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How should the center lead China's reforestation efforts?—Policy making games between central and local governments

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ABSTRACT

Over the past ten years, China has implemented one of the largest reforestation projects in the developing world. However, the reforestation efficiency has been seriously compromised by the conflicts between the central and local governments in implementing policy. While the central government tries to maximize the project's ecological benefits, the local tends to minimize its administrative efforts due to limited budgets. This paper creates a Stackelberg model to simulate central and local relationships and proposes three possible solutions: penalizing high mortality rates of trees, rewarding high survival rates, and a combination of them. It is shown that the ecologically optimal strategy for the central government is to recognize high survival rates with a reward rate quantitatively equal to the size of the reward base fund. Understanding and solving the conflicts between central and local governments in China's ecological projects is particularly important since its rising economy is being drained of natural resources, while exploiting other countries' resources. Contrary to traditional wisdom that takes local agencies for granted as subordinate organs in the environmental governance system, this work indicates that environmental policy design needs improved mechanisms to motivate local agencies in working more effectively.

1. Introduction

The booming Chinese economy requires ever increasing amounts of natural resource inputs, with forest products an important category on its demand list. In 2010, China consumed the most wood based panels, recovered paper, paper and paperboards in the world, as well as the second most industrial roundwood, sawnwood, and pulp for paper (FAO, 2012).

To satisfy this huge and growing demand, on the one hand, China imports more raw wood from neighboring subtropical countries, leading to substantive consumption of their resources (Xu and White, 2004). On the other hand, in an effort to increase domestic supply of forest products, China has launched the most ambitious reforestation efforts in the developing world, as represented by the Slope Land Conversion Program (SLCP, also known as Grain for Green). This program has been extensively cited as evidence of China's contribution to global ecological conservation. It was originally expected that the reforestation project would significantly increase China's forested area and timber supply, reduce soil and water erosion, and contribute to global carbon dioxide mitigation (Bennett, 2008). It would also have significantly alleviated the pressure to consume foreign forests, as China increases domestic timber supply to meet its own demand.

However, over ten years of implementation, these project goals had hardly been achieved due to various ecological, economic, and political reasons. This paper will (1) attempt to provide a possible explanation for the implementation failure: the conflict of interests between the central and local governments, and (2) propose some policy solutions to rescue the behemoth ecological program.

The divergence of interests between central and local governments has long been recognized as a major cause of inefficient implementation of many public policies. As Bardhan and Mookherjee (2000) point out, policy implementation at the lower level of government tends to be captured by vested interests and local elites, and therefore altered from the original policy design. China can by no means be exempt from the central local conflicts. These conflicts may even be aggravated by its particular multi-sectioned and multi-layered government structure (*tiao kuai* system). In China, a typical functional government unit at the local level is under the direction of two higher-level authorities: the local government and its parent unit. For example, a municipal environmental protection bureau receives guidance from both the municipal government and the provincial environmental protection bureau. While the functional parent unit emphasizes its operational goals, a local government tends to prioritize economic growth, since that determines career promotion of local officials. As

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local units are financially dependent on their local governments, they tend to subordinate the operational goals to local economic concerns. Such central local tensions have been extensively observed and discussed in various policy domains (Chen, 2009; Mol, 2009). For example, in regard to fiscal revenue collection, while the central government strives to increase tax revenues by increasing tax rates, local governments often counter-play by reducing tax base to promote economic activities and save local administrative costs (Wong, 1991; Ma, 1995). Similarly, (Skinner et al., 2001, 2002) find that local governments tend to selectively implement social and environmental policies in light of local priorities related to economic growth. He et al. (2012) examine implementation of several environmental policies. They show that, while environmental improvement and sustainable development programs are promoted by the Ministry of Environmental Protection and win general supports at the central level, the center cannot "motivate, direct, steer, and control local environmental protection bureaus" to effectively implement these programs, as they are financially dependent on local administrations (Jahiel, 1997).

How does the power struggles between central and local governments affect China's reforestation efforts? To answer that question, we need to first explore a broad overview of the SLCP. With a total budget of RMB 337 billion (over US $40 billion) and a goal of converting 14.67 million hectares of cropland to forests, the SLCP is one of the largest forest system rehabilitation programs in the world (Uchida et al., 2007). It was launched in 1999, soon after the devastating floods and droughts hit China's two major water systems, the Yangtze River and the Yellow River basins. Its initial aim was to restore forest cover and reduce soil erosion in the upper and middle reaches of the two basins. However, over the next five years, this program was quickly extended to a total of 1897 counties across 25 provinces and engaged millions of rural households as core implementation agents (Gao and Guo, 2012). In contrast to other forestry programs, this program is one of the first and certainly the most ambitious "payment for environmental services" (PES) in China. In the SLCP, the State Forestry Administration (SFA) pays rural households to plant timber trees on their steeply sloping crop land, as stated in the official plan that participation is on a volunteer basis (SFA, 2003). Specifically, for each hectare of reforestation from cropland, rural households will be compensated with (1) an annual in kind subsidy of grain (2250 kg in the Yangtze River Basin and 1500 kg in the Yellow River Basin), (2) a cash subsidy of RMB 300 (about $36), and (3) free seedlings at the beginning of the planting period. Subsidies last for eight years if ecological forests[1] are planted, five years if economic forests[2] are planted, and two years if grasses are planted. Such compensation standards are quite generous, even compared to the average rental payments in the US Conservation Reserve Program (Heimlich, 2003). Most participating households have become financially better off with the compensation payments (Uchida et al., 2007; Xu et al., 2010).

The original policy design of the SLCP is quite simple: the SFA pays rural households to plant trees on their croplands. In other words, the SFA buys the forest ecological services from individual rural households. However, the compensation payments cannot directly reach each household and rural households cannot directly report their reforestation achievements to the central forestry agency. Local forestry agencies are indispensable liaisons in such a large scale ecological project. They are in charge of collecting and reporting information about local social, economic, and ecological conditions, communicating central directives to individual households, allocating reforestation quota, distributing subsidy payments, and providing technical and other supports to participating households. All of these tasks are burdensome and costly. However, the local governments' administrative costs are not covered by the SLCP.

A land use change policy, such as the SLCP, may naturally be resisted by local governments since it reduces output from agricultural production. This resistance would be even stronger when local governments have to pay the administrative costs from their own budgets. This design deficiency has been identified as a major reason why many local governments fail to fully implement the central government's policy (Bennett, 2008). First, without sufficient funding, few local governments can completely evaluate the program's environmental benefits (Bennett, 2008). In the case of the SLCP, compliance has been measured based on the survival rates of trees or grasses planted in a township as a whole, or even larger areas (Wang and Chen, 2006). In addition, trees and grasses have been poorly managed because of inadequate funding, so the survival rates are low. Since the SLCP has the dual goal of ecological conservation and poverty reduction, low survival rates seldom result in a withdrawal of compensation. Because of this loophole, some local governments may at first overreach the targeted reforestation areas, and then leave some reforestation sites unattended, resulting in low survival rates among trees (Kong, 2007; Zhi et al., 2004). Since no laborers are employed to plant or manage trees on these sites, the compensation payment for them may be retained by local governments to recoup their administrative costs. The harm of such manipulation is the lost value of timber and other environmental services that could be generated under the SLCP (Jiang, 2003). Moreover, the program does not give adequate consideration to land productivity and environmental heterogeneity when selecting plots (Zuo, 2001; Xu and Cao, 2001). While high sloping, low quality land remains in crop cultivation, many low-sloping plots have been enrolled into the program (Fang and Yang, 2006). Finally, the sustainability of the SLCP has been seriously challenged. Compared to agriculture, forestry operation requires less labor input. In order to make a smooth and permanent transition from an agricultural economy to a forestry based economy, laborers have to be trained for new jobs – in the forestry industry or other jobs outside agriculture (Zhi et al., 2004). However, without sufficient funding, most local governments do not provide such training (Liu et al., 2007; Zhang et al., 2007). Thus, it is not surprising that many participating rural households stated that they would return to crop planting once the compensation period ended (Bennett, 2008).

These deficiencies of the SLCP have been extensively documented; however, most of these discussions remain at a descriptive level. Very few of them involve in-depth analysis of the root causes of the central local conflicts (Kong, 2007, Yang, 2004). In order to investigate these implementation problems, I visited four reforestation provinces with diverse biophysical and social conditions[3], and interviewed 34 local forestry officials as well as six SFA officials. The problems of low survival rates, imprecise targeting, and lack of training of laborers have all been observed and discussed with the forestry officials during the site visits. I collected comments from central and local officials in an effort to understand how they perceive the problem and the possible solutions. I use a game theoretical model to analyze the central

[1] The term used by the SFA to denote timber producing forests.

[2] The term used by the SFA to denote orchards, or forests with medicinal value.

[3] During May to August 2011, I visited four provinces participating in the SLCP: Ningxia, Chongqing, Yunnan, and Heilongjiang. Ningxia is located in the northwestern arid region and has been described as one of the world's most unsuitable areas for human habitation (UNDP, 2010). Through long term living with extreme resource scarcity, residents in this area have learned how to steward their resources. The mid western province Chongqing has hilly topography that is difficult to raise crops on (Xu, 2001), but its warm and humid climate is good for plant growth (Zhang, 1987). Chongqing residents place emphasis on individual control of land and resources. Many ethnic minorities inhabit Yunnan. Their environmental perceptions are influenced by religious beliefs and adherence to their traditional practices of collective ownership and resource governance (Guo, 2001). The northeastern province of Heilongjiang is characterized by fluvial plains and rich stocks of natural resources (Zhang, 1987; Li and Xie, 2006). Its people are characterized as generous in using and sharing resources.

Table 1
Average survival rate of trees planted under the SLCP.

Province	County	Township	SLCP standard	Inspections		
				1st	2nd	3rd
Shaanxi	Yanchuan	Yanshuiguan	70%	94.2%	93.6%	98.0%
		Majiahe		72.9%	95.8%	96.4%
		Yuji		79.0%	83.2%	95.0%
	Liquan	Yanxia		56.3%	86.8%	81.1%
		Jianling		78.8%	47.9%	39.4%
		Chigan		100.0%	46.7%	52.1%
Guansu	Jingning	Zhigan	70%	70.0%	69.0%	66.0%
		Gangou		80.0%	76.6%	71.0%
		Lingzhi		NA	75.7%	77.7%
	Linxia	Zhangzigou		56.3%	46.7%	65.0%
		Tiezhai		90.0%	61.1%	75.8%
		Hexi		87.5%	69.5%	64.0%
Sichuan	Chaotian	Datan	85%	82.0%	61.5%	67.3%
		Zhongzi		70.0%	48.7%	77.0%
		Shahe		92.5%	74.1%	40.4%
	Li	Shangmeng		100.0%	79.6%	76.1%
		Puxi		74.9%	80.7%	84.8%
		Guergo		70.0%	74.1%	77.0%

Source: 2003 CAS survey data.

local conflicts in managing the reforestation efforts. It is shown that the best way for the center to motivate its local agencies is to reward high survival rate of trees with a reward rate that quantitatively equals the size of the reward supporting fund.

The next section sets up the basic Stackelberg model and describes the central local conflicts under the current policy scenario. Section 3 introduces and compares three potential policy revisions that could align central and local interests and improve implementation efficiency. Section 4 concludes the paper by making policy suggestions.

2. The current case: utility-maximizing locales without control from the center

According to the current stipulation of the SLCP, the central authority has, on paper, control over every detail of the project, from assigning reforestation quotas to setting the compensation standards. Local forestry agencies are required to strictly carry out the plan stipulated by the center, without any local discretion, but on their own administrative budget. However, the actual situation is very different.

The SLCP's administrative costs have indeed been significant (Kong, 2007). Villages reported that in 2002, they spent on average 112 work days implementing SLCP, or an average of 6 work days per hectare of enrolled land. Start-up costs appeared to be even higher (Bennett, 2008). Uncompensated efforts could not last long. Very often, some local forestry bureaus restrict or reduce the efforts they put into the SLCP project in order to avoid high administrative costs. Accordingly, tree survival rates in these areas may be low. Table 1 summarizes the average tree survival rates in 18 townships participating in the SLCP, as indicated by so far the most comprehensive survey of the SLCP conducted by China's Academy of Science in 2003[4]. As shown in the table, 11 of the 18 townships had survival rates lower than the SLCP standards. There are also some regional specific surveys of tree survival rates under the SLCP. For example, Cao and his colleagues tracked the SLCP implementation in five Shaanxi counties during 1998 and 2005. The reported that the average tree survival rate decreased from 55.7% in their first round survey to 49% in the last round, consistently lower than the national standard (Cao et al., 2009). Even worse, Han and Li (2008) reported that one-time survival rates of trees planted under the SLCP was only 30% in the mountain areas of Luliang and Taihang in Shanxi.

Since the SLCP also targets poverty reduction, low survival rates of trees have seldom resulted in significant withdrawals of compensation payments, even when they are observed by the SFA. In this case, local forestry agencies could retain the part of compensation that is paid to the dead seedlings and use it to recoup their administrative costs. Thus, they may even lack the incentive to carefully nurture the seedlings.

This section discusses this current scenario: local forestry agencies are reluctant to invest administrative efforts in reforestation management, and the center imposes no effective restriction on that. This analysis provides a benchmark. We will compare the three potential policy revisions with the benchmark, as addressed in the following sections. It is assumed that there is one central agency (the center) and two local ones (regions) in the forestry governance system.

Let Y_1 be the reforestation quota assigned to the ith region, where $i = 1,2$. $1 - k_i$ is the survival rate in the ith region (equivalently, k_i is the mortality rate, $0 \le k_i \le 1$). The center and the two regions play a two-stage game. The timing of the game is as follows:

(1) In Stage 1, the center assigns Y_1 and Y_2 to Region 1 and Region 2, respectively.

(2) In Stage 2, after observing Y_1 and Y_2, Region 1 and Region 2 strategically determine their administrative efforts, which result in mortality rates of k_1 and k_2.

In terms of game theory, this is a three player, two stage game with imperfect information. The above assumption implies that the center plays a Stackelberg game with the regions, while the center acts as the leader and the regions as followers. This assumption embodies the fundamental feature of the current decision making process in the SLCP: at the beginning of each period, the center settles the reforestation

[4] The 2003 CAS survey has been recognized as one of the most influential empirical evaluations of the SLCP implementation. It is still cited in recent studies, for example Xu et al. (2010). Survival rates were calculated consistently in the three rounds of the survey: the SLCP technique stipulation requires 250 seedlings planted in each standard plot of land (*biaozhundi*); survival rate is calculated by dividing the number of survival trees over 250. The rate may increase in some townships as farmers conduct complementary planting in the following years, or decrease in other townships due to death of trees which may be further caused by improper species selection, limited water availability, and extreme temperature in the following years.

plan without knowing the survival rate $1-k_i$ that would only be observed at the end of the period. We assume that the two regions do not cooperate and both try to maximize their own utility. This assumption also corresponds to the observable fact that local agents compete with each other for the reforestation funding.

The equilibrium is defined by two conditions: (1) each region responds optimally, given the center's assignment of the reforestation quota; and (2) the center optimizes, given the regions' reaction function to the center's assignments.

We follow the standard procedure of backward induction to solve for the equilibrium. First, we solve for the regions' optimal choices given Y_1 and Y_2 (the regions' reaction functions to the center's assignment), and then solve for the center's optimal Y_1 and Y_2, given the regions' reaction function.

Since the regions can somehow retain the part of compensation that is paid for unsuccessful reforestation and use it to replenish their administrative budget, we set the regions' object function as follows:

$$U_i = c_i k_i Y_i,\ i = 1, 2 \tag{1}$$

where c_i is the exogenous compensation rate Region i receives from the center. As indicated above, there are two regional regimes in terms of compensation standards. If the two regions fall into the same regime, $c_1 = c_2 > 0$. If not, without loss of generality, we assume $c_1 > c_2 > 0$. Since c_i is exogenous and Y_i is given, Eq. (1) indicates that a revenue maximizing region tends to minimize their administrative efforts and raise k_i to its maximum, which is one. In this extreme scenario, there would be no trees surviving under the SLCP, no matter how the center allocates the reforestation quota and how much compensation the center pays in the SLCP. Although this scenario was rarely observed in the field due to political pressures that are not included in this model, it could partially explain local governments' strong incentive to restrict their administrative efforts and benefit from high mortality rates.

3. Potential policy revisions

3.1. Solution one: penalizing the regions for mortality rates

In order to curb the regions' demotivation, some officials proposed the solution of punishing mortality rates. The threat of penalization is credible and practically feasible because, in recent years, closer financial connections have been built within the forestry governance system. In addition to the administrative budget received from its local government, a typical local forestry bureau can secure some extra funding by fining illegal forestry activities and renting land in state forest farms, as well as from various special programs. As mentioned by my interviewees, in addition to the administrative budget funding from the municipal governments, the municipal forestry agencies also obtain funding from at least sixteen national forestry subsidy programs[5], as well as the matching provincial programs. Some auxiliary funding, such as the Forest Ecological Services Compensation Fund, the Subsidy for Forest Tending, and the Fund for Comprehensive Forestry Development, can be suspended with reasonable argument, if reforestation performance does not reach the SLCP's expectation. In one of the sample provinces Heilongjiang, local forestry officials introduced that the Forest Ecological Services Compensation Fund was used as a penalty threat for low survival rates in the SLCP. When the rates were lower than the fixed criterion, the provincial forestry agency would halt part or all of this funding allocated to municipal forestry agencies.

In order to make the penalty effective, in theory, we assume a quadratic penalty function: $d_i k_i^2$, which reflects an increasing marginal cost imposed on the regions when mortality rates are higher. One will see the critical role the quadratic penalty function plays in determining an optimal solution of the regions' problem. If the function is linear, instead of a quadratic, the regions' utility function would still be linear of the mortality rate, and the regions' optimal strategy would still be to raise that rate to one. We also assume the center uses the same criteria to penalize both regions, thus $d_1 = d_2 = d$. Since the penalty is usually based on a specific fund with a fixed size, the effective penalty imposed on a certain municipal agent cannot exceed that size, which is denoted by D. We assume D is exogenous with respect to this model. Compared to the SLCP compensation, D is usually much smaller ($E \gg D$).

Considering the penalty, the regions' utility function is:

$$U_i = \begin{cases} c_i k_i Y_i - d k_i^2 \text{ if } 0 \le k_i \le \sqrt{\dfrac{D}{d}} \\ c_i k_i Y_i - D \text{ if } \sqrt{\dfrac{D}{d}} < k_i \le 1 \end{cases},\ i = 1, 2 \tag{2}$$

If the potential penalty is less than D ($dk_i^2 \le D$), the center can effectively levy it and take dk_i^2 away. Otherwise, the maximum penalty the center could collect is D. The timing of the game remains the same. As the followers, the regions maximize U_i as expressed in Eq. (2), for any assigned reforestation quota Y_i and any penalty rate d determined by the center.

$d \le D$

If the center sets d quantitatively less than D ($\sqrt{D/d} \le 1$), it can always effectively impose the penalty, since $k_i^2 \le 1$. Then, the regions' problem is reduced to

$$\max U_i = c_i k_i Y_i - d k_i^2 0 \le k_i \le 1,\ i = 1, 2$$

[5] These programs include the SLCP, the Forest Ecological Services Compensation Fund, the Forest Pest Control Fund, the Special Fund for Poverty Reduction in National Forest Farm, the Loan with Discounted Interest for Desertification, the Subsidy on Forestry Petroleum Price, the Supporting Fund for Promotion of Forestry Technologies, the Subsidy for National Natural Reserves, the Subsidy for Improved Varieties of Forest Tree, the Forestation Subsidy, the Subsidy for Forest Tending, the Subsidy for Wetland Protection, the Subsidy for Small Scale Eco Infrastructure, the Fund for Forestry Disasters, the Fund for Comprehensive Forestry Development, and the Functional Budget from the SFA.

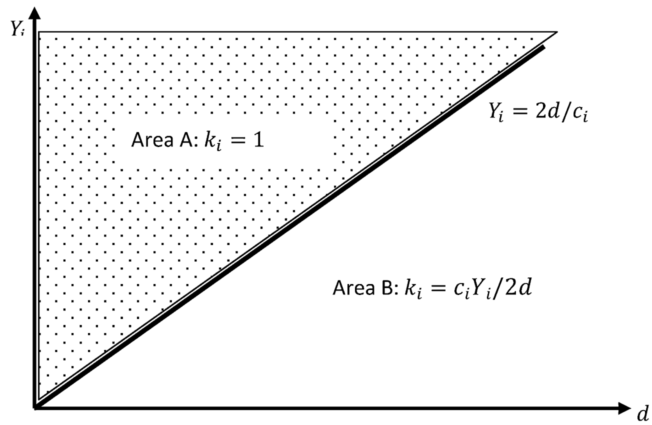

Fig. 1. The center's decision set under the strategy of penalizing.

With the Karush–Kuhn–Tucker method, the regions' optimization problem can be solved and the optimal strategy for the regions to set k_i is (See Appendix 3.1.1):

$$k_i = \begin{cases} \dfrac{c_i Y_i}{2d} \text{ if } c_i Y_i \le 2d \\ 1 \text{ if } c_i Y_i > 2d \end{cases}, i = 1, 2 \quad (3)$$

Having solved for the regions' reaction functions, we turn to look at the center's problem. It is assumed the center would like to maximize the amount of ecological services generated by the SLCP, which can be approximately measured with the area of land successfully reforested. Thus, the center's objective function is:

$$U_c = (1 - k_1(Y_1))Y_1 + (1 - k_2(Y_2))Y_2$$

The annual budget of the SLCP is fixed. Thus:

$$c_1 Y_1 + c_2 Y_2 \le E$$

where c_i represents the compensation standards as discussed above ($c_i > 0$), and E is the SLCP's annual budget ($E > 0$). Since in the game the center acts as the leader, it takes into consideration the regions' responses when solving its problem. The center knows that, if it assigned a reforestation quota $Y_i > 2d/c_i$, the regions would respond by minimizing their management efforts and the tree mortality rate would be maximized to 100%, i.e. the SLCP would generate no ecological services. As a rational player, the center should avoid these scenarios and target its decision sets in Area B as shown in Fig. 1. If that is the case, the mortality rates can be restricted to $k_1 = c_1 Y_1/2d$ and $k_2 = c_2 Y_2/2d$. Then, the center's problem can be summarized as follows:

$$\max_{Y_1, Y_2, d} U_c = \left(1 - \frac{c_1 Y_1}{2d}\right) Y_1 + \left(1 - \frac{c_2 Y_2}{2d}\right) Y_2$$

$$s.t. c_1 Y_1 + c_2 Y_2 \le E$$

$$Y_i \le 2d/c_i, i = 1, 2, \text{ and and } d \le D$$

Still with the Karush–Kuhn–Tucker method, the center's optimization problem can be solved: $d = D$, $Y_1 = D/c_1$, $Y_2 = D/c_2$ (See Appendix 3.1.2). Accordingly, the regions respond with $k_1 = k_2 = 0.5$. In this case, the total spending of the SLCP is $2D$ and the ecological benefits reaped from the program is $0.5D(\frac{1}{c_1} + \frac{1}{c_2})$. $d > D$

If the center chooses a penalty rate d quantitatively greater than the size of the penalty basis fund D ($d > D$), the regions' utility is a two sectional function, as shown in Eq. (2). It can be calculated that the two sections cross when $k_i = \sqrt{D/d}$. The shape of these functions depends on the relationship between Y_i and d, which are set by the center. As shown in Fig. 2, the parabola demonstrates the first section of the regions' utility, and the two straight lines demonstrate the possible positions of the second section. If $c_i Y_i/2d \ge \sqrt{D/d}$ (the symmetry axis of the parabola is on the right of the crossing as shown by the dashed line), the regions' utility follows OA on the parabola and then AC on the dashed line. In this case, since $\sqrt{D/d} < 1$, the regions could derive the maximized utility when $k_i = 1$. If $c_i Y_i/2d < \sqrt{D/d}$ (the symmetry axis of the parabola is on the left of the crossing as shown by the dotted line), the regions' utility follows OB on the parabola and then BD on the dotted line. In this case, the regions could derive the maximized utility at either $k_i = c_i Y_i/2d$ or $k_i = 1$, depending on which one is greater. When $k_i = c_i Y_i/2d$, the regions' utility is $c_i^2 Y_i^2/4d$. When $k_i = 1$, the regions' utility is $c_i Y_i - D$. Thus, if $c_i^2 Y_i^2/4d > c_i Y_i - D$, $k_i = 1$, and if $c_i^2 Y_i^2/4d \le c_i Y_i - D$, $k_i = c_i Y_i/2d$.

To repeat, given the center's assignment of Y_i and a penalty rate of d, the regions' responses can be summarized as follows:

- $k_i = 1$, *if* $\frac{c_i Y_i}{2d} \ge \sqrt{D/d}$
- $k_i = 1$, *if* $\frac{c_i Y_i}{2d} < \sqrt{D/d}$ and $c_i Y_i - D > \frac{c_i^2 Y_i^2}{4d}$
- $k_i = \frac{c_i Y_i}{2d}$, if $\frac{c_i Y_i}{2d} < \sqrt{D/d}$ and $c_i Y_i - D \le \frac{c_i^2 Y_i^2}{4d}$

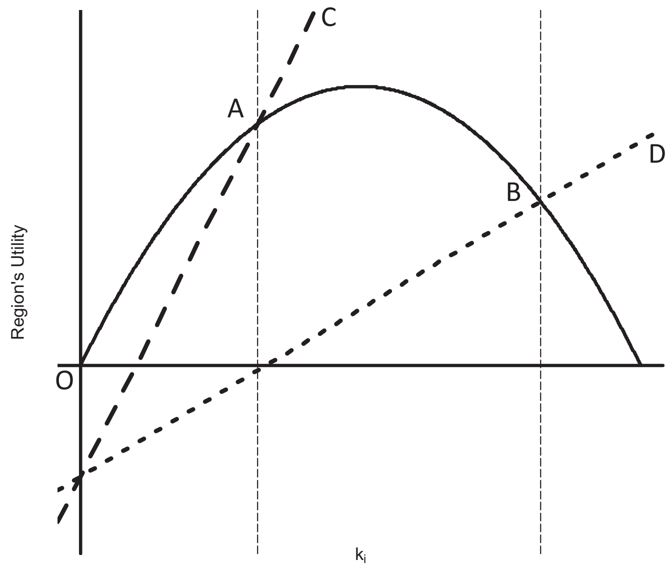

Fig. 2. Region's utility as function of k_i (Penalizing).

In order to avoid the maximum mortality rate ($k_i = 1$), as a rational player, the center should set Y_i and d that satisfy both $c_iY_i/2d < \sqrt{D/d}$ and $c_iY_i - D \le c_i^2Y_i^2/4d$. Then, the regions' response is to set $k_i = c_iY_i/2d$. Accordingly, the center's problem can be summarized as follows:

$$\max_{Y_1,Y_2,d} U_c = \left(1 - \frac{c_1Y_1}{2d}\right) Y_1 + \left(1 - \frac{c_2Y_2}{2d}\right) Y_2$$

$$s.t. c_1Y_1 + c_2Y_2 \le E$$

$$c_iY_i - D \le \frac{c_i^2Y_i^2}{4d}, \quad i = 1, 2$$

$$\text{and } d > D$$

With the Karush–Kuhn–Tucker method, this problem can be solved: $d \to +\infty$, $Y_1 \to 0$, $Y_2 \to 0$ (See Appendix 3.1.3). Accordingly, the regions' response would be $k_1 = k_2 = 0$. The theoretical predication indicated by this solution is that the center sets a penalty rate approaching infinity and assigns infinitely small reforestation quotas to each region. The infinite penalty rate works here as prohibitive deterrence, and the regions would try their best to minimize mortality rate to zero. In this scenario, the SLCP program tends to significantly diminish.

In summary, if the penalizing strategy is utilized, considering both the scenarios of $d \le D$ and $d > D$, the global optimal strategy for the center is to set $d = D$, and assign the reforestation quota to each region as $Y_1 = D/c_1$ and $Y_2 = D/c_2$. In response to such a policy combination, the regions would deliberately choose the mortality rates of $k_1 = k_2 = 0.5$. The actual amount of land reforested under the SLCP is $0.5(\frac{D}{c_1} + \frac{D}{c_2})$, and the actual spending in the SLCP equals the size of the penalty base funding D, which is much less than the initial budget allocation of E. Although this strategy could not fully utilize the potential funding prepared for the SLCP, it at least generates positive ecological benefits, representing a policy improvement compared to the benchmark scenario. Since the amount of actual ecological service supply is determined by the size of the penalty-based fund, not the SLCP budget, future policy improvement should consider enlarging D, if the solution of penalizing low survival rates is implemented.

3.2. Solution two: rewarding the regions for survival rates

Instead of punishing the regions for the trees' high mortality rates, some officials also proposed that the center should modify the regions' behaviors by rewarding them for high survival rates. Given the extensive supporting funds arranged for the SLCP in its second round implementation, the rewarding motivation is also credible and feasible. In 2007, in view of the threats to the sustainability of the SLCP's ecological benefits, the State Council issued the Notice of Perfecting the Policy of Converting Farmlands to Forests, which represented essential policy revisions from the first round (1999–2006). In the second round, the central government formally arranged funds to support local governments in developing reforestation auxiliary programs[6] that were listed but not financed in the first round (Li, 2009). For example, to encourage local governments increase tree survival and preservation rate under the SLCP, the central government established funds for complementary planting. The funding can be easily modified as rewarding payments for the local governments that effectively raise the survival rate of newly planted trees in their jurisdiction.

[6] These programs include basic farmland construction, rural energy development, eco-migration, and complementary planting in reforestation sites.

In order to make the two solutions comparable, we assume that the center finances the reward program with a fund of similar size as the penalty basis, which is D. All the other characters of the game remain the same. As the follower in the game, the regions try to maximize their utility as defined in Eq. (4):

$$U_i = \begin{cases} c_i k_i Y_i + d(1-k_i)^2 \text{if}\, 0 \le 1-k_i \le \sqrt{\dfrac{D}{d}} \\ c_i k_i Y_i + D \quad \text{if} \sqrt{\dfrac{D}{d}} < 1-k_i \le 1 \end{cases}, \ i = 1, 2 \tag{4}$$

Similar to discussion in the Section 3.1, we respectively consider two scenarios: the center sets the reward rate quantitatively greater than D ($d > D$) and smaller or equal to D ($d \le D$).

$d \le D$

If $d \le D$, the regions' goal is to maximize their utility that can be simplified to:

$$\max U_i = c_i k_i Y_i + d(1-k_i)^2,\ i = 1, 2$$

$$0 \le 1 - k_i \le 1$$

The regions' optimal response to the center's reforestation policy (Y_i, d) can be solved with the Karush–Kuhn–Tucker method (See Appendix 3.2.1):

$$k_i = \begin{cases} 1 - \dfrac{c_i Y_i}{2d} if\ \ c_i Y_i \le 2d \\ 1\ if\ \ c_i Y_i > 2d \end{cases} \tag{5}$$

In this case, the survival rates, rather than the mortality rates, increase with the assigned quota Y_i. In other words, under this strategy, quota assignments encourage active, rather than passive, forest management, which is more in line with the center's target. Similar to the discussion of the penalty policy, as the leader of the game, the center would deliberately avoid decision sets that induce 100% mortality rate ($k_i = 1$), and choose policy combinations (Y_i, d) in Region B, as shown in Fig. 1. Thus, the center's problem can be summarized as follows:

$$\max U = \frac{c_1 Y_1^2}{2d} + \frac{c_2 Y_2^2}{2d}$$

$$s.t. c_1 Y_1 + c_2 Y_2 \le E$$

$$c_i Y_i \le 2d,\ i = 1, 2$$

$$\text{and}\ d \le D$$

This optimization problem can also be solved with the Karush–Kuhn–Tucker method: $d = D$, $Y_1 = 2D/c_1$, $Y_2 = 2D/c_2$ (See Appendix 3.2.2). Accordingly, the mortality rates in both regions would be $k_1 = k_2 = 0$. In this case, the total spending of the SLCP program is $4D$ and the center's utility, or the ecological benefits generated under the SLCP, is $\frac{2D}{c_1} + \frac{2D}{c_2}$.

$d > D$

If the center chooses a reward rate d quantitatively greater than the size of the reward funding D ($d > D$), the regions' utilities is two sectional functions, as shown in Eq. (3), and it can be calculated that the two sections cross when $k_i = 1 - \sqrt{D/d}$. The shape of these functions depends on the relationship between Y_i and d, which are set by the center. If $c_i Y_i < 2d$, the relative positions of the two sections are shown in Fig. 3. The regions' utility first follows the straight line along AB, and then follows the parabola along BC, until it reaches $k_i = 1$. The maximum utility can be reached when the regions set $k_i = 1 - \sqrt{D/d}$ or $k_i = 1$, depending on which mortality rate induces higher utility for the regions. If $\sqrt{Dd} > c_i Y_i$, $k_i = 1 - \sqrt{D/d}$. Otherwise $k_i = 1$. If $c_i Y_i \ge 2d$, the relative positions of the two sections are shown in Fig. 4. The regions' utility first follows the straight line along AB, and then follows the parabola along BC. The maximum utility can be reached when the regions set $k_i = 1$.

In summary, when $d > D$, the regions' responsive function to the center's policy signal (Y_i, d) is:

- $k_i = 1$, if $c_i Y_i \ge 2d$
- $k_i = 1$, if $\sqrt{Dd} < c_i Y_i < 2d$
- $k_i = 1 - \sqrt{D/d}$, if $c_i Y_i \le \sqrt{Dd}$

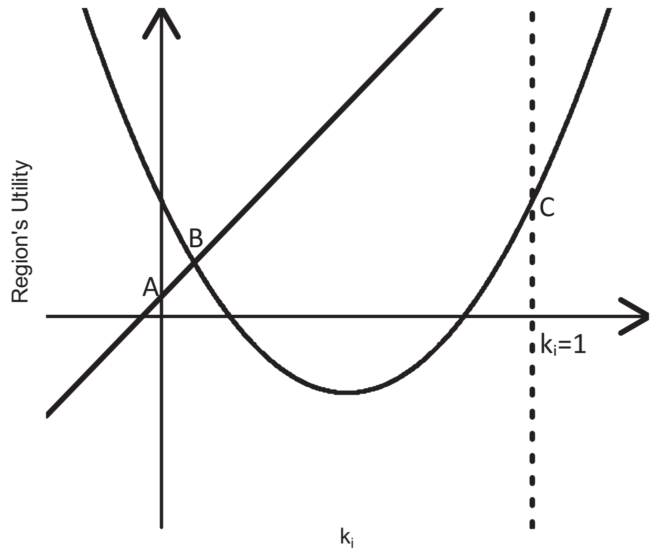

Fig. 3. Region's utility as function of k_i (Rewarding I).

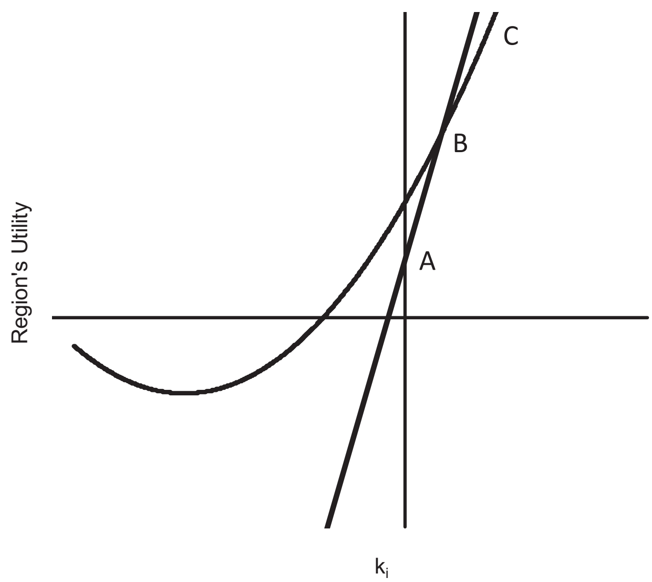

Fig. 4. Region's utility as function of k_i (Rewarding II).

As a rational leader in the game, the center should avoid any reforestation quotas and reward rate combinations (Y_i, d) that induce $k_i = 1$ and set the combination in the range of $c_iY_i \le \sqrt{Dd}$. If that is the case, $k_1 = k_2 = 1 - \sqrt{D/d}$. With these constraints, the center's decision making can be summarized with the following optimization problem:

$$\begin{aligned}
&\max U = (1-k_i)Y_1 + (1-k_2)Y_2 = \sqrt{\frac{D}{d}(Y_1+Y_2)} \\
&s.t. c_1Y_1 + c_2Y_2 \le E; \\
&o \le Y_i \le \frac{\sqrt{Dd}}{c_i},\ i = 1, 2; \\
&\text{and } d > D
\end{aligned}$$

This optimization can be solved with the Karush-Kuhn-Tucker method: $Y_1 = \sqrt{Dd}/c_1$ and $Y_2 = \sqrt{Dd}/c_2$, and a reward rate d less than or equal to $E^2/4D$ (See Appendix 3.2.3). As response to this policy combination, tree mortality rates in the regions would be $k_1 = k_2 = 1 - \sqrt{D/d}$. With this strategy, the maximized area of land reforested under the SLCP is $D(\frac{1}{c_1} + \frac{1}{c_2})$, which is an increasing function of the size of the supporting fund for the reward program, and a decreasing function of the compensation rates assigned to Region 1 and Region 2. To reach this ecological benefit level, the center's spending is $c_1Y_1 + c_2Y_2 = 2\sqrt{Dd}$. Since d can be any value in the range of $(D, E^2/4D]$, the rational center would set $d \to D$ that minimizes the SLCP's spending approaching to $2D$.

In summary, with the solution of rewarding high survival rates, the global optimal strategy for the center is to set $d = D$, and assign reforestation quota to each region as $Y_1 = 2D/c_1$ and $Y_2 = 2D/c_2$. As response to such policy combination, the regions would minimize the mortality rates to $k_1 = k_2 = 0$. Thus, the actual area of land reforested under the SLCP is $2(\frac{D}{c_1} + \frac{D}{c_2})$, and the actual spending in the SLCP would be quadruple the size of the penalty base funding, 4*D*, still much less than the SLCP budget allocation of *E*.

3.3. Solution three: simultaneously penalizing and rewarding the regions

In various policy domains, the strategies of penalizing and rewarding are often used simultaneously. For example, in order to curb water pollution, Chinese government first imposed a discharge fee on enterprises if concentration of pollutants in their waste water exceeded certain standards. On the other hand, it also rewarded the firms that install pollution prevention or clean-up equipment, with a substantial refund of the fee. As to the case of simulating central-local coordination in the SLCP implementation, the strategy of simultaneous penalizing and rewarding is also worth careful evaluation. Given the simultaneous existence of base funds for penalizing and rewarding, this strategy also seems to be credible and feasible.

Under this strategy, we assume that the center decides penalizing or rewarding a region based on a benchmark mortality rate k_0. If a region's mortality rate k_i is higher than k_0, it will be penalized with a penalty of $d(k_i - k_0)^2$. Conversely, if a region keeps its mortality rate less than k_0, it will be rewarded with a reward of $d(k_0 - k_i)^2$. If the actual mortality rate is just equal to k_0, no penalty or reward is imposed on the region. The standard mortality rate k_0 is assumed to be constant and pre-specified based on local ecological conditions. Generally, k_0 is set less than 0.3[7]. Thus, $0 \le k_0 < 1 - k_0 \le 1$. Similar to previous discussion, we also assume that the realizable penalty and reward are subject to a constant constraint *D*, which is the size of the supporting funds ($D \ll E$). Given all the other characters of the game remain the same, the region's utility function consists of four sections, as specified in Eq. (6):

$$U_i = \begin{cases} c_iY_ik_i + D & \text{if } 0 \le k_i < k_0 - \sqrt{\dfrac{D}{d}} \\ c_iY_ik_i + d(k_0 - k_i)^2 & \text{if } k_0 - \sqrt{\dfrac{D}{d}} \le k_i < k_0 \\ c_iY_ik_i - d(k_i - k_0)^2 & \text{if } k_0 \le k_i < k_0 + \sqrt{\dfrac{D}{d}} \\ c_iY_ik_i - D & \text{if } k_0 + \sqrt{\dfrac{D}{d}} \le k_i \le 1 \end{cases} \quad i = 1, 2 \tag{6}$$

If the center sets the penalty rate *d* quantitatively large enough to satisfy $0 < \sqrt{D/d} \le k_0$, all the four utility sections are possible, and the utility function takes the full form. However, if the center does not set the penalty rate that large and makes $\sqrt{D/d}$ fall in the range of $(k_0, 1 - k_0)$, the first section becomes not valid since $k_0 - \sqrt{D/d}$ is always less than zero. Thus, the region's utility becomes a three sectional function. If the center further decreases the penalty rate *d* and makes $\sqrt{D/d}$ greater than or equal to $1 - k_0$ (and also greater than k_0 since $1 - k_0 > k_0$), the first and last sections in (XX) will vanish and the region's utility is simplified to a two-sectional function with only the second and the third part. For further analysis, I examine the three scenarios respectively. $d \le D/(1 - k_0)^2$

Given $d \le D/(1 - k_0)^2$, it is equivalent to $\sqrt{D/d} \ge 1 - k_0$. Thus, the region's utility is a two sectional function that can be simplified to Eq. (7):

$$U_i = \begin{cases} c_iY_ik_i + d(k_0 - k_i)^2 \text{if } 0 \le k_i \le k_0 \\ c_iY_ik_i - d(k_i - k_0)^2 \text{if } k_0 < k_i \le 1 \end{cases} \quad i = 1, 2 \tag{7}$$

The axises of the two parabola curves are $k_i = k_0 - \frac{c_iY_i}{2d}$ and $k_i = k_0 + \frac{c_iY_i}{2d}$, respectively. Thus, the shape of the region's utility function depends on the relationship between $\frac{c_iY_i}{2d}$ and k_0, as shown in Fig. 5. Obviously, if the center sets $\frac{c_iY_i}{2d}$ greater than or equal to $1 - k_0$, the region would response by reporting $k_i = 1$. This is a case the center would defintely avoid. Or, if the center sets $\frac{c_iY_i}{2d}$ in the range of $[k_0, 1 - k_0)$, the region would response by reporting $k_i = k_0 + \frac{c_iY_i}{2d}$, as this is the strategy that helps regions maximize local utility. In this case, the center' optimization problem is rephased as follows:

$$max\, U = (1 - k_0 - \frac{c_1Y_1}{2d})Y_1 + (1 - k_0 - \frac{c_2Y_2}{2d})Y_2$$

$$s.t. c_1Y_1 + c_2Y_2 \le E$$

$$k_0 \le \frac{c_iY_i}{2d} < 1 - k_0, \ i = 1, 2$$

$$\text{and } d \le D/(1 - k_0)^2$$

This optimization problem can be solved with the Karush–Kuhn–Tucker method (See Appendix 3.3.1) and it can be demonstrated that the center's optimal strategy is to set $d = D/(1 - k_0)^2$ and assign $Y_1 = (1 - k_0)\,d/c_1$ and $Y_2 = (1 - k_0)\,d/c_2k_0 \le 1/3k_0 > 1/3k_0 \le \frac{c_iY_i}{2d} < 1 - k_0$.

[7] According to the SFA's requirements, the stipulated survival rate for the Yangtze River Basin was 85% during the pilot phase, and 70% for the Yellow River Basin. This has been revised to a nationwide standard of 75% during full scale implementation (SFA, 2004). However, these standards appear subject to significant local interpretation (Bennett, 2008).

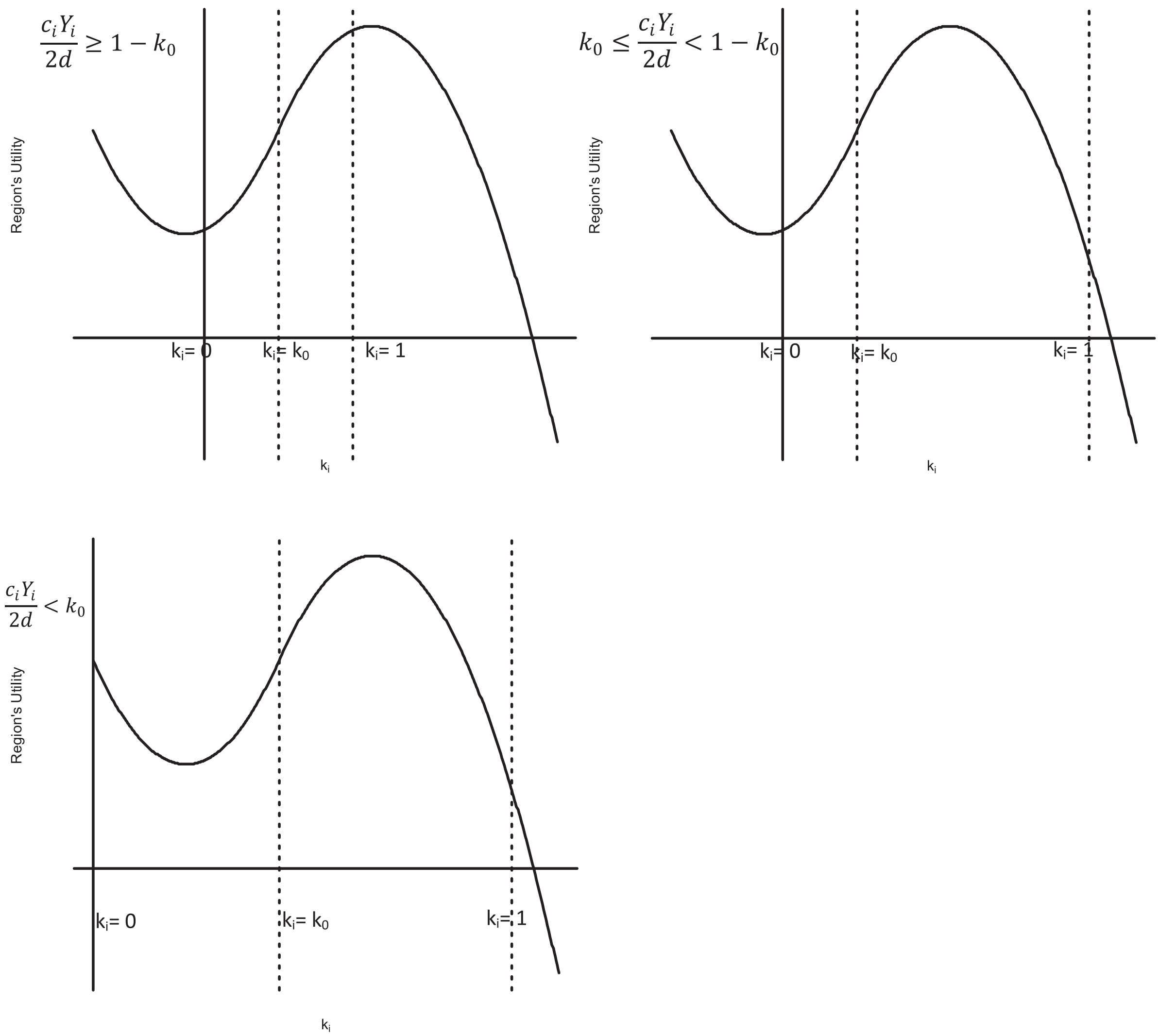

Fig. 5. Region's utility as function of k_i (Penalizing & Rewarding I).

Accordingly, the mortality rates in the regions would be $k_1 = k_2 = \frac{1+k_0}{2}$. In this case, the total spending of the SLCP program is $2D/(1-k_0)$ and the ecological benefits generated under the SLCP is $\frac{D}{2}(\frac{1}{c_1} + \frac{1}{c_2})$.

In the case that the center sets $\frac{c_iY_i}{2d}$ less than k_0, the region may respond by either reporting $k_i = 0$ or reporting $k_i = k_0 + \frac{c_iY_i}{2d}$, depending on whether the value of dk_0^2 is greater than $d(k_0 + \frac{c_iY_i}{2d})^2 - dk_0^2 k_i = 0 U_i = dk_0^2 k_i = k_0 + \frac{c_iY_i}{2d} U_i = d(k_0 + \frac{c_iY_i}{2d})^2 - dk_0^2$. If $dk_0^2 \geq d(k_0 + \frac{c_iY_i}{2d})^2 - dk_0^2$ (i.e. $\frac{c_iY_i}{2d} \leq (\sqrt{2}-1)k_0$)[8], reporting $k_i = 0$ is the best option for the regions. Thus, the center's optimization problem is specified as follows:

$$\max U = Y_1 + Y_2$$

$$s.t. c_1Y_1 + c_2Y_2 \leq E$$

$$\frac{c_iY_i}{2d} \leq (\sqrt{2}-1)k_0, i = 1, 2$$

$$\text{and } d \leq D/(1-k_0)^2$$

Solving this problem with the Karush–Kuhn–Tucker method and the following solution can be identified: $Y_1 = 2\left(\sqrt{2}-1\right)k_0 d/c_1$, $Y_2 = 2\left(\sqrt{2}-1\right)k_0 d/c_2$, and $d = D/(1-k_0)^2$ (See Appendix 3.3.2). As response to such a policy, the regions would minimize local mortality

[8] It is assumed that if the two strategies of reporting $k_i = 0$ and $k_i = k_0 + \frac{c_iY_i}{2d}$ would bring in the same utilities for the regions, they would rather choose $k_i = 0$, as that means less political resistance from the center.

rate to zero and the total ecological benefits generated under the SLCP is $2\left(\sqrt{2}-1\right)D\frac{k_0}{(1-k_0)^2}(\frac{1}{c_1}+\frac{1}{c_2})$. This scenario requires central government spending of $4\left(\sqrt{2}-1\right)D\frac{k_0}{(1-k_0)^2}$.

Otherwise, the center's policy combination falls into the range of $(\sqrt{2}-1)k_0<\frac{c_iY_i}{2d}<k_0$. It can be shown that, in this case, $d(k_0+\frac{c_iY_i}{2d})^2-dk_0^2$ is greater than dk_0^2, and the region would report mortality rate of $k_i=k_0+\frac{c_iY_i}{2d}$. The center's corresponding optimization problem is transferred to the following form:

$$\max U=(1-k_0-\frac{c_1Y_1}{2d})Y_1+(1-k_0-\frac{c_2Y_2}{2d})Y_2$$

$$s.t. c_1Y_1+c_2Y_2\le E$$

$$(\sqrt{2}-1)k_0<\frac{c_iY_i}{2d}<k_0, i=1,2$$

$$\text{and } d\le D/(1-k_0)^2$$

It can be shown that the above optimization problem has no solution under the assumption of $k_0\le 1/3$ (See Appendix 3.3.3). Thus, the center would not choose a policy combination of (Y_i, d) in the range of $\left(\sqrt{2}-1\right)k_0<\frac{c_iY_i}{2d}<k_0$.

As a summary for the sub-section, if the center chooses a penalty/reward rate d in the range of $[0, D/(1-k_0)^2]$, it would always choose $d=D/(1-k_0)^2$. In addition, it may utilize two schemes in assigning the reforestation quota, either $Y_i=(1-k_0)d/c_i$ or $Y_i=2\left(\sqrt{2}-1\right)k_0d/c_i$. This first strategy would result in total ecological benefits of $\frac{D}{2}(\frac{1}{c_1}+\frac{1}{c_2})$ and total government spending of $2D/(1-k_0)$. In comparison, the second strategy would result in total ecological benefits of $2\left(\sqrt{2}-1\right)D\frac{k_0}{(1-k_0)^2}(\frac{1}{c_1}+\frac{1}{c_2})$ and total government spending of $4\left(\sqrt{2}-1\right)D\frac{k_0}{(1-k_0)^2}$. In terms of financial burden, the second strategy is better, as it requires less government spending. However, the comparative advantages of the two strategies in terms of ecological benefits depends on the value of k_0. If k_0 is small (less than 0.29) the first strategy is better. In converse, if k_0 is large (greater than 0.3), the second strategy is better:$D/(1-k_0)^2<d<D/k_0^2$

If the penalty/reward rate is set in this range, the center can freely offer a reward to the regions, but still faces the constraint of D when imposing penalties. Thus, under this scenario, the region's utility function consists of three sections, as specified in Eq. (8):

$$U_i=\begin{cases} c_iY_ik_i+d(k_0-k_i)^2 \text{if} 0\le k_i\le k_0 \\ c_iY_ik_i-d(k_i-k_0)^2 \text{if} k_0<k_i\le k_0+\sqrt{\frac{D}{d}} \quad i=1,2 \\ c_iY_ik_i-D \quad \text{if} k_0+\sqrt{\frac{D}{d}}<k_i\le 1 \end{cases} \tag{8}$$

The three plots in Fig. 6 illustrate the shape of the region's utility function under different relationships between $\frac{c_iY_i}{2d}$ and k_0. Compared to Fig. 5, the parabola curves in Fig. 6 remain the same. Yet, a new boundary of $k_i=k_0+\sqrt{D/d}$ is involved to separate the policies of quadratic and linear penalties. As shown in the figure, if the center sets $\frac{c_iY_i}{2d}$ greater than or equal to $\sqrt{D/d}$, it would become inevitable that the region report $k_i=1$, which is a case the center would definitely avoid. Alternatively, the center may set $\frac{c_iY_i}{2d}$ in the range of $[k_0, \sqrt{D/d})$. In this case, the region would decide its responsive strategy by comparing the value of $d(k_0+\frac{c_iY_i}{2d})^2-dk_0^2$ and $c_iY_i-Dd(k_0+\frac{c_iY_i}{2d})^2-dk_0^2c_iY_i-Dk_i=1$. If the latter is greater, the region would report $k_i=1$, again this is a case the center would try to avoid. Unfortunately, it can be shown that the latter is indeed greater than the latter one, as long as $D/(1-k_0)^2$ is less than $dn=c_iY_i(k_0+\frac{c_iY_i}{2d})^2-dk_0^2nc_iY_i-Dn[k_0, \sqrt{D/d})c_iY_i-D(k_0+\frac{c_iY_i}{2d})^2-dk_0^2$. Thus, the center would also avoid policy combinations (Y_i, d) in the range of $[k_0, \sqrt{D/d})$.

After exluding the above two possiblities, the center has to choose a policy combination that satisfies $\frac{c_iY_i}{2d}<k_0$. In this scenario (as illustrated in the third plot of Fig. 6), there are three peak values on the region's utility curve: dk_0^2, $d(k_0+\frac{c_iY_i}{2d})^2-dk_0^2$, and $c_iY_i-Dk_i=0k_i=k_0+\frac{c_iY_i}{2d}k_i=1$. The region would decide its best responsive strategy by comparing the three values. It has been shown that, if $D/(1-k_0)^2$ is less than d, $d(k_0+\frac{c_iY_i}{2d})^2-dk_0^2$ is always less than c_iY_i-D, thus it would not be the maximum utility value. Therefore, the region would report either $k_i=0$ if $dk_0^2\ge c_iY_i-D$, or $k_i=1$ if $dk_0^2<c_iY_i-D$. The latter case would also be avoided by the center. It can be summarized from the above discussion that, if the center chooses a penalty/reward rate d in the range of $(\frac{D}{(1-k_0)^2}, \frac{D}{k_0^2})$, it has to choose a policy combination that satisfies $\frac{c_iY_i}{2d}<k_0$ and $dk_0^2\le c_iY_i-D$ in order to refrain itself from the worst case that regions give up their efforts in the SLCP implementation and report a mortality rate of one hundred percent. Accordingly, the center's optimization problem is specified as follows:

$$\max U=Y_1+Y_2$$

$$s.t. c_1Y_1+c_2Y_2\le E$$
$$dk_0^2+D\le c_iY_i<2k_0d, i=1,2$$
$$\text{and} \frac{D}{(1-k_0)^2}<d<\frac{D}{k_0^2}$$

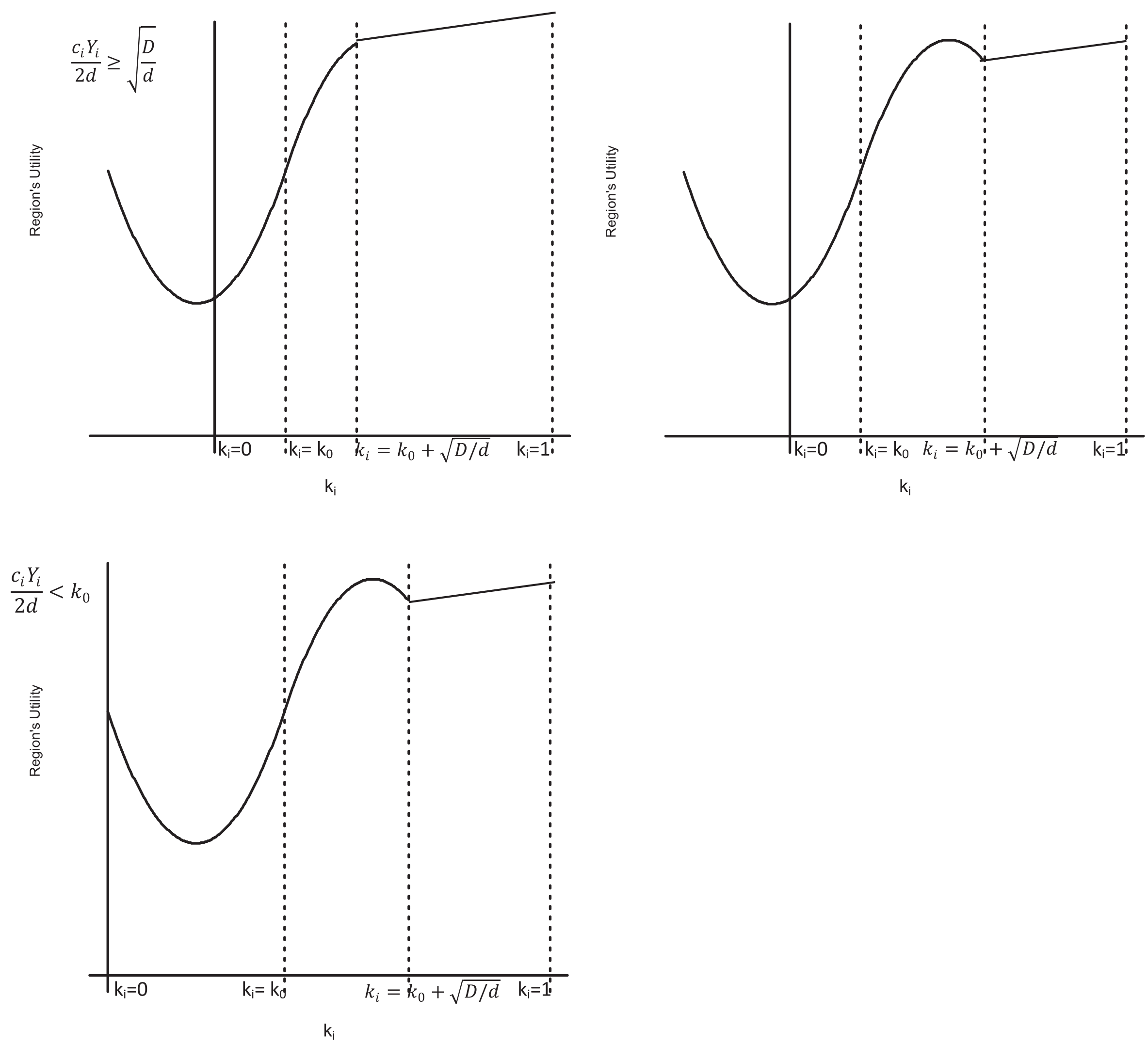

Fig. 6. Region's utility as function of k_i (Penalizing & Rewarding II).

It can be shown that the above optimization problem has no solution (See Appendix 3.3.4). Thus, the center would not choose a penalty/reward rate d in the range of $(\frac{D}{(1-k_0)^2}, \frac{D}{k_0^2})$. $d \geq D/k_0^2$

If the penalty/reward rate is set equal or greater than D/k_0^2, both penalizing and rewarding policies are constrained with the size of the supporting funds, which is D. More specifically, all the previously discussed four sections are involved in the region's utility function:

$$U_i = \begin{cases} c_i Y_i k_i + D \quad \text{if } 0 \leq k_i < k_0 - \sqrt{\frac{D}{d}} \\ c_i Y_i k_i + d(k_0 - K_i)^2 \text{ if } k_0 - \sqrt{\frac{D}{d}} \leq k_i < k_0 \\ c_i Y_i k_i - d(k_i - k_0)^2 \text{ if } k_0 \leq k_i < k_0 + \sqrt{\frac{D}{d}} \\ c_i Y_i k_i - d \quad \text{if } k_0 + \sqrt{\frac{D}{d}} \leq k_i \leq 1 \end{cases} i = 1, 2 \tag{9}$$

As shown in Fig. 7, if the center implements a policy combination (Y_i, k_i) that makes $\frac{c_i Y_i}{2d} \geq \sqrt{D/d}$, the region's utility is an increasing function of the local mortality rate $k_i \in [0, 1]$. A utility maximizing region would exaggerate the mortality rate to its maximum value, which is one. This case would definitely be avoided by a rational center. Thus, the center would set $\frac{c_i Y_i}{2d}$ less than $\sqrt{D/d}$, which is illustrated in the second plot of Fig. 7. In this case, three peak values can be identified on the region's utility curve: $c_i Y_i (k_0 - \sqrt{\frac{D}{d}})$, $d(k_0 + \frac{c_i Y_i}{2d})^2 - dk_0^2$, and $c_i Y_i - D$, which respectively correspond to $k_i = k_0 - \sqrt{\frac{D}{d}}$, $k_i = k_0 + \frac{c_i Y_i}{2d}$, and $k_i = 1$. It has been shown that, $d(k_0 + \frac{c_i Y_i}{2d})^2 - dk_0^2$ is less than $c_i Y_i - D$, when $\frac{D}{d} < (1 - k_0)^2$. This is also true given $\frac{D}{d} \leq k_0^2 < (1 - k_0)^2$. Thus, the two possible strategies the region may utilize are reporting $k_i = k_0 - \sqrt{\frac{D}{d}}$, if $c_i Y_i (k_0 - \sqrt{\frac{D}{d}}) \geq c_i Y_i - D$, and reporting $k_i = 1$, if $c_i Y_i (k_0 - \sqrt{\frac{D}{d}}) < c_i Y_i - D$. Since the center would avoid the worst

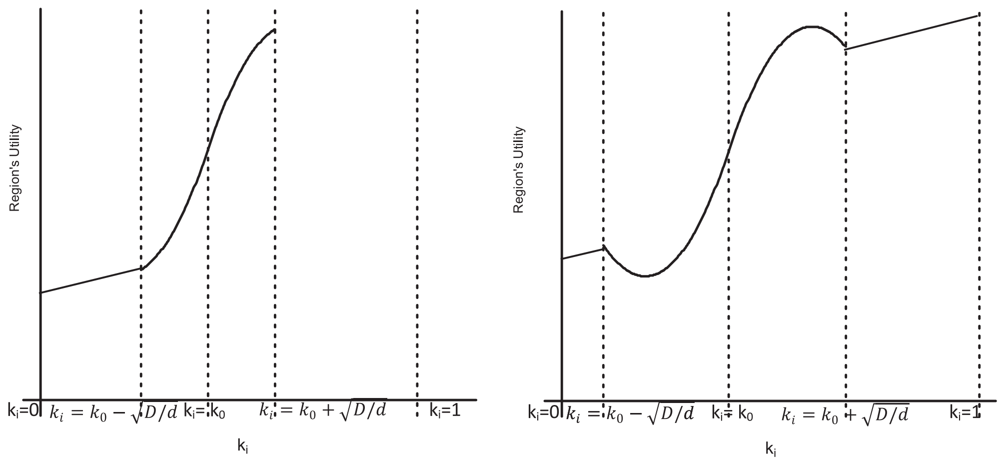

Fig. 7. Region's utility as function of k_i (Penalizing & Rewarding III)

Table 2
Comparison of the three policy revisions.

	Penalty	Reward	Penalty + Reward. I	Penalty + Reward. II
Penalty/Reward Rate (d)	D	D	$D/(1-k_0)^2$	$D/(1-k_0)^2$
Reforestation Quota_Region 1 (Y_1)	$\frac{D}{c_1}$	$\frac{2D}{c_1}$	$\frac{D}{c_1}\frac{1}{(1-k_0)}$	$\frac{2D}{c_1}\frac{(\sqrt{2}-1)k_0}{(1-k_0)^2}$
Reforestation Quota_Region 2 (Y_2)	$\frac{D}{c_2}$	$\frac{2D}{c_2}$	$\frac{D}{c_1}\frac{1}{(1-k_0)}$	$\frac{2D}{c_1}\frac{(\sqrt{2}-1)k_0}{(1-k_0)^2}$
Mortality Rate_Region 1 (k_1)	0.5	0	$\frac{1+k_0}{2}$	0
Mortality Rate_Region 2 (k_2)	0.5	0	$\frac{1+k_0}{2}$	0
SLCP Spending ($c_1Y_1 + c_2Y_2$)	$2D$	$4D$	$2D/(1-k_0)$	$4\left(\sqrt{2}-1\right)D\frac{k_0}{(1-k_0)^2}$
Reforestation Area ($(1-k_1)Y_1 + (1-k_2)Y_2$)	$\frac{1}{2}(\frac{D}{c_1}+\frac{D}{c_2})$	$2(\frac{D}{c_1}+\frac{D}{c_2})$	$\frac{1}{2}(\frac{D}{c_1}+\frac{D}{c_2})$	$2\left(\sqrt{2}-1\right)\frac{k_0}{(1-k_0)^2}(\frac{D}{c_1}+\frac{D}{c_2})$

case of $k_i = 1$, its rational strategy is to choose a policy combination that satisfies $c_iY_i(k_0 - \sqrt{\frac{D}{d}}) \geq c_iY_i - D$. Thus, in this scenario, the center's optimization problem is specified as follows:

$$\max U = (1 - k_0 + \sqrt{\frac{D}{d}})Y_1 + (1 - k_0 + \sqrt{\frac{D}{d}})Y_2$$

$$s.t. c_1Y_1 + c_2Y_2 \leq E$$

$$c_iY_i - D \leq c_iY_i(k_0 - \sqrt{\frac{D}{d}}), i = 1, 2$$

$$\frac{c_iY_i}{2d} < \sqrt{\frac{D}{d}}, i = 1, 2$$

$$\text{and } d \geq \frac{D}{k_0^2}$$

It can be shown that, for this optimization, the center could arbitrarily choose any penalty/reward rate equal to or greater than D/k_0^2 in this scenario, however, its only feasible plan for reforestation quota assignment is to set $Y_1 = Y_2 = 0$ (See Appendix 3.3.5). In other words, the reforestation project would vanish if the center determines to choose a very large penalty/reward rate ($d \geq D/k_0^2$).

In summary, if the strategy of simultaneously penalizing and rewarding is employed in the SLCP, the central government as a rational player in the Stackelberg game should set the penalty/reward rate equal to $D/(1-k_0)^2$. With this rate, it may utilize two schemes for reforestation quota assignment, either $Y_i = (1-k_0)d/c_i$ or $Y_i = 2\left(\sqrt{2}-1\right)k_0d/c_i$. The second strategy is financially better than the first one. However, their comparative advantages in terms of ecological benefits depends on the value of k_0.

4. Comparison of the three policy revisions

The four possible policy revisions are summarized in Table 2, one from the strategy of penalizing low survival rate, one from the strategy of rewarding high survival rate, and two from the strategy of simultaneous penalizing and rewarding. It includes the equilibrium outcome of the center's allocation of reforestation quota, the penalty/reward rates, the mortality rates in the two regions, the total spending of the reforestation program, and areas of land reforested under the two policy revisions, penalizing high mortality rates or rewarding high survival rates. As can be seen in the table, in order to maximize the area of reforestation under the SLCP, the center should adopt the rewarding strategy and set the reward rate just equal to the size of the supporting fund that is used to pay for the reward. In the meantime, the center should assign reforestation quotas of $Y_1 = 2D/c_1$ and $Y_2 = 2D/c_2$ to Region 1 and Region 2, respectively. In response to such policy, the mortality rate k_i will be minimized in both regions. In this case, the total area of land reforested under the SLCP is $2(\frac{D}{c_1} + \frac{D}{c_2})$ and the actual spending of this program is $4D$.

The strategy the center should avoid is to threaten to restrain high mortality rates with an infinite penalty rate (every player in the game knows that the actual penalty that can be realized cannot exceed D). If this strategy was applied, the SLCP program will vanish to null. If the strategy of penalizing was adopted, the center should set the penalty rate quantitatively equal to the size of the penalty base fund, and assign the reforestation quota of $Y_1 = D/c_1$ and $Y_2 = D/c_2$. Although the amount of reforestation area generated under this strategy is less than that generated under the strategy of rewarding, it is still positive and represents a policy improvement compared to the benchmark scenario.

Similar to penalizing high mortality rate, if the center utilizes a combination of the penalizing and rewarding strategies, it could improve the effectiveness of reforestation under the SLCP compared to the benchmark scenario. However, the improvement is minor compared to the ecological benefits generated under the strategy of rewarding. In addition, the combination strategy involves great institutional complexity, as it requires the central government determines standard mortality rate k_0 specific to each region. Thus, the benefits and transaction costs of implementing the strategy should be carefully gauged before it was put into effect.

As shown in Table 2, no matter which strategy is adopted, the actual spending, as well as the ecological benefits generated under the reforestation program, actually depends on the size of the supporting fund, not the initial budget of the SLCP. Thus, when the penalizing/rewarding strategy is used to improve the SLCP's implementation, the central government should match the support funds with the SLCP budget.

5. Conclusion

The SLCP, China's largest reforestation program, has been impeded by the central and local governments' interest conflict since it was launched. The strategic response of local forestry agencies to the center's policy has resulted in high mortality rates of trees and less output of timber, which represent great challenges to the sustainability of this program. Given the potential ecological significance of the SLCP, these problems need to be properly addressed.

This paper is the first attempt to examine the central local conflicts in China's ecological conservation programs. It employs a political-economic approach to describe the conflict and proposes three possible solutions. Under the current scenario of central and local governments' relationship, there are no effective constraints on local governments' demotivation to minimize management efforts. Accordingly, the mortality rates can reach very high levels, theoretically to one, as indicated by our simulation. In this way, local forestry agencies could retain most of their compensation subsidies to recoup their administrative costs and maximize their utilities. In order to curb the regions' demotivation, forestry officials may adopt three solutions: penalizing high mortality rates, rewarding high survival rates, and a combination of penalizing and rewarding. Comparing the three options, it would be optimal for the center to adopt the rewarding strategy and set the reward rate quantitatively equal to the size of the supporting fund that is used to pay for the rewards. In this case, the total area of land that is actually reforested will be maximized to $2(\frac{D}{c_1} + \frac{D}{c_2})$.

This study has extensively discussed potential use of economic incentives in mobilizing local efforts. Yet, it would also be valuable to point out the role of political motivations in facilitating implementation of an environmental initiative, especially in recent years when the central government starts to employ the criterion of environmental protection in evaluating local officials' administrative performance in China. In fact, the central government has heavily depended on political approaches in mobilizing local cooperation in the SLCP. It designs the SLCP as a comprehensive governmental project (*zhengfu gongcheng*), not just a sectoral one (*bumen gongcheng*). The SFA and the NDRC cooperatively represent the central government and sign liability agreements with provincial governments. In turn, the provincial governments sign liability agreements down through the administrative ladder one by one, down to the township governments. In this process, the chief executives of local governments, not forestry bureaus, take the primary responsibility in implementing the SLCP. They are expected to maneuver all resources in their jurisdiction to realize the goals of tree-planting, forest management, and supporting infrastructure building. In addition, along with the SLCP Regulation, the SFA issued a notice on punishment for unsatisfactory administrative performance (the "Notice") in the SLCP implementation. According to the Notice, given unsuccessful implementation[9], local government leaders would be penalized with political warning, demerit record, serious demerit record, criminal charges, demotion, and even decapitation, depending on the seriousness of the failure. These are credible threats: cases of punishments on local government and forestry officials due to poor SLCP implementation had been occasionally mentioned by forestry officials during my field trip to four SLCP participating provinces. Thus, it is reasonable to expect that political pressures would be a key supplement to the economic incentives in mobilizing local efforts.

While all above discussion is based on management practices of forests, the central and local conflict model developed here can be easily modified to analyze similar problems in other natural resource governance domains, such as soil and water conservation, landscape restoration, and biodiversity protection. Resource conservation policies in China have long been characterized by the heavy use of campaigns in an effort to enforce regulations and pursue initiatives at local levels. The modeling work in this paper obviously indicates the opposite: local agencies should not be considered as subordinate organs in the environmental governance system and proper environmental policy design needs effective mechanisms to motivate local efforts.

Game theory analysis may not provide a comprehensive evaluation of policy implementation, as it simplifies many realistic details. In this study, for example, local governments are assumed to be rational economic players who only care about maximizing local disposable incomes. The political pressures and the ecological constraints they are facing in implementing reforestation tasks are reduced to constant

[9] Unsuccessful implementation has been defined quite broadly in the SLCP. In addition to low survival of newly planted trees, many other faults may also cause administrative penalty on local officials. These include purchase of unqualified tree seedlings, ineffective complementary planting, appropriation of SLCP compensation, and even serious complaints from local farmers.

external factors. Similarly, the central government in this study is simplified as an ecological service buyer, which only targets at the area of reforestation, with the ecological benefits of the plantations and the transaction costs in achieving the reforestation out of their consideration. These deficits may translate into a mismatch between theoretical prediction and real world observation. For instance, the Stackelberg model predicts that local governments would exaggerate mortality rate to one under the current policy scenario. This is definitely not the case observed in the field, as no local official would take such an extreme risk that threatens their political promotion.

In spite of these disadvantages, the approach of game theory has been generally recognized as an effective tool in analyzing the less-known aspects of conflicting interests. This is especially true when players' decision-making in a policy scenario inter-depends on each other, like the central and local governments in our case. In this process, simplification is a necessary sacrifice as it helps us seek further insights into the key aspects of the problem (Gibbons, 1992). Given all the other aforementioned factors remain stable, this study demonstrates that rewarding local governments for high survival rates of trees per se would be a rewarding strategy for the central government, as it could pool the SLCP out of the low-survival rate plight and it could induce more ecological services with a fixed reforestation budget.

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Appendix A.

The regions' optimization problem with a penalty rate $d \le D$

Solving this optimization with the Karush–Kuhn–Tucker method:

$$L = c_i k_i Y_i - d k_i^2 + \lambda(1 - k_i),\ i = 1, 2$$

$$\text{Condition 1}:\ \frac{\partial L}{\partial k_i} = c_i Y_i - 2dk_i - \lambda \le 0,\ k_i \ge 0,\ (c_i Y_i - 2dk_i - \lambda)k_i = 0$$

$$\text{Condition 2}:\ 1 - k_i \ge 0,\ \lambda \ge 0,\ \lambda(1 - k_i) = 0$$

If $k_i = 0$, according to condition 2, $\lambda = 0$, then according to condition 1, $c_i Y_i \le 0$, which is impossible. If $k_i = 1$, according to condition 1, $c_i Y_i - 2d = \lambda \ge 0$. This is true if $c_i Y_i > 2d$. Or if $\lambda = 0$ and $0 < k_i < 1$, according to condition 1, $c_i Y_i - 2dk_i = 0$, i.e. $k_i = c_i Y_i / 2d$. Thus, the solution of k_i that satisfies both conditions is:

$$k_i = \begin{cases} \dfrac{c_i Y_i}{2d} \text{ if } c_i Y_i \le 2d \\ 1 \text{ if } c_i Y_i > 2d \end{cases},\ i = 1, 2$$

The center's optimization problem with a penalty rate $d \le D$

The center's optimization problem can also be solved with the Karush–Kuhn–Tucker method:

$$L = \left(1 - \frac{c_1 Y_1}{2d}\right) Y_1 + \left(1 - \frac{c_2 Y_2}{2d}\right) Y_2 + \lambda_1 (E - c_1 Y_1 - c_2 Y_2) + \lambda_2 \left(\frac{2d}{c_1} - Y_1\right) + \lambda_3 \left(\frac{2d}{c_2} - Y_2\right) + \lambda_4 (D - d)$$

$$\text{Condition 1}:\ \frac{\partial L}{\partial Y_1} = 1 - \frac{c_1 Y_1}{d} - \lambda_1 c_1 - \lambda_2 \le 0,\ Y_1 \ge 0,\ (1 - \frac{c_1 Y_1}{d} - \lambda_1 c_1 - \lambda_2) Y_1 = 0$$

$$\text{Condition 2}:\ \frac{\partial L}{\partial Y_2} = 1 - \frac{c_2 Y_2}{d} - \lambda_1 c_2 - \lambda_3 \le 0,\ Y_2 \ge 0,\ (1 - \frac{c_2 Y_2}{d} - \lambda_1 c_2 - \lambda_3) Y_2 = 0$$

$$\text{Condition 3}:\ \frac{\partial L}{\partial d} = \frac{c_1 Y_1^2 + c_2 Y_2^2}{2d^2} + \frac{2\lambda_2}{c_1} + \frac{2\lambda_3}{c_2} - \lambda_4 \le 0,\ d \ge 0,\ \left(\frac{c_1 Y_1^2 + c_2 Y_2^2}{2d^2} + \frac{2\lambda_2}{c_1} + \frac{2\lambda_3}{c_2} - \lambda_4\right) d = 0$$

$$\text{Condition 4}:\ \frac{\partial L}{\partial \lambda_1} = E - c_1 Y_1 - c_2 Y_2 \ge 0,\ \lambda_1 \ge 0,\ \lambda_1 (E - c_1 Y_1 - c_2 Y_2) = 0$$

$$\text{Condition 5}:\ \frac{\partial L}{\partial \lambda_2} = \frac{2d}{c_1} - Y_1 \ge 0,\ \lambda_2 \ge 0,\ \lambda_2 \left(\frac{2d}{c_1} - Y_1\right) = 0$$

$$\text{Condition 6}:\ \frac{\partial L}{\partial \lambda_3} = \frac{2d}{c_2} - Y_2 \ge 0,\ \lambda_3 \ge 0,\ \lambda_3 \left(\frac{2d}{c_2} - Y_2\right) = 0$$

$$\text{Condition 7}:\ \frac{\partial L}{\partial \lambda_4} = D - d \ge 0,\ \lambda_4 \ge 0,\ \lambda_4 (D - d) = 0$$

The solution that satisfies all the seven conditions is: $d = D$, $Y_1 = D/c_1$, $Y_2 = D/c_2$. Accordingly, the regions respond with $k_1 = k_2 = 0.5$.

The center's optimization problem with a penalty rate $d > D$Solving this optimization problem with the Karush–Kuhn–Tucker method:

$$L=\left(1-\frac{c_1Y_1}{2d}\right)Y_1+\left(1-\frac{c_2Y_2}{2d}\right)Y_2+\lambda_1(E-c_1Y_1-c_2Y_2)+\lambda_2\left(\frac{c_1^2Y_1^2}{4d}-c_1Y_1+D\right)$$
$$+\lambda_{32-\text{ch is conditions can be merged into one, ditions is:}}\left(\frac{c_2^2Y_2^2}{4d}-c_2Y_2+D\right)+\lambda_4(d-D)$$

$$\text{Condition 1}: \frac{\partial L}{\partial Y_1}=1-\frac{c_1Y_1}{d}(1-\frac{c_1\lambda_2}{2})-(\lambda_1+\lambda_2)c_1\le 0,\ Y_1\ge 0,\ Y_1\left[1-\frac{c_1Y_1}{d}(1-\frac{c_{1\lambda_2}}{2})-(\lambda_1+\lambda_2)c_1\right]=0$$

$$\text{Condition 2}: \frac{\partial L}{\partial Y_2}=1-\frac{c_2Y_2}{d}(1-\frac{c_2\lambda_3}{2})-(\lambda_1+\lambda_3)c_2\le 0,\ Y_2\ge 0,\ Y_2\left[1-\frac{c_2Y_2}{d}(1-\frac{c_2\lambda_3}{2})-(\lambda_1+\lambda_3)c_2\right]=0$$

$$\text{Condition 3}: \frac{\partial L}{\partial d}=\frac{1}{d^2}\left(\frac{c_1Y_1^2}{2}+\frac{c_2Y_2^2}{2}-\frac{\lambda_2c_1^2Y_1^2}{4}-\frac{\lambda_3c_2^2Y_2^2}{4}\right)+\lambda_4\le 0,\ d\ge 0,\ d\left[\frac{1}{d^2}\left(\frac{c_1Y_1^2}{2}+\frac{c_2Y_2^2}{2}-\frac{\lambda_2c_1^2Y_1^2}{4}-\frac{\lambda_3c_2^2Y_2^2}{4}\right)+\lambda_4\right]=0$$

$$\text{Condition 4}: \frac{\partial L}{\partial \lambda_1}=E-c_1Y_1-c_2Y_2\ge 0,\ \lambda_1\ge 0,\ \lambda_1(E-c_1Y_1-c_2Y_2)=0$$

$$\text{Condition 5}: \frac{\partial L}{\partial \lambda_2}=\frac{c_1^2Y_1^2}{4d}-c_1Y_1+D\ge 0,\ \lambda_2\ge 0,\ \lambda_2\left(\frac{c_1^2Y_1^2}{4d}-c_1Y_1+D\right)=0$$

$$\text{Condition 6}: \frac{\partial L}{\partial \lambda_3}=\frac{c_2^2Y_2^2}{4d}-c_2Y_2+D\ge 0,\ \lambda_3\ge 0,\ \lambda_3\left(\frac{c_2^2Y_2^2}{4d}-c_2Y_2+D\right)=0$$

$$\text{Condition 7}: \frac{\partial L}{\partial \lambda_4}=d-D>0,\ \lambda_4\ge 0,\ \lambda_4(d-D)=0$$

The solution that satisfies all the seven conditions is: $d\to+\infty$, $Y_1\to 0$, and $Y_2\to 0$.
The regions' optimization problem with a reward rate $d\le D$
The regions' optimal response to the center's reforestation policy (Y_i, d) can be solved with the Karush–Kuhn–Tucker method:

$$L=c_ik_iY_i+d(1-k_i)^2+\lambda(1-k_i),\ i=1,2$$

$$\text{Condition 1}: \frac{\partial L}{\partial k_i}=c_iY_i-2d(1-k_i)-\lambda\le 0,\ k_i\ge 0,\ [c_iY_i-2d(1-k_i)-\lambda]k_i=0$$

$$\text{Condition 2}: 1-k_i\ge 0,\ \lambda\ge 0,\ \lambda(1-k_i)=0$$

The solution that satisfies both conditions is:

$$k_i=\begin{cases}1-\frac{c_iY_i}{2d}\text{if}\, c_iY_i\le 2d\\ 1\quad \text{if}\, c_iY_i>2d\end{cases}$$

The center's optimization problem with a reward rate $d\le D$
This optimization problem can also be solved with the Karush–Kuhn–Tucker method:

$$L=\frac{c_1Y_1^2}{2d}+\frac{c_2Y_2^2}{2d}+\lambda_1(E-c_1Y_1-c_2Y_2)+\lambda_2(2d-c_1Y_1)$$
$$+\lambda_{32-\text{ch isconditions can be merged into one, ditions is:}}(2d-c_2Y_2)+\lambda_4(D-d)$$

$$\text{Condition 1}: \frac{\partial L}{\partial Y_1}=\frac{c_1Y_1}{d}-(\lambda_1+\lambda_2)c_1\le 0,\ Y_1\ge 0,\ Y_1\left[\frac{c_1Y_1}{d}-(\lambda_1+\lambda_2)c_1\right]=0$$

$$\text{Condition 2}: \frac{\partial L}{\partial Y_2}=\frac{c_2Y_2}{d}-(\lambda_1+\lambda_3)c_2\le 0,\ Y_2\ge 0,\ Y_2\left[\frac{c_2Y_2}{d}-(\lambda_1+\lambda_3)c_2\right]=0$$

$$\text{Condition 3}: \frac{\partial L}{\partial d}=-\frac{1}{d^2}\left(\frac{c_1Y_1^2}{2}+\frac{c_2Y_2^2}{2}\right)+2(\lambda_2+\lambda_3)-\lambda_4\le 0,\ d\ge 0,\ d\left[-\frac{1}{d^2}\left(\frac{c_1Y_1^2}{2}+\frac{c_2Y_2^2}{2}\right)+2(\lambda_2+\lambda_3)-\lambda_4\right]=0$$

$$\text{Condition 4}: \frac{\partial L}{\partial \lambda_1}=E-c_1Y_1-c_2Y_2\ge 0,\ \lambda_1\ge 0,\ \lambda_1(E-c_1Y_1-c_2Y_2)=0$$

$$\text{Condition 5}: \frac{\partial L}{\partial \lambda_2} = 2d - c_1 Y_1 \geq 0,\ \lambda_2 \geq 0,\ \lambda_2 (2d - c_1 Y_1) = 0$$

$$\text{Condition 6}: \frac{\partial L}{\partial \lambda_3} = 2d - c_2 Y_2 \geq 0,\ \lambda_3 \geq 0,\ \lambda_3 (2d - c_2 Y_2) = 0$$

$$\text{Condition 7}: \frac{\partial L}{\partial \lambda_4} = D - d \geq 0,\ \lambda_4 \geq 0,\ \lambda_4 (D - d) = 0$$

The solution that satisfies all the seven conditions is: $d = D$, $Y_1 = 2D/c_1$, $Y_2 = 2D/c_2$.
The center's optimization problem with a reward rate $d > D$
This optimization can be solved with the Karush–Kuhn–Tucker method:

$$L = \sqrt{\frac{D}{d}}(Y_1 + Y_2) + \lambda_1 (E - c_1 Y_1 - c_2 Y_2) + \lambda_2 \left(\sqrt{Dd} - c_1 Y_1\right)$$
$$+\lambda_{32-\text{ch is conditions can be merged into one, ditions is:}} \left(\sqrt{Dd} - c_2 Y_2\right) + \lambda_4 (d - D)$$

$$\text{Condition 1}: \frac{\partial L}{\partial Y_1} = \sqrt{\frac{D}{d}} - (\lambda_1 + \lambda_2) c_1 \leq 0,\ Y_1 \geq 0,\ Y_1 \left[\sqrt{\frac{D}{d}} - (\lambda_1 + \lambda_2) c_1\right] = 0$$

$$\text{Condition 2}: \frac{\partial L}{\partial Y_2} = \sqrt{\frac{D}{d}} - (\lambda_1 + \lambda_3) c_2 \leq 0,\ Y_2 \geq 0,\ Y_2 \left[\sqrt{\frac{D}{d}} - (\lambda_1 + \lambda_3) c_2\right] = 0$$

$$\text{Condition 3}: \frac{\partial L}{\partial d} = \frac{\sqrt{\frac{D}{d}}}{2}(-\frac{Y_1 + Y_2}{d} + \lambda_2 + \lambda_3) + \lambda_4 \leq 0,\ d > 0,\ d\left[\frac{\sqrt{\frac{D}{d}}}{2}\left(-\frac{Y_1 + Y_2}{d} + \lambda_2 + \lambda_3\right) + \lambda_4\right] = 0$$

$$\text{Condition 4}: \frac{\partial L}{\partial \lambda_1} = E - c_1 Y_1 - c_2 Y_2 \geq 0,\ \lambda_1 \geq 0,\ \lambda_1 (E - c_1 Y_1 - c_2 Y_2) = 0$$

$$\text{Condition 5}: \frac{\partial L}{\partial \lambda_2} = \sqrt{Dd} - c_1 Y_1 \geq 0,\ \lambda_2 \geq 0,\ \lambda_2 \left(\sqrt{Dd} - c_1 Y_1\right) = 0$$

$$\text{Condition 6}: \frac{\partial L}{\partial \lambda_3} = \sqrt{Dd} - c_2 Y_2 \geq 0,\ \lambda_3 \geq 0,\ \lambda_3 \left(\sqrt{Dd} - c_2 Y_2\right) = 0$$

$$\text{Condition 7}: \frac{\partial L}{\partial \lambda_4} = d - D > 0,\ \lambda_4 \geq 0,\ \lambda_4 (d - D) = 0$$

The solution that satisfies all the seven conditions is: $Y_1 = \sqrt{Dd}/c_1$ and $Y_2 = \sqrt{Dd}/c_2$, and a reward rate d less than or equal to $E^2/4D$.
The center's optimization problem with a penalty/reward rate $d \leq D/(1 - k_0)^2$ and $k_0 \leq \frac{c_i Y_i}{2d} < 1 - k_0$
Solving this optimization problem with the Karush–Kuhn–Tucker method:

$$L = \left(1 - k_0 - \frac{c_1 Y_1}{2d}\right) Y_1 + \left(1 - k_0 - \frac{c_2 Y_2}{2d}\right) Y_2 + \lambda_1 (E - c_1 Y_1 - c_2 Y_2) + \lambda_2 \left(\frac{c_1 Y_1}{2d} - k_0\right) + \lambda_3 \left(1 - k_0 - \frac{c_1 Y_1}{2d}\right) + \lambda_4 \left(\frac{c_2 Y_2}{2d} - k_0\right)$$
$$+\lambda_5 \left(1 - k_0 - \frac{c_2 Y_2}{2d}\right) + \lambda_6 [\frac{D}{(1 - k_0)^2} - d]$$

$$\text{Condition 1}: \frac{\partial L}{\partial Y_1} = 1 - k_0 - \frac{c_1 Y_1}{d} - c_1 \lambda_1 + \frac{c_1}{2d}\lambda_2 - \frac{c_1}{2d}\lambda_3 \leq 0,\ Y_1 \geq 0,\ Y_1 \left[1 - k_0 - \frac{c_1 Y_1}{d} - c_1 \lambda_1 + \frac{c_1}{2d}\lambda_2 - \frac{c_1}{2d}\lambda_3\right] = 0$$

$$\text{Condition 2}: \frac{\partial L}{\partial Y_2} = 1 - k_0 - \frac{c_2 Y_2}{d} - c_2 \lambda_1 + \frac{c_2}{2d}\lambda_4 - \frac{c_2}{2d}\lambda_5 \leq 0,\ Y_2 \geq 0,\ Y_2 \left[1 - k_0 - \frac{c_2 Y_2}{d} - c_2 \lambda_1 + \frac{c_2}{2d}\lambda_4 - \frac{c_2}{2d}\lambda_5\right] = 0$$

$$\text{Condition 3}: \frac{\partial L}{\partial d} = \frac{c_1 Y_1^2}{2d^2} + \frac{c_2 Y_2^2}{2d^2} - \lambda_2 \frac{c_1 Y_1}{2d^2} + \lambda_3 \frac{c_1 Y_1}{2d^2} - \lambda_4 \frac{c_2 Y_2}{2d^2} + \lambda_5 \frac{c_2 Y_2}{2d^2}$$
$$-\lambda_6 \leq 0,\ d \geq 0,\ d[\frac{c_1 Y_1^2}{2d^2} + \frac{c_2 Y_2^2}{2d^2} - \lambda_2 \frac{c_1 Y_1}{2d^2} + \lambda_3 \frac{c_1 Y_1}{2d^2} - \lambda_4 \frac{c_2 Y_2}{2d^2} + \lambda_5 \frac{c_2 Y_2}{2d^2} - \lambda_6] = 0$$

$$\text{Condition 4}: \frac{\partial L}{\partial \lambda_1} = E - c_1 Y_1 - c_2 Y_2 \geq 0,\ \lambda_1 \geq 0,\ \lambda_1 (E - c_1 Y_1 - c_2 Y_2) = 0$$

$$\text{Condition 5}: \frac{\partial L}{\partial \lambda_2} = \frac{c_1Y_1}{2d} - k_0 \geq 0,\ \lambda_2 \geq 0,\ \lambda_2\left(\frac{c_1Y_1}{2d} - k_0\right) = 0$$

$$\text{Condition 6}: \frac{\partial L}{\partial \lambda_3} = 1 - k_0 - \frac{c_1Y_1}{2d} > 0,\ \lambda_3 = 0$$

$$\text{Condition 7}: \frac{\partial L}{\partial \lambda_4} = \frac{c_2Y_2}{2d} - k_0 \geq 0,\ \lambda_4 \geq 0,\ \lambda_4\left(\frac{c_2Y_2}{2d} - k_0\right) = 0$$

$$\text{Condition 8}: \frac{\partial L}{\partial \lambda_5} = 1 - k_0 - \frac{c_2Y_2}{2d} > 0,\ \lambda_5 = 0$$

$$\text{Condition 9}: \frac{\partial L}{\partial \lambda_6} = \frac{D}{(1-k_0)^2} - d \geq 0,\ \lambda_6 \geq 0,\ \lambda_6\left[\frac{D}{(1-k_0)^2} - d\right] = 0$$

The solution that satisfies all the nine conditions is: $d = D$, $Y_1 = (1-k_0)d/c_1$ and $Y_2 = (1-k_0)d/c_2$.
The center's optimization problem with a penalty/reward rate $d \leq D/(1-k_0)^2$ and $\frac{c_iY_i}{2d} < k_0$
Solving this problem with the Karush–Kuhn–Tucker method:

$$L = Y_1 + Y_2 + \lambda_1(E - c_1Y_1 - c_2Y_2) + \lambda_2\left[\left(\sqrt{2}-1\right)k_0 - \frac{c_1Y_1}{2d}\right] + \lambda_3\left[\left(\sqrt{2}-1\right)k_0 - \frac{c_2Y_2}{2d}\right] + \lambda_4\left[\frac{D}{(1-k_0)^2} - d\right]$$

$$\text{Condition 1}: \frac{\partial L}{\partial Y_1} = 1 - \lambda_1c_1 - \frac{\lambda_2c_1}{2d} \leq 0,\ Y_1 \geq 0,\ Y_1\left[1 - \lambda_1c_1 - \frac{\lambda_2c_1}{2d}\right] = 0$$

$$\text{Condition 2}: \frac{\partial L}{\partial Y_2} = 1 - \lambda_1c_2 - \frac{\lambda_3c_2}{2d} \leq 0,\ Y_2 \geq 0,\ Y_2\left[1 - \lambda_1c_2 - \frac{\lambda_3c_2}{2d}\right] = 0$$

$$\text{Condition 3}: \frac{\partial L}{\partial d} = \frac{\lambda_2c_1Y_1}{2d^2} + \frac{\lambda_3c_2Y_2}{2d^2} - \lambda_4 \leq 0,\ d \geq 0,\ d\left[\frac{\lambda_2c_1Y_1}{2d^2} + \frac{\lambda_3c_2Y_2}{2d^2} - \lambda_4\right] = 0$$

$$\text{Condition 4}: \frac{\partial L}{\partial \lambda_1} = E - c_1Y_1 - c_2Y_2 \geq 0,\ \lambda_1 \geq 0,\ \lambda_1(E - c_1Y_1 - c_2Y_2) = 0$$

$$\text{Condition 5}: \frac{\partial L}{\partial \lambda_2} = \left(\sqrt{2}-1\right)k_0 - \frac{c_1Y_1}{2d} \geq 0,\ \lambda_2 \geq 0,\ \lambda_2\left(\left(\sqrt{2}-1\right)k_0 - \frac{c_1Y_1}{2d}\right) = 0$$

$$\text{Condition 6}: \frac{\partial L}{\partial \lambda_3} = \left(\sqrt{2}-1\right)k_0 - \frac{c_2Y_2}{2d} \geq 0,\ \lambda_3 \geq 0,\ \lambda_3\left(\left(\sqrt{2}-1\right)k_0 - \frac{c_2Y_2}{2d}\right) = 0$$

$$\text{Condition 7}: \frac{\partial L}{\partial \lambda_4} = \frac{D}{(1-k_0)^2} - d \geq 0,\ \lambda_4 \geq 0,\ \lambda_4\left[\frac{D}{(1-k_0)^2} - d\right] = 0$$

The solution that satisfies all the seven conditions is: $Y_1 = 2\left(\sqrt{2}-1\right)k_0d/c_1$, $Y_2 = 2\left(\sqrt{2}-1\right)k_0d/c_2$, and $d = D/(1-k_0)^2$.
The center's optimization problem with a penalty/reward rate $d \leq D/(1-k_0)^2$ and $(\sqrt{2}-1)k_0 < \frac{c_iY_i}{2d} < k_0$
This problem can be solved with the Karush–Kuhn–Tucker method:

$$L = \left(1 - k_0 - \frac{c_1Y_1}{2d}\right)Y_1 + \left(1 - k_0 - \frac{c_2Y_2}{2d}\right)Y_2 + \lambda_1(E - c_1Y_1 - c_2Y_2) + \lambda_2\left(k_0 - \frac{c_1Y_1}{2d}\right)$$
$$+\lambda_3\left(\frac{c_1Y_1}{2d} - (\sqrt{2}-1)k_0\right) + \lambda_4\left(k_0 - \frac{c_2Y_2}{2d}\right) + \lambda_5\left(\frac{c_2Y_2}{2d} - (\sqrt{2}-1)k_0\right) + \lambda_5\left(\frac{D}{(1-k_0)^2} - d\right)$$

$$\text{Condition 1}: \frac{\partial L}{\partial Y_1} = 1 - k_0 - \frac{c_1Y_1}{d} - \lambda_1c_1 - \frac{c_1}{2d}\lambda_2 + \frac{c_1}{2d}\lambda_3 \leq 0,\ Y_1 \geq 0,\ (1 - k_0 - \frac{c_1Y_1}{d} - \lambda_1c_1 - \frac{c_1}{2d}\lambda_2 + \frac{c_1}{2d}\lambda_3)Y_1 = 0$$

$$\text{Condition 2}: \frac{\partial L}{\partial Y_2} = 1 - k_0 - \frac{c_2Y_2}{d} - \lambda_1c_2 - \frac{c_2}{2d}\lambda_4 + \frac{c_2}{2d}\lambda_5 \leq 0,\ Y_2 \geq 0,\ (1 - k_0 - \frac{c_2Y_2}{d} - \lambda_1c_2 - \frac{c_2}{2d}\lambda_4 + \frac{c_2}{2d}\lambda_5)Y_2 = 0$$

$$\text{Condition 3}: \frac{\partial L}{\partial d} = \frac{c_1Y_1^2 + c_2Y_2^2}{2d^2} + \frac{(\lambda_2 - \lambda_3)c_1Y_1}{2d^2} + \frac{(\lambda_4 - \lambda_5)c_1Y_1}{2d^2} - \lambda_6 \leq 0,\ d \geq 0,$$
$$\left(\frac{c_1Y_1^2 + c_2Y_2^2}{2d^2} + \frac{(\lambda_2 - \lambda_3)c_1Y_1}{2d^2} + \frac{(\lambda_4 - \lambda_5)c_1Y_1}{2d^2} - \lambda_6\right)d = 0$$

$$\text{Condition 4}: \frac{\partial L}{\partial \lambda_1} = E - c_1Y_1 - c_2Y_2 \geq 0,\ \lambda_1 \geq 0,\ \lambda_1 (E - c_1Y_1 - c_2Y_2) = 0$$

$$\text{Condition 5}: \frac{\partial L}{\partial \lambda_2} = k_0 - \frac{c_1Y_1}{2d} > 0,\ \lambda_2 = 0$$

$$\text{Condition 6}: \frac{\partial L}{\partial \lambda_3} = \frac{c_1Y_1}{2d} - \left(\sqrt{2} - 1\right) k_0 > 0,\ \lambda_3 = 0$$

$$\text{Condition 7}: \frac{\partial L}{\partial \lambda_4} = k_0 - \frac{c_2Y_2}{d} > 0,\ \lambda_4 = 0$$

$$\text{Condition 8}: \frac{\partial L}{\partial \lambda_5} = \frac{c_2Y_2}{2d} - \left(\sqrt{2} - 1\right) k_0 > 0,\ \lambda_5 = 0$$

$$\text{Condition 9}: \frac{\partial L}{\partial \lambda_6} = \frac{D}{(1-k_0)^2} - d \geq 0,\ \lambda_6 = 0,\ \lambda_6 \left(\frac{D}{(1-k_0)^2} - d\right) = 0$$

This case requires $c_iY_i < 2dk_0 \leq 2Dk_0/(1-k_0)^2$. Thus, $c_1Y_1 + c_2Y_2 < E$. According to Condition 4, $\lambda_1 = 0$. According to Condition 5 to 8, λ_2 to λ_4 are all zero. Then, according to Condition 1 and 2, $c_iY_i \geq d(1-k_0)$, which is impossible under the restriction of $c_iY_i < 2dk_0$ and $k_0 < 0.3$.

The center's optimization problem with a penalty/reward rate $\boldsymbol{D}/(1-\boldsymbol{k}_0)^2 < \boldsymbol{d} < \boldsymbol{D}/\boldsymbol{k}_0^2$ and $\boldsymbol{dk}_0^2 + \boldsymbol{D} \leq \boldsymbol{c_iY_i} < 2\boldsymbol{k}_0\boldsymbol{d}$

This problem can be solved with the Karush-Kuhn-Tucker method:

$$L = Y_1 + Y_2 + \lambda_1 (E - c_1Y_1 - c_2Y_2) + \lambda_2 \left(c_1Y_1 - dk_0^2 - D\right)$$
$$+\lambda_{32\text{–ch isconditions can be merged into one, ditions is:}} (2k_0d - c_1Y_1)$$
$$+\lambda_4 \left(c_2Y_2 - dk_0^2 - D\right) + \lambda_{52\text{–ch is conditions can be merged into one,ditions is:}}$$
$$(2k_0d - c_2Y_2) + \lambda_{62\text{–ch isconditions can be merged into one, ditions is:}} \left(\frac{D}{k_0^2} - d\right)$$
$$+\lambda_{72\text{–ch is conditions can be merged into one, ditions is:}} \left(d - \frac{D}{(1-k_0)^2}\right)$$

$$\text{Condition 1}: \frac{\partial L}{\partial Y_1} = 1 - c_1\lambda_1 + c_1\lambda_2 - c_1\lambda_3 \leq 0,\ Y_1 \geq 0,\ Y_1 [1 - c_1\lambda_1 + c_1\lambda_2 - c_1\lambda_3] = 0$$

$$\text{Condition 2}: \frac{\partial L}{\partial Y_2} = 1 - c_2\lambda_1 + c_2\lambda_4 - c_2\lambda_5 \leq 0,\ Y_2 \geq 0,\ Y_2 [1 - c_2\lambda_1 + c_2\lambda_4 - c_2\lambda_5] = 0$$

$$\text{Condition 3}: \begin{array}{l} \frac{\partial L}{\partial d} = -\lambda_2k_0^2 + 2\lambda_3k_0 - \lambda_4k_0^2 + 2\lambda_5k_0 - \lambda_{62\text{–ch is conditions can be merged into one, ditions is:}} + \lambda_{72\text{–ch is conditions can be merged into one, ditions is:}} \leq 0,\ d \geq 0 \\ d\left[-\lambda_2k_0^2 + 2\lambda_3k_0 - \lambda_4k_0^2 + 2\lambda_5k_0 - \lambda_{62\text{–ch is conditions can be merged into one, ditions is:}} + \lambda_{72\text{–ch is conditions can be merged into one, ditions is:}}\right] = 0 \end{array}$$

$$\text{Condition 4}: \frac{\partial L}{\partial \lambda_1} = E - c_1Y_1 - c_2Y_2 \leq 0,\ \lambda_1 \geq 0,\ \lambda_1(E - c_1Y_1 - c_2Y_2) = 0$$

$$\text{Condition 5}: \frac{\partial L}{\partial \lambda_2} = c_1Y_1 - dk_0^2 - D \geq 0,\ \lambda_2 \geq 0,\ \lambda_2 \left(c_1Y_1 - dk_0^2 - D\right) = 0$$

$$\text{Condition 6}: \frac{\partial L}{\partial \lambda_3} = 2k_0d - c_1Y_1 > 0,\ \lambda_3 = 0$$

$$\text{Condition 7}: \frac{\partial L}{\partial \lambda_4} = c_2Y_2 - dk_0^2 - D \geq 0,\ \lambda_4 \geq 0,\ \lambda_2 \left(c_2Y_2 - dk_0^2 - D\right) = 0$$

$$\text{Condition 8}: \frac{\partial L}{\partial \lambda_5} = 2k_0d - c_2Y_2 > 0,\ \lambda_5 = 0$$

$$\text{Condition 9}: \frac{\partial L}{\partial \lambda_6} = \frac{D}{k_0^2} - d > 0,\ \lambda_6 = 0$$

$$\text{Condition 10}: \frac{\partial L}{\partial \lambda_7} = d - \frac{D}{(1-k_0)^2} > 0,\ \lambda_7 = 0$$

Since $\lambda_3 = \lambda_5 = \lambda_6 = \lambda_7 = 0$, the first part of Condition 3 requires $\lambda_2 = \lambda_4 = 0$. Thus, Condition 1 and 2 can be reduced to $1 \leq 0$, which is impossible. Therefore, the optimization problem has no real solution.

The center's optimization problem with a penalty/reward rate $d \geq D/k_0^2$

This optimization problem can be solved with the Karush–Kuhn–Tucker method:

$$L = (1 - k_0 + \sqrt{\frac{D}{d}})Y_1 + (1 - k_0 + \sqrt{\frac{D}{d}})Y_2 + \lambda_1(E - c_1Y_1 - c_2Y_2) + \lambda_2[c_1Y_1\left(k_0 - \sqrt{\frac{D}{d}}\right) - c_1Y_1 + D]$$
$$+\lambda_{32-\text{ch is conditions can be merged into one, ditions is:}}\left(\sqrt{\frac{D}{d}} - \frac{c_1Y_1}{2d}\right) + \lambda_4[c_2Y_2\left(k_0 - \sqrt{\frac{D}{d}}\right) - c_2Y_2 + D] + \lambda_{52-\text{ch is conditions can be merged into one, ditions is:}}\left(\sqrt{\frac{D}{d}} - \frac{c_2Y_2}{2d}\right) + \lambda_{62-\text{ch is conditions can be merged into one, ditions is:}}\left(d - \frac{D}{k_0^2}\right)$$

$$\text{Condition 1}: \begin{array}{l} \frac{\partial L}{\partial Y_1} = 1 - k_0 + \sqrt{\frac{D}{d}} - c_1\lambda_1 + c_1\lambda_2(k_0 - \sqrt{\frac{D}{d}}) - c_1\lambda_2 - \frac{c_1}{2d}\lambda_{32-\text{ch is conditions can be merged into one, ditions is:}} \leq 0, \\ Y_1\left[1 - k_0 + \sqrt{\frac{D}{d}} - c_1\lambda_1 + c_1\lambda_2(k_0 - \sqrt{\frac{D}{d}}) - c_1\lambda_2 - \frac{c_1}{2d}\lambda_{32-\text{ch is conditions can be merged into one, ditions is:}}\right] = 0 \end{array} \quad Y_1 \geq 0$$

$$\text{Condition 2}: \begin{array}{l} \frac{\partial L}{\partial Y_2} = 1 - k_0 + \sqrt{\frac{D}{d}} - c_2\lambda_1 + c_2\lambda_4(k_0 - \sqrt{\frac{D}{d}}) - c_2\lambda_4 - \frac{c_2}{2d}\lambda_{52-\text{ch is conditions can be merged into one, ditions is:}} \leq 0, \ Y_2 \geq 0 \\ Y_2\left[1 - k_0 + \sqrt{\frac{D}{d}} - c_2\lambda_1 + c_2\lambda_4(k_0 - \sqrt{\frac{D}{d}}) - c_2\lambda_4 - \frac{c_2}{2d}\lambda_{52-\text{ch is conditions can be merged into one, ditions is:}}\right] = 0 \end{array}$$

$$\text{Condition 3}: \begin{array}{l} \frac{\partial L}{\partial d} = -\frac{Y_1 + Y_2}{2d}\sqrt{\frac{D}{d}} \\ + \frac{c_1Y_1\lambda_{22-\text{ch is conditions can be merged into one, ditions is:}} + c_2Y_2\lambda_{42-\text{ch is conditions can be merged into one, ditions is:}}}{2d} \\ \sqrt{\frac{D}{d}} - \frac{\lambda_3 + \lambda_{52-\text{ch is conditions can be merged into one, ditions is:}}}{2d}\sqrt{\frac{D}{d}} \\ + \frac{c_1Y_1\lambda_{32-\text{ch is conditions can be merged into one, ditions is:}} + c_2Y_2\lambda_{52-\text{ch is conditions can be merged into one, ditions is:}}}{2d^2} \leq 0 \\ d - \frac{Y_1 + Y_2}{2d}\sqrt{\frac{D}{d}} + \frac{c_1Y_1\lambda_{22-\text{ch is conditions can be merged into one, ditions is:}} + c_2Y_2\lambda_{42-\text{ch is conditions can be merged into one, ditions is:}}}{2d} \\ \sqrt{\frac{D}{d}} - \frac{\lambda_3 + \lambda_{52-\text{ch is conditions can be merged into one, ditions is:}}}{2d} \\ \left[\sqrt{\frac{D}{d}} + \frac{c_1Y_1\lambda_{32-\text{ch is conditions can be merged into one, ditions is:}} + c_2Y_2\lambda_{52-\text{ch is conditions can be merged into one, ditions is:}}}{2d^2}\right] d = 0, \\ d \geq 0 \end{array}$$

$$\text{Condition4}: \frac{\partial L}{\partial \lambda_1} = E - c_1Y_1 - c_2Y_2 \leq 0, \ \lambda_1 \geq 0, \ \lambda_1(E - c_1Y_1 - c_2Y_2) = 0$$

$$\text{Condition 5}: \frac{\partial L}{\partial \lambda_2} = c_1Y_1\left(k_0 - \sqrt{\frac{D}{d}}\right) - c_1Y_1 + D \geq 0, \ \lambda_2 \geq 0, \ \lambda_2[c_1Y_1\left(k_0 - \sqrt{\frac{D}{d}}\right) - c_1Y_1 + D] = 0$$

$$\text{Condition 6}: \frac{\partial L}{\partial \lambda_3} = \sqrt{\frac{D}{d}} - \frac{c_1Y_1}{2d} > 0, \ \lambda_3 = 0$$

$$\text{Condition 7}: \frac{\partial L}{\partial \lambda_4} = c_2Y_2\left(k_0 - \sqrt{\frac{D}{d}}\right) - c_2Y_2 + D \geq 0, \ \lambda_4 \geq 0, \ \lambda_4[c_2Y_2\left(k_0 - \sqrt{\frac{D}{d}}\right) - c_2Y_2 + D] = 0$$

$$\text{Condition 8}: \frac{\partial L}{\partial \lambda_5} = \sqrt{\frac{D}{d}} - \frac{c_2Y_2}{2d} > 0, \ \lambda_5 = 0$$

$$\text{Condition 9}: \frac{\partial L}{\partial \lambda_6} = d - \frac{D}{k_0^2} \geq 0,\ \lambda_6 \geq 0,\ \lambda_6[d - \frac{D}{k_0^2}] = 0$$

The solution that satisfies all the nine conditions is: $Y_1 = Y_2 = 0$, and the penalty/reward rate can be determined arbitrarily in the range of $d \geq D/k_0^2$.

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