Sustainable endogenous growth model of multiple regions

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Sustainable endogenous growth model of multiple regions: Reconciling OR and economic perspectives

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Abstract

By combining the two-sector endogenous growth model and the dynamic game of remediation (utilization) activities, we propose a theoretical framework to investigate conflict in the sustainable growth path of multiple regions. We analyze the effects of two types of activities that differ in externalities on other regions' stock of natural resources. In the case of inclusive remediation with a positive externality, the region that moves firstly will pass all the remediation responsibility to the other region and enjoy faster growth. However, in the case of exclusive utilization with a negative externality, both regions will experience the same growth rate, because each region could adopt exclusive utilization and reduce the stock of common resources available to the other region in the next period, which result in a symmetric equilibrium. We also find that regions have a stronger incentive to implement exclusive utilization than inclusive remediation. Although exclusive utilization seems fair to regions, it may deteriorate the social welfare, because regions may fall into a 'prisoner's dilemma' by using exclusive utilization. Three extensions of the model (i.e., increasing number of regions, asymmetric regions, and knowledge as a public capital good) are provided.

Keywords*:* Economics; Endogenous economic growth; OR approach; Renewable natural resources; Inclusive remediation; Exclusive utilization; Externality.

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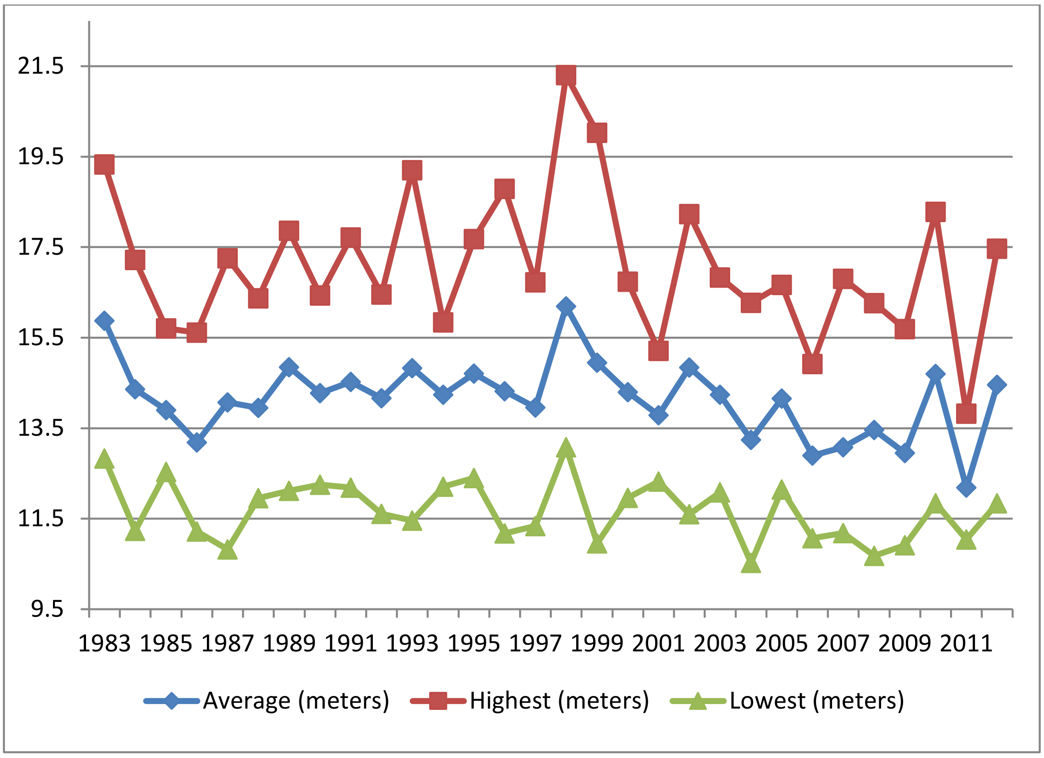
1. Introduction

The motivation of this research comes from the conflict of utilizing water resources among regional governments around the Poyang Lake, China. Poyang Lake has been suffered a severe shortage of water resources in recent years. The following Figure 1 shows the average, highest and lowest monthly water levels of Poyang Lake from 1983 to 2012.[1] We can see that all three indicators decreased, especially after 2000. Zhang et al. (2016) point out that the impounding activity of Three Gorges Dam, the largest operating hydroelectric facility in the world, may be the main reason. However, another possible explanation of such a shortage is the increasing demand of water form regions around the lake. Those regions utilize more and more water resources in a process of fast economic growth (the annual GDP growth rates of regions are about 10%) in recent years. We want to analyze the interactive decision making of constructing dams or impounding reservoirs among regions by using game theory, while regional governments also target the sustainable economic growth path as the endogenous growth model suggests.



Source: Jiangxi Provincial Bureau of Water Resources, China.

Figure 1. Water Levels of Poyang Lake

To deal with the shortage of water resources, some regional governments have started the construction of dams or impounding reservoirs, or asked permission of the central

[1] We collect the daily observations of water levels from 10 stations around the Poyang Lake and calculate the monthly water levels.

government to construct such projects, in order to increase their own stock of natural resources. However, these activities may worsen social welfare, because they are Beggar-Thy-Neighbor policies, in the sense of decreasing the stock of common natural resources available to other regions. We define this type of activity that causes negative externalities to other regions as exclusive utilization. There is also another type of activity, inclusive remediation, which increases the stock of common natural resources available to other regions. One possible example of inclusive remediation is planting trees for the water and soil conservation. Tree planting increases the stock of common water resources, and benefits all regions. Both inclusive remediation and exclusive utilization activities of some region increase its own stock of natural resources, but these activities are differ in the externalities on other regions. In fact, inclusive remediation is not the main policy adopted by regional governments to regenerate natural resources in real practice in China.

Why do regional governments have a stronger incentive to implement exclusive utilization than inclusive remediation? How can these activities influence the sustainable growth path of regions? How do we solve the conflict among activities of regions? To answer these questions, we combine the two-sector endogenous growth model with the dynamic game of remediation (utilization) activities, and propose a theoretical framework to investigate the sustainable growth path of multiple regions. We find that the region that moves firstly will pass all the remediation responsibility to the other region, and enjoy a faster growth in the case of inclusive remediation with a positive externality. In the case of exclusive utilization, both regions will experience the same growth rate, because each region could adopt exclusive utilization and reduce the stock of common resources available to the other region in the next period, which result in a symmetric equilibrium. We also show that if regions are able to choose inclusive remediation or exclusive utilization, both regions will choose the latter one, which implies that a ‘prisoner's dilemma’ will occur if no intervention from the central government is imposed. Finally, we provide three extensions of the benchmark model: if there are multiple regions, if regions are asymmetric, and if knowledge is a public capital good. These extensions provide several interesting results, and illustrate the applications of our theoretical model.

Many scholars have contributed to the study of the relationship between economic growth and environmental quality, and the effects of technological change on this relationship. (See the reviews of Brock and Taylor, 2005; Foray and Grübler, 1996; Löschel, 2002; Nijkamp and Van Den Bergh, 1997; Van Den Bergh and Hofkes, 1998) An important theoretical branch of this literature is the economic modeling of sustainable development using the endogenous growth model. Based on the work of Lucas (1988) and Rebelo (1991), Bovenberg and Smulders (1995) present a two-sector endogenous model in which the production of new technical knowledge in the knowledge sector will improve the effective use of renewable resources and reduce pollution. Hofkes (1996) introduces the concept of abatement into the two-sector endogenous model, which assumes that a proportion of final output can be used as abatement to reduce the level of pollution and recover the regenerative capacities of natural resources.

Current theoretical literature focuses on either optimal pollution/abatement choices (Breton et al., 2008; Byrne, 1997; Grimaud, 1999; Michel and Rotillon, 1995; Schou, 2000; Withagen, 1995) or the endogenous technical change and optimal environmental regulation (Acemoglu et al., 2009; Barbier, 1999; Bendoly, 2007; Groth and Schou, 2007; Hart, 2004; Rosendahl, 2004; Smulders and De Nooij, 2003). Though theoretical analysis of the optimal management of ground water resources has been provided (Esteban and Dinar, 2013; Roseta-Palma, 2002, 2003), it has not been in the framework of the endogenous growth model. Munda (2009) gives a conflict analysis approach for illuminating distributional issues in sustainability policy. However, the main methodology of Munda (2009) is the cost-benefit analysis, instead of game theory. Theoretical studies on the sustainable endogenous growth of multiple regions using game model are still lacking. Our study addresses this gap by combining the two-sector endogenous growth model and the dynamic game of remediation (utilization) activities.

Many empirical studies have investigated the relationship between economic growth and environmental quality (Brock and Taylor, 2010; De Bruyn, 2012; Färe et al., 2005), including several on China (Choi et al., 2015; Sun et al., 2008; Yang and Yang, 2015; Yu, 2015; Zhang and Cheng, 2009; Zhang et al., 2014, 2015; Zhang and Xie, 2015). In the context of conflict between regions, Cai et al. (2015) analyzes the effect of pollution reduction mandates on the pollution location choices of regional governments. Olmstead and Sigman (2014) provide a study of conflict in dam location. However, the empirical study on the conflict in remediation activities between regions is still missing. For future research, we could give an empirical analysis on the conflict based on our theoretical model.

In this paper, we provide a theoretical framework that incorporates the regeneration of natural resources and the interaction of remediation activities between multiple regions with the sustainable endogenous economic growth model. We construct a dynamic game of regions' choices on natural resources (i.e., gross extractive use and remediation activities); meanwhile the region's decisions are subjected to the feasible condition of a sustainable economic growth path. Hence, the contribution of our study can be summarized as the combination of game model and sustainable growth model in study of an OR problem. In fact, game theory has been widely used as the research tool of OR. One can find many applications of game theory in the studies of supply chain (Cachon and Netessine, 2006; Kogan and Tapiero, 2007; Tapiero, 2007; Santibanez-Gonzalez and Diabat, 2016) and energy management (Campos-Nañez et al., 2008; Qi et al., 2015). We also identify the effects of inclusive remediation and exclusive utilization and give three extensions of our model, which may provide meaningful policy implications for the policy maker.

The paper is organized as follows. Section 2 presents the model. Section 3 analyzes the sustainable growth path with the interaction between regions, in the cases of inclusive remediation and exclusive utilization. Three extensions of the model are provided in Section 4. Finally, Section 5 concludes.

2. Model setting

2.1. Regenerative capacities of natural resources

First, we introduce assumptions about the regenerative capacities of natural resources. The natural resource (N) is modeled as a renewable resource, and can be regenerated by itself. The regenerative capacities of natural resources will decrease as the gross extractive use of resources (denoted as Q) increases. Meanwhile, the regenerative capacities will be restored with increasing intensity of remediation (utilization) activities (denoted as R).[2] We introduce a variable of the net extractive use of natural resources, $X \equiv X(Q, R)$. It is clear that $X_Q > 0$ and $X_R < 0$.

The regenerative capacities of natural resources are described by the following function E:

$$\frac{\Delta N}{\Delta t} = E(N, X(Q, R)). \tag{1}$$

Eq. (1) shows that the regenerative capacities of natural resources depend on the stock of natural resources (N), and the net extractive use of natural resources (X). We are going to analyze the effects of two types of activities (R), which derive two different regenerative functions of natural resources. More assumptions about the remediation will be provided in Section 3.

2.2. The two-sector economy

There are n regions in the country. The economy of each region consists of two sectors, a production-sector producing final (consumption) goods (Y), and a knowledge or R&D sector producing knowledge (h) about efficient use of natural resources, following Bovenberg and Smulders (1995). The output of the knowledge sector only accumulates technological knowledge. It does not contribute to the production of final goods. The production functions for the final goods and for knowledge are as follows:

$Y_i = Y\left(K_i^Y, Z_i^Y, N_i\right),$

[2] Because both the inclusive remediation and exclusive utilization activities of some region increases its own regenerative capacities of natural resources, we use the same variable, R, to denote these activities for simplicity.

$H_i = H(K_i^H, Z_i^H), i = 1, 2, \ldots, n.$

The n regions are symmetric, because they have the same production functions for final goods and for knowledge. We assume that both Y and H are twice continuously differentiable and concave. The variable K_i^Y represents the stock of physical capital allocated to the final goods sector in region i, while K_i^H represents the stock of physical capital allocated to the knowledge sector in region i. Analogously, Z_i^Y represents the effective input of natural resources in the final goods sector in region i, and Z_i^H represents the effective input of natural resources in the knowledge sector in region i. Hence, $K_i = K_i^Y + K_i^H$ and $Z_i = Z_i^Y + Z_i^H$ represent the total stock of physical capital and the total effective input of natural resources in region i. The effective input of natural resources is a function of knowledge and the gross extractive use of natural resources, i.e., $Z_i = hQ_i$. For instance, the efficiency of water use increases as the stock of knowledge increases, given that the gross extractive use remains unchanged. Finally, the aggregate stock of natural resources (N_i) matters to the production of final goods, because a low (high) stock of natural resources will increase (reduce) the cost of producing final goods.

The final good can either be consumed (C_i), used for remediation (utilization) activities (R_i) to restore the regenerative capacities of natural resources, or invested ($\Delta K_i/\Delta t$) to accumulate physical capital that increases future consumption and remediation activities. The accumulation of physical capital is given by the following equation:

$$\frac{\Delta K_{it}}{\Delta t} = Y(K_{it}^Y, Z_{it}^Y, N_{it}) - C_{it} - R_{it},\ \ i = 1, 2, \ldots, n. \quad (2)$$

The accumulation of knowledge is given by:

$$\frac{\Delta h_{it}}{\Delta t} = H(K_{it}^H, Z_{it}^H), i = 1, 2, \ldots, n. \quad (3)$$

Note that we assume knowledge is a private capital good, because each region may choose to keep its own innovation secret, especially when the government officials of regions compete with each other for promotion opportunities.[3]

The total stock of physical capital and total effective use of natural resources are allocated between two sectors. Let u_i and v_i denote the share of physical capital, and the share of effective natural resources used in the final goods sector of region i, respectively, then $(1 - u_i)$ and $(1 - v_i)$ denote the share of physical capital and the share of effective natural resources used in the knowledge sector of region i, respectively:

$K_{it}^Y = u_i K_{it},$

$K_{it}^H = (1 - u_i) K_{it},$

$Z_{it}^Y = v_i h_t Q_{it},$

[3] We will discuss the extension that knowledge is a public capital good in Section 4. In that case, knowledge is public to all regions, and they can adopt any knowledge and accumulate their stock of knowledge without any cost. The accumulation of knowledge is the sum of the knowledge productions of the two regions.

$Z_{it}^H = (1 - v_i)h_t Q_{it},\ i = 1, 2, \dots, n.$

Social welfare (W_i) is described by the utility of a representative consumer of region i, who lives infinitely. The individual's utility (U_i) depends upon her consumption c_i ($c_i = C_i/L_i$, where C_i is aggregate consumption, and L_i which is assumed to be constant over time)[4], and also the stock of natural resources (N_i). By introducing the discount rate as the indicator of time preference (θ_i), we can construct the welfare function of the representative consumer:

$$W_i = \sum_{t=1}^{\infty} e^{-\theta_i t} U(c_{it}, N_{it}),\ i = 1, 2, \dots, n.$$

After introducing the basic assumptions of the model, we will examine the feasibility conditions of long-run sustainable growth in Section 3.

2.3. Timing of the game

We first analyze the benchmark model with two regions.[5] The timing of the game is as follows[6]:

1. Nature decides the initial stock of common natural resources, N_0.
2. In the first period (i.e., $t = 1$), the region that moves firstly (i.e., region 1) decides the allocations of physical capital and natural resources used in production, and the consumption and amount of remediation activities, so that final goods and knowledge are produced, and the stock of natural resources available to region 2 is determined.
3. In the first period (i.e., $t = 1$), after receiving the choices of the region 1, region 2 decides the allocations of physical capital and natural resources used in production, and the consumption and amount of remediation activities, so that final goods and knowledge are produced, and the stock of natural resources available to region 1 in the next period ($t = 2$) is determined.
4. The game infinitely repeats.

Note that this is a dynamic game of complete information. Although it infinitely repeats, we can take one period as a sample and analyze the interaction of regions' choices by using backwards induction. The timing of the game in period t is shown in Figure 2. At period t, by facing the stock of natural resources available (N_{1t}), region 1 decides the allocations of physical capital and natural resources used in production, and the consumption and amount of remediation activities, so that the amount of gross extractive use of natural resources (Q_{1t})

[4] One can also assume that the population will grow at a constant rate, which will not change the main results of our model. However, labor is not included in the production function. We use this assumption to simplify the analysis.

[5] The discussion of the case of multiple regions is in Section 4.

[6] For simplicity, we present the timing of game in sense of the case of inclusive remediation. Similar timing of game applies to the case of exclusive utilization.

and the amount of remediation (R_{1t}) are determined. Hence, the stock of natural resources available to region 2 (N_{2t}) is determined. Then, region 2 makes its' decisions of the amount of gross extractive use of natural resources (Q_{2t}) and the amount of remediation (R_{2t}), that determines the stock of natural resources available to region 1 in the next period $t+1$ ($N_{1,t+1}$). This procedure infinitely repeats.

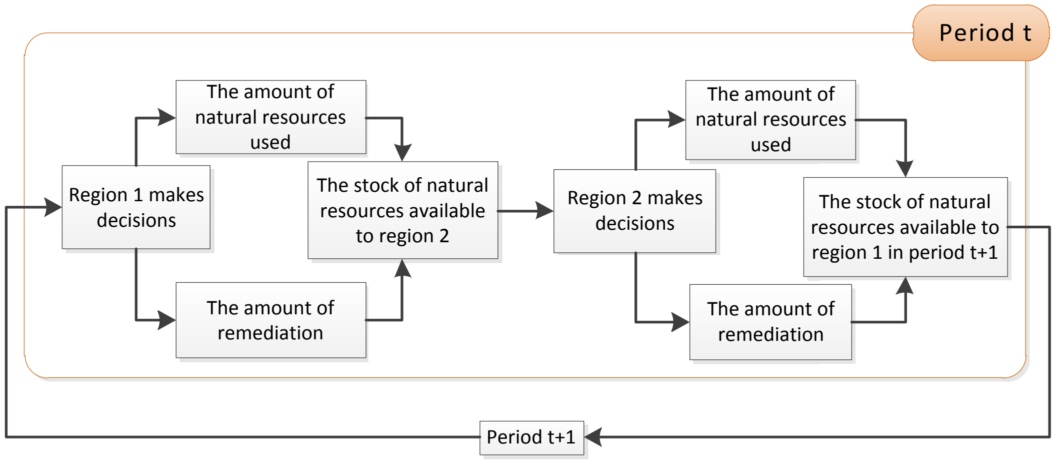


Figure 2. Timing of the game

One can see that remediation activities are crucial to the regeneration of natural resources, therefore to the sustainable growth path of each region. Next, we will introduce two types of activities, inclusive remediation and exclusive utilization, which have different externalities on the stock of natural resources available to the other region.

2.4. Inclusive remediation

Inclusive remediation activities of each region create a positive externality to the other region, by increasing the stock of natural resources available. One possible example of inclusive remediation is tree planting for water and soil conservation. Tree planting increases the stock of common water resources, and benefits both regions. By modifying Eq. (1), we can get the regenerative capacities of region 1's natural resources:

$$\frac{\Delta N_{1t}}{\Delta t} = E\left(N_{2,t-1}, Q_{2,t-1}, R_{2,t-1}\right).$$

We assume that the stock of natural resources available to region 1 (N_{1t}) should increase as the stock of natural resources available to region 2 in the previous period ($N_{2,t-1}$) increases, the amount of gross extractive use of natural resources used by region 2 in the previous period ($Q_{2,t-1}$) decreases, and the amount of remediation adopted by region 2 in the previous period ($R_{2,t-1}$). To derive the analytical solution of the model, we can specify the notion of E by linearizing the three effects:

$$N_{1t} = N_{2,t-1} - Q_{2,t-1} + f\left(R_{2,t-1}\right), \tag{4}$$

$$N_{2t} = N_{1t} - Q_{1t} + f(R_{1t}). \tag{5}$$

Note that $N_{1,t=1} = N_0$. The inclusive remediation function, $f(R)$, is a strictly concave function of remediation inputs (R), such that $f'(R) > 0 > f''(R)$, and $f(0) = 0$. We can see that the marginal benefit of inclusive remediation is positive and decreasing, or the marginal cost of inclusive remediation is positive and increasing, which is a realistic assumption.

2.5. Exclusive utilization

In contrast to inclusive remediation, the exclusive utilization activity of each region creates a negative externality to the other region by decreasing the stock of natural resources available. Possible examples of exclusive utilization are dams or reservoirs that impound water within the region, and reduce the stock of water resources available to the other region. Hence, exclusive utilization can be seen as a Beggar-Thy-Neighbor policy. By adopting a similar procedure as above, we can derive the regenerating functions of natural resources as follows:

$$N_{1t} = N_{2,t-1} - Q_{2,t-1} - k\left(R_{2,t-1}\right) + 2k\left(R_{1,t-1}\right), \tag{6}$$

$$N_{2t} = N_{1t} - Q_{1t} - k(R_{1t}) + 2k(R_{2,t-1}). \tag{7}$$

Note that the exclusive utilization function, $k(R)$[7], is a strictly concave function of utilization inputs (R), such that $k'(R) > 0 > k''(R)$, and $k(0) = 0$. The marginal benefit of exclusive utilization is decreasing, or the marginal cost of exclusive utilization is increasing. We also make an extra assumption that the marginal benefit of an exclusive utilization is always larger than that of an inclusive remediation, which is

$$k'(R) > f'(R) > 0. \tag{8}$$

Otherwise, regions have no incentive to adopt such a Beggar-Thy-Neighbor policy. In fact, we observe a lot of exclusive utilization in practice (i.e., the regional governments have constructed many dams and impounding reservoirs around the Poyang Lake). We can use this condition to compare the effects of two types of activities. In the next section, the sustainable growth paths of regions with inclusive remediation and exclusive utilization are analyzed.

3. Sustainable growth path of regions

3.1. The growth rates of the sustainable growth path

[7] To keep the consistence of formulas, we still use the variable R to denote the amount of exclusive utilization.

We first consider the conditions under which sustainable (balanced) growth is feasible in our model. Sustainable growth is defined as a situation in which all variables grow at a constant (maybe zero) rate and in which the allocative variables, i.e., for region i, the share of consumption in final output C_i/Y_i and the share of remediation activities in final output R_i/Y_i, are constant. In any situation of sustainable growth, Y_i, C_i, K_i, and R_i should grow at the same common rate. Let us denote this common rate by g_i and the growth rates of Y_i, C_i, K_i, R_i, Q_i, X_i, N_i, H_i, and h_i by g_i^Y, g_i^C, g_i^K, g_i^R, g_i^Q, g_i^X, g_i^N, g_i^H, and g_i^h, respectively. Hence, the first three growth rates should be the same, and equal to the common growth rate in a sustainable growth path of region i:

$$g_i = g_i^Y = g_i^C = g_i^K, i = 1, 2. \tag{9}$$

Note that $g_i = g_i^R$ may not hold because there are only two regions, and the activities of one region may cause positive or negative externalities on the natural resources of the other region. Bovenberg and Smulders (1995) show that sustainable growth requires that production elasticities be constant over time. Hence, let us denote the production elasticities of K_i^Y, Z_i^Y, and N_i and the knowledge elasticities of K_i^H and Z_i^H by η^K, η^Z, η^N, ζ^K, and ζ^Z, respectively. Note that two symmetric regions have the same production elasticities and knowledge elasticities. By log-linearizing the production function of the final good, we can approximately derive the relationship of the growth rates related to the production of final goods:[8]

$$g_i^Y = \eta^K g_i^K + \eta^Z\left(g_i^Q + g_i^h\right) + \eta^N g_i^N, i = 1, 2. \tag{10}$$

By log-linearizing the production function of the knowledge, we can approximately derive the relationship of the growth rates related to the production of knowledge:

$$g_i^H = \zeta^K g_i^K + \zeta^Z\left(g_i^Q + g_i^h\right), i = 1, 2. \tag{11}$$

Furthermore, in a situation of sustainable growth:

$$\frac{\Delta g_i^h}{\Delta t} = g_i^H - g_i^h = 0. \tag{12}$$

Hence, we can derive that $g_i^H = g_i^h, i = 1, 2$. The knowledge should grow at constant rate g_i^h. However, the growth rate of knowledge does not necessarily equal the common growth rate g_i since remediation activities are used to increase the regenerative capacities of natural resources. Finally, by log-linearizing the net extractive use of water, we can approximately derive the relationship of the growth rates related to the net extractive use of natural resources:

[8] Although this is a discrete time growth model, the game period is infinity. We can use the procedure of log-linearizing to derive the relationship of the growth rates related to the production of final goods approximately.

$$g_i^X = \eta^Q g_i^Q + \eta^R g_i^R, i = 1, 2, \quad (13)$$

where η^Q is the regeneration-elasticity of the gross extractive use of natural resources Q_i and η^R is the regeneration-elasticity of the remediation activities R_i in region i. Two symmetric regions have the same regeneration-elasticities, i.e., η^Q and η^R. Then we will introduce the inclusive remediation and exclusive utilization into our model.

3.2. Sustainable growth path with inclusive remediation

The inclusive remediation activities of each regional government create a positive externality for the other region, by increasing the stock of natural resources available. By using Eqs. (4) and (5), we can derive the growth rate of natural resources for region 1,

$$g_1^N = \frac{N_{1t} - N_{1,t-1}}{N_{1,t-1}} = \frac{f(R_{1,t-1}) + f(R_{2,t-1}) - Q_{1,t-1} - Q_{2,t-1}}{N_{1,t-1}} = \frac{-X_{1,t-1} - X_{2,t-1}}{N_{1,t-1}},$$

where $X_{1,t-1} = Q_{1,t-1} - f(R_{1,t-1})$ and $X_{2,t-1} = Q_{2,t-1} - f(R_{2,t-1})$ are the net extractive uses of natural resources of two regions at period $t-1$. Similarly, we can derive the growth rate of natural resources for region 2,

$$g_2^N = \frac{N_{2t} - N_{2,t-1}}{N_{2,t-1}} = \frac{f(R_{2,t-1}) + f(R_{1t}) - Q_{2,t-1} - Q_{1t}}{N_{2,t-1}} = \frac{-X_{2,t-1} - X_{1t}}{N_{1,t-1}},$$

where $X_{1,t} = Q_{1t} - f(R_{1t})$ and $X_{2,t-1} = Q_{2,t-1} - f(R_{2,t-1})$ are the net extractive uses of natural resources of two regions.

In any sustainable growth path of two regions, the stocks of natural resources should at least grow at a rate of zero, i.e., $g_1^N = g_2^N = 0$. This equality implies that the net extractive use of natural resources of two regions must satisfy the following two equations in every period,

$$X_{1,t-1} + X_{2,t-1} = 0,$$

$$X_{2,t-1} + X_{1t} = 0.$$

In each period, region 1 moves first, its optimal level of remediation should be zero because it can pass all the remediation responsibility to region 2, and enjoy a positive net extractive use of natural resources, $X_{1,t-1} > 0$. To keep the sustainable growth path, region 2 has to bear all the costs of inclusive remediation activities, and suffers a negative net extractive use of natural resources, $X_{2,t-1} = -X_{1,t-1} < 0$. Given $X_{2,t-1} < 0$, the optimal choice of region 1 in the next period is $X_{1t} = -X_{2,t-1} > 0$. These strategies infinitely repeat. We can summarize the finding as the following proposition:

Proposition 1. *In each period of the sustainable growth path with inclusive remediation, region 1 will make zero effort on remediation, i.e.,* $R_{1t} = 0$*, resulting in a positive growth* *rate of the net extractive use of natural resources, i.e.,* $g_1^X > 0$. *Region 2 has to bear all the costs of remediation activities, i.e.,* $R_{2t} = Q_{1t} + Q_{2t} > 0$, *with a negative growth rate of the net extractive use of natural resources, i.e.,* $g_2^X < 0$.

After knowing the optimal inclusive remediation of two regions, we can also derive the properties about the sustainable growth path of the gross extractive use of natural resources (g_i^Q) and knowledge production (g_i^h):

Proposition 2. *In any sustainable growth path with inclusive remediation, the growth rate of the gross use of natural resources, and the growth rate of knowledge are as follows:*

$$g_i^Q = \frac{(1-\eta^K)(1-\zeta^Z)-\zeta^K\eta^Z}{\eta^Z} g_i, \tag{14}$$

$$g_i^h = \frac{(1-\eta^K)\zeta^Z+\zeta^K\eta^Z}{\eta^Z} g_i, i = 1, 2. \tag{15}$$

Proof: By substituting $g_i^H = g_i^h$, and Eq. (9) into (10) and (11), we can derive that:

$$g_i^Q + g_i^h = \frac{(1-\eta^K)}{\eta^Z} g_i,$$

$$\zeta^Z g_i^Q - (1-\zeta^Z) g_i^h = \zeta^K g_i.$$

By solving for the unknowns, g_Q and g_h, of the two equations above, we can get Eqs. (14) and (15).

Proposition 2 specifies the relationship between the growth rate of the gross use of natural resources (g_i^Q), the growth rate of knowledge accumulation (g_i^h), and the common growth rate (g_i). In this case of inclusive remediation, the equality $g_i^X = 0$ does not hold, since region 1 takes advantage of region 2 to restore the regenerating ability of the common natural resources, $g_1^X > 0 > g_2^X$. However, the aggregate effects of the net extractive use of natural resources are offset by the inclusive remediation activities of region 2, the equality $g_i^N = 0, i = 1, 2$ holds in the sustainable growth path. Then we can derive a property in relation to the values of common growth rates (g_i).

Lemma 1. *In the sustainable growth path with inclusive remediation, region 1 achieves a higher economic growth rate than that of region 2, i.e.,* $g_1 > g_2 > 0$, *given that region 2 is able to afford all remediation responsibility.*

Proof: From Proposition 2, we know that in the sustainable growth path with inclusive remediation, $R_{1t} = 0$ and $R_{2t} = Q_{1t} + Q_{2t} > 0$, we can rewrite Eq. (2) of the accumulation of physical capital for two regions:

$$\frac{\Delta K_{1t}}{\Delta t} = Y(K_{1t}^Y, Z_{1t}^Y, N_{1t}) - C_{1t},$$

$\frac{\Delta K_{2t}}{\Delta t} = Y(K_{2t}^Y, Z_{2t}^Y, N_{2t}) - C_{2t} - R_{2t}$.

Hence, in the sustainable growth path of region 1, the output of final goods (Y_1), the consumption (C_1), and the investment (K_1) should grow at the same common rate g_1, which is

$g_1 = g_1^Y = g_1^C = g_1^K$.

Similarly, in the sustainable growth path of region 2, the output of final goods (Y_2), the consumption (C_2), the investment (K_2), and the remediation inputs (R_2) should grow at the same common rate g_2, which is

$g_2 = g_2^Y = g_2^C = g_2^K = g_2^R$.

Although both regions have the same production functions of final goods, region 2 has to bear all the costs of remediation activities, $R_{2t} = Q_{1t} + Q_{2t} > 0$, which is still affordable for region 2. Hence, we can derive that the common growth rate of region 1 is higher than that of region 2, i.e., $g_1 > g_2 > 0$.

Note that Lemma 1 holds if the marginal cost of inclusive remediation is significantly low, so that region 2 can afford all the costs of remediation activities and achieve a positive sustainable growth rate, $g_1 > g_2 > 0$. Otherwise, the growth rate of region 2 should be lower than zero, i.e., $g_2 < 0$, which is not a case of sustainable growth. In such a situation, a reasonable outcome of the growth path is that region 1 takes some part of the remediation responsibility, and region 2 experiences a zero growth rate, i.e., $g_1 > g_2 = 0$. We can also derive a property in relation to the values of knowledge accumulation rates (g_i^h).

Lemma 2. *In the sustainable growth path with inclusive remediation, region 1 will achieve a higher knowledge accumulation rate than that of region 2, i.e.,* $g_1^h > g_2^h > 0$, *given that region 2 is able to afford all remediation responsibility.*

Proof: Recall the result of Proposition 2:

$g_i^h = \frac{(1-\eta^K)\zeta^Z + \zeta^K \eta^Z}{\eta^Z} g_i, i = 1, 2.$

Because we have $g_1 > g_2 > 0$ from Lemma 1, and two symmetric regions have the same production elasticities and knowledge elasticities, then we can derive that $g_1^h > g_2^h > 0$.

As a conclusion, because region 1 moves firstly, it can pass all remediation responsibility to region 2 and enjoy a faster economic growth rate, a positive growth rate of the net extractive use of natural resource, and a higher knowledge accumulation rate, given both regions have exactly the same technologies on producing final goods, producing knowledge, and implementing remediation. However, such an advantage does not exist in the case of exclusive utilization.

3.3. Sustainable growth path with exclusive utilization

The exclusive utilization activities of each regional government create a negative externality for the other region, by decreasing the stock of natural resources available. By using Eqs. (6) and (7), we can derive the growth rate of natural resources for region 1,

$$g_1^N = \frac{N_{1t} - N_{1,t-1}}{N_{1,t-1}} = \frac{2k(R_{2,t-2}) - 2k(R_{2,t-1}) - X_{1,t-1} - X_{2,t-1}}{N_{1,t-1}},$$

where $X_{1,t-1} = Q_{1,t-1} - k(R_{1,t-1})$, and $X_{2,t-1} = Q_{2,t-1} - k(R_{2,t-1})$ are the net extractive uses of natural resources of two regions in period $t-1$. Then we can derive the growth rate of natural resources for region 2:

$$g_2^N = \frac{N_{2t} - N_{2,t-1}}{N_{2,t-1}} = \frac{2k(R_{1,t-1}) - 2k(R_{1t}) - X_{2,t-1} - X_{1t}}{N_{1,t-1}},$$

where $X_{1,t} = Q_{1t} - k(R_{1t})$, and $X_{2,t-1} = Q_{2,t-1} - k(R_{2,t-1})$ are the net extractive uses of natural resources of two regions. In this case, we can derive the regeneration-elasticity of the gross extractive use of natural resources, $\eta^Q = 1$.

Note, that in the sustainable growth path of two regions, the stocks of natural resources should at least grow at zero rates, i.e., $g_1^N = g_2^N = 0$. This equality implies that the net extractive use of natural resources of two regions must satisfy the following two equations in every period:

$$X_{1,t-1} + X_{2,t-1} + 2\Delta k_{2,t-1} = 0,$$

$$X_{2,t-1} + X_{1t} + 2\Delta k_{1t} = 0,$$

where $\Delta k_{1t} = k(R_{1t}) - k(R_{1,t-1})$, $\Delta k_{2,t-1} = k(R_{2,t-1}) - k(R_{2,t-2})$, are the growth rates of exclusive utilization for region 1 in period t, and region 2 in period $t-1$. First, we should focus on the growth rate of exclusive utilization, Δk_{it}, $i = 1, 2$. In any sustainable growth path, Δk_{it} cannot be a positive value. We have assumed that the exclusive utilization ($k(R)$) is a concave function of the utilization inputs (R). The marginal output of exclusive utilization is decreasing, i.e., $k''(R) < 0$. Hence, it is impossible for exclusive utilization to infinitely increase, there must exist some optimal value of remediation inputs, R_i^*, that equates the marginal benefit of utilization and the marginal benefit of consumption. On the other side, Δk_{it} cannot be a negative value. If $\Delta k_{it} < 0$, the value of utilization inputs will eventually decrease to zero, $R_{it} = 0$, which makes $k_{it}(R_{it}) = 0$. Then the inequality $\Delta k_{i,t+1} < 0$ cannot hold since a negative level of utilization is impossible. As a conclusion, the only possible value of the growth rates of exclusive utilization should be zero, i.e., $\Delta k_{it} = 0, i = 1, 2$. The regions should adopt some constant level of exclusive utilization, R_i^*, at every period in the sustainable growth path. Then the equations become:

$X_{1,t-1} + X_{2,t-1} = 0,$

$X_{2,t-1} + X_{1t} = 0.$

Note that this case is different from the previous case of inclusive remediation, because the region's behaviors (both Q_i and R_i) cause the negative externalities to the other region. It is impossible for region 1 to rely on region 2 to restore its' stock of natural resources. Therefore, both regions have to adopt some amount of exclusive utilization, R_i, to offset the effect of the gross extractive use of natural resources, Q_i. The following proposition tells the growth rates of the gross use of natural resources, the growth rates of knowledge, and the growth rates of utilization of two regions in any sustainable growth path with exclusive utilization.

Proposition 3. *In the sustainable growth path with exclusive utilization, both regions will choose the same level of utilization activities in each period (R_t).The growth rates of the gross use of natural resources, the growth rates of knowledge, and the growth rates of utilization of two regions are the same as follows:*

$$g_1^Q = g_2^Q = \frac{(1-\eta^K)(1-\zeta^Z)-\zeta^K\eta^Z}{\eta^Z} g, \tag{16}$$

$$g_1^h = g_2^h = \frac{(1-\eta^K)\zeta^Z+\zeta^K\eta^Z}{\eta^Z} g, \tag{17}$$

$$g_1^R = g_2^R = \frac{\zeta^K\eta^Z-(1-\eta^K)(1-\zeta^Z)}{\eta^R\eta^Z} g \tag{18}$$

Proof: Given a sustainable growth path, the stock of natural resources can only increase at a constant rate if the net extractive use decreases at an increasing rate. On a sustainable growth path the net extractive uses have to be constant ($g_i^N = g_i^X = 0$, where the stock of natural resources increases at a zero rate). By rearranging Eq. (13), we have:

$$g_i^Q = -\eta^R g_i^R, i = 1, 2. \tag{19}$$

Substituting $g_i^X = 0$, $g_i^H = g_i^h$, $g_1 = g_2 = g$, and Eq. (9) into (10) and (11), we can derive that:

$g_i^Q + g_i^h = \frac{(1-\eta^K)}{\eta^Z} g,$

$\zeta^Z g_i^Q - (1-\zeta^Z) g_i^h = \zeta^K g.$

By solving for the unknowns, g_Q and g_h, of the two equations above, we can get Eqs. (16) and (17). Substituting Eq. (19) into Eq. (16) and rearranging, we can derive Eq. (18).

Proposition 3 specifies the relationship between the growth rates of the gross use of natural resources, the growth rates of knowledge accumulation, the growth rates of utilization activities, and the common growth rates. Unlike Lemma 1 and 2 in the case of inclusive remediation, all of those growth rates are the same for two regions.

Substituting $g = g_i^R$ into Eq. (18), we have:

$$\eta^R = \zeta^K - \frac{(1-\eta^K)(1-\zeta^Z)}{\eta^Z}. \quad (20)$$

Eq. (20) implies that given the assumptions of the regeneration function, a feasible sustainable growth path exists only for a very specific relationship between the gross extractive use of natural resources and the utilization activities. The stock of natural resources, N_i, will only be constant if the regeneration-elasticities of Q_i and R_i exactly offset each other, such that the net extractive use of natural resources, X_i, remains constant. Hence, the equality $g_i^X = g_i^N = 0$ holds in any feasible sustainable growth path.

3.4. Choice of activity type

What happen if regions have the right to choose the type of activity? Which type is the optimal choice of regions: inclusive remediation or exclusive utilization? In such a case, the timing of the game becomes:

1. Nature decides the initial stock of natural resources, N_0.
2. In the first period (i.e., $t = 1$), region 1 decides the allocations of physical capital and natural resources used in production, the consumption, and the type and amount of activity, so that final goods and knowledge are produced, and the stock of natural resources available to region 2 is determined.
3. In the first period (i.e., $t = 1$), after receiving the choices of region 1, region 2 decides the allocations of physical capital and natural resources used in production, the consumption, and the type and amount of activity, so that final goods and knowledge are produced, and the stock of natural resources available to region 1 in the next period ($t = 2$) is determined.
4. The game infinitely repeats.

The following proposition shows the regions' optimal choices when they are able to choose the type of remediation.

Proposition 4. *If regions can freely choose to adopt inclusive remediation or exclusive utilization, both regions will adopt exclusive utilization and the growth rates of exclusive utilization are as follows:*

$$g_1^R = g_2^R = \frac{\zeta^K \eta^Z - (1-\eta^K)(1-\zeta^Z)}{\eta^R \eta^Z} g. \quad (21)$$

Proof: If region 1 chooses inclusive remediation, the optimal response of region 2 is to adopt exclusive utilization, because region 2 can take advantage of the positive externality created by region 1's behavior. If region 1 chooses exclusive utilization, the optimal response of region 2 is to adopt exclusive utilization, because the economic growth rate will become lower if it chooses inclusive remediation. Hence, inclusive remediation is a strictly dominated strategy for region 2, and will not be adopted. By knowing the strictly dominating strategy of region 2 is exclusive utilization, the optimal choice of region 1 is exclusive utilization; otherwise, it will suffer a lower economic growth rate.

Proposition 4 implies that if there are no restrictions from the central government, both regions will adopt exclusive utilization on the common natural resources and cause negative externalities to each other. The situation could be a 'prisoner's dilemma' because inclusive remediation causes positive externalities to each other, meanwhile exclusive utilization may result in the duplication of sunk costs (i.e., the costs of constructing dams and impounding reservoirs). To improve social welfare in China, the central government should pay special attention to the permitting of exclusive utilization activities of regional governments.

4. Extensions of the model

In this section, we provide some discussion about three extensions of the model and show some insights for modifying and applying our theoretical framework.

4.1. Multiple regions

If the number of regions in the model increases from 2 to N, the analysis should be similar to the benchmark model. Hence, we can summarize the properties in relation to inclusive remediation for regions as follows:

Lemma 3. *In each period of the sustainable growth path with inclusive remediation, the leading N-1 regions will make zero effort on remediation, i.e.,* $R_{it} = 0, i = 1, 2, \dots, N-1$, *resulting in a positive growth rate of the net extractive use of natural resources, i.e.,* $g_i^X > 0$, $i = 1, 2, \dots, N-1$. *Region N that moves at the last has to bear all costs of remediation activities, i.e.,* $R_{Nt} = \sum_1^{N-1} Q_{it} > 0$, *with a negative growth rate of the net extractive use of natural resources, i.e.,* $g_N^X < 0$, *given that region N is able to afford all remediation responsibility.*

Note that Lemma 3 requires the condition that the marginal cost of inclusive remediation is significantly low so that the last region N can afford all costs of remediation activities.

However, if the previous condition does not hold, it should be the case that the last $N - j$ regions can afford all costs of remediation activities and experience zero economic growth; meanwhile the leading j regions make zero effort on remediation. The result of the N regions case is similar to that of the benchmark model.

4.2. Asymmetric regions

If the production functions of final goods ($Y_i = Y_i\left(K_i^Y, Z_i^Y, N_i\right)$), the production functions of knowledge ($H_i = H_i\left(K_i^H, Z_i^H\right)$), and remediation functions ($f_i(R_i)$ and $k_i(R_i)$) are different for two regions, the elasticities of production and marginal costs of remediation are different. In the interest of saving space, we will not provide the explicit forms of those complicated expressions of functions here. However, we can still derive some properties of the asymmetric regions case. The region with advanced technologies for producing final goods, producing knowledge, and implementing remediation will achieve a higher growth rate than that in the benchmark model.

Lemma 4. *In the sustainable growth path with inclusive remediation, if region 1 better technologies for producing final goods, producing knowledge, and implementing remediation, the economic development will become more unbalanced; if region 2 has better technologies, the economic development will become more balanced. In the sustainable growth path with exclusive utilization, the region with better technologies can achieve a higher economic growth rate.*

A direct policy implication of Lemma 4, is that if the economic growth rate of some region is lower than that of the other region, the central government may forbid the adaptation of exclusive utilization. Hence, inclusive remediation has the potential to cure the economic imbalance between regions.

4.3. Knowledge as a public capital good

If knowledge is a public capital good, instead of a private capital good, both regions benefit from the knowledge production of each other. The accumulation function of knowledge becomes:

$$\frac{\Delta h_t}{\Delta t} = H(K_{1t}^H, Z_{1t}^H) + H(K_{2t}^H, Z_{2t}^H) \tag{22}$$

In this case, the knowledge production of each region has a positive externality on the other, so that regions will allocate more physical capital and effective use of natural resources into the production of final goods, resulting in a higher growth rate.

Lemma 5. *If the central government forces two regions to share the knowledge of utilizing natural resources, and makes knowledge a public capital good, both regions will experience higher growth rates in any sustainable growth path with inclusive remediation or exclusive utilization.*

Due to the promotion competition between the leading officials of regional governments, regions may not have the incentives to disclose innovation and new knowledge production. Intervention from the central government is necessary to make knowledge become a public capital good. Although both regions achieve faster economic growth as the knowledge of utilizing natural resources becomes public, there may still be under-production of knowledge from the perspective of social welfare. Too many resources are allocated to the production of final goods because of the positive externality of knowledge. To improve social welfare, the central government should adopt some policy measures to increase the incentives of knowledge production for both regions.

5. Conclusions

In this paper, we propose a theoretical framework to investigate the sustainable growth path of multiple regions, by combining the two-sector endogenous growth model and the dynamic game of remediation (utilization) activities. We analyze the effects of inclusive remediation and exclusive utilization in this theoretical framework. The results show that the region that moves firstly will pass all the remediation responsibility to the other region, and enjoy faster economic growth in the case of inclusive remediation. However, in the case of exclusive utilization, both regions will have the same growth rate in a symmetric equilibrium because each region will adopt exclusive utilization and reduce the stock of natural resources available to the other in the next period. We also show that exclusive utilization may deteriorate the social welfare, because regions may fall into a 'prisoner's dilemma'. Finally, we provide three extensions of the benchmark model: if there are multiple regions, if regions are asymmetric, and if knowledge is a public capital good. These extensions provide several interesting results, and policy implications for the central government.

The limitation of our theoretical framework is that we are not able to derive the optimal growth path of multiple regions due to the complexity of the model. Only feasible conditions of the sustainable growth path are considered in the dynamic game of regions' choices on efficiently utilizing natural resources. However, the results of our model can be seen as the feasible or necessary conditions for the sustainable growth path of multiple regions in different cases. For future research, we may choose some specific forms of the production functions of final goods and knowledge, and the remediation functions, to derive the optimal conditions of the sustainable growth path with the interaction of remediation between regions.

Other than extending our model to derive the optimal sustainable growth path, there are several interesting directions for future research. First, we can apply our theoretical framework to the specific study of the conflict between regional governments around those large lakes (i.e., Poyang Lake, Dongting Lake, Chao Lake and Tai Lake) in China. The interactive decision making of constructing impounding and hydropower projects may provide some meaningful policy implications for the sustainable economic growth of all regions sharing the some water resources. Second, we can also apply our model to empirical analysis. By collecting more data related to the natural resources of lakes, and the economic development of surrounding regions, we can add proper specifications and parameter values of the production and regenerating functions to test the results of the theoretical model.

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