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# Research on Multi-regional Sustainable Endogenous Growth Model with Artificial Intelligence

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Abstract: This paper establishes an endogenous growth model with artificial intelligence technology. Under the dynamic game of remediation (utilization) activities, we study the economic growth relationship among multiple regions in the sustainable growth path. The results show that in the case of inclusive remediation, the region that moves first will pass all the remediation responsibility to the next region, so that the last region will bear all remediation responsibility; However, in the case of exclusive utilization, all regions will bear the responsibility for the restoration of the region, and at the same time will have a negative externality to other regions. Therefore, on the sustainable growth path, these $n$ regions have the same growth rate.

Keywords: Endogenous growth model; Sustainable growth; Inclusive remediation; Exclusive utilization; Artificial Intelligence

## 1 Introduction

Since the 20th century, due to the continuous growth of the world's population and the rapid development of the economy, as well as the increasing demand for energy by mankind, it has led to a shortage of energy resources. Therefore, how to achieve sustainable economic growth on the basis of taking into account energy has become the goal pursued by countries around the world.

In this paper, renewable energy is included in the production function. Taking into account the positive effect of artificial intelligence technology on product production, the relationship between production activities in multiple regions under the condition of sustainable growth is studied.

For the production sector, Bovenberg and Smulders [1] established a two-sector endogenous growth model to explore the relationship between environmental quality and economic growth. In this model, they also considered technological changes driven by pollution. On this basis, Lucas [2] and Rebelo [3] proposed a two-sector endogenous model, in which the generation of new technical knowledge in the knowledge sector will increase the use efficiency of renewable resources and reduce pollution. Ikefuji[4] introduced the accumulation of human capital into the endogenous growth model, and studied the conditions for sustainable economic growth. Wu et al. [5] incorporated environmental quality into the endogenous growth model and studied the theoretical framework of multi-regional conflicts by using the dynamic game of remediation and utilization activities. In China, based on neoclassical growth model and endogenous growth model, Peng and Bao [6] analyzed the relationship between resource environment and sustained economic growth through dynamic optimization methods, respectively. He et al. [7] studied the possibility of sustainable economic growth by introducing environmental pollution and non-renewable resources into the model based on the Romer model.

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For artificial intelligence technology, Berg et al. [8] found that it would improve social productivity and promote economic growth. In China, Guo [9] found that artificial intelligence technology has an impact on the transformation and upgrading of industrial structure and the change of labor income share.

In summary, how to achieve sustainable and efficient economic development has become an important issue for economists. Therefore, by constructing an endogenous growth model with artificial intelligence technology and renewable energy, this paper studies the economic relationship under the conditions of sustainable growth in multiple regions.

# 2 Model

In order to pursue sustainable and efficient economic development, and at the same time consider the impact of natural resources, environmental quality and artificial intelligence technology innovation on economic growth, this paper will introduce the natural resource sector on the basis of the final product sector and the knowledge sector to build a green growth model that reflects the characteristics of sustainable growth.

## 2.1 Renewable energy

The natural environment ($E$) is regarded as a kind of renewable energy, and its regeneration capacity is described by the following function:

$$\dot{E} = N\left(E, S, R\right), \tag{1}$$

where $S$ is the gross amount of energy exploitation, $R$ represents the intensity of remediation (utilization) activities.

This paper assumes that with the increase of the gross amount of energy exploitation ($S$), the renewable energy stock ($E$) will decrease ($E_S < 0$); however, as the remediation (utilization) activity intensity ($R$) increase, the renewable energy stock ($E$) will increase ($E_R > 0$).

## 2.2 Production sector

There are $n$ regions in the country. According to Wu et al. [5], set the production function of the final product as:

$$Y_i = Y\left(K_i^Y, Z_i^Y, M_i, E_i\right), i = 1, 2, ..., n. \tag{2}$$

where $Y_i$ represents final goods in region $i$; $K_i^Y$, $Z_i^Y$ represent the physical capital stock and effective input of renewable energy in region $i$, respectively; $M_i$ is the number of artificial intelligence services in region $i$; and $E_i$ represents the stock of renewable energy in region $i$.

According to Guo [9], the number of artificial intelligence services ($M_i$) is related to the new infrastructure ($H_i$), satisfying the following equation:

$$M_i = BH_i, \tag{3}$$

where $H_i$ is the number of new infrastructure in region $i$, $B \in (0, \infty)$ represents the efficiency of the new infrastructure in providing artificial intelligence services. The stock of new infrastructure is related to the following function: $\dot{H}_i = \left(1 - \delta^{H_i}\right) H_i + G_i$, where $\delta^{H_i} \in (0, 1)$ represents the depreciation rate of new infrastructure in region $i$, $G_i$ represents the cost of the government's investment in new infrastructure construction in region $i$.

According to Bovenberg and Smulders [1], $\xi^K, \xi^Z, \xi^E$ and $\xi^M$ represent the production elasticity of $K_i^Y, Z_i^Y, E_i$ and $M_i$, respectively. In this paper, it is assumed that these $n$ regions are symmetric, so they have the same production elasticity and knowledge elasticity. After log-linearizing the production function of the final product, it can be approximately deduced that:

$$g_i^Y = \xi^K g_i^K + \xi^Z g_i^Z + \xi^M g_i^M + \xi^E g_i^E, i = 1, 2, ..., n. \tag{4}$$

The final product can be consumed ($C_i$), used in remediation (utilization) activities ($R_i$), to restore renewable energy capacity, used to pay taxes ($G_i$), or invested ($\dot{K_{it}}$) to accumulate physical capital. Therefore, the accumulation of physical capital can be expressed as:

$$\dot{K_{it}} = Y_{it} - C_{it} - R_{it} - G_{it}. \tag{5}$$

## 2.3 Knowledge sector

According to Wu et al. [5], the knowledge sector produces knowledge about the efficient use of renewable energy, and its production function is as follows:

$$A_i = A\left(K_i^A, Z_i^A\right), i = 1, 2, ..., n. \tag{6}$$

where $K_i^A$ , $Z_i^A$ represent the physical capital stock and effective input of renewable energy in the knowledge sector in region $i$, respectively.

After log-linearizing the production function of the knowledge, it is also approximately derived that:

$$g_i^A = \zeta^K g_i^K + \zeta^Z g_i^Z, i = 1, 2, ..., n. \tag{7}$$

where $\zeta^K$ and $\zeta^Z$ represent the knowledge elasticity of $K_i^A$ and $Z_i^A$ respectively.

The accumulation of knowledge is as follows:

$$\dot{a_{it}} = A_{it} = A\left(K_{it}^A, Z_{it}^A\right). \tag{8}$$

Note that the knowledge in this paper is a private capital good.

The total stock of physical capital $(K_i)$ and the total effective input of renewable energy $(Z_i)$ are allocated between the final product production and knowledge sectors. At the same time, it is assumed that the effective input of renewable energy is related to knowledge and the gross amount of energy exploitation, i.e., $Z_i = aS_i$. Let $w_i$ and $v_i$ denote the share of physical capital and effective input of renewable energy for the final product sector in region $i$ , respectively. Then, $K_i^Y = w_i K_i$, $K_i^A = (1 - w_i) K_i$, $Z_i^Y = v_i Z_i$, $Z_i^A = (1 - v_i) Z_i$.

## 2.4 Household sector

It is assumed that the representative consumer lifetime of region $i$ is infinite. Considering that the utility of representative consumer is jointly determined by the current consumption level $C_i$ and environmental quality $E_i$, the welfare function $(W_i)$ of representative consumer can be expressed as:

$$W_i = \sum_{t=1}^{\infty} U\left(C_{it}, E_{it}\right) e^{-\rho_i t}, i = 1, 2, ..., n. \tag{9}$$

where $\rho_i$ represents the discount rate in region $i$.

## 2.5 Inclusive remediation and exclusive utilization

According to Wu et al. [5], by increasing the available renewable energy stocks, inclusive remediation activities in each region create positive externalities for other regions. Rewriting Eq. (1), the regeneration function of renewable energy in region 1 can be expressed as:

$$\dot{E_{1t}} = N\left(E_{n,t-1}, S_{n,t-1}, R_{n,t-1}\right). \tag{10}$$

It is assumed that the stock of renewable energy in region 1 $(E_{1t})$ increases with the increase of the stock of renewable energy in region $n$ in the previous period $(E_{n,t-1})$ and the number of remediation $(R_{2,t-1})$, as well as the decrease of the gross exploitation of renewable energy in region $n$ in the previous period $(S_{n,t-1})$. By linearizing the three effects of the regeneration functions, we can derive:

$$\begin{array}{l} E_{1t} = E_{n,t-1} - S_{n,t-1} + f\left(R_{n,t-1}\right) \\ E_{2t} = E_{1t} - S_{1t} + f\left(R_{1t}\right) \\ ... \\ E_{nt} = E_{n-1,t} - S_{n-1,t} + f\left(R_{n-1,t}\right) \\ E_{1,t+1} = E_{nt} - S_{nt} + f\left(R_{nt}\right) \\ ... \end{array}, \tag{11}$$

where $E_{1,t=1} = E_0$. The inclusive remediation function $f\left(R\right)$ is a strictly concave function of remediation inputs $(R)$, such that $f'\left(R\right) > 0 > f''\left(R\right)$ and $f\left(0\right) = 0$.

In contrast to inclusive remediation, exclusive utilization activities in each region create negative externalities for other regions by reducing the stock of renewable energy. Similar to inclusive remediation, the regeneration functions of renewable energy are as follows:

$$\begin{array}{l} E_{1t} = E_{n,t-1} - S_{n,t-1} + k\left(R_{n,t-1}\right) + 2k\left(R_{1,t-1}\right) \\ E_{2t} = E_{1t} - S_{1t} + k\left(R_{1t}\right) + 2k\left(R_{2,t-1}\right) \\ ... \\ E_{nt} = E_{n-1,t} - S_{n-1,t} + k\left(R_{n-1,t}\right) + 2k\left(R_{n,t-1}\right) \\ E_{1,t+1} = E_{nt} - S_{nt} + k\left(R_{nt}\right) + 2k\left(R_{1t}\right) \\ ... \end{array}, \tag{12}$$

The exclusive utilization function $k\left(R\right)$ is a strictly concave function, such that $k'\left(R\right) > 0 > k''\left(R\right)$, $k\left(0\right) = 0$. In order to satisfy the common beggar-thy-neighbor policy between regions, this paper assumes that the marginal benefit of an exclusive utilization is always larger than that of an inclusive remediation, then: $k'\left(R\right) > f'\left(R\right) > 0$.

# 3 Sustainable growth path in multiple-regions

## 3.1 Growth rate of sustainable growth

According to the definition of sustainable growth, $Y_i$, $C_i$ , $K_i$ and $G_i$ have the same growth rate in the equilibrium path, that is:

$$g_i = g_i^Y = g_i^C = g_i^G, i = 1, 2, ..., n. \tag{13}$$

where $g_i$ represents the common growth rate of region $i$. It should be noted that $g_i = g_i^R$ may not hold, because the external effects between regions are different under different remediation (utilization) activities. At the same time, we can deduce $g_i^M = g_i^H = g_i^G$.

In addition, under conditions of sustainable growth, there is:

$$\frac{\triangle g_i^a}{\triangle t} = g_i^A - g_i^a = 0. \tag{14}$$

Therefore, $g_i^A = g_i^a$, which means that knowledge grows at constant rate $g_i^a$ .

According to Bovenberg and Smulders [1], Wu et al. [5], we define the net exploitation use of renewable energy can be expressed as $X \equiv X\left(S, R\right)$. After log-linearizing the net exploitation use, we can derive:

$$g_i^X = \xi^S g_i^S + \xi^R g_i^R, i = 1, 2, ..., n. \tag{15}$$

where $\xi^S$ is the regeneration elasticity of the gross amount of energy exploitation $S_i$, and $\xi^R$ is the regeneration elasticity of remediation activity $R_i$.

## 3.2 Sustainable growth path with inclusive remediation

In the case of inclusive remediation, the remediation activities in each region will increase its renewable energy stock and create a positive externality for other regions. Using equations (11), we can derive the growth rate of renewable energy for region 1, that is:

$$g_1^E = \frac{E_{1t} - E_{1,t-1}}{E_{1,t-1}} = \frac{-X_{1,t-1} - X_{2,t-1} - ... - X_{n,t-1}}{E_{1,t-1}}, \tag{16}$$

where $X_{i,t-1}$ represents the net exploitation use of renewable energy in region $i$ at period $t-1$.

Therefore, the growth rate of renewable energy in region $i$ can be expressed as:

$$g_i^E = \frac{E_{it} - E_{i,t-1}}{E_{i,t-1}} = \frac{-X_{i-1,t} - X_{i-2,t} - ... - X_{1,t} - X_{i,t-1} - ... - X_{n,t-1}}{E_{i,t-1}}. \tag{17}$$

In any sustainable growth path of $n$ regions, the stocks of renewable energy should grow at least at a rate of zero, that is, $g_i^E = 0$, $i = 1, 2, ...n$. It shows that the net exploitation use of renewable energy of $n$ regions must satisfy the following $n$ equations in every period:

$$\begin{aligned}
&X_{1,t-1} + X_{2,t-1} + X_{3,t-1} + ... + X_{n,t-1} = 0,\\
&X_{1,t} + X_{2,t-1} + X_{3,t-1} + ... + X_{n,t-1} = 0,\\
&X_{1,t} + X_{2,t} + X_{3,t-1} + ... + X_{n,t-1} = 0,\\
&...\\
&X_{1,t} + X_{2,t} + X_{3,t} + ... + X_{n-1,t} + X_{n,t-1} = 0.
\end{aligned} \tag{18}$$

In every period, region 1 moves first, which can pass all the remediation responsibility to region 2, so its optimal remediation level should be zero, at this time, its net renewable energy exploitation use $X_{1,t-1} > 0$. According to equations (18), we can deduce $X_{2,t-1} + X_{3,t-1} + ... + X_{n,t-1} = -X_{1,t-1} < 0$ , then $X_{1,t} = -(X_{2,t-1} + X_{3,t-1} + ... + X_{n,t-1}) > 0$. Similarly, for region $i \in \{2, ..., n-1\}$, it can also pass the remediation responsibility to the next region, so there are $X_{i,t-1} > 0$, $X_{i,t} > 0$. For region $n$, it must bear the total cost of inclusive remediation activities, that is, $X_{n,t-1} = -(X_{2,t} + X_{3,t} + ... + X_{n-1,t} + X_{n,t-1}) < 0$ . The findings can be summarized as the following proposition:

Proposition 1 In the sustainable growth path with inclusive remediation, for region $i \in \{2, ..., n-1\}$, there is $R_{it} = 0$. At this time, the growth rate of net exploitation use of renewable energy is positive, i.e., $g_i^X > 0, i = 1, 2, ..., n$. The region $n$ has to bear all the costs of remediation activities, $R_{nt} = \sum_{i=1}^{n-1} S_{it} > 0$, and the growth rate of net exploitation use of renewable energy is negative, $g_n^X < 0$ .

Note that the premise of proposition 1 is that the marginal cost of inclusive remediation is significantly lower, so that the last region can bear all the costs of remediation activities.

Proposition 2 In the sustainable growth path with inclusive remediation, the growth rate of the gross use of renewable energy and the growth rate of knowledge are as follows:

$$g_i^S = \frac{\left(1 - \xi^K - \xi^M\right)\left(1 - \zeta^Z\right) - \xi^Z \zeta^K}{\xi^Z} g_i, \tag{19}$$

$$g_i^a = \frac{\left(1 - \xi^K - \xi^M\right)\zeta^Z + \xi^Z \zeta^K}{\xi^Z} g_i, i = 1, 2, ..., n. \tag{20}$$

Proposition 2 details the relationship between the growth rate of gross exploitation uses of renewable energy ($g_i^S$), the growth rate of knowledge accumulation ($g_i^a$) and the common growth rate ($g_i$).

Lemma 1 It is known that these $n$ regions are symmetric. In the sustainable growth path with inclusive remediation, if region $n$ can bear all the remediation responsibility, then $g_i = g_j > g_n$ , where $i, j \in \{1, 2, ..., n-1\}$.

### 3.3 Sustainable growth path with exclusive utilization

The exclusive utilization activities between regions create a negative externalities to other regions by reducing the stock of renewable energy. Similar to Section 3.2, it can also be deduced that the net exploitation uses of renewable energy of $n$ regions satisfy the following $n$ equations:

$$\begin{aligned}
&X_{1,t-1} + X_{2,t-1} + X_{3,t-1} + ... + X_{n,t-1} = 0,\\
&X_{1,t} + X_{2,t-1} + X_{3,t-1} + ... + X_{n,t-1} = 0,\\
&X_{1,t} + X_{2,t} + X_{3,t-1} + ... + X_{n,t-1} = 0,\\
&...\\
&X_{1,t} + X_{2,t} + X_{3,t} + ... + X_{n-1,t} + X_{n,t-1} = 0,
\end{aligned} \tag{21}$$

where $X_{i,t-1}$ represents the net exploitation uses of renewable energy in region $i$ at the $t-1$ period.

However, unlike the case of inclusive remediation, the utilization behavior between regions will cause negative externalities,and it is impossible to rely on each other to restore the renewable energy stock. Therefore, these $n$ regions need to adopt some amount of exclusive utilization to offset the effect of the gross extractive use of renewable energy.

Proposition 3 In the path of sustainable growth with exclusive utilization, $n$ regions all satisfy the following equation: $g_i^X = g_i^E = 0$, $i = 1, 2, ..., n$.

Proposition 4 In the sustainable growth path with exclusive utilization, the growth rate of the gross use of renewable energy, knowledge and utilization activities satisfy the following equations:

$$g_i^S = \frac{\left(1 - \xi^K - \xi^M\right)\left(1 - \zeta^Z\right) - \xi^Z \zeta^K}{\xi^Z} g, \tag{22}$$

$$g_i^a = \frac{\left(1 - \xi^K - \xi^M\right)\zeta^Z + \xi^Z \zeta^K}{\xi^Z} g, \tag{23}$$

$$g_i^R = \frac{\xi^Z \zeta^K - \left(1 - \xi^K - \xi^M\right)\left(1 - \zeta^Z\right)}{\xi^R \xi^Z} g, i = 1, 2, ..., n. \tag{24}$$

Note that because each region will carry out utilization activities, and these $n$ regions are symmetrical, the common growth rate $g$ is the same.

## 4 Conclusions

In this paper, an endogenous growth model with artificial intelligence technology is established. Through the dynamic game of different regional remediation (utilization) activities, we study the relationship between regional economic activities under the condition of sustainable growth. The results show that in the case of inclusive remediation, the first $n - 1$ regions will pass all the remediation responsibility to other regions, and enjoy faster economic growth, the last region will bear all responsibility; while in the case of exclusive utilization, all regions will bear the responsibility for the restoration of the region, and at the same time will have a negative externality to other regions.


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