping point of R&D for knowledge accumulation, the economic transition will occur and take short time periods to adjust both capital-knowledge ratio and consumption-capital ratio to lower levels 4.04 and 0.059 that corresponds to the sustainable growth phase.

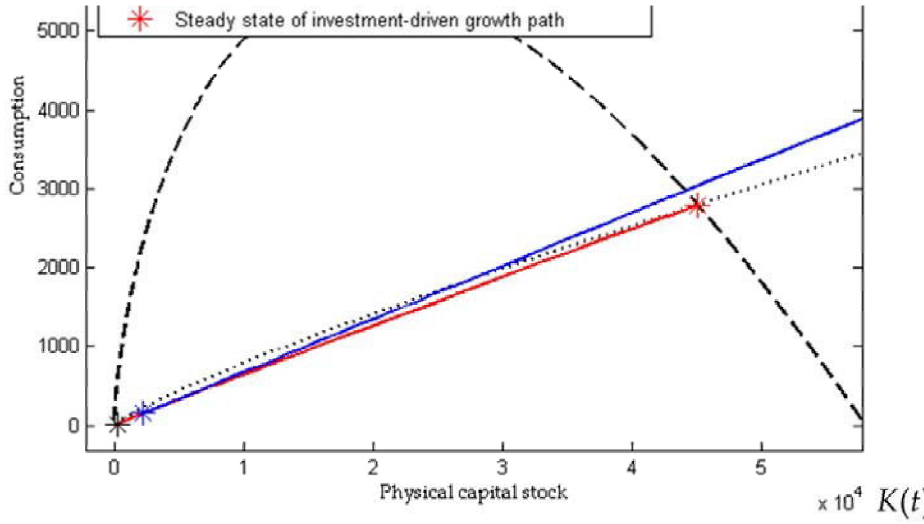

Figure 1. China's economic dynamics along the investment-driven growth path and the transition to a sustainable growth path. The red line corresponds to the stable manifold: starting with the initial consumption-capital pair (the black star), China's economy will evolve along the investment-driven growth path (the red line), and tend towards the steady state (the red star). Alternatively, if R&D-induced technological innovation is incorporated into the growth mechanism, then at the tipping point in time (the blue star) when marginal welfare gains of R&D becomes equalized with that of capital investment, China's economy will launch a transition to a sustainable growth path (the blue line) along which consumption, capital stock, and knowledge stock can continuously grow without stagnation at the steady state.

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