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Bilateral information asymmetry and irreversible practice adoption through agri-environmental policy: an application to peat land retirement in Norway

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Abstract

Achieving greenhouse gas reduction in agriculture may require irreversible changes in production practices and land use. In this context, we examine the design of a peat land retirement programme to mitigate GHG emissions in Norway using the *informed* principal model with private values introduced by Maskin and Tirole (1990). We first derive the optimal contract when the agent has private information about the costs of implementing peat land retirement and assuming that the principal's type is common knowledge. This corresponds to the standard asymmetric information model. In the second case, we employ an *informed* principal model with private values to address bilateral information asymmetry. We show that when the principal has private information, principals with differing valuations on the environmental benefits of peat land retirement can be better off by offering the same menu of contracts to agents, i.e., a *pooling offer*. With this offer agents expect to satisfy their individual rationality (IR) and incentive compatibility (IC) constraints on average, so a principal can relax the more costly constraint and tighten the less costly constraint. A numerical example shows that a principal with high valuation on peat land retirement relaxes IC constraint and enforces IR constraint. In contrast, the principal with a low valuation on peat land retirement tightens the IC constraint and loosens the IR constraint.

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1. Introduction

Agri-environmental policy is becoming important for mitigating greenhouse gas (GHG) emissions from agriculture. Agriculture accounts for 52% and 84% of global anthropogenic methane and nitrous oxide emissions, respectively (Smith *et al.*, 2008). The Intergovernmental Panel on Climate Change (IPCC, 2007) reports that agricultural production causes approximately 14% of global GHG emissions, even though agriculture contributes only 6% of world GDP.

Several policy instruments can be used to mitigate GHG emissions: (1) environmental taxes; (2) command-and-control regulation; (3) integrated conservation and development projects (ICDPs); and (4) voluntary agri-environmental schemes (Engel *et al.*, 2008). Existing agri-environmental policies primarily address marginal changes in farm practices. With respect to GHG mitigation this includes changes in manure management, nitrogen application, and crop rotations. With growing concern about climate change, irreversible practice adoption, such as major changes in land use, is likely to be considered as a policy option.

Although peat soils cover only about 3% of the world's land area, they are a major source of carbon storage. Peat soils store approximately one-third of the world's total organic carbon, which is roughly equal to the total amount of carbon stored in the atmosphere or in all terrestrial biomass (Joosten and Clarke, 2002). In Norway, peat soils cover 6.5% of the land area and 85,000-150,000 ha of peat lands are used in agriculture (Maljanen *et al.*, 2010). The major threat for the release of carbon from peat soils results from drainage for agriculture and forestry uses. Grønlund *et al.* (2008) estimate that the carbon loss from cultivated peat soils in Norway is 0.6-0.8 kg C m²year⁻¹ and that 1.8-2 million tons of CO₂ year⁻¹ are released due to peat degradation. This is equivalent to roughly 3-4% of total anthropogenic GHG emissions in Norway. Despite this, cultivated peat soils have received little attention as a source of CO₂ emissions. Efforts to

remove peat land from cultivation deserve serious consideration if GHG emissions from agriculture in Norway are to be reduced.

The major analytical approach used to examine the design of agri-environmental policies is the principal-agent model. This model posits that the *principal* (government) offers a contract and that *agents* (farmers) decide whether to accept or refuse the contract; farmers cannot affect the structure of the contract. If agents accept, they carry out required actions, i.e., provide a certain level of agri-environmental services specified by the contract. The major obstacle to the effective implementation of agri-environmental policy in the principal-agent model is dealing with *information asymmetry*. Agents have an informational advantage in terms of private knowledge of the costs of supplying environmental services. In other words, government may not have access to the information possessed by agents and can only monitor their activities. The asymmetric information problem can detract from the effectiveness of agri-environmental policy and make it expensive to implement (Ferraro, 2008).

Two types of asymmetric information problems can arise when designing agri-environmental policy: *adverse selection* (hidden information) and *moral hazard* (hidden action). Adverse selection occurs when principal and agent negotiate a contract. Agents have better information than the principal about the cost of supplying environmental services and have an incentive to disguise these costs. Agents can procure higher payments than the costs of supplying services and this makes policy implementation more expensive. Adverse selection has been a focus in the literature (Wu and Bacock, 1995, 1996; Moxey *et al.*, 1999; Smith and Tomasi, 1999; Ferraro, 2008). Moral hazard can arise after a contract comes into effect. The principal cannot monitor an agent's compliance perfectly and agents have an incentive to avoid complying with their contractual responsibilities. Moral hazard can limit the effectiveness of agri-environmental policy and increase the cost of monitoring by an environmental service purchaser (Ozanne *et al.*, 2001; Fraser, 2002; Hart and Latacz-Lohmann, 2005; Ozanne and White, 2008; Yano and Blandford, 2009, 2011).

Previous studies of the design of agri-environmental policy using the principal-agent model assume that information asymmetry is one-sided. This means that only agents have an informational advantage when contracting. This hypothesis is too restrictive, particularly in relation to the design agri-environmental policies to address climate change. For example, the principal is likely to have private information about the potential effectiveness of peat land retirement for GHG mitigation or better knowledge about the cost of implementing irreversible practices, such as permanent land retirement. With this point of view ***bilateral information asymmetry*** may apply in the design and implementation of agri-environmental policy.

Myerson (1983) and Maskin and Tirole (1990, 1992) pioneered the development of the principal-agent model under bilateral asymmetric information. They called it the *informed* principal model. Myerson (1983) studied the general properties of mechanism design for an *informed* principal and paid attention to the non-emptiness of the core (i.e., the existences of a solution to the

problem) using cooperative game theory. He shows that there is always equilibrium of the informed principal game. This result is called the *Inscrutability Principle* which notes that without loss of generality we can restrict attention to the pooling offer in which the principal, whatever his type, offers the same contract to the agent. Maskin and Tirole (1990, 1992) analysed bilateral asymmetric information under non-cooperation. In particular, they studied two forms of the *informed* principal model: private values and common values. The model of the *informed* principal with private values assumes that the principal's private information is not an argument in the agent's payoff. This implies that the agent's utility does not depend on the principal's private information. In contrast, the model of the informed principal with common values assumes that the principal's private information is an argument of the agent's objective function. In the common values model, the agent's utility is directly affected by the principal's private information.

By adding the information structure possessed by the principal to the principal-agent relationship, the *informed* principal model becomes a sequential game with incomplete information. The equilibrium concept of a sequential game with incomplete information will be a Perfect Bayesian Equilibrium (PBE). The perfect Bayesian equilibrium is characterized by the following properties: (i) the principal's offer is optimal given the agent's strategy and belief; (ii) the agent's strategy is optimal given her/his belief and the principal's strategy; (iii) both parties update their belief using Bayes' rule, when applicable.

These properties imply that a contract proposed by a privately *informed* principal is a signalling device. The contract itself reveals the principal's private information. Given this offer, the agent updates her/his beliefs about the principal's private information. The principal updates her/his beliefs about the agent's type (characteristics with respect to the achievement of the agent's objective) after observing the agent's decision whether to accept or reject the contract. Using the PBE concept, Maskin and Tirole (1990) showed that the principal in a private values model can guarantee at least the same payoff he/she would obtain in the benchmark case where the principal's type is common knowledge. They also show that when both principal and agent have a quasi-linear utility function the principal neither gains nor loses if her/his private information is revealed before contracting takes place. In other words, the equilibrium payoff in the informed principal with private values model is equal to the payoff in the benchmark case.

Cella (2005) analyses an informed principal model with the private value assumption when the principal is risk-neutral and the agent is risk-averse. The result shows that the risk-neutral informed principal can be better off than in the benchmark case where the principal's type is common knowledge. Fleckinger (2007) proves that even though both the principal and the agent have quasi-linear utility functions, the principal in the private value model can obtain additional surplus when the agent faces countervailing incentives. Cella (2008) examines the informed principal with private value model with both a risk-neutral principal and agent. She imposes the additional assumption that the principal's type is correlated with the agent's type. Results show that even if both the principal and the agent are risk-neutral, the informed principal can achieve

higher payoffs than the principal whose type is common knowledge since the principal can use the contract to signal her/his type to the agent.

In this paper, we examine contract issues in the design of peat land retirement programmes in Norway using two cases. First, we use a benchmark case in which only the agent has private information about the costs of implementing peat land retirement and assume that the principal's type is common knowledge (i.e., the principal's knowledge of the impact of peat land retirement by a particular farm type on GHG emissions). This represents the standard design of agri-environmental policy on which most of the principal-agent literature has focused. In the second case, we assume that the principal has private information about the potential GHG mitigation of peat land retirement but this private information does not directly affect the agent's payoff from land retirement. The agent still has private information about her/his type (e.g., land use characteristics of his/her farm) that can cause adverse selection problems. This is an *informed* principal model with private values.

Previous studies about the informed principal model with private values mainly prove the existence of an equilibrium depending on the functional forms of the principal's and agent's utility. The objective of this study is to derive the optimal contract to implement the permanent retirement of peat land based on Maskin and Tirole (1990) and Cella (2005) to show the existence of an equilibrium in which the informed principal can be better off. We provide numerical examples in order to compare and characterize the principal's and the agent's payoff, information rent, and downward distortion under various situations.

In the next section we outline the theoretical framework for the optimal design of agri-environmental policy. First, we derive an optimal agri-environmental policy with one-sided asymmetric information for the benchmark case (section 2.1). Then we prove that the informed principal can achieve higher payoffs than in the benchmark case due to slack variables in constraints. In section 2.2 we examine the optimal contract under bilateral information asymmetry – the pooling offer. In section 3, we provide numerical analysis and compare principal and agent payoffs that depend on information asymmetry. Section 4 summarizes our results and their policy implications.

2. Theoretical Framework

We consider that the principal and agent play a three-stage game. In stage 1, the principal offers contracts to retire the agent's peat land from agricultural production. The contract consists of the amount of peat land retired and the monetary transfer corresponding to the land retirement. In the second stage, the agent updates prior belief based on the contract offered by the principal and decides whether to accept or reject the contract. If the agent rejects the contract, the game is over. If the agent accepts the contract, in the third stage the principal and the agent implement the proposed action and the monetary transfer is made. Agents retire areas of peat land specified in the contract and the principal pays compensation for the reduction in income that this creates.

We assume that both the principal (government) and agent (farmer) have two independent types, $i = 1, 2$ and $j = 1, 2$, respectively.³ Superscript i stands for principal type i and subscript j denotes agent type j in this paper. The agent's common prior belief in type i principal is denoted by q^i such that $q^1 + q^2 = 1$. Also, p_j is the proportion of type j agent such that $p_1 + p_2 = 1$.

The risk-neutral principal (government) has a linear payoff function:

$$V^i = b^i \cdot y_j^i - t_j^i \quad (1)$$

where y_j^i is the size of retired peat land by agent type j after accepting the contract offered by principal type i , t_j^i is a monetary transfer from principal type i to agent type j in compensation for income foregone through programme participation. b^i is a principal i 's marginal environmental benefit obtained from peat land retirement. Different principals are assumed to have different environmental valuation on peat land retirement, b^i , in order to represent the principal's private information. Each b^i may reflect spatial heterogeneity of abatement potential resulting from peat land retirement or represent unequal valuations on peat land retirement programme by different interest groups. We assume that peat land retirement (y) is an observable and verifiable environmental service thereby ruling out the moral hazard problem in this model.

The risk-averse agent (farmer) has a von Neumann-Morgenstern utility function U_j which is continuous, increasing and concave. The agent's utility function has following form:

$$U_j = U(t_j^i - \psi_j(y_j^i)) \quad (2)$$

where t_j^i is a monetary transfer received from principal i associated with income foregone through programme participation and $\psi_j(y)$ is a retirement cost of y peat land by agent j . $\psi_j(y)$ is continuous, increasing and convex in y for every agent j . We assume $\psi_2(y) > \psi_1(y)$ so that type 1 agent has a lower abatement cost and it is therefore more efficient to retire her/his peat land than that of the type 2 agent. For the sorting condition, $\psi_2'(y) > \psi_1'(y)$ holds for any y . This ensures that the principal can distinguish between types of agent by offering an incentive compatible contract. And the agent's utility function U implies that the principal's private information or type does not affect agent utility, which is the private values assumption.

2.1. Benchmark Case: One-Sided Asymmetric Information

As a benchmark case we examine the optimal contract for a peat land retirement programme when the principal's type is common knowledge. Since the principal's type is public information, in this case, different principals offer different contracts based on their private information on the

³ Cella (2008) examines the informed principal model when the principal's and the agent's type are correlated.

implications of peat land retirement. Agents know the value of implementing peat land retirement before contracting.⁴ We posit that the principal knows the retirement costs and the proportion of each type of agent but the agent's type is still private information. This corresponds to the standard design of agri-environmental policy with one-sided asymmetric information. We can derive the optimal contract for peat land retirement programme for each type i principal by solving the following problem (F^i):

$$(F^i) = \begin{cases} \max_{\{y_j^i, t_j^i\}} \sum_{j=1}^2 p_j (b^i \cdot y_j^i - t_j^i) \\ IR_1^i : U(t_1^i - \psi_1(y_1^i)) \geq 0 \\ IR_2^i : U(t_2^i - \psi_2(y_2^i)) \geq 0 \\ IC_1^i : U(t_1^i - \psi_1(y_1^i)) \geq U(t_2^i - \psi_1(y_2^i)) \\ IC_2^i : U(t_2^i - \psi_2(y_2^i)) \geq U(t_1^i - \psi_2(y_1^i)) \end{cases}$$

where superscript i indicates the type of principal and subscript j denotes the type of agent. IR (Individual Rationality) constraints imply that agents can guarantee at least the same utility level they would obtain before participation in the peat land retirement programme. The RHS of the IR constraints is the agent's reservation utility and is normalized to zero. If IR constraints are not satisfied, no agent will participate in the agri-environmental programme. IC (Incentive Compatibility) constraints mean that each type of agent prefers his designated contract to all other options. Due to the revelation principal, the principal can offer a menu of contracts for all types of agent, agents truthfully reveal their type and choose the contract designated only for their own type.

The optimal contracts that we obtain by solving the problem above are separating equilibriums where different types of agents receive different contracts. To avoid confusion it is useful to note that in next section we will show that the pooling offer is a dominant strategy when the principal's type is private information. That means that different types of principal offer the same menu of contracts but different types of agent receive different contracts because contracts offered are incentive compatible and individually rational for all types of agent. A well-known result of the adverse selection problem is that only IR_2 and IC_1 are binding constraints at the equilibrium (for details, see Moxey *et. al.* 1990). We can rewrite the principal's maximization problem as follows:

⁴ Maskin and Tirole (1990) call this the full information case even if the agent's type is still private information.

$$(F^i) = \begin{cases} \max_{\{y_j^i, t_j^i\}} \sum_{j=1}^2 p_j (b^i \cdot y_j^i - t_j^i) & \text{such that} \\ IR_2^i : U(t_2^i - \psi_2(y_2^i)) = 0 & (\rho^i) \\ IC_1^i : U(t_1^i - \psi_1(y_1^i)) = U(t_2^i - \psi_1(y_2^i)) & (\gamma^i) \end{cases}$$

where ρ^i and γ^i are the Lagrange multipliers associated with the IR and IC constraint, respectively. Solutions of the problem above are the optimal contract for the peat land retirement programme when the principal's type is common knowledge. Each principal i will offer contracts $\{(y_1^i, t_1^i), (y_2^i, t_2^i)\}$ as follows:⁵

$$\{y_1^i, t_1^i\} = \{b^i = \psi_1'(y_1^i), \psi_1(y_1^i) + \psi_2(y_2^i) - \psi_1(y_2^i)\}$$

$$\{y_2^i, t_2^i\} = \left\{ b^i = \psi_2'(y_2^i) + \frac{p_2}{p_1} (\psi_1'(y_2^i) + \psi_2'(y_2^i)), \psi_2(y_2^i) \right\}$$

The optimal contract shows that efficient farmers retire their peat land in line with marginal environmental benefits equal to marginal retirement costs. But the monetary transfer for efficient farmers is more than the retirement costs. This means efficient farmers receive an information rent. On the other hand, the retirement level for inefficient farmers is distorted downward from the environmentally efficient level. And inefficient farmers only receive a monetary transfer equal to income foregone by implementing peat land retirement. The utility level of inefficient farmers is unchanged by participating in the peat land retirement programme. This is common results of the discrete-type adverse selection problem: (i) the high type agent has an efficient allocation and a positive surplus, information rent; (ii) the low type agent has an inefficient allocation and zero surplus (Salanié, 2005).

2.1.1. Ratio of Lagrange Multipliers

It is worth noting that different types of principal have a different ratio of Lagrange multipliers for the optimal contract. This is the reason why informed principals can achieve higher payoffs compare to principals in benchmark case. From equation (A3) and (A4) in the Appendix, the ratio of Lagrange multipliers associated with the IR constraint (ρ^i) and the IC constraint (γ^i) is:

$$\rho^i = \frac{p_2 + \gamma^i \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial(t_2^i - \psi_1(y_2^i))}}{\frac{\partial U(t_2^i - \psi_2(y_2^i))}{\partial(t_2^i - \psi_2(y_2^i))}} = \frac{p_2 + p_1}{\frac{\partial U(t_2^i - \psi_2(y_2^i))}{\partial(t_2^i - \psi_2(y_2^i))}} = \frac{1}{\frac{\partial U(t_2^i - \psi_2(y_2^i))}{\partial(t_2^i - \psi_2(y_2^i))}} \quad \text{and} \quad \gamma^i = \frac{p_1}{\frac{\partial U(t_1^i - \psi_1(y_1^i))}{\partial(t_1^i - \psi_1(y_1^i))}}$$

⁵ See Appendix I for details.

$$\frac{\rho^i}{\gamma^i} = \frac{U'(t_1^i - \psi_1(y_1^i))}{p_1 \cdot U'(t_2^i - \psi_2(y_2^i))} = \frac{U'(\psi_1(y_1^i) + \psi_2(y_2^i) - \psi_1(y_2^i) - \psi_1(y_1^i))}{p_1 \cdot U'(t_2^i - \psi_2(y_2^i))} = \frac{U'(\psi_2(y_2^i) - \psi_1(y_2^i))}{p_1 \cdot U'(0)} \quad (3)$$

Since the Lagrange multipliers are the shadow prices for satisfying the IR and IC constraints, different types of principal have different relative costs in satisfying these constraints. For instance, if $\rho^1/\gamma^1 < \rho^2/\gamma^2$, the IC constraint is relatively more costly for the type 1 principal and the IR constraint is relatively more expensive for the type 2 principal. Principal 1 can obtain a surplus which comes from relaxing the IC constraint and enforcing the IR constraint. Principal 2, on the other hand, can achieve higher payoffs by relaxing the IR constraint and tightening the IC constraint.

Maskin and Tirole (1990) explain that when the principal's type is private information different types of principal offer the same menu of contracts (the *pooling offer*) in order to obtain additional surplus. This implies that the contract offered by the type 1 principal also contains the allocation that is designed for the type 2 principal and vice versa. Since both types of principal propose the same menu of contracts, agents cannot distinguish one type of principal from another. So when agents decide whether to accept or reject the contract in the second stage, the agent's belief remains the same as her/his prior belief. Because of this agents only expect to achieve their IR and IC constraints on average. The fact that principals are merely supposed to satisfy these constraints on average makes the informed principal relax the more costly constraint and tighten the less costly constraint. Therefore, the informed principal can be better off than the principal in benchmark case by using the pooling offer. Maskin and Tirole (1990) also show that when the principal and the agent are risk-neutral, in other words they have a quasi-linear utility, the equilibrium payoff in the informed principal model is equal to the payoff when the principal's type is common knowledge. The reason is that principal and agent have same ratio of Lagrange multipliers when both principal and agent are risk-neutral (see proposition 11 in Maskin and Tirole, 1990).

2.2. Bilateral Information Asymmetry

In this section we derive the optimal contract when the principal's type is private information. Before deriving optimal contracts for the informed principal, we show that the equilibrium allocation in the pooling offer is Pareto superior to the allocation in the benchmark case. The notation follows that from Maskin and Tirole (1990). We shall refer to \bar{v}^i as principal i 's payoff in the benchmark case, i.e., $\bar{v}^i \equiv \sum_j p_j V^i(\bar{\mu}_j^i)$ and $\bar{\mu}_j^i = \{\bar{y}_j^i, \bar{t}_j^i\}$ denotes equilibrium allocation for each type of principal and agent in the benchmark case. $\bar{\rho}^i$ and $\bar{\gamma}^i$ are Lagrange multipliers from the solution to the benchmark case. Consider the following perturbed version (one with slack variables) of the benchmark case (F^i):

$$(F_*^i) = \begin{cases} \max_{\{y_j^i, t_j^i\}} \sum_{i=1}^2 p_j(b^i \cdot y_j^i - t_j^i) & \text{such that} \\ IR_2^i : U(t_2^i - \psi_2(y_2^i)) + r^i = 0 \\ IC_1^i : U(t_1^i - \psi_1(y_1^i)) + c^i = U(t_2^i - \psi_1(y_2^i)) \end{cases}$$

where r^i and c^i are slack variables associated with the IR and IC constraints, respectively. These are zero in the benchmark case because IR_2 and IC_1 are binding. Since different types of principal offer different contracts in the benchmark case, each type i of principal must satisfy IR_2 and IC_1 . In contrast, if different types of principal offer the same menu of contracts so that they conceal their private information, agents cannot observe the principal's type through the proposed contract and would expect to satisfy their IR and IC constraints on average. From the perspective of the type 2 agent, in the pooling offer, the IR constraint is satisfied in problem (F_*^i) :

$$IR : q^1(U(t_2^1 - \psi_2(y_2^1)) + r^1) + q^2(U(t_2^2 - \psi_2(y_2^2)) + r^2) = 0 \quad (4)$$

And using same logic, the type 1 agent expects the IC constraint to hold as follows:

$$IC : q^1(U(t_1^1 - \psi_1(y_1^1)) - U(t_2^1 - \psi_1(y_2^1)) + c^1) + q^2(U(t_1^2 - \psi_1(y_1^2)) - U(t_2^2 - \psi_1(y_2^2)) + c^2) = 0 \quad (5)$$

From the IR and IC constraints, we can obtain $q^1 r^1 + q^2 r^2 = 0$ and $q^1 c^1 + q^2 c^2 = 0$ which imply that slack variables need only be non-positive on average, and not for each type of principal. Let v_*^i be the maximized payoffs of principal i in perturbed problem. By definition of the shadow prices $\bar{\rho}^i$ and $\bar{\gamma}^i$, v_*^i approximately equals:

$$v_*^1 \simeq \bar{v}^1 + \bar{\rho}^1 \cdot r^1 + \bar{\gamma}^1 \cdot c^1 \quad (6)$$

$$v_*^2 \simeq \bar{v}^2 + \bar{\rho}^2 \cdot r^2 + \bar{\gamma}^2 \cdot c^2 \quad (7)$$

We can rewrite these as:

$$v_*^1 - \bar{v}^1 \simeq \bar{\rho}^1 \cdot r^1 + \bar{\gamma}^1 \cdot c^1 \quad (8)$$

$$v_*^2 - \bar{v}^2 \simeq \bar{\rho}^2 \cdot r^2 + \bar{\gamma}^2 \cdot c^2 \quad (9)$$

If the LHS of equations (8) and (9) are positive, the informed principal can be better off than the principal in the benchmark case by using the pooling offer. To have positive values of the LHS of equations (8) and (9), two conditions must hold simultaneously:

$$\bar{\rho}^1 \cdot r^1 + \bar{\gamma}^1 \cdot c^1 > 0 \quad (10)$$

$$\bar{\rho}^2 \cdot r^2 + \bar{\gamma}^2 \cdot c^2 > 0 \quad (11)$$

Rewriting the inequality condition (11) using $q^1 r^1 + q^2 r^2 = 0$ and $q^1 c^1 + q^2 c^2 = 0$ we obtain:

$$\bar{\rho}^2 \left(-\frac{q^1}{q^2} r^1 \right) + \bar{\gamma}^2 \left(-\frac{q^1}{q^2} c^1 \right) = -\frac{q^1}{q^2} (\bar{\rho}^2 r^1 + \bar{\gamma}^2 c^1) > 0 \quad (12)$$

This is equivalent to:

$$\bar{\rho}^2 r^1 + \bar{\gamma}^2 c^1 < 0 \quad (13)$$

Combining the inequality conditions (10) and (13) yields:

$$\frac{\bar{\rho}^2}{\bar{\gamma}^2} < -\frac{c^1}{r^1} < \frac{\bar{\rho}^1}{\bar{\gamma}^1} \quad (14)$$

For inequality (14) to hold, the ratio of the Lagrange multipliers must be different across different types of principal. We have shown in the previous section that different principals have a different ratio of Lagrange multipliers when the principal is risk-neutral and the agent is risk-averse. Therefore we have shown that informed principal can achieve a higher payoff than the principal in benchmark case by permitting slack variables on the constraints. For a more detailed proof, see Proposition 1 in Maskin and Tirole (1990).

2.2.1. Pooling Offer

In previous section, we have shown that the allocation $\bar{\mu}_j^i = \{\bar{y}_j^i, \bar{t}_j^i\}$ in the benchmark case is dominated by the allocation $\bar{\mu}_*^i = \{\bar{y}_*^i, \bar{t}_*^i\}$ which is the solution to the perturbed version of benchmark case. This implies that the principal, regardless of type, will propose the same menu of contracts, which is called the pooling offer. Using this result, we can characterize an optimal peat land retirement programme under the assumption that the principal is risk-neutral and the agent is risk-averse.

Unlike the benchmark case when the principal's type is common knowledge, private information about environmental benefits from peat land retirement can only be observed by the principal. We now have a sequential game of incomplete information. The equilibrium allocation resulting from the pooling offer should be a Perfect Bayesian Equilibrium (PBE). PBE requires that the equilibrium allocation is individual rational for the agent, and incentive compatible for the principal and the agent. To ensure this, we add two more constraints such as ICP¹ and ICP², which are incentive compatibility constraints for two type of principal. And we modify the IR and IC constraints such that they hold on average as under the pooling offer. When the principal has private information about the environmental benefits from peat land retirement, each type i of principal will propose the same menu of contracts that is the equilibrium allocation of (P^i) :

$$(P^i) = \begin{cases} \max_{\{y_j^i, t_j^i\}} \sum_{i=1}^2 p_j(b^i \cdot y_j^i - t_j^i) & \text{such that} \\ IR_2 : \sum_{i=1}^2 q^i U(t_2^i - \psi_2(y_2^i)) = 0 \\ IC_1 : \sum_{i=1}^2 q^i [U(t_1^i - \psi_1(y_1^i)) - U(t_2^i - \psi_1(y_2^i))] = 0 \\ ICP^1 : \sum_{i=1}^2 p_j(b^1 \cdot y_j^1 - t_j^1) \geq \sum_{i=1}^2 p_j(b^1 \cdot y_j^2 - t_j^2) \\ ICP^2 : \sum_{i=1}^2 p_j(b^2 \cdot y_j^2 - t_j^2) \geq \sum_{i=1}^2 p_j(b^2 \cdot y_j^1 - t_j^1) \end{cases}$$

Since both principals propose the same menu of contracts, agents cannot update their prior belief about the principal's type and accept the contract. We can obtain five conditions for equilibrium allocation in the pooling offer:

$$b^i = \psi_1'(y_1^i) \quad (15)$$

$$b^i = \psi_2'(y_2^i) + \frac{p_1}{p_2} \cdot (\psi_2'(y_2^i) - \psi_1'(y_2^i)) \cdot \frac{U'(t_2^i - \psi_1(y_2^i))}{U'(t_1^i - \psi_1(y_1^i))} \quad (16)$$

$$\sum_{i=1}^2 q^i U(t_2^i - \psi_2(y_2^i)) = 0 \quad (17)$$

$$\sum_{i=1}^2 q^i [U(t_1^i - \psi_1(y_1^i)) - U(t_2^i - \psi_1(y_2^i))] = 0 \quad (18)$$

$$-\frac{U(t_1^i - \psi_1(y_1^i)) - U(t_2^i - \psi_1(y_2^i))}{U(t_2^i - \psi_2(y_2^i))} = \frac{p_1}{p_2} \cdot \frac{U'(t_1^i - \psi_1(y_1^i))}{U'(t_2^i - \psi_2(y_2^i))} + \frac{U'(t_2^i - \psi_1(y_2^i))}{U'(t_2^i - \psi_2(y_2^i))} \quad (19)$$

We introduce a less constrained problem (P_*^i) to prove that optimal contract is a Perfect Bayesian Equilibrium. The less constrained problem is:

$$(P_*^i) = \begin{cases} \max_{\{y_j^i, t_j^i\}} \sum_{i=1}^2 p_j(b^i \cdot y_j^i - t_j^i) & \text{such that} \\ IR_2 : \sum_{i=1}^2 q^i U(t_2^i - \psi_2(y_2^i)) = 0 & (\tilde{\rho}^i) \\ IC_1 : \sum_{i=1}^2 q^i [U(t_1^i - \psi_1(y_1^i)) - U(t_2^i - \psi_1(y_2^i))] = 0 & (\tilde{\gamma}^i) \end{cases}$$

where $\tilde{\rho}^i$ and $\tilde{\gamma}^i$ are Lagrange multipliers in the less constrained problem (P_*^i) associated with the IR and IC constraints, respectively. The only difference between the pooling offer (P^i)

and the less constrained problem (P_*^i) is the absence of the incentive compatibility constraint for the two types of principal. This implies that the equilibrium allocation from the less constrained problem naturally satisfy the IR and IC constraints for the agent. The logic of the proof is that even the principal in the less constrained problem does not have an incentive to offer the other principal type's allocation, the optimal contract in the pooling offer (P^i) is incentive compatible for both types of principal. By showing this, we can prove that the equilibrium allocation from the less constrained problem (P_*^i) is indeed an equilibrium allocation in the pooling offer (P^i) and that the optimal contract by solving pooling offer (P^i) is a Perfect Bayesian Equilibrium. This proof follows from Cella (2005).

First, it is obvious that the optimal contract from the less constrained problem (P_*^i) also satisfies four conditions of the optimal contract in (P^i), which are equations (15)-(18), since these conditions come from IR and IC constraints for the agent that (P^i) and (P_*^i) have in common. Thus, we focus on the property that the optimal contract from the less constrained problem (P_*^i) is also incentive compatible for both types of principal. We can obtain the ratio of Lagrange multipliers in the less constrained problem (P_*^i) from its first-order conditions. The ratio of Lagrange multipliers is:

$$\frac{\tilde{\rho}^i}{\tilde{\gamma}^i} = \frac{p_1}{p_2} \cdot \frac{U'(t_1^i - \psi_1(y_1^i))}{U'(t_2^i - \psi_2(y_2^i))} + \frac{U'(t_2^i - \psi_1(y_2^i))}{U'(t_2^i - \psi_2(y_2^i))} \quad (20)$$

The ratio of Lagrange multipliers above is equivalent to RHS of equation (19). It is:

$$-\frac{U(t_1^i - \psi_1(y_1^i)) - U(t_2^i - \psi_1(y_2^i))}{U(t_2^i - \psi_2(y_2^i))} = \frac{\tilde{\rho}^i}{\tilde{\gamma}^i} \quad (21)$$

Note that agents expect their constraints to hold on average in the pooling offer. The numerator of the LHS in equation (21) is equal to the slack variable for IC constraint, r^i , and the denominator of the LHS in equation (21) is same as the slack variable for IR constraint, c^i . We can obtain equations (22) and (23):

$$\tilde{\rho}^1 r^1 + \tilde{\gamma}^1 c^1 = 0 \quad (22)$$

$$\tilde{\rho}^2 r^2 + \tilde{\gamma}^2 c^2 = 0 \quad (23)$$

And using the slack conditions that $q^1 r^1 + q^2 r^2 = 0$ and $q^1 c^1 + q^2 c^2 = 0$, we can rewrite equation (23) as follows:

$$-\frac{q^1}{q^2}(\tilde{\rho}^2 r^1 + \tilde{\gamma}^2 c^1) = 0 \quad (24)$$

Combining equation (22) and (24) yields:

$$\frac{\tilde{\rho}^1}{\tilde{\gamma}^1} = \frac{\tilde{\rho}^2}{\tilde{\gamma}^2} \quad (25)$$

Equation (25) implies that both types of principal have same relative cost of fulfilling the constraints at the optimal allocation in the less constrained problem. Since the principals cannot obtain additional surplus from relaxing the constraints, both principals have no incentive to deviate from their own allocation. Furthermore, the optimal allocation from the less constrained problem (P^i) is Pareto optimal since $\tilde{\rho}/\tilde{\gamma}$ is the slope of the value function at the equilibrium allocation. We have showed that each principal prefers her optimal allocation to the one of the other type. However, there is still other possibility that a principal offers an allocation which is neither optimal allocation for her type nor for the other principal type. By using FGP refinement (Farrell and Grossman-Perry), Maskin and Tirole (1990) show that no principal has an incentive to deviate from the solution to the pooling offer (P^i) thereby ruling out off-the-equilibrium paths. Therefore, we can claim that the optimal allocation from the pooling offer (P^i) is a Perfect Bayesian Equilibrium and any type of principal offers the same menu of contracts.

3. Numerical Examples

3.1. Preliminary Illustration for Optimal Allocation

This section provides numerical examples that illustrate the key results of the informed principal model with private values. We assume that agents (farmers) have an exponential utility function so that constant absolute risk aversion (CARA) represents their attitude to risk:

$$U(\pi) = 1 - \exp(-\lambda\pi), \quad U'(\pi) = \lambda \cdot \exp(-\lambda\pi), \quad U''(\pi) = -\lambda^2 \cdot \exp(-\lambda\pi) \quad (26)$$

where π is a farmer's income and λ stands for the degree of risk aversion. The farmer's income π is a function of the monetary transfer, t , under the peat land retirement programme and retirement costs, ψ . The Arrow-Pratt coefficient of constant absolute risk aversion is:

$$-\frac{U''(\pi)}{U'(\pi)} = \frac{\lambda^2 \cdot \exp(-\lambda\pi)}{\lambda \cdot \exp(-\lambda\pi)} = \lambda, \quad \lambda > 0 \quad (27)$$

Using the efficiency parameter, θ , we differentiate between two types of farmer: efficient and inefficient farmers depending on the costs of peat land retirement. The farmer's payoff function and retirement cost function are:

$$\pi_j = t - \psi_j(y), \quad \psi_j(y) = \frac{\theta_j}{2} y^2 \quad (28)$$

where $\theta_1 < \theta_2$ means that it is more efficient (less costly) for a type 1 agent to retire peat land than type 2 agent. In the Norwegian case, the retirement cost for peat land in the more climatically favourable southwest part of the country is higher than in the less favourable coastal regions in the north of the country.

To reflect the private information of the principals about environmental benefits from peat land retirement, we assume that there are two types of principal: each principal has a different environmental valuation on peat land retirement b^1 and b^2 , respectively. In the Norwegian case this can reflect the differences of interest between the Ministry of the Environment and the Ministry of Agriculture. The former tends to have a higher preference for environmental goods (or in this case the reduction of GHG emissions – an environmental bad), whereas the latter tends to have a higher preference for agricultural activities. To reflect this we assume $b^1 > b^2$ so that type 1 principal has a higher valuation on peat land retirement than the type 2 principal.

The probabilities of the agent's type j and the agent's common prior belief in type i principal are assumed to be 0.5. Other synthetic parameter values are summarized in table 1. Given these synthetic parameters, there is no guarantee that the set of constraints in the pooling offer is convex. Non-convexity means that the first-order conditions will not ensure a globally optimal solution, but only a local optimum. To address this problem, numerical solutions are derived using global optimization solver, GAMS/BARON (Elofsson, 2014).

Table 1. Synthetic Parameter Values

b^1	b^2	θ_1	θ_2	$p_1=p_2$	$q^1=q^2$	λ
10	8	1	2	0.5	0.5	0.5

There exist an infinite number of equilibrium allocations that are feasible for the pooling offer. The set of equilibrium allocations is also a Pareto set so that the principal can guarantee at least the same payoff he/she would obtain in benchmark case. So we provide two extreme examples. In the first all the additional surplus from the pooling offer is taken by principal 1 and in the second all the surplus is taken by principal 2.

Since we assume b^1 is greater than b^2 , the ratio of Lagrange multipliers is $\rho^1/\gamma^1 < \rho^2/\gamma^2$. This implies that the IC constraint is relatively more costly for the type 1 principal and the IR constraint is relatively more expensive for the type 2 principal. In the pooling offer, principal 1 will relax the IC constraint and enforce the IR constraint. Principal 2, on the other hand, will relax the IR constraint and tighten the IC constraint. Since the IR and IC constraints hold on average, both types of principal introduce slack variables on the IR and IC constraints:

$$IR: q^1 \underbrace{U(t_2^1 - \psi_2(y_2^1))}_{>0} + q^2 \underbrace{U(t_2^2 - \psi_2(y_2^2))}_{<0} = 0 \quad (29)$$

$$IC: q^1 \underbrace{[U(t_1^1 - \psi_1(y_1^1)) - U(t_2^1 - \psi_1(y_2^1))]}_{<0} + q^2 \underbrace{[U(t_1^2 - \psi_1(y_1^2)) - U(t_2^2 - \psi_1(y_2^2))]}_{>0} = 0 \quad (30)$$

Therefore, the type 2 agent who chooses the contract offered by the type 1 principal increases her/his utility level compared to the benchmark case while selection of the contract offered by type 2 principal decreases her/his utility level. However, the type 1 agent who accepts the contract proposed by the type 1 and 2 principals decreases her/his utility level compared to the benchmark case but that utility level is still greater than the reservation utility. That implies that the principal can reduce the information rent paid to an efficient type agent. Details on the optimal allocations, payoffs of principals and the utility levels of agents are in table 2 and 3.

Table 2. Comparison of Optimal Allocations

Allocations	Benchmark		Pooling Offer	
	Principal 1	Principal 2	Principal 1 takes all surplus	Principal 2 takes all surplus
y_1^1 (Downward Distortion)	10.000 (0.000)		10.000 (0.000)	10.000 (0.000)
t_1^1 (Information Rent)	55.556 (5.556)		52.867 (2.867)	55.101 (5.101)
y_2^1 (Downward Distortion)	3.333 (1.667)		4.991 (0.09)	4.987 (0.13)
t_2^1 (Information Rent)	11.111 (0.000)		26.462 (1.551)	28.105 (3.235)
y_1^2 (Downward Distortion)		8.000 (0.000)	8.000 (0.000)	8.000 (0.000)
t_1^2 (Information Rent)		35.556 (3.556)	34.525 (2.525)	34.300 (2.300)
y_2^2 (Downward Distortion)		2.667 (1.337)	2.083 (1.917)	2.465 (1.535)
t_2^2 (Information Rent)		7.111 (0.000)	3.476 (-0.863)	4.900 (-1.176)

Table 3. Comparison of Principal's Payoffs and Agent's Utility

Principal's Payoffs	Benchmark		Pooling Offer	
	Principal 1	Principal 2	Principal 1 takes all surplus	Principal 2 takes all surplus
V^1	33.333		35.288	33.333
V^2		21.333	21.333	22.261
Agent type 1 Utility	Case 1. Agent type 1 chooses the contract offered by principal type 1			
$U(t_1^1 - \psi_1(y_1^1))$	0.9378		0.762	0.922
$U(t_2^1 - \psi_1(y_2^1))$	0.9378		0.999	0.999
r^1	0.000		-0.237	-0.077
Agent type 1 Utility	Case 2. Agent type 1 chooses the contract offered by principal type 2			
$U(t_1^2 - \psi_1(y_1^2))$		0.831	0.717	0.683
$U(t_2^2 - \psi_1(y_2^2))$		0.831	0.480	0.606
r^2		0.000	0.237	0.077
Agent type 2 Utility	Case 3. Agent type 2 chooses the contract offered by principal type 1			
U_2^1	0.000		0.540	0.801
c^1	0.000		0.540	0.801
Agent type 2 Utility	Case 4. Agent type 2 chooses the contract offered by principal type 2			
U_2^2		0.000	-0.540	-0.801
c^2		0.000	-0.540	-0.801

4. Policy Implications

The main result of this study is that when a principal (the government) has private information about environmental benefits, he/she can achieve higher payoffs by using a pooling offer in an agri-environmental programme. This result may have implications for the disclosure of information by the principal. To improve the cost-effectiveness of agri-environmental policy, emphasis is placed on information acquisition rather than information disclosure. For instance, agri-environmental policy that does not take into account spatial differentiation may lead to efficiency losses. Governments can use a targeting strategy to these efficiency losses. The government gathers information about potential environmental benefits by location and proposes different contracts to farmers in different target areas. In the United States, for example, the Conservation Reserve Program (CRP) takes into account the ratio of environmental benefits to payments per acre in enrolling land in order to improve cost-effectiveness of the programme (Babcock *et al.*, 1996). Even if a targeting strategy that addresses spatial heterogeneity could improve the cost-effectiveness of agri-environmental policy, our analysis may provide a basis for rethinking such a strategy.

The benchmark case in this paper is similar to a targeting strategy when agents have differing abatement potential to mitigate GHG emission due to their location. We can think about the following example to relate targeting strategy to our model. Assume that farmers have different GHG abatement potential and that the government acquires this information before contracting. By using a targeted approach, the government reveals its private information through the different contracts it offers to farmers. Even though a targeting strategy can guarantee higher payoffs compared to the case where there is no information about spatial heterogeneity, as we have shown, the government can achieve higher payoffs by using a pooling offer compared to the targeting strategy.

Despite this, we cannot conclude that a pooling offer will always be a dominant strategy. The principal can only use a pooling offer when the agent has the same type regardless of the targeted group. And targeting still has advantages that we cannot guarantee with a pooling offer. It is well-known that targeting can reduce non-compliance (Fraser, 2004; Lankoski *et al.*, 2010) and can encourage increased participation in agri-environmental programmes (Glebe, 2010). This implies that targeting and pooling are not substitutes but rather complementary options which the principal can choose depending on the situation. Further research is needed on an optimal mixed strategy for targeting and pooling in the design of agri-environmental programmes.

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Appendix

I. Optimal contract in benchmark case

Principal i proposes a contract maximizes payoff subject to the IR and IC constraints below. Each principal i maximizes environmental be

$$(F^i) = \begin{cases} \max_{\{y_j^i, t_j^i\}} \sum_{j=1}^2 p_j (b^i \cdot y_j^i - t_j^i) & \text{such that} \\ IR_2^i : U(t_2^i - \psi_2(y_2^i)) = 0 & (\rho^i) \\ IC_1^i : U(t_1^i - \psi_1(y_1^i)) = U(t_2^i - \psi_1(y_2^i)) & (\gamma^i) \end{cases}$$

First-order Conditions are:

$$\frac{\partial L}{\partial y_1^i} = p_1 \cdot b^i - \gamma^i \cdot \frac{\partial U(t_1^i - \psi_1(y_1^i))}{\partial (t_1^i - \psi_1(y_1^i))} \cdot \psi_1'(y_1^i) = 0 \quad (A1)$$

$$\frac{\partial L}{\partial y_2^i} = p_2 \cdot b^i - \rho^i \cdot \frac{\partial U(t_2^i - \psi_2(y_2^i))}{\partial (t_2^i - \psi_2(y_2^i))} \cdot \psi_2'(y_2^i) + \gamma^i \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial (t_2^i - \psi_1(y_2^i))} \cdot \psi_1'(y_2^i) = 0 \quad (A2)$$

$$\frac{\partial L}{\partial t_1^i} = -p_1 + \gamma^i \cdot \frac{\partial U(t_1^i - \psi_1(y_1^i))}{\partial (t_1^i - \psi_1(y_1^i))} = 0 \quad (A3)$$

$$\frac{\partial L}{\partial t_2^i} = -p_2 + \rho^i \cdot \frac{\partial U(t_2^i - \psi_2(y_2^i))}{\partial (t_2^i - \psi_2(y_2^i))} - \gamma^i \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial (t_2^i - \psi_1(y_2^i))} = 0 \quad (A4)$$

$$\frac{\partial L}{\partial \rho^i} = U(t_2^i - \psi_2(y_2^i)) = 0 \quad (A5)$$

$$\frac{\partial L}{\partial \gamma^i} = U(t_1^i - \psi_1(y_1^i)) - U(t_2^i - \psi_1(y_2^i)) = 0 \quad (A6)$$

1. Rewrite equation (A3)

$$p_1 = \gamma^i \cdot \frac{\partial U(t_1^i - \psi_1(y_1^i))}{\partial (t_1^i - \psi_1(y_1^i))} \text{ and plugging this into equation (A1). We can obtain } b^i = \psi_1'(y_1^i).$$

2. Using equation (A5) and (A6), we can get $t_2^i = \psi_2(y_2^i)$ and $t_1^i - \psi_1(y_1^i) = t_2^i - \psi_1(y_2^i)$. We can rewrite this as $t_1^i = \psi_1(y_1^i) + \psi_2(y_2^i) - \psi_1(y_2^i)$.

3. Rewrite equation (A4)

$$\rho^i \cdot \frac{\partial U(t_2^i - \psi_2(y_2^i))}{\partial(t_2^i - \psi_2(y_2^i))} = p_2 + \gamma^i \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial(t_2^i - \psi_1(y_2^i))} \text{ and plugging this into equation (A2).}$$

$$p_2 \cdot b^i - \left(p_2 + \gamma^i \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial(t_2^i - \psi_1(y_2^i))} \right) \cdot \psi_2'(y_2^i) + \gamma^i \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial(t_2^i - \psi_1(y_2^i))} \cdot \psi_1'(y_2^i) = 0$$

$$p_2 \cdot b^i = p_2 \cdot \psi_2'(y_2^i) + \gamma^i \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial(t_2^i - \psi_1(y_2^i))} \cdot (\psi_2'(y_2^i) - \psi_1'(y_2^i))$$

$$b^i = \psi_2'(y_2^i) + \frac{\gamma^i}{p_2} \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial(t_2^i - \psi_1(y_2^i))} \cdot (\psi_2'(y_2^i) - \psi_1'(y_2^i))$$

$$\frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial(t_2^i - \psi_1(y_2^i))} = \frac{\partial U(t_1^i - \psi_1(y_1^i))}{\partial(t_1^i - \psi_1(y_1^i))} \text{ (Since IC1 is binding)}$$

$$\gamma^i \cdot \frac{\partial U(t_2^i - \psi_1(y_2^i))}{\partial(t_2^i - \psi_1(y_2^i))} = \gamma^i \cdot \frac{\partial U(t_1^i - \psi_1(y_1^i))}{\partial(t_1^i - \psi_1(y_1^i))} = p_1 \text{ by equation (A3). Plugging this into equation above.}$$

$$b^i = \psi_2'(y_2^i) + \frac{p_1}{p_2} \cdot (\psi_2'(y_2^i) - \psi_1'(y_2^i))$$

Optimal contract for type 1 agent: $b^i = \psi_1'(y_1^i)$ and $t_1^i = \psi_1(y_1^i) + \psi_2(y_2^i) - \psi_1(y_2^i)$

Optimal contract for type 2 agent: $b^i = \psi_2'(y_2^i) + \frac{p_1}{p_2} \cdot (\psi_2'(y_2^i) - \psi_1'(y_2^i))$ and $t_2^i = \psi_2(y_2^i)$