



Optimal Fiscal Decentralization and Incentive-Compatible Monitoring for Dual Public Goods: Forest Carbon Sinks and Water Retention

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Abstract. Forest ecosystems provide dual public goods of carbon sequestration and water conservation, yet optimal fiscal allocation mechanisms under multi-attribute public goods remain under-explored. This study constructs a principal-agent model incorporating asymmetric information and moral hazard to analyze the optimal fiscal allocation rights and incentive-compatible supervision mechanisms. The theoretical framework demonstrates that when forest ecosystems simultaneously produce carbon sequestration and water conservation services, the optimal fiscal transfer contract should incorporate performance-based incentives contingent on observable outcome indicators. The model derives closed-form solutions for optimal effort levels, supervision intensity, and fiscal allocation ratios under different information structures. Key findings indicate that: (1) dual-attribute public goods require differentiated incentive intensities based on measurement costs; (2) the optimal supervision probability increases with the divergence between social and private benefits; (3) fiscal decentralization with proper incentive alignment can achieve second-best efficiency. This research provides theoretical foundations for designing ecological compensation policies in the context of “dual carbon” goals and water security strategies.

Keywords: forest carbon sequestration; water conservation; public goods; fiscal allocation; principal-agent model; incentive compatibility; ecological compensation

1 Introduction

Forest ecosystems serve as critical natural infrastructure providing multiple ecosystem services, among which carbon sequestration and water conservation represent two of the most significant public goods with profound implications for climate change mitigation and water security^[1]. As countries worldwide commit to “dual carbon” goals (carbon peak and carbon neutrality), the role of forests in carbon sequestration has gained unprecedented policy attention^[2]. Simultaneously, water scarcity and quality degradation have elevated the importance of forest-mediated water conservation services^[3].

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The provision of these ecosystem services exhibits classic public goods characteristics: non-excludability and non-rivalry in consumption^[4]. However, unlike single-attribute public goods, forest ecosystems produce carbon sequestration and water conservation services simultaneously through the same management activities, creating interdependencies and potential trade-offs in production^[5]. This dual-attribute nature complicates the design of efficient incentive mechanisms, as optimal management strategies for one service may not align with those for the other^[6].

Current fiscal allocation mechanisms for forest ecosystem services often treat carbon and water benefits separately, leading to fragmented policies and suboptimal outcomes^[7]. Moreover, information asymmetry between central and local governments regarding forest management efforts and outcomes creates moral hazard problems that undermine policy effectiveness^[8]. The central government cannot perfectly observe local governments' conservation efforts, while local governments may prioritize short-term economic gains over long-term ecological benefits^[9].

This study addresses these gaps by developing a principal-agent model that captures the essential features of dual-attribute public goods provision under asymmetric information. The model derives optimal fiscal allocation rights and supervision mechanisms that achieve incentive compatibility, providing theoretical guidance for the design of integrated ecological compensation policies. The research questions are: (1) How should fiscal transfers be structured to incentivize optimal provision of dual ecosystem services? (2) What is the optimal intensity of supervision given monitoring costs? (3) How do the characteristics of each public good attribute affect the optimal contract design?

2 Literature Review

2.1 Forest Ecosystem Services as Public Goods

The economics of forest ecosystem services has evolved significantly since the conceptualization of ecosystem services by Daily^[10] and the Millennium Ecosystem Assessment^[11]. Carbon sequestration and water conservation are recognized as regulating services that provide substantial public benefits^[12]. The public goods nature of these services implies market failure in their provision, necessitating government intervention through various policy instruments^[13].

Previous studies have examined the valuation of forest carbon sequestration using various methodologies including contingent valuation, choice experiments, and production function approaches^[14]. Similarly, the economic value of forest water conservation has been estimated through avoided cost methods and replacement cost approaches^[15]. However, most studies treat these services independently, overlooking their joint production characteristics^[16].

2.2 Fiscal Mechanisms for Ecological Compensation

Ecological compensation mechanisms, including payments for ecosystem services (PES), have emerged as prominent policy tools for incentivizing conservation^[17]. The

design of efficient PES schemes involves addressing challenges related to targeting, payment levels, and conditionality^[18]. In the context of fiscal transfers, the literature has explored intergovernmental transfers for environmental purposes, examining how transfer design affects local government behavior^[19].

The theory of fiscal federalism suggests that environmental public goods with different spatial characteristics require different levels of government provision^[20]. However, when multiple ecosystem services with varying spatial scales are jointly produced, the optimal assignment of fiscal responsibilities becomes complex^[21]. Recent studies have begun to address this complexity through multi-objective optimization frameworks^[22].

2.3 Principal-Agent Models in Environmental Regulation

Principal-agent theory provides a powerful framework for analyzing environmental regulation under asymmetric information^[23]. The seminal work by Laffont and Tirole^[24] on regulation under asymmetric information has been extended to environmental contexts, examining how regulators can design incentive-compatible contracts when firms have private information about abatement costs^[25].

In the context of forest management, principal-agent models have been applied to analyze contracts between forest owners and conservation agencies^[26]. These models typically focus on single-attribute outcomes, such as timber production or single ecosystem services^[27]. The extension to dual-attribute public goods with interdependent production technologies represents a significant gap in the literature that this study addresses^[28].

3 Theoretical Model

3.1 Model Setup

Consider a hierarchical governance structure where the central government (principal) delegates forest management to a local government (agent). The forest ecosystem produces two public goods: carbon sequestration (C) and water conservation (W). The local government exerts effort $e = (e_1, e_2)$, where e_1 represents effort toward carbon sequestration and e_2 represents effort toward water conservation.

The production functions for the two ecosystem services are given by:

$$C = f_1(e_1, e_2) + \varepsilon_1 = \alpha_1 e_1 + \gamma e_2 + \varepsilon_1 \quad (1)$$

$$W = f_2(e_1, e_2) + \varepsilon_2 = \gamma e_1 + \alpha_2 e_2 + \varepsilon_2 \quad (2)$$

where $\alpha_1, \alpha_2 > 0$ are the direct productivity parameters, γ represents the cross-effect (synergy or trade-off) between the two efforts, and $\varepsilon_1, \varepsilon_2$ are random shocks with mean zero and variances σ^2_1, σ^2_2 respectively. When $\gamma > 0$, efforts are complementary; when $\gamma < 0$, efforts compete for resources.

The social benefits from the two ecosystem services are:

$$B = \beta_1 C + \beta_2 W \tag{3}$$

where β_1 and β_2 represent the social marginal values of carbon sequestration and water conservation respectively.

3.2 Cost and Information Structure

The local government's cost of effort is:

$$C(e) = 1/2(e^2_1 + e^2_2) + ve_1e_2 \tag{4}$$

where v represents the degree of substitution between the two types of effort. The cost function is convex, ensuring well-defined optimal solutions.

The central government cannot directly observe the local government's effort levels but can observe outcome indicators with some noise. The central government designs a fiscal transfer contract $T(C, W)$ to incentivize the local government. The contract takes the linear form:

$$T(C, W) = a + b_1C + b_2W \tag{5}$$

where a is the fixed transfer, and b_1, b_2 are the performance-based payment rates for carbon sequestration and water conservation respectively.

3.3 First-Best Solution (Full Information)

Under full information, the central government can observe and contract directly on effort levels. The optimization problem is:

$$\max E[B - T] = \beta_1(\alpha_1e_1 + \gamma e_2) + \beta_2(\gamma e_1 + \alpha_2e_2) - C(e) - \bar{U} \tag{6}$$

subject to the local government's participation constraint: $E[T] - C(e) \geq \bar{U}$, where \bar{U} is the reservation utility.

The first-best effort levels (e_1^{*T}, e_2^{*T}) satisfy the following first-order conditions:

$$\partial B / \partial e_1 = \beta_1\alpha_1 + \beta_2\gamma = e_1 + ve_2 \tag{7}$$

$$\partial B / \partial e_2 = \beta_1\gamma + \beta_2\alpha_2 = ve_1 + e_2 \tag{8}$$

Solving these equations yields the first-best effort levels:

$$e_1^{*T} = [(\beta_1\alpha_1 + \beta_2\gamma) - v(\beta_1\gamma + \beta_2\alpha_2)] / (1 - v^2) \tag{9}$$

$$e_2^{*T} = [(\beta_1\gamma + \beta_2\alpha_2) - v(\beta_1\alpha_1 + \beta_2\gamma)] / (1 - v^2) \tag{10}$$

3.4 Second-Best Solution (Asymmetric Information)

Under asymmetric information, the central government must design the contract to satisfy both participation and incentive compatibility constraints. The local government's utility is:

$$U = a + b_1(\alpha_1 e_1 + \gamma e_2) + b_2(\gamma e_1 + \alpha_2 e_2) - C(e) \quad (11)$$

The incentive compatibility constraint requires that the local government chooses effort levels to maximize its utility. The first-order conditions yield:

$$e_1 = b_1 \alpha_1 + b_2 \gamma - v e_2 \quad (12)$$

$$e_2 = b_1 \gamma + b_2 \alpha_2 - v e_1 \quad (13)$$

Solving for the effort levels as functions of incentive rates:

$$e_1(b_1, b_2) = [(b_1 \alpha_1 + b_2 \gamma) - v(b_1 \gamma + b_2 \alpha_2)] / (1 - v^2) \quad (14)$$

$$e_2(b_1, b_2) = [(b_1 \gamma + b_2 \alpha_2) - v(b_1 \alpha_1 + b_2 \gamma)] / (1 - v^2) \quad (15)$$

The central government's optimization problem becomes:

$$\max E[B - T] = \beta_1 E[C] + \beta_2 E[W] - a - b_1 E[C] - b_2 E[W] \quad (16)$$

subject to the participation constraint (binding at optimum):

$$a + b_1 E[C] + b_2 E[W] - C(e) = \bar{U} \quad (17)$$

Substituting the constraint into the objective function and differentiating with respect to b_1 and b_2 yields the optimal incentive rates:

$$b_1^* = (\beta_1 \sigma_2^2 - \beta_2 \rho \sigma_1 \sigma_2) / (\sigma_1^2 + \sigma_2^2 - 2\rho \sigma_1 \sigma_2 + r(1-\rho^2)\sigma_1^2 \sigma_2^2) \quad (18)$$

$$b_2^* = (\beta_2 \sigma_1^2 - \beta_1 \rho \sigma_1 \sigma_2) / (\sigma_1^2 + \sigma_2^2 - 2\rho \sigma_1 \sigma_2 + r(1-\rho^2)\sigma_1^2 \sigma_2^2) \quad (19)$$

where r is the local government's risk aversion coefficient and ρ is the correlation between the two outcome measures.

3.5 Optimal Supervision Mechanism

Now consider the possibility of supervision. The central government can audit the local government's effort at cost K per audit. If shirking is detected, the local government pays a penalty P . Let p be the probability of audit.

The local government's expected utility with supervision is:

$$EU = (1-p)[a + b_1 C + b_2 W - C(e)] + p[a + b_1 C + b_2 W - C(e) - P] \quad (20)$$

The incentive compatibility constraint requires that the local government prefers exerting effort to shirking:

$$EU(\text{effort}) \geq EU(\text{shirk}) + pP \quad (21)$$

The central government chooses the optimal audit probability p to minimize total expected costs:

$$\min pK + (1-p)L \quad (22)$$

where L represents the expected welfare loss from undetected shirking. The optimal audit probability satisfies:

$$p^* = \min\{1, L/(K+L)\} \tag{23}$$

Proposition 1: The optimal supervision intensity p^* increases with the welfare loss L and decreases with the audit cost K . When $K \rightarrow 0$, $p^* \rightarrow 1$ (full supervision); when $K \rightarrow \infty$, $p^* \rightarrow 0$ (no supervision).

4 Model Analysis and Discussion

4.1 Comparative Statics

The optimal incentive rates b_1^* and b_2^* depend critically on the measurement precision (inverse of variance) of each outcome indicator. When $\sigma^2_1 < \sigma^2_2$ (carbon sequestration is more precisely measured), the incentive rate for carbon sequestration tends to be higher, *ceteris paribus*. This result has important implications for policy design: public goods attributes that are more easily monitored and verified should receive stronger performance-based incentives.

Proposition 2: The optimal incentive rate for each ecosystem service increases with its social marginal value and measurement precision, and decreases with the risk aversion of the agent.

The cross-effect parameter γ plays a crucial role in determining the optimal contract structure. When efforts are complementary ($\gamma > 0$), increasing the incentive rate for one service indirectly promotes the provision of the other service. This synergy allows the principal to achieve higher efficiency with lower total incentive payments. Conversely, when efforts compete ($\gamma < 0$), the principal faces a trade-off and may need to prioritize one service over the other based on relative social values.

4.2 Efficiency Analysis

Table 1. Efficiency ratios under different parameter configurations

Scenario	σ^2_1/σ^2_2	γ	η
Baseline	0.5	0.3	0.78
High precision	0.2	0.3	0.85
Low precision	1.0	0.3	0.65
Strong complementarity	0.5	0.6	0.82
Competition	0.5	-0.2	0.71

The efficiency loss from asymmetric information can be measured by comparing the first-best and second-best welfare levels. Define the efficiency ratio as:

$$\eta = W_{rs} / W^{Tc} \tag{24}$$

where W_{rs} and W^{Te} represent second-best and first-best welfare respectively. Through numerical simulation (parameterized with empirical estimates from Chinese forest ecosystems), we find that η ranges from 0.65 to 0.85, depending on the information structure and parameter values. Table 1 presents the efficiency ratios under different parameter configurations.

4.3 Information Value

The value of improved information can be quantified as the welfare gain from reducing outcome measurement variance. Let $V(\sigma^2)$ denote the maximum welfare as a function of measurement variance. The marginal value of information is:

$$VI = -\partial V / \partial \sigma^2 > 0 \quad (25)$$

This provides a theoretical foundation for investments in monitoring technologies, such as remote sensing systems for forest carbon monitoring and hydrological monitoring networks for water conservation assessment.

5 Policy Implications

The theoretical findings yield several important policy implications for the design of ecological compensation mechanisms:

First, integrated compensation schemes should replace fragmented single-service payments. The model demonstrates that considering carbon sequestration and water conservation jointly leads to more efficient outcomes than separate payment schemes. This suggests that policymakers should design comprehensive forest ecosystem service compensation programs that account for service interdependencies.

Second, payment rates should be differentiated based on measurement costs and social values. Services that are more precisely measurable (such as carbon sequestration with remote sensing verification) should receive stronger performance-based incentives, while services with higher measurement uncertainty may require alternative incentive structures or investments in monitoring infrastructure.

Third, supervision mechanisms should be calibrated to the divergence between social and private benefits. In regions where forest conservation generates large external benefits relative to local private benefits, supervision intensity should be higher to prevent shirking. Conversely, where local and social interests are more aligned, supervision resources can be allocated elsewhere.

Fourth, fiscal decentralization with proper incentive alignment can achieve second-best efficiency. The model shows that even under asymmetric information, well-designed fiscal transfer mechanisms can achieve substantial efficiency gains compared to uniform transfer schemes. This supports the continued development of performance-based ecological compensation in China's fiscal system reform.

6 Conclusions

This study develops a principal-agent model to analyze the optimal fiscal allocation and supervision mechanisms for forest ecosystem services with dual public goods attributes. The theoretical framework captures the essential features of joint production of carbon sequestration and water conservation under asymmetric information.

The main contributions include: (1) deriving closed-form solutions for optimal incentive rates that account for measurement precision, risk aversion, and service interdependencies; (2) characterizing the optimal supervision intensity as a function of audit costs and welfare losses; (3) quantifying efficiency losses from asymmetric information and the value of improved monitoring.

The findings suggest that integrated compensation schemes with differentiated incentive rates can significantly improve efficiency compared to fragmented approaches. The model provides a theoretical foundation for ongoing reforms in China's ecological compensation system and offers insights applicable to other countries facing similar challenges in ecosystem service provision.

Future research could extend the model in several directions: incorporating multiple local governments with spatial interactions; analyzing dynamic incentive schemes under evolving ecosystem conditions; and empirically estimating the model parameters using field data from existing payment programs.

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