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EFFICIENT AGRI-ENVIRONMENTAL POLICY DESIGN FOR JOINTLY PRODUCED MULTIPLE ENVIRONMENTAL GOODS

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Abstract

This paper focuses on environmental goods production when contracted by means of agri-environmental agreements. It is explicitly accounted for jointness among environmental goods and for heterogeneity among farms. Two different types of agri-environmental programmes are considered: 1) part farm programmes, which give to the farmer the liberty to subscribe only a part of the eligible land, and 2) whole farm programmes, which explicitly ask for involving of all the land. Applicability of menus of contracts designed to deal with the adverse selection problem in the Principal-Agent framework is analysed using a general quadratic multi-output cost function. Obtained results are compared with the uniform payment contract option. It is proved that in some cases whole farm programmes are less expensive than part farm programmes and thus Government can save public funds by asking farmers to produce more environmental goods. Also the adverse selection is less a problem in whole farm programmes than in part farm programmes. A numerical simulation is carried out using parameters of the cost function estimated for environmental goods production by suckler cow farms in the Protected Landscape Area White Carpathians in the Czech Republic by a mathematical programming farm level model.

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1. Introduction

Joint supply of several outputs can be considered as a typical characteristic of agricultural production. A well known example is the one of mutton and wool discussed already by Marshall (1959). Although it is possible to change the produced proportion of mutton and wool, it is impossible to separate them completely. They are technically joint. This type of jointness can be translated into jointness due to a non-allocable input, e.g. hay, whose consumption cannot be attributed unambiguously between mutton and wool. In the 80s of the last century, Shumway et al. (1984) pointed out another type of jointness in production, jointness due to an allocable fixed input. Land can be often considered as such. Its fixity causes that a change in the demand for one crop may change the supply of another crop even if there is no other technical linkage between these two outputs.

At the beginning of this century, OECD (2001) re-examined the different types of jointness focusing this time not on jointness between agricultural commodities but on jointness between commodities and non-commodities, in order to formalise the multifunctional character of agriculture. The topic was treated also empirically by Peerlings and Polman (2004) and by Havlík et al. (2005). The aim was to find whether agricultural policies may be justified by the jointness between agricultural commodities and non-commodities. In some specific cases the answer is affirmative but generally, targeted agri-environmental programmes are necessary to attain environmental objectives mainly if jointness between commodities and non-commodities is negative. In order to design agri-environmental agreements efficiently, the interest in jointness has to shift once again, this time from jointness between commodities and non-commodities to jointness between non-commodities themselves.

The jointness between non-commodities was for the first time dealt with by Havlík et al. (2006) in a case study from White Carpathians, the Czech Republic. They analysed the grassland biodiversity production by suckler cow farms under the Czech agri-environmental programme, the “Sound Grassland Management” (SGM) programme. This programme proposes to farmers several agreements. Agreements for hay meadows are different from agreements for grazed grassland. As the agreements are signed for five years, it can be supposed that different types of biodiversity, meadow biodiversity and pasture biodiversity, develop under different agreements. The overall biodiversity production is maximised if both types of biodiversity are produced thus the Government is not indifferent concerning the structure of subscribed agreements. It was demonstrated that because of the negative jointness between the two types of biodiversity, unsatisfactory production of one of them may be corrected not only by increasing the payment for the corresponding agreements but also by decreasing payments for agreements aiming at production of the other biodiversity type.

It is not exceptional that Governments aim at production of several environmental goods produced on one farm as can be seen from the number of agreements usually proposed to a farmer. The agreements are often incompatible, in the sense that a particular spot of land can be subscribed under one agreement only. Land can be considered as a fixed factor causing negative jointness between the environmental goods. Some efficiency gains could be probably obtained by specialisation of different farms in production of different environmental goods. Specialisation supposes heterogeneity in farms. But heterogeneity causes the adverse selection problem due to asymmetric information because the Government ignores which farm is of which type or because although the Government has this information, it cannot use it (Chambers, 1992).

Wu and Babcock (1995) dealt explicitly with the problem of adverse selection concerning agri-environmental agreements by applying the principles of mechanism design developed in the general form by Baron and Myerson (1982), Guesnerie and Laffont (1984), and others. Wu and Babcock considered that the Government has only one environmental objective - the pollution reduction. They presented the analysis first within a two farm types framework, later they analysed the problem solution also with a continuum of farm types (Wu and Babcock, 1996). Their work inspired many other authors but to the best of our knowledge only the paper by Jayet and Bontemps (1996) considers explicitly more than one Government's objectives and more than one policy instruments to attain them.

Jayet and Bontemps analysed the case where the Government applies two different instruments to regulate the farmers: set asides and an agri-environmental programme aiming at reduction of fertilisation. In their paper the Government's aim is not only to reduce negative environmental externalities but also to reduce the agricultural supply excess on farms specialised in wheat production. They consider a continuum of farms indexed by a productivity parameter. Their main result is that under perfect as well as under asymmetric information the welfare maximisation requires that one farm participates at maximum in one of the programmes. They stress that this outcome relies heavily on the hypothesis of land homogeneity within a farm which makes that the cost of compliance with one programme increases for a farm linearly with the area subscribed under the programme and that it is independent from the area subscribed under the other programme.

The reason of the reluctance of other economists to deal with the politically pertinent problem of optimal contract design for several environmental goods, is probably the one mentioned by Laffont and Martimort (2002). They state that the optimal solutions are hard to analyse without further specifying the Principal's general value function and the Agent's general cost function if the Principal aims at more than one good.

The aim of our paper is to check whether the mechanism design applied usually to one environmental good is applicable also when two environmental goods are to be produced. The analysis is carried out for an agri-environmental programme containing two different agreements aiming at production of two different environmental goods. Each good is produced by applying different land management therefore the land subscribed under one agreement cannot be subscribed under the other one. It is supposed that there is negative jointness between agricultural production and environmental good production as well as in the production of environmental goods themselves. We overcome the problem of the general value function by externalising completely the decision about optimal quantities supposing that they were determined by a panel of experts and representatives of different interest groups and the Government's only task is to ensure their supply by farmers for minimal budgetary expenditure. The farmer's cost function takes the general quadratic form which enables to account explicitly for jointness in production between different environmental goods.

Solutions for two different programme structures are analysed here: part farm programmes and whole farm programmes. With part farm programmes, the farmer has the liberty to decide not only which area he subscribes under which agri-environmental agreement but also which area he subscribes under both agreements in total. With a whole farm programme, the whole farm, or all the eligible land, is to be subscribed under the programme. This restriction of the farmer's liberty can be used, as we will demonstrate, to reduce the farmer's overcompensation from the agri-environmental programme.

The structure of the paper is as follows: the first part is an analytical one; it starts by presentation of the general Principal's problem and analysis progressively the part farm programmes and the whole farm programmes. In the second part, the analytically obtained results are tested numerically on the case study introduced in Havlík et al. (2006) concerning production of different types of biodiversity by suckler cow farms from White Carpathians. At the end some conclusions are given.

2. Analytical approach

Designing efficient agri-environmental programmes means matching the Government's problem of welfare maximisation with the farmer's problem of profit maximisation. We suppose that the Government aims at production of two environmental goods, environmental good 1 and environmental good 2, by means of two agri-environmental agreements, agreement 1 and agreement 2. The problem of farm heterogeneity is simplified by considering existence of only two different farm types: L-farms with low land productivity and H-farms with high land productivity. We adopt the hypothesis of constant returns to scale, each farm is considered being of size 1 and all the farm is eligible for the agri-environmental programme. L-farms occupy the share *s* of the total eligible land *Y*. As there are no other farm types, H-farms occupy the share (1-*s*) of *Y*. The area subscribed by a k-farm (k = L, H) under an agreement *i* (*i* = 1, 2) will be labelled y_i^k. As the eligible land occupied by a farm is of size 1, y_i^k will take values between 0 and 1. Thus more generally we can interpret it as the share of land to be subscribed under the agreement *i* by a k-farm. Finally, the total area subscribed under agreement *i* by all k-farms will be denoted Y_i^k. (The total area of land subscribed for example under agreement 1 by all L-farms is determined as $Y_1^L = y_1^L\ s\ Y$). In order to simplify the notation, *Y* is in what follows considered equal to 1.

The Government's problem of welfare maximisation can be decomposed into two sub-problems: definition of optimal quantities of environmental goods to be produced and setting up of a contractual mechanism to obtain these quantities for minimum budgetary expenditure. In this paper, we suppose that the first sub-problem was solved externally, and we focus on the second sub-problem.[1] Thus the Government's problem, G, reduces to minimisation of budgetary expenditure subject to an environmental objective expressed as the area to be subscribed under the agri-environmental programme, O, and to the farmers' economic rationality constraints, F^k. The environmental objective is expressed by a coefficient q, $0 \le q \le 1$. The exact meaning of *q* will differ depending on the analysed programme structure but for the moment we can consider it as the portion of total eligible land to be involved under the agri-environmental programme. The farmer's economic rationality is summarised here in the profit maximising behaviour. The Principal's problem can be written formally as follows

G: $\underset{y_i^k, t_i^k}{\text{Min}}\ E(q)$

s.t.

O: $\sum_i \sum_k Y_i^k = q$, $i = 1, 2$, $k = L, H$,

F^k: $\underset{y_1^k, y_2^k}{\text{Max}}\ \pi^k(t_1^k, t_2^k)$, $k = L, H$,

where *E*() is the budgetary expenditure as a function of the environmental objective *q*. The Principal's decision variables are the share of land to be subscribed under agreement *i* by

[1] Only budgetary expenditure due to transfer payments is considered here, other cost like the administrative one is neglected.

farms of type k, y_i^k, and the per hectare payment for the agreement i to farms of type k, t_i^k. Farmer's decision variables are the shares of land to be subscribed under particular agreements. In order to ensure implementability of the programme, the Principal has to design the contracts in such a way that the shares of land to be subscribed under particular agreements by particular farm-types are the profit maximising ones for these farm types.[2]

The profit function $\pi^k()$ can be detailed as follows

$$\pi^k(p_1^k, p_2^k) = \tilde{\pi}^k + t_1^k y_1^k + t_2^k y_2^k - c^k(y_1^k, y_2^k),$$

where $\tilde{\pi}^k$ is the maximum profit attainable by the k-farm if it does not participate in the agri-environmental programme and $c^k(y_1^k, y_2^k)$ is the compliance cost with the agri-environmental programme as a function of the areas subscribed under particular agreements. The maximum attainable profit is considered fixed thus solving the problem of profit maximisation is equivalent to maximising the difference between transfer payments from the agri-environmental programme and the compliance cost.

The compliance cost function takes a specific form here, the quadratic one

$$c^k(y_1^k, y_2^k) = \theta^k(a_1 y_1^k + a_2 y_2^k + a_3 {y_1^k}^2 + a_4 {y_2^k}^2 + a_5 y_1^k y_2^k).$$

We suppose that the coefficients a are positive. Thus the compliance cost is zero if no environmental good is produced, and it is positive for any positive quantity produced. The compliance cost function is increasing in quantities of both environmental goods, which expresses the fact that the jointness between agricultural production and any of the environmental goods is negative. Also jointness between environmental goods themselves is negative. (The marginal cost of compliance with agreement i increases as the share of land subscribed under agreement j increases, $\delta^2 c^k/\delta y_i \delta y_j = \theta^k a_5$.) The marginal cost of compliance with each agreement is increasing.[3] To ensure that the first order conditions are not only necessary but also sufficient for profit maximisation, we suppose that the coefficients respect the convexity condition $a_5 \leq 2\sqrt{a_3 a_4}$. The farm heterogeneity is expressed by the land productivity parameter θ^k, ($\theta^L < \theta^H$). As the cost of compliance is constituted mainly by the loss of income from agricultural production due to the restrictions contained in the agri-environmental programme, it is higher for farms with higher land productivity.

Constraints resulting for the policy maker from the farmer's maximisation behaviour differ according to the programme structure and the contract type. For both programme structures, part farm programmes and whole farm programmes, three contract types will be designed and compared: differentiated contracts with perfect information, uniform payment contracts, and differentiated contracts with asymmetric information. Perfectly differentiated contracts represent the first best solution which could be applied if we had complete information about the type of each farm and if we could use it. They determine the area to be subscribed under each agreement and the per hectare payment for each farm type. Uniform payment contracts determine only the per hectare payments for each agreement and the farmers choose which

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[2] The farmer's profit maximisation is also a constrained problem because the land is considered as a fixed factor, ($y_1^k + y_2^k \leq 1$). This constraint is neglected in the analytical part but it is accounted for in the applied one.

[3] Increasing marginal compliance cost can represent two different phenomena: 1) heterogeneity of land within a farm, thus the marginal cost increases because progressively more and more productive land is to be subscribed, or 2) decreasing substitutability for the production lost on the subscribed land by the production on the not subscribed land. Because the land is considered being a fixed factor, an increase in the share of land subscribed under an agreement decreases the share of land farmed without restrictions. The second interpretation is especially pertinent for grassland based livestock systems.

area they subscribe under which agreement. Contracts differentiated under asymmetric information are the result of applying the classical mechanism design and they determine a menu of contracts differentiated by the shares of land to be subscribed under different agreements and by the per hectare payment.

Although it is not the aim of this paper to analyse the case where the Principal is interested in production of one environmental good only, we start with this problem because it enables to position the applied analytical framework towards its predecessors and because it will be useful as a benchmark for comparison with the two goods programmes. Then the part farm programme with two environmental goods is analysed, and we finish by presenting the whole farm programme with two environmental goods. The corresponding solutions are briefly discussed in the text. The exact expressions for optimal quantities and for the corresponding values of budgetary expenditure are reported in Annex 1.

2.1 Part farm programmes – one environmental good

The Principal's objective in terms of environmental goods can be for the one good problem written as follows

$$\text{O: } y_1^L s + y_1^H (1-s) = q \,,$$

where q represents the portion of the farm to be subscribed under agreement 1. There are no other agreements proposed so the land which is not subscribed under agreement 1 is not concerned by the agri-environmental programme and the farmer can use it without restrictions.

a) Perfect information: Differentiated contracts

If the Principal has perfect information about which farm is of which type, he can offer to it a take-it-or-leave-it contract specifying the share of land to be subscribed under the agreement. Thus a menu of contracts [y_1^k, t^k] can be elaborated. Budgetary expenditure is

$$E \;=\; t^L y_1^L s \;+\; t^H y_1^H (1\text{-}s)\,.$$

With a take-it-or-leave-it contract, the farmer's optimisation problem reduces to the comparison of compliance cost with the specified share of land to be subscribed under the agreement, and the offered transfer payment. Thus the only constraints added to the Principal's problem from the farmer's one are the well known *individual rationality constraints* (IR)

$$\text{IR}^{\text{L}}\text{: } t^L y_1^L \;\geq\; c^L(y_1^L)\; (=\; \theta^L (a_1 y_1^L \;+\; a_3 {y_1^L}^2))$$

$$\text{IR}^{\text{H}}\text{: } t^H y_1^H \;\geq\; c^H(y_1^H)\; (=\; \theta^H (a_1 y_1^H \;+\; a_3 {y_1^H}^2))\,.$$

The Principal's aim is to minimise budgetary expenditure therefore these constraints will be always satisfied as equalities. As the transfer payment to a k-farm is equal to its average compliance cost, the Principal's problem simplifies to finding the cost minimising distribution of the environmental good production between the two farm types

Min $c(Y_1) \;=\; c^L(y_1^L)s \;+\; c^H(y_1^H)(1\text{-}s)$

s. t.

O.

This simple problem can be solved by the following Lagrangian

$$L(y_1^L, y_1^H, \mu) = c^L(y_1^L)s + c^H(y_1^H)(1\text{-}s) + \mu O .$$

The first order conditions after having substituted the complete expressions for cost functions are

L_{y1L}: $\theta^L(a_1 + 2a_3 y_1^L) = \mu$

L_{y1H}: $\theta^H(a_1 + 2a_3 y_1^H) = \mu$

L_{μ}: $y_1^L s + y_1^H(1\text{-}s) = q$.

At the optimum, marginal cost of compliance of an L-farm is equal to marginal cost of compliance of an H-farm, which is equal to the Lagrange multiplier μ. It follows directly that the share of land to be subscribed under agreement 1 by an L-farm, y_1^L, will be always higher than the share of land to be subscribed by an H-farm, y_1^H. Generally, the more the compliance cost function will be convex, the lower will be the difference between shares of land to be subscribed by respective farm types.

b) Asymmetric information: Uniform payment contracts

Under asymmetric information, we cannot impose the quantities to be produced together with a transfer payment remunerating just the cost of compliance of a particular farm because we do not know it. The usual way to overcome this problem is to propose a uniform per hectare payment and to leave the farmer to choose which area he subscribes. Thus the Government's proposition reduces from a menu of contracts to a single parameter, the payment for agreement 1, t_1.[4] The budgetary expenditure in general form is

$$E = t_1(y_1^L s + y_1^H(1\text{-}s)) .$$

The farmer's decision problem differs substantially from the perfect information case because he has not only to decide whether he participates or not but also which share of land he subscribes under the agreement. The profit maximisation behaviour leads farmers to subscribe the share of land for which their marginal cost of compliance, *mc*, equals to the proposed payment. In parallel to the individual rationality constraints, which demand that the total transfer is equal or higher than the total cost of compliance, we will call the constraints resulting from the profit maximisation by farmers *marginal individual rationality constraints* (mIR)

$$\text{mIR}^{\text{L}}: \ t_1 = mc^L \ (= \theta^L(a_1 + 2a_3 y_1^L))$$
$$\text{mIR}^{\text{H}}: \ t_1 = mc^H \ (= \theta^H(a_1 + 2a_3 y_1^H)) .$$

[4] This contract type called "uniform payment contracts" differs from "undifferentiated contracts". The "undifferentiated contracts" would similarly as the differentiated contract under perfect information determine both the quantity to be produced and the payment for it. In what we call a "uniform payment contract", only per hectare payments are determined and the farmer chooses the area to subscribe. The payments are uniform with respect to farm types but they are differentiated with respect to environmental goods; there is a different payment for each agreement.

These conditions are at the equilibrium satisfied as equalities because otherwise the farmer is motivated to subscribe a share of land which differs from the one desired by the Principal.[5]

The solution to the Principal's problem was already obtained in the preceding subsection. The cost minimising quantities are the optimal solution also here and the per hectare payment t_1 is equal to the Lagrange multiplier μ, which is the marginal cost of production of a supplementary hectare of environmental good 1. (The solution could be alternatively obtained by solving the system of 3 equations (mIR^L, mIR^H, O) with 3 unknowns (y_1^L, y_1^H, t_1)).

Budgetary expenditure with a uniform payment will be always higher than budgetary expenditure with perfectly differentiated contracts. The difference between budgetary expenditure with uniform payment contracts and budgetary expenditure with differentiated contracts will increase if the share of total land to be subscribed under the agreement q increases.

c) Asymmetric information: Differentiated contracts

Under asymmetric information a menu of contracts can be designed, combining different transfer payments with different quantities to be produced similarly as with perfect information [y_1^k, t^k]. Thus the general expression for budgetary expenditure is also the same

$$E = t^L y_1^L s + t^H y_1^H (1\text{-}s).$$

In this case, the farmer's decision problem is an intermediate one between the case of perfectly differentiated contracts and uniform payment contracts because he can now choose between several take-it-or-leave-it contracts. First, the farmer has to check whether the transfer payment covers his cost of compliance, individual rationality constraints are to be respected, and than he chooses which contract is more profitable for him, *incentive compatibility constraints* (IC) are to be added to the perfect information problem in order for the farmer to voluntarily choose the contract designed for him. No adjustments at the margin are possible, thus marginal individual rationality constraints do not apply

$$\text{IC}^L\!: \; t^L y_1^L - \theta^L (a_1 y_1^L + a_3 y_1^{L^2}) \geq t^H y_1^H - \theta^L (a_1 y_1^H + a_3 y_1^{H^2})$$
$$\text{IC}^H\!: \; t^H y_1^H - \theta^H (a_1 y_1^H + a_3 y_1^{H^2}) \geq t^L y_1^L - \theta^H (a_1 y_1^L + a_3 y_1^{L^2}).$$

It can be easily demonstrated that IC^L and IR^H are at the optimum satisfied as equalities, and that their satisfaction implies also satisfaction of IC^H and IR^L therefore the latter two equations can be neglected. For a formal demonstration, see for example Moxey et al. (1999). Thus as with perfect information, the transfer payment to H-farmers will be equal to their compliance cost but the transfer payment to L-farmers will be equal to their compliance cost plus the difference in compliance cost with the quantity to be produced by an H-farm between H-farms and L-farms, the *information rent*, $(\theta^H\text{-}\theta^L)(a_1 y_1^H + a_3 y_1^{H2})$.

The Principal's problem has four unknowns (y_1^L, t_1^L, y_1^H, t_1^H) and three equations (O, IC^L, IR^H). It can be solved as a constrained minimisation problem using a Lagrangian.

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[5] It can be easily seen than not only for the considered quadratic cost function, but for every increasing convex cost function, satisfaction of marginal individual rationality constraints implies satisfaction of individual rationality constraints. Thus we can neglect them here.

The share of land to be subscribed under the agreement by an L-farm will be always higher than the share of land to be subscribed by an H-farm. The share of land subscribed by an H-farm will be lower than the cost minimising one. This is a common result in adverse selection problems because decreasing the quantity produced by the less efficient farmer enables to decrease the information rent to be paid to L-farmers. But because of the definition of Principal's objective in terms of quantities, the share of land subscribed by an L-farmer has to be higher than the cost minimising one.[6]

It can be proved that budgetary expenditure with differentiated contracts under asymmetric information is always higher than budgetary expenditure with perfect information, but it is always lower than budgetary expenditure with uniform payment contracts.

2.2 Part farm programmes - two environmental goods

In this section we analyse the case where the Principal aims at production of two different environmental goods, each one defined by an agri-environmental agreement. The agri-environmental agreements are incompatible in the sense that particular land can be subscribed under one or another of these agreements but not under both agreements at the same time. The parameter q represents now the portion of total eligible land to be involved under the agri-environmental programme and we suppose that similarly as the parameter q is determined exogenously, also the preferences about which portion of the involved land should be subscribed under which agreement are given exogenously. For sake of simplicity we consider that the objective is that one half of the land involved under the programme is subscribed under the agreement 1 and the other half under the agreement 2

$$\mathrm{O}_1:\ y_1^L s + y_1^H(1\text{-}s) = q/2$$
$$\mathrm{O}_2:\ y_2^L s + y_2^H(1\text{-}s) = q/2\,.$$

a) Perfect information: Differentiated contracts

The menu of contracts with two environmental goods contains three parameters for each farm type $[y_1^k, y_2^k, t^k]$: the share of land to be subscribed under agreement 1, the share of land to be subscribed under agreement 2, and the payment per hectare of land involved under the agri-environmental programme. Thus the general form of budgetary expenditure will be as follows

$$E \;=\; t^L(y_1^L + y_2^L)s \;+\; t^H(y_1^H + y_2^H)(1\text{-}s)\,.$$

The farmers' rationality can be summarised in two individual rationality constraints. They differ from those of the single good case only by the cost function, which accounts now for both environmental goods

$$\mathrm{IR^L}:\ t^L(y_1^L + y_2^L) \ge c^L(y_1^L, y_2^L)\ (= \theta^L(a_1 y_1^L + a_2 y_2^L + a_3 {y_1^L}^2 + a_4 {y_2^L}^2 + a_5 y_1^L y_2^L))$$
$$\mathrm{IR^H}:\ t^H(y_1^H + y_2^H) \ge c^H(y_1^H, y_2^H)\ (= \theta^H(a_1 y_1^H + a_2 y_2^H + a_3 {y_1^H}^2 + a_4 {y_2^H}^2 + a_5 y_1^H y_2^H))\,.$$

Budgetary expenditure minimisation is thus equivalent to minimisation of the total compliance cost by optimally distributing production of the environmental goods among the respective farm types

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[6] If the objective is defined in terms of a value function, the common result is that L-farmers continue to produce the cost minimising quantity.

$$\text{Min } c(Y) = c^L(y_1^L, y_2^L)s + c^H(y_1^H, y_2^H)(1\text{-}s)$$
s. t.
O_1, O_2.

This problem can be transformed in the following Lagrangian

$$L(y_1^L, y_2^L, y_1^H, y_2^H, \mu_1, \mu_2) = c^L(y_1^L, y_2^L)s + c^H(y_1^H, y_2^H)(1\text{-}s) + \mu_1 O_2 + \mu_2 O_2$$

The first order conditions after substituting for the cost functions are

L_{y1L}: $\theta^L(a_1 + 2a_3 y_1^L + a_5 y_2^L) = \mu_1$

L_{y2L}: $\theta^L(a_2 + 2a_4 y_2^L + a_5 y_1^L) = \mu_2$

L_{y1H}: $\theta^H(a_1 + 2a_3 y_1^H + a_5 y_2^H) = \mu_1$

L_{y2H}: $\theta^H(a_2 + 2a_4 y_2^H + a_5 y_1^H) = \mu_2$

$L_{\mu 1}$: $y_1^L s + y_1^H(1\text{-}s) = q/2$

$L_{\mu 2}$: $y_2^L s + y_2^H(1\text{-}s) = q/2$.

Because of the jointness parameter a_5, the optimal production distribution of both environmental goods is to be carried out simultaneously. Contrary to the one good case, it is not possible to state that an L-farm will have to subscribe more land under both agreements than an H-farm which would be the case if the jointness parameter were equal to zero.

The difference in the optimal shares of land to be subscribed under respective agreements by an L-farm will depend on the sign of the following term $(2(a_2 a_3 - a_1 a_4) + a_5(a_2 - a_1))$. If it is positive, which means that the cost of production of environmental good 1 is generally lower than the cost of production of environmental good 2 and that the cost of production of environmental good 1 is relatively convex, the share of land subscribed under the agreement 2 by an L-farm will be higher than the share of land subscribed under the agreement 1. We can notice that the higher the jointness parameter a_5 will be the larger will be the difference between the two quantities. The difference in shares of land subscribed under respective agreements by an H-farm will depend on exactly the same term but its impact will be the opposite from above. Thus an H-farm will have to subscribe relatively less of the more restrictive agreement and to produce rather the less restrictive environmental good.

The difference in shares of land subscribed under the agreement 1 by respective farm types will depend on the sign of the following term $q(4a_3 a_4 - a_5^2) + 2(2a_1 a_4 - a_2 a_5)$. If it is negative, an L-farm will subscribe less land under the agreement 1 than an H-farm. Similarly, the share of land subscribed under the agreement 2 by an L-farm will be higher than the share of land subscribed under this agreement by an H-farm if the term $q(4a_3 a_4 - a_5^2) + 2(2a_2 a_3 - a_1 a_5)$ is negative.

b) Asymmetric information: Uniform payment contracts

If the Government wants to ensure production of specific quantities of respective environmental goods with uniform payment contracts it has to propose different per hectare payments for each good, t_1 and t_2. The budgetary expenditure can be expressed as

$$E = t_1(y_1^L s + y_1^H(1\text{-}s)) + t_2(y_2^L s + y_2^H(1\text{-}s)).$$

As the farmers are free to decide which portion of their land they subscribe under which agreement, marginal individual rationality conditions are to be respected. They are not two as in the one good case, they are four

$$\text{mIR}_1{}^{\text{L}}\text{: } t_1 = mc_1^L \ (= \theta^L(a_1 + 2a_3 y_1^L + a_5 y_2^L))$$
$$\text{mIR}_2{}^{\text{L}}\text{: } t_2 = mc_2^L \ (= \theta^L(a_2 + 2a_4 y_2^L + a_5 y_1^L))$$
$$\text{mIR}_1{}^{\text{H}}\text{: } t_1 = mc_1^H \ (= \theta^H(a_1 + 2a_3 y_1^H + a_5 y_2^H))$$
$$\text{mIR}_2{}^{\text{H}}\text{: } t_2 = mc_2^H \ (= \theta^H(a_2 + 2a_4 y_2^H + a_5 y_1^H)).$$

The individual rationality constraints have to be satisfied as well but similarly as in the single good case they can be neglected because satisfaction of marginal individual rationality constraints implies also their satisfaction.

As in the one good case, the cost minimising quantities determined for the perfect information problem are the optimal solution also to the uniform payment problem. And the payments for respective goods are equal to the Lagrange multipliers from the perfect information problem. It can be proved that budgetary expenditure with uniform payments will be always higher than budgetary expenditure with perfectly differentiated contracts.

c) Asymmetric information: Differentiated contracts

The menu of contracts differentiated under asymmetric information has the same structure as the menu of contracts differentiated under perfect information, [$y_1{}^k$, $y_2{}^k$, t^k], therefore the general form of budgetary expenditure is also the same

$$E = t^L(y_1^L + y_2^L)s + t^H(y_1^H + y_2^H)(1\text{-}s).$$

Farmers' rationality can be expressed by the individual rationality constraints from the perfect information case and by the incentive compatibility constraints which take now the following form

$$\text{IC}^{\text{L}}\text{: } t^L(y_1^L + y_2^L) - \theta^L(a_1 y_1^L + a_2 y_2^L + a_3 {y_1^L}^2 + a_4 {y_2^L}^2 + a_5 y_1^L y_2^L)$$
$$\geq t^H(y_1^H + y_2^H) - \theta^L(a_1 y_1^H + a_2 y_2^H + a_3 {y_1^H}^2 + a_4 {y_2^H}^2 + a_5 y_1^H y_2^H)$$
$$\text{IC}^{\text{H}}\text{: } t^H(y_1^H + y_2^H) - \theta^H(a_1 y_1^H + a_2 y_2^H + a_3 {y_1^H}^2 + a_4 {y_2^H}^2 + a_5 y_1^H y_2^H)$$
$$\geq t^L(y_1^L + y_2^L) - \theta^H(a_1 y_1^L + a_2 y_2^L + a_3 {y_1^L}^2 + a_4 {y_2^L}^2 + a_5 y_1^L y_2^L).$$

The main question is whether in the case of two jointly produced goods, we can simplify the problem as we did it in the case of one good. In other words, whether satisfaction of the incentive compatibility constraint for L-farms and of the individual rationality constraint for H-farms implies satisfaction of the individual rationality constraint for L-farms and the incentive compatibility constraint for H-farms. As is demonstrated in Annex 2a, this is valid at least for the optimal solution. Thus it is possible to reduce the problem from four economic rationality constraints expressed as inequalities to two constraints expressed as equalities. The problem contains then six unknowns and four equations (O_1, O_2, IC^L, IR^H) and can be solved by a Langrangian.

The sign of the difference between the share of land subscribed under agreement 1 and the share of land subscribed under agreement 2 by an L-farm follows the same rule as the difference in quantities with perfect information. But under asymmetric information the difference in these two quantities will be higher compared to the cost minimising solution. The same is true also for the difference in shares of land subscribed under the same agreement by respective farm types.

It can be proven that budgetary expenditure with differentiated contracts will be always lower than budgetary expenditure with a uniform payment.

2.3 Whole farm programmes - two environmental goods

Whole farm programmes demand that all eligible land is subscribed under an agreement but a spot of land must be subscribed under one agreement only. Thus the Principal's environmental objective can be written as follows

$$\text{O:}\ y_1^L s + y_1^H (1-s) = q$$
$$\text{Ow}^k\text{:}\ y_1^k + y_2^k = 1,\ \text{k = L, H,}$$

where parameter q represents the share of total land to be subscribed under agreement 1, considered here as the more restrictive one, and constraints Ow^k demand that all the eligible land is involved under the agreement 1 or under the more general agreement 2.

With a single good the optimisation of the production distribution proceeded by optimisation of the shares of land to be involved under the programme by the respective farm types. If two goods were to be produced with a part farm programme, the optimisation gained one supplementary dimension in the possibility not only to adjust the share of land involved under the programme but also to decide about the environmental goods production structure on this share of land. With a whole farm programme, this new dimension represents the only optimisation mechanism because the possibility to decide about the share of land to be involved under the programme is lost by setting it explicitly to 1 for both farm types.

a) Perfect information: Differentiated contracts

Although we are in the case of two goods, the explicit obligation to subscribe the whole farm enables to substitute from Ow^k for y_2^k and to reduce the number of unknowns from 6 to four (y_1^L, t^L, y_1^H, t^H). The menu of contracts proposed to each farm type [y_1^k, 1, p^k] thus contains the share of land to be subscribed under agreement 1, the obligation to subscribe all the land under the programme, and the amount of the payment. The budgetary expenditure can be written as follows

$$E = t^L s + t^H (1-s)\ .$$

The only economic constraints to be respected are the IR^L and IR^H constraints

$$\text{IR}^\text{L}\text{:}\ t^L \geq c^L(y_1^L, 1)\ (= \theta^L (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5) y_1^L + (a_3 + a_4 - a_5) {y_1^L}^2))$$
$$\text{IR}^\text{H}\text{:}\ t^H \geq c^H(y_1^H, 1)\ (= \theta^H (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5) y_1^H + (a_3 + a_4 - a_5) {y_1^H}^2))$$

and in order to minimise budgetary expenditure they are to be satisfied as equalities. Thus the problem becomes one of cost minimisation subject to the environmental objective as in all the previously discussed perfect information cases

Min $c(Y_1,1) = c^L(y_1^L,1)s + c^H(y_1^H,1)(1\text{-}s)$
s. t.
O,

where $c(Y_1,1)$ is the total cost of production of Y_1, $c^L(y_1^L,1)$ is the cost of compliance of an L-farm with the agreement 1 on the share of its land y_1^L if all the farm is to be involved under the programme, and $c^H(y_1^H,1)$ is the cost of compliance of an H-farm. We solve this problem by a Lagrangian

$$L(y_1^L, y_1^H, \mu) = c^L(y_1^L,1)s + c^H(y_1^H,1)(1\text{-}s) + \mu O\,.$$

The first order conditions after substituting for the cost functions are

L_{y1L}: $\theta^L(a_1 - a_2 - 2a_4 + a_5 + 2(a_3 + a_4 - a_5)y_1^L) = \mu$

L_{y1H}: $\theta^H(a_1 - a_2 - 2a_4 + a_5 + 2(a_3 + a_4 - a_5)y_1^H) = \mu$

L_μ: $y_1^L s + y_1^H(1\text{-}s) = q\,.$

The derivative of the compliance cost function with respect to the share of land subscribed under agreement 1 is equal to the difference in marginal cost of compliance with the agreement 1 and the marginal compliance cost with the agreement 2 as they were derived for the part farm programmes above, if we substitute for the y_2^k from Ow^k. Concerning the shares of land subscribed by the respective farm types, it can be stated directly that if the marginal cost of compliance with the agreement 1 is higher than the marginal cost of compliance with the agreement 2, the Lagrange multiplier is positive, then the share of land subscribed under the agreement 1 by an L-farm is to be higher than the share of land to be subscribed by an H-farm. If the difference in marginal cost is negative, the opposite is true. With negative jointness, the difference in shares of land subscribed under an agreement by respective farm types will be more pronounced than if there where no jointness.

With perfect information, the problem solution is not much different from the one good case, only the cost function coefficients are to be adjusted to account for the fact that the land which is not subscribed under the agreement 1 is to be subscribed under the agreement 2. Thus to the coefficient a_1 from the one good case corresponds now expression (a_1-a_2-2a_4+a_5), and to the coefficient a_3 corresponds the expression (a_3+a_4-a_5). Newly an independent term a_0 appears which is equal to a_2+a_4 and represents the cost of subscription of the total farm under agreement 2.

b) Asymmetric information: Uniform payment contracts

If the Government wants to ensure production of specific quantities of respective environmental goods with uniform payments it has to propose different per hectare payments for each good as with the part farm programme, t_1 and t_2. Thus the budgetary expenditure can be expressed as

$$E = t_1(y_1^L s + y_1^H(1\text{-}s)) + t_2(y_2^L s + y_2^H(1\text{-}s))\,.$$

The farmers are free to decide which portion of their land they subscribe under which agreement but the obligation to involve under the programme all the eligible land or nothing changes substantially marginal individual rationality conditions compared to part farm programmes

$$\text{mIR}^{\text{L}}\text{: } t_1 - t_2 = \theta^L (a_1 - a_2 - 2a_4 + a_5 + 2(a_3 + a_4 - a_5) y_1^L)$$
$$\text{mIR}^{\text{H}}\text{: } t_1 - t_2 = \theta^H (a_1 - a_2 - 2a_4 + a_5 + 2(a_3 + a_4 - a_5) y_1^H)\,.$$

Similarly to part farm programmes, the right hand side of these constraints is equal to the Lagrange multiplier μ obtained for the perfect information case. But it does not give us the values of the necessary payments, only the values of their difference. The system of these two equations has infinity of solutions and there is no guarantee that a solution satisfies the individual rationality constraints. Thus we have to account explicitly for them

$$\text{IR}^{\text{L}}\text{: } t_1 y_1^L + t_2 (1\text{-}y_1^L) \geq \theta^L (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5) y_1^L + (a_3 + a_4 - a_5) {y_1^L}^2)$$
$$\text{IR}^{\text{H}}\text{: } t_1 y_1^H + t_2 (1\text{-}y_1^H) \geq \theta^H (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5) y_1^H + (a_3 + a_4 - a_5) {y_1^H}^2)\,.$$

It can be demonstrated that satisfaction of the individual rationality constraint for H-farms implies satisfaction of the individual rationality constraint for L-farms, thus the latter can be neglected. The optimal quantities are the cost minimising ones obtained with the perfect information and the necessary payments can be obtained by solving the system of two equations (mIR^{L}, IR^{H}) and two unknowns (t_1,t_2). Interestingly, with whole farm programmes, the application of uniform payment contracts enables to remunerate H-farms just for their compliance cost. This was not possible with part farm programmes. With part farm programmes, differentiated contracts are to be applied if we want to extract the rent accruing to H-farms.

Budgetary expenditure with uniform payments will be always higher than budgetary expenditure with perfectly differentiated contracts. But if we compare budgetary expenditure with uniform payments for the whole farm programme with budgetary expenditure for the one good part farm programme, we can see that for the same quantities of the environmental good 1 budgetary expenditure may be lower if we apply the whole farm programme and produce the environmental good 2 on the remaining land than if we produce the same quantity q of the environmental good 1 with a one good part farm programme. The sign of this difference will depend on the parameters of the problem. For example, if the Government desires to produce the environmental good 1 on a relatively large portion of the total eligible land, it will be less expensive to apply the whole farm programme than to apply the part farm one.

c) Asymmetric information: Differentiated contracts

The menu of contracts proposed to each farm type has the same structure as with perfect information [y_1^k,1,t^k] thus the general form of budgetary expenditure is also the same

$$E = t^L s + t^H (1 - s)\,.$$

Similarly as with the part farm programmes, in order for the differentiated contracts to be implementable not only the individual rationality constraints but also the incentive compatibility constraints are to be respected

$$\text{IC}^\text{L}:\ t^L - \theta^L (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5) y_1^L + (a_3 + a_4 - a_5) y_1^{L^2})$$
$$\geq t^H - \theta^L (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5) y_1^H + (a_3 + a_4 - a_5) y_1^{H^2})$$
$$\text{IC}^\text{H}:\ t^H - \theta^H (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5) y_1^H + (a_3 + a_4 - a_5) y_1^{H^2})$$
$$\geq t^L - \theta^H (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5) y_1^L + (a_3 + a_4 - a_5) y_1^{L^2}) .$$

It can be proved (see Annex 2b) that IC^L and IR^H imply IR^L and IC^H. IC^L and IR^H are to be satisfied as equalities because we minimise budgetary expenditure. As with the one good part farm programme, the Principal's problem has, after substituting for y_2^k from Ow^k, four unknowns (y_1^L,t^L,y_1^H,t^H) and 3 equations (O, IC^L, IR^H). It can be solved as a constrained minimisation of budgetary expenditure using a Lagrangian.

The share of land subscribed under the agreement 1 by an L-farm will be higher than the share of land subscribed by an H-farm. The difference is the higher, the stronger is the jointness. The difference will be always higher than the difference between the cost minimising quantities.

It can be demonstrated that budgetary expenditure under asymmetric information is always lower with differentiated contracts than with uniform payment contracts and that this difference is the higher the stronger is the negative jointness.

3. Applied approach

Common objection to different types of theoretically elaborated systems of contracts is that their application is too complicated to pay the public fund savings due to decreased transfer payments. Therefore we consider as important to illustrate the relative advantage of different programmes and contract types on a case study. The case study is applied to the White Carpathians PLA (Protected Landscape Area), a mountainous area on the border between the Czech and the Slovak Republic. White Carpathians meadows belong to the most species-rich plant associations in Europe (about 70 species of vascular plants per m^2) and their importance is given by the total acreage of these meadows too. Their vegetation is characterised by a huge mosaic of meadow, bordering and forest plant associations and by a rich occurrence of both xerophile and humid species. (Pražan et al, 2002) These meadows are mainly utilised for suckler cow and sheep rearing.

The analysed agri-environmental measures and the corresponding environmental goods are those defined in the "Sound Grassland Management" (SGM) programme, the main instrument of the Czech agricultural policy designed for grassland biodiversity promotion. This programme proposes to farmers six different agreements. The agreements are divided into two groups; the first one concerns hay meadows (hay meadows are defined for SGM as exclusively mowed grassland with prohibition of pasture) and the second one concerns pastures (pastures can be mowed but must be also grazed at least once a year). Each group contains one general agreement, which can be subscribed by all farms willing to comply with the prescriptions, and supplementary agreements which can be subscribed only by farms in formally designated protected areas like the White Carpathians PLA. As the agreements are signed for 5 years, it is supposed that different (qualitatively or quantitatively) environmental goods will be produced on a particular spot of land depending on which measure is applied to it.

The analysis is carried out using compliance cost function coefficients estimated on the basis of results obtained with BEGRAB_PRO.1 – a mathematical programming model for BEef and GRAssland Biodiversity PRoduction Optimisation – elaborated by the authors for analysis of organic suckler cow farms in the White Carpathians PLA. It is a linear annual deterministic farm level model which represents a typical suckler cow farm of 300 ha constituted by 87% by grassland. The SGM programme is represented in the model by sets of constraints corresponding to requirements involved in the particular agreements. A detailed description of the model exceeds the scope of this paper but it can be found in Havlík et al. (2006).

After some preliminary simulations, three agri-environmental agreements contained in the SGM programme were retained for the present analysis as the most likely to be subscribed by the modelled farm: 1) the pasture agreement, prohibiting the nitrogen fertilisation and limiting the instantaneous stocking density to 0.5 LU/ha, 2) the general pasture agreement, limiting nitrogen fertilisation to 40 kg/ha/year and the stocking density to 0.7 LU/ha[7], and 3) the meadow agreement, which prohibits nitrogen fertilisation and demands postponing of the first cut after July 15. The corresponding environmental goods will be called: pasture biodiversity, current pasture biodiversity and meadow biodiversity.

The compliance cost functions were estimated for 1) pasture biodiversity and meadow biodiversity production bundle and 2) pasture biodiversity and current pasture biodiversity production bundle. First, the cost of compliance with different shares of land subscribed under different agreements was calculated using BEGRAB_PRO.1. It was calculated as the loss of income if the agri-environmental agreements are applied without compensation on different shares of land. The coefficients of the compliance cost functions were estimated using the nonlinear regression and they are normalised to represent a farm with one hectare of grassland. The quantities y_i represent thus, similarly as in the theoretical part, shares of the grassland subscribed under particular agreements.

The estimated compliance cost function for the joint production of pasture biodiversity *pb*, y_{pb}, and meadow biodiversity *mb*, y_{mb}, is as follows

$$CC_{pbxmb} = 28.00\, y_{pb} + 103.21\, y_{mb} + 23.57\, y_{pb}^2 + 64.61\, y_{mb}^2 + 65.80\, y_{pb} y_{mb}$$
$$(R^2 = 0.999)$$

It can be observed that meadow biodiversity is much more costly than pasture biodiversity and that the negative jointness in production of these two goods is quite important (a_5=65.80).

The estimated compliance cost function for pasture biodiversity, y_{pb}, and current pasture biodiversity *cb*, y_{cb}, is as follows

$$CC_{pbxcb} = 29.90\, y_{pb} + 5.92\, y_{cb} + 21.28\, y_{pb}^2 + 9.66\, y_{cb}^2 + 25.71\, y_{pb} y_{cb}$$
$$(R^2 = 0.998)$$

[7] In reality, the agri-environmental measures contain also minimum stocking density requirements but as they did not appear restrictive during preliminary simulations, they are neglected here. The original maximum stocking density limits are 0.8 LU/ha and 1.0 LU/ha for the pasture agreement and the general pasture agreement respectively. But especially the maximum stocking density limit for the general pasture agreement was not restrictive during the preliminary simulations thus to make also this agreement effective, maximum stocking density limits have been decreased.

The current pasture biodiversity production is considerably cheaper than pasture biodiversity production but also here the jointness parameter a_5 is relatively important.

Estimated cost functions exhibit high performance (R^2) and their coefficients take economically reasonable values; all the coefficients are positive and they respect the convexity condition ($a5^2 < 4*a3*a4$). Thus we can state that the quadratic cost function is not only comfortable for a theoretical analysis but it is also suitable for the applied one.

In what follows, CC_{pbxcb} is utilised for illustration of the part farm programme with one environmental good, in that case y_{cb} is set equal to zero, and for analysis of the whole farm programme. This corresponds well to the reality where all the pasture not subscribed under the pasture agreement is to be involved under the general pasture agreement if the farmer wants to participate in the programme. The meadow agreement is not suitable for the whole farm programme analysis because of the contained requirements. Especially the prohibition to graze the subscribed area excludes application of this agreement on shares of land approaching 100% of the grassland. CC_{pbxmb} is utilised for analysis of part farm programmes with two environmental goods.

For all three types of programmes (part farm – one good, part farm – two goods, and whole farm – two goods) first the results obtained with different contract types for a base scenario are presented. In the base scenario, the difference in farm types is considered equal to 0.2 (θ^L=0.9 and θ^H=1.1) and each farm type occupies one half of the total land (s=0.5). The base scenario quantities are defined depending on which type of programme is analysed. These results are completed by a discussion of their sensitivity to changes in the difference in farm types, in the distribution of farm types and in the quantity of environmental goods to be produced. To illustrate not only the relative performance of different contract types but to give also some idea about the absolute value of budgetary expenditure, we consider that there are 10 000 hectares of eligible grassland in the studied region.

3.1. Part farm programmes – one environmental good

The case of contracting for a single good is presented here on the example of “pasture biodiversity” production. The base scenario supposes that the Government wants 50% of the eligible grassland to be subscribed under the pasture agreement. The simulation results are summarised in Table 1.

Table 1. Part farm programmes – one good: Base scenario

		Perfect information: Differentiated contracts	Uniform payment contracts	Asymmetric information: Differentiated contracts
y_{pb}^L		0.62	0.62	0.72
y_{pb}^H		0.38	0.38	0.28
t^L	€/ha	38.79	50.67	43.48
t^H	€/ha	41.78	50.67	39.48
R^L	%	0	23.44	6.46
R^H	%	0	17.54	0
E	**€**	**199 623**	**253 341**	**211 780**

R^k – rent as percentage of the transfer payment accruing to k-farms.

The cost minimising distribution of biodiversity production, which is the one to be applied with perfectly differentiated contracts or with uniform payment contracts, demands that L-farms involve 62% and H-farms 38% of their land under the pasture agreement. The corresponding payments for the pasture agreement are 39 euros per hectare and 42 euros per hectare for L-farms and H-farms respectively if perfectly differentiated contracts are applied. The optimal uniform payment is 51 euros per hectare. Thus budgetary expenditure with a uniform payment amounts to 253 341 euros which is by 27% more than with perfectly differentiated contracts. While the rent left to farmers, R^k, is zero with perfectly differentiated contracts, an L-farm captures a rent equal to 23% of the total transfer payment and an H-farm's rent amounts to 18% of its transfer payment.

The optimal shares to be subscribed if differentiated contracts are applied with asymmetric information change by +10 percentage points for L-farms and by –10 percentage points for H-farms. The budgetary expenditure is by 6% higher than with perfectly differentiated contracts but by 16% lower than with a uniform payment. An H-farm's rent is zero and an L-farm gets a rent equal to some 6% of the total transfer payment.

In tables A1-A3 in Annex, we summarised the sensitivity analysis results with respect to the difference in farm types, the distribution of the land between the farm types and the quantity of environmental good to be produced. In Table A1, we observe that the increase in the difference in farm types leads under all contract types to an increase in the share of land to be subscribed by an L-farm and to a decrease of the share of land to be subscribed by an H-farm. Budgetary expenditure decreases as the difference in farm types increases if perfectly differentiated contracts or uniform payments are applied. But with differentiated contracts under asymmetric information, budgetary expenditure first increases and only above a certain value of the difference in farm types it starts to fall.

An increase in the share of land farmed by L-farms leads to a decrease of the share of land subscribed under the pasture agreement by both types of farms. For high values of *s*, this leads even to the situation that only L-farms participate in the programme.[8] For all three contract types the budgetary expenditure falls as the area farmed by L-farms increases. It is by some 17% lower if L-farms occupy 95% of the land than if this farm type occupies only 5% of the land.

If the quantity of pasture biodiversity to be produced, *q*, increases, the shares of land subscribed under the pasture agreement increase for both farm types as well. For relatively low values of *q* with respect to *s*, all the environmental good is produced by L-farms. On the other hand, if the quantity of environmental good to be produced becomes relatively important with respect to the area farmed by L-farms, the L-farms are to be entirely involved under the agreement and the rest is to be produced by H-farms.[9] Budgetary expenditure increases as the quantity of environmental good to be produced increases under all three contract types.

Concerning the choice of the optimal contract type under asymmetric information, it can be stated that it is nearly independent from the difference in farm types and from the distribution

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[8] The unconstrained solution presented in the analytical part cannot be applied; it would lead to negative quantities for H-farms. But self-selecting contracts can still be designed. As the quantity to be produced by H-farms is zero, also their payment is set equal to zero. Then it is sufficient to remunerate L-farms for their cost of compliance to satisfy both the individual rationality and incentive compatibility constraints.

[9] This is another type of deviation from the unconstrained solution. This time it is due to the farm level land availability constraints. The optimal contract design in this case proceeds in two steps: first the quantities are determined and then according to the individual rationality condition for H-farms and incentive compatibility condition for L-farms the payments are calculated. Also in this case it is valid that satisfaction of these two constraints implies satisfaction of the remaining individual rationality and incentive compatibility constraints.

of the land between farm types because the difference in budgetary expenditure between uniform payment contracts and differentiated contracts varies always between 16 and 21%. On the other hand, the quantity of environmental good to be produced will play an important role. If 20% of all the grassland is to be subscribed, differentiated contracts enable to decrease budgetary expenditure not even by 10% compared to the uniform payment option. But if 80% of the land is to be subscribed, differentiated contracts may decrease budgetary expenditure by more than 20% compared to the uniform payment, which could be interesting although if we accounted for additional budgetary expenditure generated by the contract differentiation.

3.2. Part farm programmes – two environmental goods

Pasture biodiversity and meadow biodiversity production bundle is used for illustration of the part farm programme with two goods. In the base scenario, the Government wants 75% of the grassland to be enrolled under the programme (q=0.75). As in the theoretical part, one half of the enrolled grassland is to be subscribed under each agreement. Results for the base scenario are summarised in Table 2.

The cost minimising solution for environmental goods production distribution requires that an L-farm subscribes 58% of its grassland under the more expensive meadow agreement and only 23% under the pasture agreement. In total this farm type should involve 82% of its grassland under the programme. The H-farms should involve 68% of their grassland under the programme but they should produce on 52% the pasture biodiversity and only 17% of their grassland should be subscribed under the meadow agreement. Thus while the cost minimisation was attained by differentiating the shares of land to be subscribed under the programme in the case with a single good, in the presence of two goods, the percentage of land under the programme is similar for both farm types and the cost minimisation proceeds by relative specialisation of each farm type in production of a different environmental good.

The average per hectare payment for L-farms is with uniform payment contracts by 33% higher than the per hectare payment with perfectly differentiated contracts and thus L-farms get a rent equal to 25% of the transfer payment they receive. For H-farms, the difference in payments amounts to 30% creating a rent of 23% of their transfer payment. Concerning budgetary expenditure, it amounts to 695 172 euros with perfectly differentiated contracts and is by 32% higher if uniform payments are applied.

Table 2. Part farm programmes – two goods: Base scenario

		Perfect information: Differentiated contracts	Uniform payment contracts	Asymmetric information: Differentiated contracts
y_{pb}^{L}		0.23	0.23	0.12
y_{mb}^{L}		0.58	0.58	0.75
y_{pb}^{L}+y_{mb}^{L}		**0.82**	**0.82**	**0.87**
y_{pb}^{H}		0.52	0.52	0.63
y_{mb}^{H}		0.17	0.17	0.00
y_{pb}^{H}+y_{mb}^{H}		**0.68**	**0.68**	**0.63**
t_{pb}^{L}	€/ha	109.18	69.65	133.60
t_{mb}^{L}	€/ha	109.18	174.58	133.60
t_{pb}^{H}	€/ha	72.99	69.65	47.06
t_{mb}^{H}	€/ha	72.99	174.58	47.06
R^{L}	%	0	24.56	4.60
R^{H}	%	0	23.25	0
E	**€**	**695 172**	**915 875**	**730 653**

Differentiated contracts under asymmetric information demand an increase of the share of land involved under the programme by L-farms and a decrease by H-farms, by +/-5 percentage points respectively. Adjustments in the structure of the production bundle to be produced by each farm type lead to further specialisation. Thus L-farms should subscribe 75% of their land under the meadow agreement and only 12% under the pasture agreement. H-farms should become completely specialised in pasture biodiversity production, subscribing 63% of their land under the pasture agreement.[10] The contracts differentiation enables to decrease budgetary expenditure by 20% compared to uniform payment contracts. The rent of H-farms is zero and the L-farms' rent is considerably decreased, from 25% to 5%.

The sensitivity analysis reported in Tables A4-A6 in Annex confirms that, similarly as in the single good case, the cost minimising share of land involved under the programme by L-farms increases as the difference in farm types increases, the opposite is true for H-farms. This applies also for the optimal quantities with differentiated contracts under asymmetric information, where it leads even to the situation that for higher values of the difference, all the grassland occupied by L-farms is involved under the programme. Concerning the structure of production bundles produced by respective farm types, the increase in the difference in farm types favourites specialisation, thus for relatively high values of the difference H-farms become fully specialised in pasture biodiversity production. The increasing difference in farm types enables a decrease in budgetary expenditure if perfectly differentiated contracts or uniform payments are applied. If differentiated contracts are applied under asymmetric information, budgetary expenditure first increases and starts to fall only for higher values of the difference. These results compare well to those obtained with a single good.

An increase in the share of land occupied by L-farms leads to a decrease of the optimal portion of land to be subscribed under the programme by individual farms of both farm types under all three contract options. This causes, for high values of s, exclusion of H-farms from the programme. While L-farms are nearly completely specialised in meadow biodiversity production, if the share of total grassland they occupy is small, an H-farm's production bundle is rather balanced. But as the share of land occupied by L-farms increases the difference in the percentage of land subscribed under both agreements by an L-farm diminishes. H-farms decrease rapidly the share of land subscribed under the meadow agreement and become specialised in pasture biodiversity production. Budgetary expenditure decreases as the share of land occupied by L-farms increases for all contract types by similar relative amounts.

The cost minimising solution suggests that the percentage of land involved under the programme will increase on both farm types as the share of total grassland to be involved under the programme increases. The specialisation of both farm types decreases as q increases. With differentiated contracts under asymmetric information, the unconstrained solution applies only if some 80% of the total grassland is to be involved under the programme. For lower values, H-farms specialise in pasture biodiversity production or they are excluded from the programme, for higher values all the grassland occupied by L-farms should be involved under the programme, thus the problem is restricted by land availability

[10] The unconstrained solution presented in the theoretical part would lead to a negative share of land to be subscribed under the meadow agreement by H-farms. Thus we have to account explicitly for the non-negativity constraints here. Deviations from the unconstrained solutions occur more frequently with two environmental goods than with a single good and the solutions to the differentiated contract option under asymmetric information are especially prone to them because the differences in quantities of particular goods to be produced by respective farm types are more important than with the cost minimising quantities. We will not explain these solutions in detail as we did it in the single good case but their algebraic forms can be obtained on request from the authors.

constraints. Budgetary expenditure obviously increases with the increasing quantity of environmental goods to be produced.

The farm group characteristics like difference in the farm types or the farm types distribution will not influence dramatically the choice of the contract type under asymmetric information; for all considered values of these parameters, the difference between differentiated contracts and uniform payments varies between 20 and 23%. Similarly to the single good case, the decisive parameter is the quantity of environmental goods to be produced. For low quantities, the difference in budgetary expenditure between differentiated contracts and uniform payments is less than 10%, for high quantities it exceeds 20%.

To summarise, we can state that the sensitivity analysis results obtained for the two environmental goods part farm programme approach in relative terms those obtained with a single good programme concerning shares of land subscribed under the programme and budgetary expenditure. Newly, attention is to be paid to the distribution of production of particular goods within each farm type. As it was shown, the values of analysed parameters strongly influence this distribution and may lead to a complete specialisation of a farm type or even to its exclusion from the programme.

3.3. Whole farm programmes – two environmental goods

Numerical analysis of different contract types with a whole farm programme is illustrated on the production bundle of pasture biodiversity and current pasture biodiversity. In the base scenario, the Government wants one half of the grassland to be subscribed under the pasture agreement and the other half to be subscribed under the general pasture agreement (q=0.50). The results are summarised in Table 3.

Table 3. Whole farm programmes – two goods: Base scenario

		Perfect information: Differentiated contracts	Uniform payment contracts	Asymmetric information: Differentiated contracts
y_{pb}^{L}		0.84	0.84	1.00
y_{cb}^{L}		0.16	0.16	0.00
$\mathbf{y_{pb}^{L}+y_{cb}^{L}}$		**1.00**	**1.00**	**1.00**
y_{pb}^{H}		0.16	0.16	0.00
y_{cb}^{H}		0.84	0.84	1.00
$\mathbf{y_{pb}^{H}+y_{cb}^{H}}$		**1.00**	**1.00**	**1.00**
t_{pb}^{L}	€/ha	40.32	52.24	49.18
t_{cb}^{L}	€/ha	40.32	16.99	49.18
t_{pb}^{H}	€/ha	22.62	52.24	17.14
t_{cb}^{H}	€/ha	22.62	16.99	17.14
R^{L}	%	0.00	13.50	6.34
R^{H}	%	0.00	0.00	0.00
E	**€**	**314 667**	**346 134**	**331 580**

Cost minimising distribution of the production requires that L-farms subscribe 84% of their grassland under the pasture agreement and only 16% under the general pasture agreement. On the other hand, H-farms should subscribe 84% of their grassland under the general pasture agreement and only 16% under the more costly pasture agreement. With this distribution, the average payment per hectare amounts for L-farms with uniform payments to 46.61 euros which is by 16% more than the payment with perfectly differentiated contracts and leads to a rent of 14% of the total transfer payment. The average payment for H-farms is with uniform payments equal to that one of perfectly differentiated contracts thus H-farms' rent is zero. The budgetary expenditure with uniform payment contracts is by only 10% higher than budgetary expenditure with perfectly differentiated contracts.

These results illustrate the potential of whole farm programmes to extract the rents usually accruing to farmers if uniform payment contracts are applied. For the same quantity of pasture biodiversity to be produced under a part farm single good programme (subsection 3.1) the rent accruing to L-farms represented 23% of the total transfer payment, and for H-farms it amounted to 18%, leading to a difference in budgetary expenditure of 27% between perfectly differentiated contracts and uniform payment contracts. (Similar values were obtained also with the part farm programme with two environmental goods.) Thus the efficiency can be considerably increased by forcing the farmers to involve also the rest of their grassland under the programme.

Under asymmetric information, if the contracts are differentiated, the optimal solution requires that L-farms specialise completely in pasture biodiversity production and that H-farms participate only in the general pasture agreement. This tendency to more pronounced specialisation compared to the cost minimisation quantities was already observed with the part farm programme. Differentiation of contracts enables to decrease the L-farmers' rent to 6% of the total transfer payment, and to hold the H-farmers' rent equal to zero. Thus budgetary expenditure under asymmetric information is with differentiated contracts by 4% lower than with uniform payment contracts. This improvement seems rather negligible compared to the part farm programmes results, where differentiation of contracts enabled to decrease budgetary expenditure by 16% and 20% in the one good case and in the two goods case, respectively.

Sensitivity analysis of the obtained results is reported in Tables A7-A9 in the Annex. Concerning the difference in farm types, its increase leads to higher specialisation of the farm types in production of different goods. Thus above a certain range each farm type specialises in production of one environmental good. The budgetary expenditure with perfectly differentiated contracts falls as the difference in farm types increases and the relative values are similar to those obtained for the part farm programmes. The impact on budgetary expenditure with differentiated contracts under asymmetric information is also similar as in the part farm programmes; if the difference increases, budgetary expenditure first increases and above a certain range it starts to fall. In contradiction to the results for part farm programmes, budgetary expenditure with uniform payment contracts does not decrease but systematically increases as the difference in farm types increases.

While the relative advantage of different contract types under asymmetric information was nearly independent of the difference in farm types with the part farm programmes (differentiation enabled to decrease budgetary expenditure by some 20% independently of the difference in farm types), it depends directly on this parameter if whole farm programmes are applied. If the difference in farm types is zero, budgetary expenditure with uniform payments is equal to budgetary expenditure with perfectly differentiated contracts thus no differentiation under asymmetric information is needed. But as the difference in farm types increases, differentiation enables some savings; 15% of budgetary expenditure can be saved if the difference in farm types is 0.50.

Increase in the share of land occupied by L-farms leads progressively to concentration of pasture biodiversity production on L-farms and to specialisation of H-farms in general pasture biodiversity production. Budgetary expenditure decreases for all three contract types but in the case of uniform payment contracts and contracts differentiated under asymmetric information this decrease is less important for the whole farm programme than for the part farm programmes. Similarly as with part farm programmes, distribution of the farm types does not change significantly the relative advantage of differentiated contracts over uniform payment contracts, which does not exceed 5% for the tested values.

If the quantity of pasture biodiversity to be produced increases, the shares of land to be subscribed under the pasture agreement increase for both farm types, and budgetary expenditure increases as well, independently from the contract type applied. The difference between contracts differentiated under asymmetric information and uniform payment contracts is the highest (4%) if some 50% of the grassland is to be subscribed under the pasture agreement. For very low or very high values of q this difference approaches zero. Thus the choice whether to apply differentiated contracts under asymmetric information or uniform payment contracts will for whole farm programmes depend mainly on the difference in farm types. This result contrasts with those obtained for part farm programmes, where the quantity of environmental goods to be produced was the decisive parameter.

Whole farm programmes are generally more efficient than part farm programmes in the sense that the overcompensation of farmers is less a problem.[11] But this does not necessarily mean that the budgetary expenditure is lower with whole farm programmes than with part farm programmes. We end up this section by comparing budgetary expenditure with uniform payment contracts for the single good part farm programme and the whole farm programme, when 50% of all grassland is to be subscribed under the pasture agreement and the other 50% is out of the programme with the part farm programme, or is subscribed under the general pasture agreement with the whole farm programme. The sensitivity analysis results are reported in Tables 4-6.

Table 4. Whole farm vs. part farm programmes: sensitivity analysis with respect to (θ^H-θ^L)

θ^H-θ^L	0.00	0.10	0.20	0.30	0.40	0.50
%	25.33	31.31	36.63	41.44	50.28	60.30

Table 5. Whole farm vs. part farm programmes: sensitivity analysis with respect to s

s	0.05	0.20	0.40	0.60	0.80	0.95
%	26.71	30.57	34.75	38.33	41.20	43.20

Table 6. Whole farm vs. part farm programmes: sensitivity analysis with respect to q

q	0.05	0.20	0.40	0.60	0.80	0.95
%	1106.99	207.11	65.72	17.06	-6.58	-24.16

In Table 4 we can read on the first line that for the base scenario (θ^H-θ^L = 0.20) the whole farm programme is by 37% more expensive than the part farm programme. In this situation we would need some information about the value of supplementary biodiversity produced on the land subscribed under the general pasture agreement to decide which type of programme is preferable. As the difference in farm types increases, the difference in budgetary expenditure increases as well which favourites the part farm programme. Similar results can be observed concerning the impact of the distribution of farms among the farm types.

[11] By comparing the sensitivity analysis results for the part farm programme, Tables A1-A3, with the results for the whole farm programme, Tables A7-A9, it can be seen that only for very high values of the difference in farm types (θ^L-θ^H=0.50) or for very low quantities of the pasture biodiversity to be produced (q=0.05) the overcompensation is higher with a whole farm programme than with a part farm programme.

Budgetary expenditure is always higher with a whole farm programme than with a part farm programme and the difference increases as the share of land occupied by L-farms increases.

The decisive parameter for the choice between a part farm programme and a whole farm one is the share of land to be subscribed under the pasture agreement, *q*. As this share increases, the difference in budgetary expenditure between whole farm and part farm programmes decreases so that for high values of *q* it becomes even negative. In the present case study, this “high value” is equal to 0.73. It means that if the Government wants more than 73% of the land to be subscribed under the pasture agreement and she applies uniform payments, she should adopt the whole farm programme even if the social value of supplementary biodiversity produced under the general pasture agreement were zero. We assist here on the phenomenon “Demand more to pay less!”.

3.4 ... and without jointness?

Let us finish by briefly discussing what the results would be if the environmental goods were not joint in production with each other. For this purpose we estimated an individual compliance cost function for each environmental good applying the same procedure as for the 2-outputs cost functions presented above.

$$CC_{pb} = 27.47\, y_{pb} + 24.56\, y_{pb}^2$$
$$CC_{mb} = 100.85\, y_{mb} + 67.82\, y_{mb}^2$$
$$CC_{cb} = 5.02\, y_{cb} + 10.57\, y_{cb}^2$$

The compliance cost functions with two independent outputs are then as follows

$$CC_{pbxmb} = CC_{pb} + CC_{mb}$$
$$CC_{pbxcb} = CC_{pb} + CC_{cb}$$

The simulation results for the base scenario are reported for the two goods part farm programmes and the whole farm programmes in Annex in Tables A10 and A11 respectively.

First, we observe a substantial reduction in differences in the shares of land subscribed under different agreements by different farm types compared to the results when jointness is present. Under the part farm programme, the cost minimising solution requires that L-farms subscribe 47% of their grassland under the pasture agreement and 49% under the meadow agreement. With jointness, these shares were 23% and 48% respectively, thus the difference falls from some 25 percentage points to 2 percentage points only. For H-farms, the cost minimising quantities without jointness require 28% of the grassland to be subscribed under the pasture agreement and 26% to be subscribed under the meadow agreement, instead of 52% and 17% respectively with jointness. While the difference in shares of land subscribed under particular agreements is negligible if there is no jointness, the difference in shares of land subscribed under the whole programme is more pronounced than if there is jointness; L-farms should involve 96% of their grassland and H-farms 54%, instead of 82% and 68% respectively with the full cost function. The results are similar also for optimal quantities with differentiated payments under asymmetric information.

With whole farm programmes, the specialisation was originally even more important than with the part farm programmes; L-farms had to subscribe under the pasture agreement 84% of their grassland and H-farms 16% only. But also here the specialisation would be considerably reduced if there were no jointness. The cost minimising solution would require that L-farms subscribe under the pasture agreement 55% of their grassland, and H-farms 45%.

Second, if there were no jointness, uniform payment contracts would perform better. The differentiation of contracts under asymmetric information with the part farm programme enables to decrease budgetary expenditure compared to uniform payment contracts by 13% only, instead of 20% if jointness is present. This is not due to a worse performance of differentiated contracts which overcompensates the farmers by 6%, but to a better performance of the uniform payment contracts; without jointness, framers are overcompensated by 22% only, instead of 32% if there is jointness. With the whole farm programme, contract differentiation enables to decrease budgetary expenditure compared to uniform payment contracts by 4% only if jointness is present, and it performs even worse if there is no jointness; budgetary expenditure with differentiated contracts is by 1% lower than budgetary expenditure with uniform payment contracts. The total cost of compliance without jointness is always lower than if there is jointness therefore also budgetary expenditure in absolute terms is always lower.

Finally, if there were no jointness, the whole farm programmes would outperform single good part farm programmes more frequently. In the above section we found that the critical share of total grassland to be subscribed under the pasture agreement to make whole farm programmes preferable even if the value of current pasture biodiversity were nil, was 73%. If there were no jointness this critical share would fall to 55% of the grassland.

4. Conclusion

The reason why the problem of contracting for two jointly produced environmental goods was never treated in the literature, is probably the difficulty to obtain clear conclusions on the highest level of generality; this means with general compliance cost functions. To get some insight into the problem, we decided to give up some generality and to use a specific cost function, the quadratic one. Its capacity to account explicitly for the joint production and the linearity in coefficients enabled to deduce several analytical results. The numerical example confirmed that this functional form may represent well a compliance cost function with real-world agri-environmental agreements.

The most important result concerning part farm programmes with two jointly produced environmental goods is that if the compliance cost function has the quadratic form, self selecting menu of contracts can be designed similarly as with one environmental good only; the individual rationality constraint is binding for H-farms and the incentive compatibility constraint is binding for L-farms, the other two constraints are at the optimum automatically satisfied. In the numerical example, contract differentiation proved to be an interesting option under asymmetric information as it enabled to decrease budgetary expenditure by some 20% compared to uniform payment contracts. The advantage is the higher, the more important is the quantity of environmental goods to be produced.

Contract differentiation is easily applicable if whole farm programmes with two environmental goods are to be used. The obligation to subscribe the total farm approaches in fact the solution procedure to that one of a single good problem. The question is whether the differentiation will be needed with this type of programmes. With whole farm programmes, uniform payment contracts can be designed so that H-farms get no rent and L-farms' rent is considerably decreased compared to the part farm programmes. Thus in the numerical example, if one half of all grassland is to be subscribed under the pasture agreement and the other half under the current pasture agreement, contract differentiation enables to reduce budgetary expenditure by less than 5% in comparison to uniform payment contracts. The supplementary administrative cost due to the contract differentiation would probably not be covered by these savings thus uniform payment contracts may represent the optimal option if whole farm programmes are to be applied.

With uniform payment contracts, whole farm programmes will be generally more costly than part farm programmes with one good, if the quantity of the principal environmental good is the same, because production of the supplementary environmental good in the whole farm programme causes some additional cost. But if the quantity of the principal environmental good to be produced is sufficiently large, the cost of production of the additional environmental good may be lower than the reduction of overcompensation obtained by applying a whole farm programme instead of a part farm programme. Then whole farm programmes will be preferable to part farm programmes even if the value of the additional environmental good is zero.

The research can be extended in several directions. As we applied a specific functional form, some more research would be interesting to find whether the good fit of this form to the problem was specific for our case study or whether this function performs well also with other environmental goods. We treated only environmental goods, which exhibit negative jointness in production with agricultural commodities and between themselves. But there are also non-commodities which are complementary to agricultural commodities. These cases should be analysed too.

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ANNEX 1: Analytical solutions

Part farm programmes – one environmental good

Perfect information: Differentiated contracts

$$y_1^L = q\frac{\theta^H}{(1-s)\theta^L + s\theta^H} + \frac{a_1(1-s)(\theta^H - \theta^L)}{2a_3((1-s)\theta^L + s\theta^H)}$$

$$y_1^H = q\frac{\theta^L}{(1-s)\theta^L + s\theta^H} - \frac{a_1 s(\theta^H - \theta^L)}{2a_3((1-s)\theta^L + s\theta^H)}$$

$$E = \frac{(a_1 + a_3 q)q\theta^L\theta^H}{(1-s)\theta^L + s\theta^H} - \frac{{a_1}^2 s(1-s)(\theta^H - \theta^L)^2}{4 * a_3 * ((1-s)\theta^L + s\theta^H)}$$

Asymmetric information: Uniform payment contracts

- quantities are those from the perfect information case

$$E = \frac{(a_1 + 2a_3 q)q\theta^L\theta^H}{(1-s)\theta^L + s\theta^H}$$

Asymmetric information: Differentiated contracts

$$y_1^L = q\frac{(\theta^H - s\theta^L)}{(1-s)\theta^L + s(\theta^H - \theta^L)} + \frac{a_1(1-s)(\theta^H - \theta^L)}{2a_3((1-s)\theta^L + s(\theta^H - \theta^L))}$$

$$y_1^H = q\frac{(1-s)\theta^L}{(1-s)\theta^L + s(\theta^H - \theta^L)} - \frac{a_1 s(\theta^H - \theta^L)}{2a_3((1-s)\theta^L + s(\theta^H - \theta^L))}$$

$$E = \frac{(a_1 + a_3 q)q\theta^L\theta^H}{(1-s)\theta^L + s(\theta^H - \theta^L)} - \frac{(a_1 + a_3 q)qs{\theta^L}^2}{(1-s)\theta^L + s(\theta^H - \theta^L)} - \frac{{a_1}^2 s(\theta^H - \theta^L)^2}{4a_3((1-s)\theta^L + s(\theta^H - \theta^L))}$$

Part farm programmes – two environmental goods

Perfect information: Differentiated contracts

$$y_1^L = \frac{q}{2}\frac{\theta^H}{(1-s)\theta^L + s\theta^H} + \frac{(2a_1a_4 - a_2a_5)(1-s)(\theta^H - \theta^L)}{(4a_3a_4 - {a_5}^2)((1-s)\theta^L + s\theta^H)}$$

$$y_2^L = \frac{q}{2}\frac{\theta^H}{(1-s)\theta^L + s\theta^H} + \frac{(2a_2a_3 - a_1a_5)(1-s)(\theta^H - \theta^L)}{(4a_3a_4 - {a_5}^2)((1-s)\theta^L + s\theta^H)}$$

$$y_1^H = \frac{q}{2}\frac{\theta^L}{(1-s)\theta^L + s\theta^H} - \frac{(2a_1a_4 - a_2a_5)s(\theta^H - \theta^L)}{(4a_3a_4 - {a_5}^2)((1-s)\theta^L + s\theta^H)}$$

$$y_2^H = \frac{q}{2}\frac{\theta^L}{(1-s)\theta^L + s\theta^H} - \frac{(2a_2a_3 - a_1a_5)s(\theta^H - \theta^L)}{(4a_3a_4 - {a_5}^2)((1-s)\theta^L + s\theta^H)}$$

$$E = \frac{(2a_1 + 2a_2 + (a_3 + a_4 + a_5)q)q\theta^L\theta^H}{4((1-s)\theta^L + s\theta^H)} - \frac{({a_1}^2 a_4 - a_5a_1a_2 + {a_2}^2 a_3)(\theta^H - \theta^L)^2 s(1-s)}{((1-s)\theta^L + s\theta^H)(4a_3a_4 - {a_5}^2)}$$

Asymmetric information: Uniform payment contracts
- quantities are those from the perfect information case

$$E = \frac{(a_1 + a_2 + (a_3 + a_4 + a_5)q)q\theta^L\theta^H}{2((1-s)\theta^L + s\theta^H)}$$

Asymmetric information: Differentiated contracts

$$y_1^L = \frac{q}{2}\frac{\theta^H - s\theta^L}{(1-s)\theta^L + s(\theta^H - \theta^L)} + \frac{(2a_1a_4 - a_2a_5)(1-s)(\theta^H - \theta^L)}{(4a_3a_4 - a_5{}^2)((1-s)\theta^L + s(\theta^H - \theta^L))}$$

$$y_2^L = \frac{q}{2}\frac{\theta^H - s\theta^L}{(1-s)\theta^L + s(\theta^H - \theta^L)} + \frac{(2a_2a_3 - a_1a_5)(1-s)(\theta^H - \theta^L)}{(4a_3a_4 - a_5{}^2)((1-s)\theta^L + s(\theta^H - \theta^L))}$$

$$y_1^H = \frac{q}{2}\frac{(1-s)\theta^L}{(1-s)\theta^L + s(\theta^H - \theta^L)} - \frac{(2a_1a_4 - a_2a_5)s(\theta^H - \theta^L)}{(4a_3a_4 - a_5{}^2)((1-s)\theta^L + s(\theta^H - \theta^L))}$$

$$y_2^H = \frac{q}{2}\frac{(1-s)\theta^L}{(1-s)\theta^L + s(\theta^H - \theta^L)} - \frac{(2a_2a_3 - a_1a_5)s(\theta^H - \theta^L)}{(4a_3a_4 - a_5{}^2)((1-s)\theta^L + s(\theta^H - \theta^L))}$$

$$E = \frac{(2a_1 + 2a_2 + (a_3 + a_4 + a_5)q)q\theta^L\theta^H}{4((1-s)\theta^L + s(\theta^H - \theta^L))} - \frac{(2a_1 + 2a_2 + (a_3 + a_4 + a_5)q)qs\theta^{L^2}}{4((1-s)\theta^L + s(\theta^H - \theta^L))}$$
$$- \frac{(a_1{}^2a_4 - a_5a_1a_2 + a_2{}^2a_3)s(\theta^H - \theta^L)^2}{((1-s)\theta^L + s(\theta^H - \theta^L))(4a_3a_4 - a_5{}^2)}$$

<u>Whole farm programmes – two environmental goods</u>

Only shares of land to be subscribed under the agreement 1 are presented because the shares of land to be subscribed under the agreement 2 are equal to 1-$y_1{}^k$.

Perfect information: Differentiated contracts

$$y_1^L = q\frac{\theta^H}{(1-s)\theta^L + s\theta^H} + \frac{(a_1 - a_2 - 2a_4 + a_5)(1-s)(\theta^H - \theta^L)}{2(a_3 + a_4 - a_5)((1-s)\theta^L + s\theta^H)}$$

$$y_1^H = q\frac{\theta^L}{(1-s)\theta^L + s\theta^H} - \frac{(a_1 - a_2 - 2a_4 + a_5)s(\theta^H - \theta^L)}{2(a_3 + a_4 - a_5)((1-s)\theta^L + s\theta^H)}$$

$$E = (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5)q + (a_3 + a_4 - a_5)q^2)(\theta^H - s(\theta^H - \theta^L))$$
$$- \frac{(a_1 - a_2 - 2a_4 + a_5 + 2(a_3 + a_4 - a_5)q^2)(\theta^H - \theta^L)^2 s(1-s)}{4(a_3 + a_4 - a_5)((1-s)\theta^L + s\theta^H)}$$

Asymmetric information: Uniform payment contracts
- quantities are those from the perfect information case

$$E = (a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5)q + (a_3 + a_4 - a_5)q^2)\theta^H$$
$$- \frac{(a_1 - a_2 - 2a_4 + a_5 + 2(a_3 + a_4 - a_5)q)^2 s^2(\theta^H - \theta^L)^2\theta^H}{4(a_3 + a_4 - a_5)((1-s)\theta^L + s\theta^H)^2}$$

Asymmetric information: Differentiated contracts

$$y_1^L = q\frac{\theta^H - s\theta^L}{(1-s)\theta^L + s(\theta^H - \theta^L)} + \frac{(a_1 - a_2 - 2a_4 + a_5)(1-s)(\theta^H - \theta^L)}{2(a_3 + a_4 - a_5)((1-s)\theta^L + s(\theta^H - \theta^L))}$$

$$y_1^H = q\frac{\theta^L(1-s)}{(1-s)\theta^L + s(\theta^H - \theta^L)} - \frac{(a_1 - a_2 - 2a_4 + a_5)s(\theta^H - \theta^L)}{2(a_3 + a_4 - a_5)((1-s)\theta^L + s(\theta^H - \theta^L))}$$

$$E = (a2 + a4 + (a_1 - a_2 - 2a_4 + a_5)q + (a_3 + a_4 - a_5)q^2)\theta^H - \frac{(a_1 - a_2 - 2a_4 + a_5 + 2(a_3 + a_4 - a_5)q)^2 s(\theta^H - \theta^L)^2}{4(a_3 + a_4 - a_5)((1-s)\theta^L + s(\theta^H - \theta^L))}$$

ANNEX 2a: Demonstration IC^L + IR^H → IR^L and IC^H: Part farm programme – two goods

(Demonstration adapted from Moxey et al. (1999))

In order to simplify the notation, we substitute

$c(y_1^L, y_2^L) = a_1 y_1^L + a_2 y_2^L + a_3 {y_1^L}^2 + a_4 {y_2^L}^2 + a_5 y_1^L y_2^L$

and

$c(y_1^H, y_2^H) = a_1 y_1^H + a_2 y_2^H + a_3 {y_1^H}^2 + a_4 {y_2^H}^2 + a_5 y_1^H y_2^H$

$$\text{IR}^L\text{: } t^L (y_1^L + y_2^L) \geq \theta^L c(y_1^L, y_2^L)$$
$$\text{IR}^H\text{: } t^H (y_1^H + y_2^H) \geq \theta^H c(y_1^H, y_2^H)$$

$$\text{IC}^L\text{: } t^L (y_1^L + y_2^L) - \theta^L c(y_1^L, y_2^L) \geq t^H (y_1^H + y_2^H) - \theta^L c(y_1^H, y_2^H)$$
$$\text{IC}^H\text{: } t^H (y_1^H + y_2^H) - \theta^H c(y_1^H, y_2^H) \geq t^L (y_1^L + y_2^L) - \theta^H c(y_1^L, y_2^L)$$

By IC^L and IR^H we obtain

$$t^L (y_1^L + y_2^L) - \theta^L c(y_1^L, y_2^L) \geq (\theta^H - \theta^L) c(y_1^H, y_2^H)$$

As θ^H-$\theta^L > 0$, $t^L (y_1^L + y_2^L) - \theta^L c(y_1^L, y_2^L) > 0$, thus **$IC^L$ and IR^H imply IR^L**.

Now we want to show that IC^L and IR^H are binding:
Since $\theta^L < \theta^H$, we have $t^H (y_1^H + y_2^H) - \theta^L c(y_1^H, y_2^H) > t^H (y_1^H + y_2^H) - \theta^H c(y_1^H, y_2^H)$.

Since by IR^H $t^H (y_1^H + y_2^H) - \theta^H c(y_1^H, y_2^H) \geq 0$, $t^H (y_1^H + y_2^H) - \theta^L c(y_1^H, y_2^H) > 0$. From IC^L this implies $t^L (y_1^L + y_2^L) - \theta^L c(y_1^L, y_2^L) > 0$. Thus IR^L cannot be binding. If the regulator wishes to minimise budgetary expenditure, **IC^L will be binding**.

IC^L + IR^H → IC^H ?

If IC^L is binding, IC^H can be transformed to

IC^H: $c(y_1^L, y_2^L) \geq c(y_1^H, y_2^H)$,

or

IC^H: $a_1 (y_1^L - y_1^H) + a_2 (y_2^L - y_2^H) + a_3 ({y_1^L}^2 - {y_1^H}^2) + a_4 ({y_2^L}^2 - {y_2^H}^2) + a_5 (y_1^L y_2^L - y_1^H y_2^H) > 0$.

IC^H is obviously always satisfied if $y_1^L > y_1^H$ and $y_2^L > y_2^H$. With negative jointness, this is not a frequent case. Thus in order to find whether IC^H is implied by IC^L and IR^H, we have to check whether the optimal solution obtained when only the latter two constraints are considered satisfies IC^H. The answer is affirmative. Thus for the optimal solution **IC^L and IR^H imply IC^H**.

ANNEX 2b: Demonstration $IC^L + IR^H \rightarrow IR^L$ and IC^H: Whole farm programme – two goods

(Demonstration adapted from Moxey et al. (1999))

In order to simplify the notation we substitute

$c(y_1^L, 1) = a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5)y_1^L + (a_3 + a_4 - a_5)y_1^{L\,2}$

and

$c(y_1^H, 1) = a_2 + a_4 + (a_1 - a_2 - 2a_4 + a_5)y_1^H + (a_3 + a_4 - a_5)y_1^{H\,2}$

$$IR^L:\ t^L \geq \theta^L c(y_1^L, 1)$$
$$IR^H:\ t^H \geq \theta^H c(y_1^H, 1)$$

$$IC^L:\ t^L - \theta^L c(y_1^L, 1) \geq t^H - \theta^L c(y_1^H, 1)$$
$$IC^H:\ t^H - \theta^H c(y_1^H, 1) \geq t^L - \theta^H c(y_1^L, 1)$$

By IC^L and IR^H

$$t^L - \theta^L c(y_1^L, 1) \geq (\theta^H - \theta^L) c(y_1^H, 1)\,.$$

As θ^H-$\theta^L > 0$, $t^L - \theta^L c(y_1^L, 1) > 0$, thus **$IC^L$ and IR^H imply IR^L**.

Now we want to show that IC^L and IR^H are binding:
Since $\theta^L < \theta^H$, we have $t^H - \theta^L c(y_1^H, 1) > t^H - \theta^H c(y_1^H, 1)$.

Since by IR^H $t^H - \theta^H c(y_1^H, 1) \geq 0$, $t^H - \theta^L c(y_1^H, 1) > 0$. From IC^L, $t^L - \theta^L c(y_1^L, 1) > 0$. Thus IR^L cannot be binding. If the regulator wishes to minimise t^L, **IC^L will be binding**.

If IC^H were binding then

$$t^H - \theta^H c(y_1^H, 1) = t^L - \theta^H c(y_1^L, 1)$$

Using the result that IC^L is binding we obtain

$c(y_1^L, 1) = c(y_1^H, 1)$,

which is never true if $\theta^L \neq \theta^H$, thus IC^H is not binding, but **IR^H is binding**.

$IC^L + IR^H \rightarrow IC^H$?

The left hand side of IC^H is equal to zero if IR^H is binding

IC^H: $0 \geq t^L - \theta^H c(y_1^L, 1)$

IC^L: $t^L = \theta^H c(y_1^L, 1) - \theta^L c(y_1^H, 1) + \theta^L c(y_1^L, 1)$

From IC^L we can substitute for t^L and we obtain

IC^H: $(a_1 - a_2 - 2a_4 + a_5)y_1^L + (a_3 + a_4 - a_5)y_1^{L\,2} \geq (a_1 - a_2 - 2a_4 + a_5)y_1^H + (a_3 + a_4 - a_5)y_1^{H\,2}$,

which is always true. (If the marginal cost of compliance with y_1 is higher than marginal cost of compliance with y_2 for $y_1 = y_2$, then $y_1^L > y_1^H$ and $(a_1 – a_2 – 2a_4 + a_5) > 0$. If the marginal cost of compliance with y_1 is lower than marginal cost of compliance with y_2 for $y_1 = y_2$, then $y_1^L < y_1^H$ and $(a_1 – a_2 – 2a_4 + a_5) < 0$.) Thus **$IC^L + IR^H$ imply IC^H**.

ANNEX 3: Simulation results

Table A1. Part farm programmes - one good: Sensitivity analysis with respect to (θ^H-θ^L)

	θ^H-θ^L		**0.00**	**0.10**	**0.20**	**0.30**	**0.40**	**0.50**
Perfect information: Differentiated contracts	y_{pb}^L		0.50	0.56	0.62	0.68	0.74	0.80
	y_{pb}^H		0.50	0.44	0.38	0.32	0.26	0.20
	E	€	202 700	201 931	199 623	195 776	190 391	183 467
	d E	**%**	**0.00**	**-0.38**	**-1.52**	**-3.42**	**-6.07**	**-9.49**
Uniform payment contracts	E	€	255 900	255 260	253 341	250 142	245 664	239 906
	d E	**%**	**0.00**	**-0.25**	**-1.00**	**-2.25**	**-4.00**	**-6.25**
Asymmetric information: Differentiated contracts	y_{pb}^L		0.50	0.61	0.72	0.81	0.90	0.98
	y_{pb}^H		0.50	0.39	0.28	0.19	0.10	0.02
	E	€	202 700	209 904	211 780	209 022	202 209	191 829
	d E	**%**	**0.00**	**3.55**	**4.48**	**3.12**	**-0.24**	**-5.36**
Comparison of budgetary expenditure	UP-PI	%	26.25	26.41	26.91	27.77	29.03	30.76
	AI-PI	%	0.00	3.95	6.09	6.77	6.21	4.56
	AI-UP	%	-20.79	-17.77	-16.41	-16.44	-17.69	-20.04

(PI – Perfect information: Differentiated contracts, UP – Asymmetric information: Uniform payment contracts, AI-Asymmetric information: Differentiated contracts)

Table A2. Part farm programmes - one good: Sensitivity analysis with respect to *s*

	s		**0.05**	**0.20**	**0.40**	**0.60**	**0.80**	**0.95**
Perfect information: Differentiated contracts	y_{pb}^L		0.75	0.70	0.65	0.59	0.55	0.51
	y_{pb}^H		0.49	0.45	0.40	0.36	0.32	0.29
	E	€	220 300	212 767	203 740	195 750	188 680	183 921
	d E	**%**	**0.00**	**-3.42**	**-7.52**	**-11.14**	**-14.35**	**-16.51**
Uniform payment contracts	E	€	278 397	269 512	258 511	248 374	239 001	232 423
	d E	**%**	**0.00**	**-3.19**	**-7.14**	**-10.78**	**-14.15**	**-16.51**
Asymmetric information: Differentiated contracts	y_{pb}^L		0.76	0.75	0.73	0.70	0.63	0.53
	y_{pb}^H		0.49	0.44	0.34	0.20	0.00	0.00
	E	€	222 258	219 731	215 029	207 584	194 400	184 950
	d E	**%**	**0.00**	**-1.14**	**-3.25**	**-6.60**	**-12.53**	**-16.79**
Comparison of budgetary expenditure	UP-PI	%	26.37	26.67	26.88	26.88	26.67	26.37
	AI-PI	%	0.89	3.27	5.54	6.05	3.03	0.56
	AI-UP	%	-20.16	-18.47	-16.82	-16.42	-18.66	-20.43

Table A3. Part farm programmes - one good: Sensitivity analysis with respect to *q*

	q		**0.05**	**0.20**	**0.40**	**0.60**	**0.80**	**0.95**
Perfect information: Differentiated contracts	y_{pb}^L		0.10	0.29	0.51	0.73	0.95	1.00
	y_{pb}^H		0.00	0.11	0.29	0.47	0.65	0.90
	E	€	14 413	66 579	151 061	252 398	370 588	473 117
	d E	**%**	**0.00**	**361.95**	**948.12**	**1651.23**	**2471.28**	**3182.67**
Uniform payment contracts	E	€	15 370	76 056	185 819	329 290	506 468	712 732
	d E	**%**	**0.00**	**394.83**	**1108.96**	**2042.39**	**3195.13**	**4537.10**
Asymmetric information: Differentiated contracts	y_{pb}^L		0.10	0.36	0.60	0.84	1.00	1.00
	y_{pb}^H		0.00	0.04	0.20	0.36	0.60	0.90
	E	€	14 413	68 840	159 606	268 480	396 715	517 264
	d E	**%**	**0.00**	**377.64**	**1007.41**	**1762.82**	**2652.56**	**3488.97**
Comparison of budgetary expenditure	UP-PI	%	6.64	14.23	23.01	30.46	36.67	50.65
	AI-PI	%	0.00	3.40	5.66	6.37	7.05	9.33
	AI-UP	%	-6.23	-9.49	-14.11	-18.47	-21.67	-27.43

Table A4. Part farm programmes - two goods: Sensitivity analysis with respect to (θ^H-θ^L)

	θ^H-θ^L		**0.00**	**0.10**	**0.20**	**0.30**	**0.40**	**0.50**
Perfect information: Differentiated contracts	y_{pb}^L		0.38	0.30	0.23	0.16	0.15	0.22
	y_{mb}^L		0.38	0.48	0.58	0.69	0.75	0.75
	y_{pb}^H		0.38	0.45	0.52	0.59	0.60	0.53
	y_{mb}^H		0.38	0.27	0.17	0.06	0.00	0.00
	E	€	708 593	705 238	695 172	678 395	655 258	628 795
	d E	**%**	**0.00**	**-0.47**	**-1.89**	**-4.26**	**-7.53**	**-11.26**
Uniform payment contracts	E	€	925 126	922 813	915 875	904 311	883 265	851 767
	d E	**%**	**0.00**	**-0.25**	**-1.00**	**-2.25**	**-4.52**	**-7.93**
Asymmetric information: Differentiated contracts	y_{pb}^L		0.37	0.24	0.12	0.24	0.25	0.25
	y_{mb}^L		0.37	0.57	0.75	0.75	0.75	0.75
	y_{pb}^H		0.37	0.51	0.63	0.51	0.50	0.50
	y_{mb}^H		0.37	0.18	0.00	0.00	0.00	0.00
	E	€	708 593	731 240	730 653	716 099	697 400	678 679
	d E	**%**	**0.00**	**3.20**	**3.11**	**1.06**	**-1.58**	**-4.22**
Comparison of budgetary expenditure	UP-PI	%	30.56	30.85	31.75	33.30	34.80	35.46
	AI-PI	%	0.00	3.69	5.10	5.56	6.43	7.93
	AI-UP	%	-23.41	-20.76	-20.22	-20.81	-21.04	-20.32

Table A5. Part farm programmes - two goods: Sensitivity analysis with respect to *s*

	s		**0.05**	**0.20**	**0.40**	**0.60**	**0.80**	**0.95**
Perfect information: Differentiated contracts	y_{pb}^L		0.08	0.13	0.20	0.26	0.32	0.36
	y_{mb}^L		0.81	0.73	0.63	0.54	0.45	0.39
	y_{pb}^H		0.39	0.44	0.49	0.54	0.59	0.62
	y_{mb}^H		0.35	0.29	0.20	0.13	0.06	0.01
	E	€	769 564	741 971	709 617	681 789	657 974	642 480
	d E	**%**	**0.00**	**-3.59**	**-7.79**	**-11.41**	**-14.50**	**-16.51**
Uniform payment contracts	E	€	1 006 456	974 335	934 566	897 916	864 033	840 252
	d E	**%**	**0.00**	**-3.19**	**-7.14**	**-10.78**	**-14.15**	**-16.51**
Asymmetric information: Differentiated contracts	y_{pb}^L		0.06	0.07	0.10	0.27	0.42	0.39
	y_{mb}^L		0.83	0.82	0.78	0.63	0.47	0.39
	y_{pb}^H		0.39	0.45	0.56	0.53	0.20	0.00
	y_{mb}^H		0.35	0.26	0.11	0.00	0.00	0.00
	E	€	776 349	765 324	744 816	715 614	682 601	647 990
	d E	**%**	**0.00**	**-1.42**	**-4.06**	**-7.82**	**-12.08**	**-16.53**
Comparison of budgetary expenditure	UP-PI	%	30.78	31.32	31.70	31.70	31.32	30.78
	AI-PI	%	0.88	3.15	4.96	4.96	3.74	0.86
	AI-UP	%	-22.86	-21.45	-20.30	-20.30	-21.00	-22.88

Table A6. Part farm programmes - two goods: Sensitivity analysis with respect to *q*

	q		**0.05**	**0.20**	**0.40**	**0.60**	**0.80**	**0.95**
Perfect information: Differentiated contracts	y_{pb}^L		0.05	0.04	0.04	0.15	0.26	0.29
	y_{mb}^L		0.05	0.20	0.39	0.50	0.61	0.71
	y_{pb}^H		0.00	0.16	0.36	0.45	0.54	0.66
	y_{mb}^H		0.00	0.00	0.01	0.10	0.19	0.24
	E	€	31 256	140 058	314 448	520 571	757 183	954 910
	d E	**%**	**0.00**	**348.10**	**906.04**	**1565.52**	**2322.53**	**2955.14**
Uniform payment contracts	E	€	32 988	157 646	381 759	664 102	1 007 421	1 319 902
	d E	**%**	**0.00**	**377.89**	**1057.26**	**1913.15**	**2953.89**	**3901.14**
Asymmetric information: Differentiated contracts	y_{pb}^L		0.05	0.11	0.12	0.12	0.15	0.08
	y_{mb}^L		0.05	0.20	0.40	0.60	0.78	0.92
	y_{pb}^H		0.00	0.09	0.28	0.48	0.65	0.87
	y_{mb}^H		0.00	0.00	0.00	0.00	0.02	0.03
	E	€	31 256	143 802	326 134	543 973	797 270	1 011 908
	d E	**%**	**0.00**	**360.08**	**943.43**	**1640.39**	**2450.79**	**3137.50**
Comparison of budgetary expenditure	UP-PI	%	5.54	12.56	21.41	27.57	33.05	38.22
	AI-PI	%	0.00	2.67	3.72	4.50	5.29	5.97
	AI-UP	%	-5.25	-8.78	-14.57	-18.09	-20.86	-23.33

Table A7. Whole farm programmes - two goods: Sensitivity analysis with respect to (θ^H-θ^L)

	θ^H-θ^L		0.00	0.10	0.20	0.30	0.40	0.50
Perfect information: Differentiated contracts	y_{pb}^L		0.50	0.67	0.84	1.00	1.00	1.00
	y_{cb}^L		0.50	0.33	0.16	0.00	0.00	0.00
	y_{pb}^H		0.50	0.33	0.16	0.00	0.00	0.00
	y_{cb}^H		0.50	0.67	0.84	1.00	1.00	1.00
	E	€	320 725	319 210	314 667	307 100	298 200	289 300
	d E	**%**	**0.00**	**-0.47**	**-1.89**	**-4.25**	**-7.02**	**-9.80**
Uniform payment contracts	E	€	320 725	335 171	346 134	353 798	369 180	384 563
	d E	**%**	**0.00**	**4.50**	**7.92**	**10.31**	**15.11**	**19.90**
Asymmetric information: Differentiated contracts	y_{pb}^L		0.50	0.82	1.00	1.00	1.00	1.00
	y_{cb}^L		0.50	0.18	0.00	0.00	0.00	0.00
	y_{pb}^H		0.50	0.18	0.00	0.00	0.00	0.00
	y_{cb}^H		0.50	0.82	1.00	1.00	1.00	1.00
	E	€	320 725	330 992	331 580	330 470	329 360	328 250
	d E	**%**	**0.00**	**3.20**	**3.38**	**3.04**	**2.69**	**2.35**
Comparison of budgetary expenditure	UP-PI	%	0.00	5.00	10.00	15.21	23.80	32.93
	AI-PI	%	0.00	3.69	5.37	7.61	10.45	13.46
	AI-UP	%	0.00	-1.25	-4.20	-6.59	-10.79	-14.64

Table A8. Whole farm programmes - two goods: Sensitivity analysis with respect to *s*

	s		0.05	0.20	0.40	0.60	0.80	0.95
Perfect information: Differentiated contracts	y_{pb}^L		1.00	1.00	0.92	0.77	0.63	0.53
	y_{cb}^L		0.00	0.00	0.08	0.23	0.38	0.47
	y_{pb}^H		0.47	0.38	0.22	0.10	0.00	0.00
	y_{cb}^H		0.53	0.63	0.78	0.90	1.00	1.00
	E	€	348 436	335 921	321 205	308 609	297 826	290 830
	d E	**%**	**0.00**	**-3.59**	**-7.82**	**-11.43**	**-14.52**	**-16.53**
Uniform payment contracts	E	€	352 758	351 899	348 357	343 574	337 464	332 819
	d E	**%**	**0.00**	**-0.24**	**-1.25**	**-2.60**	**-4.34**	**-5.65**
Asymmetric information: Differentiated contracts	y_{pb}^L		1.00	1.00	1.00	0.83	0.63	0.53
	y_{cb}^L		0.00	0.00	0.00	0.17	0.38	0.47
	y_{pb}^H		0.47	0.38	0.17	0.00	0.00	0.00
	y_{cb}^H		0.53	0.63	0.83	1.00	1.00	1.00
	E	€	351 550	347 003	332 789	327 658	322 754	320 432
	d E	**%**	**0.00**	**-1.29**	**-5.34**	**-6.80**	**-8.19**	**-8.85**
Comparison of budgetary expenditure	UP-PI	%	1.24	4.76	8.45	11.33	13.31	14.44
	AI-PI	%	0.89	3.30	3.61	6.17	8.37	10.18
	AI-UP	%	-0.34	-1.39	-4.47	-4.63	-4.36	-3.72

Table A9. Whole farm programmes - two goods: Sensitivity analysis with respect to *q*

	q		0.05	0.20	0.40	0.60	0.80	0.95
Perfect information: Differentiated contracts	y_{pb}^L		0.10	0.40	0.73	0.95	1.00	1.00
	y_{cb}^L		0.90	0.60	0.27	0.05	0.00	0.00
	y_{pb}^H		0.00	0.00	0.07	0.25	0.60	0.90
	y_{cb}^H		1.00	1.00	0.93	0.75	0.40	0.10
	E	€	169 702	214 232	279 941	350 429	426 576	489 631
	d E	**%**	**0.00**	**26.24**	**64.96**	**106.50**	**151.37**	**188.52**
Uniform payment contracts	E	€	185 517	233 577	307 935	385 472	473 154	540 524
	d E	**%**	**0.00**	**25.91**	**65.99**	**107.78**	**155.05**	**191.36**
Asymmetric information: Differentiated contracts	y_{pb}^L		0.10	0.40	0.80	1.00	1.00	1.00
	y_{cb}^L		0.90	0.60	0.20	0.00	0.00	0.00
	y_{pb}^H		0.00	0.00	0.00	0.20	0.60	0.90
	y_{cb}^H		1.00	1.00	1.00	0.80	0.40	0.10
	E	€	185 282	229 812	295 774	372 421	462 261	536 780
	d E	**%**	**0.00**	**24.03**	**59.63**	**101.00**	**149.49**	**189.71**
Comparison of budgetary expenditure	UP-PI	%	9.32	9.03	10.00	10.00	10.92	10.39
	AI-PI	%	9.18	7.27	5.66	6.28	8.37	9.63
	AI-UP	%	-0.13	-1.61	-3.95	-3.39	-2.30	-0.69

Table A10. Part farm programmes – two goods: base scenario (independent goods)

		Perfect information: Differentiated contracts	Uniform payment contracts	Asymmetric information: Differentiated contracts
y_{pb}^{L}		0.47	0.47	0.45
y_{mb}^{L}		0.49	0.49	0.55
$\mathbf{y_{pb}^{L}+y_{mb}^{L}}$		**0.96**	**0.96**	**1.00**
y_{pb}^{H}		0.28	0.28	0.30
y_{mb}^{H}		0.26	0.26	0.20
$\mathbf{y_{pb}^{H}+y_{mb}^{H}}$		**0.54**	**0.54**	**0.50**
t_{pb}^{L}	€/ha	78.60	45.43	90.23
t_{mb}^{L}	€/ha	78.60	150.20	90.23
t_{pb}^{H}	€/ha	82.62	45.43	74.17
t_{mb}^{H}	€/ha	82.62	150.20	74.17
R^{L}	%	0	20.46	7.47
R^{H}	%	0	13.97	0
E	**€**	**600 469**	**733 599**	**636 571**

Table A11. Whole farm programmes – two goods: base scenario (independent goods)

		Perfect information: Differentiated contracts	Uniform payment contracts	Asymmetric information: Differentiated contracts
y_{pb}^{L}		0.55	0.55	0.59
y_{cb}^{L}		0.45	0.45	0.41
$\mathbf{y_{pb}^{L}+y_{cb}^{L}}$		**1.00**	**1.00**	**1.00**
y_{pb}^{H}		0.45	0.45	0.41
y_{cb}^{H}		0.55	0.55	0.59
$\mathbf{y_{pb}^{H}+y_{cb}^{H}}$		**1.00**	**1.00**	**1.00**
t_{pb}^{L}	€/ha	24.31	45.46	30.28
t_{cb}^{L}	€/ha	24.31	9.39	30.28
t_{pb}^{H}	€/ha	25.55	45.46	24.09
t_{cb}^{H}	€/ha	25.55	9.39	24.09
R^{L}	%	0	17.02	14.47
R^{H}	%	0	0.00	0
E	**€**	**249 300**	**274 230**	**271 834**