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Short communication

A circular economy model of economic growth

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ABSTRACT

The main purpose of this paper is to present a theoretical model incorporating the concept of circular economic activities. We construct a circular economy model with two types of economic resources, namely, a polluting input and a recyclable input. Overall, our results indicate that the factors affecting economic growth include the marginal product of the recyclable input, the recycling ratio, the cost of using the environmentally polluting input and the level of pollution arising from the employment of the polluting input. Our analysis also shows that, contrary to the Environmental Kuznets Curve (EKC), environmental quality cannot be maintained or improved via economic growth. Instead, the improvement in environmental quality, as measured by a reduction in pollution, can only be achieved by an increase in the environmental self-renewal rate or the recycling ratio.

The ultimate physical product of economic life is garbage.

— Kenneth E. Boulding, 1970, p.162

1. Introduction

The conventional wisdom for analyzing economic activities is rooted in a unidirectional concept of production, i.e., natural resources entering one end of the production process and economic products emerging at the other end. In a market economy, attention is focused on the value of economic products, while the depletion of natural resources and the resultant accumulation of economic waste are typically ignored. We can rationally expect that, if people do not engage in recycling resources and managing waste, the reserves of many resources will soon vanish from the earth.

The aim of this paper is straightforward: to present a theoretical model incorporating the concept of circular economic activities. In the 1960s, the embryonic idea of a circular economy was first developed by Professor Kenneth E. Boulding, a pioneer environmental economist. To Boulding (1966), the earth can be best understood as a single spaceship with limited reservoirs of anything, either for extraction or for pollution. In the spaceman economy, the essential measure of the success is “the nature, extent, quality, and complexity of the total capital stock” rather than economic throughput (Boulding, 1966, p. 9). As for the carrying capacity of an economy, Daly (1991) uses the analogy of a sinking boat and points out that the boat on which the cargos are optimally allocated might still sink under too much weight. Andersen (2007) discusses the environmental economics of the circular economy emphasizing the contributions of Pearce and Turner (1990) and argues that, in Europe, significant advances have been achieved by the pricing of externalities.

To date, more and more countries in the world have taken measures to promote the circular economy. Japan, Austria, Germany, and the Netherlands, for example, have to some extent already developed strategies compatible with circular economic activities (Heck, 2006). In China, the circular economy has even been accepted by the central government as a vital strategy for achieving sustainable development (see, e.g., Yuan et al., 2006; Geng et al., 2012). On August 29, 2008, the Standing Committee of the Chinese 11th National People's Congress (NPC) passed the Circular Economy Law. Former Chinese President Hu Jintao immediately signed it into law and it came into force in China on January 1, 2009.

It is well known that Romer (1986) and Lucas (1988) were the primary developers of the new growth theory in the mainstream

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literature. However, the growth-oriented exposition of this literature is rooted in the conventional unidirectional concept of production and consumption. Recycling is now a significant aspect of most developed economies and an important objective of policy, so it is time to bring the aforementioned concept of the circular economy into theoretical consideration. That is, economic waste and economic resources are interrelated and they can no longer be considered to be independent. It is now time to weave them tightly together.

To the best of our knowledge, a theoretical circular economy (CE) model has yet to appear in the literature. By utilizing a simple model with two types of economic resources, namely a polluting input and a recyclable input, this paper not only analyses the impact of the recyclable resource on economic growth, but it also offers a new perspective on achieving sustainability. Overall, our results indicate that economic growth is subject to the following factors, a) the marginal product of the recyclable input, b) the recycling ratio, c) the cost of using the environmentally polluting input and d) the level of pollution arising from the employment of the polluting input. The remainder of the paper proceeds as follows. Section 2 sets up the basic model and analyzes the dynamic behavior of a circular economy. Section 3 explains the driving force behind sustainability. Section 4 concludes.

2. The circular economy model

2.1. The social objective function

We consider a closed economy with zero population growth. The model is designed to focus on the ecologically crucial issues of recycling and pollution so, for the sake of tractability, we abstract from capital accumulation and technical progress. Our model may be contrasted with the Green Solow model developed by Brock and Taylor (2010) which focuses on technological progress in pollution abatement and establishes the Environmental Kuznets Curve (EKC) as a necessary by-product of convergence to a sustainable growth path. We focus on the optimization problem faced by a benevolent social planner allocating resources in a centralized economy. The optimal conditions would be targets for the government in a decentralized economy to meet. Such a planner would take the competitive equilibrium into account and design tax systems or regulations to offset externalities, and thereby implement the optimal allocation. In this paper, we characterize the optimal growth path: how such a growth path could be implemented is left for further research.

The social planner maximizes a social welfare function equal to the discounted present value of a future utility stream dependent on consumption and the stock of pollution, given by:

$$U = \int_0^\infty e^{-\rho t} u(c,P) dt \tag{1}$$

The instantaneous utility function is given by $u(c,P)$ where c and$P$ stand for consumption and the stock of pollution, respectively. We further assume $u_c > 0$, $u_P < 0$, $u_{cc} < 0$ and $u_{PP} > 0$ so that the social planner is assumed to like consumption and dislike pollution and his preferences are concave. The parameter ρ is the rate of time preference. The intertemporal elasticity of substitution (σ) is assumed constant, so that $\sigma = \frac{-u_c}{u_{cc}c}$.

2.2. The waste accumulation equation

Suppose that output, q is produced via a concave production function ϕ:

$$q = \phi(x,z) \tag{2}$$

using two factors of production, x (the rate of use of the recyclable resource, such as paper, glass, bottles, plastic or animal waste) and z (the rate of use of the environmentally polluting resource, which can usefully be thought of as an extracted resource such as coal, oil, or natural gas). Over time the two inputs evolve, but at each instant in time they can be treated as independent, with well-defined marginal products. The unit cost of using the polluting resource is denoted by α and the total flow cost of employing the polluting resource is equal to αz. Output produced in any given period but not consumed or used for the employment of the polluting resource, accumulates as (potentially recyclable) waste. Suppose a proportion β (the recycling ratio) of the waste stock can be recycled each period, and denote the waste stock as S. The dynamics of waste accumulation in the circular economy can therefore be written as follows:

$$\dot{S} = \phi(x,z) - c - \alpha z - \beta S \tag{3}$$

Recycling turns waste into a useful factor of production so that: $x = \beta S$. Substituting for x in Equation (3) yields the waste accumulation equation:

$$\dot{S} = \phi(\beta S,z) - c - \alpha z - \beta S \tag{4}$$

2.3. The pollution accumulation equation

The level of pollution generated in this economy depends on the amount of the polluting resource used, the recycling ratio, and the self-renewal capability of the natural environment. We assume that each unit of the polluting input (z) generates θ units of pollution. In each period, there also exists a quantity of waste denoted by $(1-\beta)S$ that cannot be recycled for the next period. This non-recyclable waste is assumed to generate units of pollution one for one. Finally, the natural environment is assumed to self-renew in such a way that stock of pollution decays naturally at a rate δ. Putting all these considerations together, the net rate of environmental degradation can be captured by the following pollution accumulation equation. That is:

$$\dot{P} = \theta z - \delta P + (1-\beta)S \tag{5}$$

2.4. Optimal growth in the circular economy

Given the laws of motion of Equations (4) and (5) for the two state variables, P and S, the benevolent social planner chooses the control variables, c and z, to maximize the social welfare function. Taking costate variables λ for the state variables S and μ for the state variable P, the circular economy can be analyzed by setting up the following Hamiltonian function:

$$H = e^{-\rho t} u(c,P) + \lambda[\phi(\beta S,z) - c - \alpha z - \beta S] + \mu[\theta z - \delta P + (1-\beta)S] \tag{6}$$

where λ and μ are the discounted shadow prices of waste and pollution, respectively. The first-order conditions for this problem are given by Equations (7)–(10):

$$H_c = e^{-\rho t} u_c - \lambda = 0 \tag{7}$$

$$H_z = \lambda(\phi_z - \alpha) + \mu\theta = 0 \tag{8}$$

$$H_S = \lambda(\beta\phi_x - \beta) + \mu(1 - \beta) = -\dot{\lambda} \tag{9}$$

$$H_P = e^{-\rho t}u_P - \mu\delta = -\dot{\mu} \tag{10}$$

Rearranging (8) we obtain:

$$\mu = \lambda\left(\frac{\alpha - \phi_z}{\theta}\right) \tag{11}$$

and differentiating wrt t yields:

$$\dot{z} = \left(\frac{\dot{\mu}}{\mu} - \frac{\dot{\lambda}}{\lambda}\right)\left(\frac{\phi_z - \alpha}{\phi_{zz}}\right) \tag{12}$$

Taking the derivative of (7) wrt time gives:

$$u_{cc}\dot{c} = \rho e^{\rho t}\lambda + \dot{\lambda}e^{\rho t} \tag{13}$$

Substituting for $\dot{\lambda}$ using (9) and for λ using (7), yields:

$$\frac{\dot{c}}{c} = \left(\frac{-u_c}{u_{cc}c}\right)\left[\beta(\phi_x - 1) - \rho + \left(\frac{\phi_z - \alpha}{\theta}\right)(\beta - 1)\right] \tag{14}$$

where the expression $\frac{-u_c}{u_{cc}c}$ corresponds to the intertemporal elasticity of substitution, which we assume to take the constant value σ, giving the following expression for the growth rate of consumption.

$$\frac{\dot{c}}{c} = \sigma\left[\beta(\phi_x - 1) - \rho + \left(\frac{\phi_z - \alpha}{\theta}\right)(\beta - 1)\right] \tag{15}$$

The expression in (15) is similar to the standard consumption time path if we ignore the two sets of parentheses. The marginal product of the recyclable input appears in (15) and affects the optimal growth rate of consumption. A higher marginal product of the recyclable input will increase the growth rate of consumption. In addition, it is clear from (15) that, comparing optimal growth paths, the growth rate of consumption decreases with ρ (the rate of time preference) and increases with β (the recycling ratio), α (the unit cost of using the polluting input) and θ (the incremental pollution from using an additional unit of the polluting input). If the cost of using the environmentally polluting input increases, the economy will substitute the recyclable input for the polluting input and the optimal rate of economic growth will increase.

To derive the optimal path of the polluting resource usage we substitute Equations (9) and (11) into Equation (12) to obtain:

$$\dot{z} = \left(\frac{\phi_z - \alpha}{\phi_{zz}}\right)\left[\frac{\dot{\mu}}{\mu} + \beta(\phi_x - 1) + (\beta - 1)\frac{(\phi_z - \alpha)}{\theta}\right] \tag{16}$$

It is relatively straightforward to show that the dynamic system consisting of Equations (4), (5), (15) and (16) has two eigenvalues with positive real parts. Taking c and z to be jump variables ensures that our model satisfies the Blanchard/Kahn stability condition. Imposing the transversality condition $\lambda S + \mu P \to 0$ as $t \to \infty$, ensures that optimal paths converge to a steady state. According to (16), the quantity of the polluting input employed depends on $\frac{\dot{\mu}}{\mu}$ and the usage of the recyclable input. To meet the transversality condition, we assume that $\lim_{t\to\infty} \mu P = 0$ and $\frac{\dot{\mu}}{\mu} < 0$. In the early stage, the recycling technology has yet to mature. Only a small quantity of the recyclable input emerges and this phenomenon results in a higher marginal product of the recyclable input. The negative sign of $\dot{z}$ indicates that the economy uses a larger amount of the polluting resource in production. As the recyclable input creates a higher marginal product, society gradually substitutes the recyclable input for the polluting input in production. Over time, the economy uses a larger amount of the recyclable resource for production and the marginal product of the recyclable input begins to fall. At this stage, the sign of $\dot{z}$ turns positive.

3. The driving force behind sustainability

According to (15), consumption has been increasing when the relative size of x/z is small (or ϕ_x is larger than ϕ_z). After x/z increases to a certain threshold, the marginal product of the recyclable input has gradually diminished and the level of consumption at this time reaches its maximum, i.e., $\dot{c} = 0$. After the turning point, $\dot{c} < 0$, this single-peaked relationship is shown in the upper right-hand quadrant in Fig. 1. The bottom left-hand quadrant shows the relationship between the recyclable-polluting input ratio and the pollution level measured in terms of the polluting input. The slope is dependent on the environmental self-renewal rate, δ, and the recycling ratio, β. The slope becomes steeper if δ or β becomes larger.

The inverted U-curve in the upper left-hand quadrant depicts the relationship between consumption and pollution. Such an inverted U-shape relation is reminiscent of the EKC. They, however, differ in several respects. First, the vertical and horizontal axes of the EKC are the opposite axes of our inverted U-curve as shown in Fig. 1. Second, our inverted U-curve shows that the level of pollution increases as the economy grows. When the economy begins to slow down and consumption declines, the level of pollution continues to increase, implying a departure from sustainability. Third, our inverted U-curve implies that environmental quality cannot be maintained or improved via economic growth, a result that is significantly different from conventional wisdom such as the EKC hypothesis.

The innovation of our paper is the formal introduction of recycling into a macroeconomic model. For the sake of analytical tractability we have omitted population growth, capital accumulation and technical progress. Our model could, at the expense of increased mathematical complexity, be generalized to incorporate these issues. This could introduce a third state variable, namely the

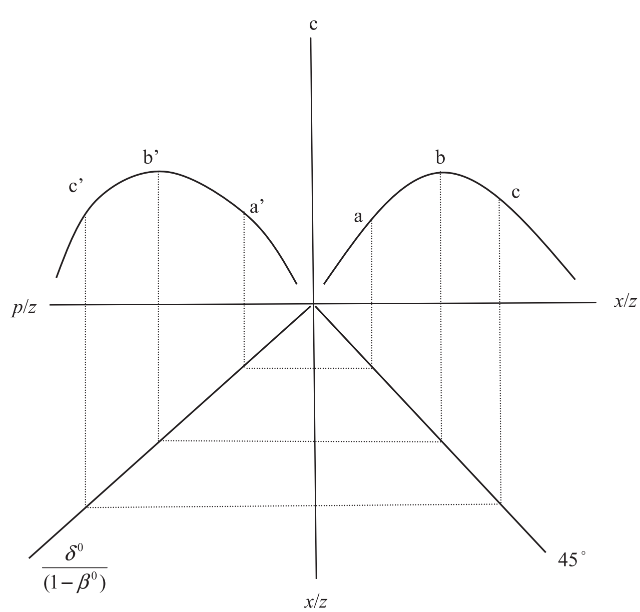

Fig. 1. Relationships among consumption, the recyclable input, the polluting input, and pollution. Note: The slope of the curve shown in the bottom left-hand quadrant is dependent on the ratio $\frac{\delta}{(1-\beta)}$.

physical capital stock and a corresponding costate variable. The simplest formulation would be to treat population growth and technical progress as exogenous, the latter taking a Harrod-neutral form. A more complex approach would be to allow biased technical progress (for example in pollution-abatement). It is possible that such an analysis could reinstate the EKC, although the precise shape of the curve would depend on the details of the underlying assumptions (i.e. it would vary across economies).

Our analysis shows that environmental quality can be improved upon or upgraded via an increase in either the environmental self-renewal rate, δ, or the recycling ratio, β. It might be also mentioned that the cost of recycling is absent in our model. Incorporating such cost indicates that the effectiveness of recycling would not be as prominent as the case where the recycling cost equals zero, because a fraction of the resources must be devoted to covering the cost of recycling. However, imposing the assumption of fixed or moderate marginal cost of recycling does not hinder the acquisition of our main result. Therefore, factors that might not be decisive to the derivation of our results are removed, because this simple model primarily addresses the importance of recycling.

In practice, the social planner or the government can properly initiate various indicators and/or mechanisms for promoting sustainability, for example by including estimates of pollution and recycling in the national income accounts. Assuming that the government adopts an environmentally-friendly policy and the population also begins to practice the "don't waste waste" philosophy, the natural self-renewal capability and/or the recycling ratio will accordingly rise. Under these circumstances, an increase in the environmental self-renewal rate, δ, or the recycling ratio, β, as shown in Fig. 2, shifts the inverted U-curve inward, implying a positive movement towards sustainability.

4. Conclusion

Not surprisingly, the emergence of circular economic activities is instrumental for promoting sustainability and has attracted increasing attention in recent years. To resolve the problem of dwindling economic resources, it is necessary to develop an integrated perspective of the economy, namely, a circular economy. In this regard, we suggest a new perspective on achieving sustainable growth and treat economic waste as a useful economic resource. We argue that it is time to substitute the circular economy for the conventional unidirectional concept of resources and products in the market economy.

There are at least three extensions of our simplified work. First, we have not analyzed the implementation of the circular optimal growth path in a decentralized market economy. Second, capital accumulation and technical change are not modeled and thus their potential impact is not accounted for. One could develop an updated version of the model in which the production of physical capital generates pollution and technical progress increases recycling. Finally, it would be interesting to introduce an open circular economy model in which country A is a resource-abundant country and country B is a high-tech country which develops the recycling technology. An international circular economy can come into existence as long as both countries reuse and recycle more waste for production and consumption.

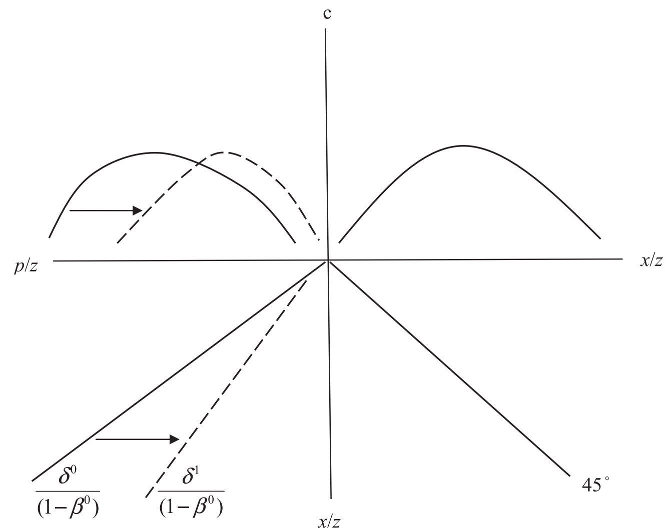

Fig. 2. Effect of self-renewal capability on consumption, pollution, and sustainability.

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