Combining performance-based and action-based payments to provide environmental goods under uncertainty

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Abstract: Payments for environmental services (PES) are widely adopted to support the conservation of biodiversity and other environmental goods. Challenges that PES schemes have to tackle are (i) environmental uncertainty and (ii) information asymmetry between the provider of the service (typically a farmer) and the regulator. Environmental uncertainty calls for action-based payment schemes, because of the more favorable risk allocation if the farmer is risk-averse. Information asymmetry, on the other hand, calls for a performance-based payment because of the more direct incentives for the farmer. Bases on a principal-agent model, we study the optimal combination of both, performance-based and action-based payments. We find that for a risk-neutral regulator a combination is optimal in the majority of cases and that the welfare gain of the combined scheme over a pure action-based (performance-based) payment increases with information asymmetry (environmental uncertainty). We further show that for a regulator who is risk-averse against fluctuations in environmental goods provision the optimal performance-based payment is lower than for a risk-neutral regulator. We quantitatively illustrate our findings in a case study for the enhancement of the butterfly Scarce Large Blue (*Maculinea teleius*) in Landau/Germany.

Keywords: Conservation Contracts, Payments for Ecosystem Services, Payments for Environmental Services, Biodiversity, Uncertainty

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1 Introduction

The protection and enhancement of environmental assets is an objective shared by many governments around the globe. Often these assets depend on how farmers manage their private land, but as they typically have characteristics of public goods, farmers have little incentives to make socially optimal decisions (Bardsley and Burfund 2008). For this reason policy instruments such as payments for environmental or ecosystem services (PES) have been advocated to create incentives similar to those that would be provided by market prices, if markets for environmental services would exist (e.g. Bulte et al. 2008, Corbera et al. 2007, Vatn 2009).

Two types of payment schemes are used in practice: Action-based payments are bound to a predefined action or measure, whereas performance-based payments are directly bound to the outcome of a desired ecosystem good or service.[1] Performance-based payments have the advantage that they set the direct incentive to provide ecosystem services efficiently (Matzdorf 2004, Zabel and Roe 2009). A performance-based payment presupposes that the desired environmental service is well-defined and quantitatively measurable. A drawback of performance-based payment schemes is that the risk of producing an ecosystem good gets at the expense of the farmer, since the quantity of environmental service also depends on external influences beyond the farmer's control. If the farmer is risk-averse, and the regulator is risk-neutral, a performance-based payment scheme thus leads to an inefficient risk allocation. As a result, most existing schemes are action-based, with the exception that performance-based payments are sometimes applied for the conservation of an already given state or of existing biodiversity (Osterburg 2006, Hampicke 2001). Action-based payments may be a cost-effective alternative if there is a clear action that is required to provide the environmental good, known

[1] Many labels for these payment schemes can be found within the literature. Other common names for action-based payments are e.g. input- or measure-based payments, for performance-based payments the terms output-oriented, outcome- or result-based payments are also common.

and observable by the regulator (Gibbons et al. 2011). If there is informational asymmetry between farmer and regulator, however, a pure action-based payment is likely to lead to an inefficient outcome.

In this paper, we consider payment schemes that combine performance-based and action-based payments. We set up a principal-agent model to study what combination of both is optimal when there is both environmental uncertainty affecting the provision of the environmental good and asymmetric information about how productive a management action is for providing the environmental good.

We find that the optimal payment typically will be a combination of performance-based and action-based payments. A pure performance-based payment is optimal for a risk-neutral regulator only if either there is no environmental risk or the farmer is risk-neutral. A pure action-based payment is optimal only if the regulator has full information about the marginal productivity of the actions for providing the environmental good. The performance-based fraction of the optimal payment increases with environmental uncertainty, while the action-based fraction increases with information asymmetry. These findings are also reflected in the welfare gains of the combined scheme over the pure performance-based or action-based schemes: the welfare gain, measured as the payoff of a risk-neutral regulator, of the optimally combined scheme over an optimally chosen, pure action-based (performance-based) payment increases with information asymmetry (environmental uncertainty).

The assumption of a risk-neutral regulator may be inappropriate, because society's marginal willingness to pay for the environmental asset may increase if an environmental asset becomes increasingly scarce. For this reason we also consider a regulator who is risk-averse against fluctuations in environmental goods provision. As the argument for an action-based payment scheme is the more favorable allocation of risk if the farmer is risk-averse but the regulator is risk-neutral, one might expect that the performance-based fraction of the optimal payment might be relatively higher when the regulator is risk-averse. We find, however, that the optimal performance-based payment actually decreases with the regulator's degree of risk aversion.

We apply our analysis to the case study for the enhancement of the butterfly Scarce Large Blue (*Maculinea teleius*) in Landau/Germany, based on data from the literature (Drechsler et al. 2007, Wätzold et al. 2008). We find that the optimal combination of the performance-based and action-based payments may lead to a welfare gain of several thousand euros per hectare.

2 Principal-agent model of environmental good provision under uncertainty

We consider a principal-agent setting where a regulator (the principal) offers a PES to a single farmer (the agent), who chooses an action that contributes to the production of an environmental good. We thereby extend the approach of Zabel and Roe (2009), allowing for a combination of a performance-based payment with an action-based payment, and risk aversion on the regulator's side.

The temporal structure of the problem is that first the principal announces the payment scheme. Second, the agent decides on whether or not he would like to participate in the program and receives (or pays) a base-payment. Third, the agent chooses his action and fourth, nature chooses stochastic disturbance. Finally, the agent receives the performance-based and action-based payments from the principal.

The quantity y of the environmental good is produced according to the technology

$$y = \phi x + \varepsilon_e. \tag{1}$$

The provision of the environmental good can be increased by the farmer's action x with a constant marginal productivity ϕ. For example, x can be thought of as the area of farmland set aside for biodiversity protection.

In addition, growth of the environmental good is affected by a stochastic disturbance ε which captures environmental noise, which is independent and identically normally distributed with zero mean and standard deviation σ_e. Note that the net growth of the environmental good may be negative even with a positive effort x, due to environmental uncertainty.

Marginal productivity ϕ of the action x is known to the farmer, but not to the regulator. This information asymmetry arises, because the farmer knows the peculiarities of his farmland while the regulator does not. The regulator only knows a prior probability distribution over ϕ. We assume that this is any probability distribution with a mean $\bar{\phi}$ and variance σ_ϕ^2. The quantity x of the action exerted by the farmer is common knowledge of both farmer and regulator.[2]

We consider a payment ω for the provision of the environmental good that is composed of a base payment b, a payment for the action, $a\,x$, and of a payment for the performance, i.e. the provision of the environmental good, $p\,y$,[3]

$$\omega = b + a\,x + p\,y. \tag{2}$$

Because of environmental uncertainty, y may be negative. Thus also the overall payment ω may be negative (although its expected value will be positive). The base payment b is chosen such that the farmer nevertheless has an incentive to participate in the PES scheme. If the farmer participates in the program, his payoff Y is given by

$$Y = \omega - \frac{c}{2}\,x^2. \tag{3}$$

Here we use c to denote the cost parameter of the action, with linearly increasing

[2]Taking asymmetry with regard to the observability of the farmer's action into account has similar effects as the information asymmetry with regard to marginal productivity and could be included in the model in a straightforward way. In either case the essential assumption is that the farmer may have more information about his contribution to the provision of the environmental good than the regulator. We do not consider this issue further, because it would increase the complexity of the analysis without generating additional insights.

[3]Note that we restrict our analysis to linear combinations of the three payment parts here. An analysis of more general payment structures is left for future research.

marginal costs. If the farmer does not participate, both payment and costs are zero, and thus the net payoff is zero.

The farmer maximizes expected utility. We assume a risk-averse farmer with preferences that exhibit constant absolute risk aversion (CARA):[4]

$$U = E_\varepsilon \left[-\exp\left(-\eta Y\right)\right], \tag{4}$$

where η is the coefficient of constant absolute risk aversion and E_ε denotes the expectation with respect to environmental uncertainty ε.

While participation is voluntary, expected utility of participation in the program must at least equal utility from not participating in the program and receiving a zero net payoff for sure. With $U(0) = -\exp(0) = -1$ denoting the reservation utility level of the farmer, the participation constraint is

$$E_\varepsilon \left[-\exp\left(-\eta Y\right)\right] \geq -1. \tag{5}$$

The regulator receives a benefit

$$v(y) = y - \frac{\rho}{2}\, y^2 \tag{6}$$

from the provision of the environmental good. The quadratic benefit function (6) captures in a simple form that the regulator may be averse against uncertainty in the provision of the environmental good, with ρ being the regulator's coefficient of risk aversion. The benefit $v(y)$ is measured in monetary terms, such that the regulator's net benefit is given by $v(y) - \omega$. This assumption may actually be quite restrictive. It presupposes that the environmental good desired by the regulator is well-defined and that further its benefit can be measured in monetary terms.[5] We nevertheless make this assumption here, as we are not interested in studying the

[4]We make this assumption to be able to solve the model analytically. It is in line with most models of this type. More realistic is the case of decreasing absolute risk aversion (Gollier 2001). A deeper exploration of this case is, again, left for future research.

[5]For the case study, we use published results from a contingent valuation study for this purpose.

effects of ill-defined objectives.[6] The quadratic benefit function (6) is equivalent to a linearly decreasing willingness to pay for the provision of the environmental good.

The optimal payment scheme (a, b, p) is derived by solving the regulator's optimization problem to maximize expected net benefit

$$\max_{a,p,b} E_\phi \left[E_\varepsilon[v(y) - \omega]\right] \tag{7}$$

subject to the constraints that the action x is chosen by the farmer such as to maximize the farmer's expected utility and the participation constraint (5).

3 Analytical results: Optimal combination of performance-based and action-based payments

The problem is solved backwards by first considering the farmer's optimization for given payment levels (b, a, p). Inserting (1) and (3) into (4), the farmer's expected utility is

$$E_\varepsilon \left[-\exp\left(-\eta \left(b + (a + p\,\phi)\,x + p\,\varepsilon_e - \frac{c}{2}\,x^2\right)\right)\right]. \tag{8}$$

Taking the expectation over environmental uncertainty we obtain

$$\tilde{U} = -\frac{1}{\eta}\,\ln(-U) = b + (a + p\,\phi)\,x - \frac{c}{2}\,x^2 - \frac{\eta}{2}\,p^2\,\sigma_e^2, \tag{9}$$

which is the certainty equivalent of the income lottery generated by participating in the PES with uncertain provision of the environmental good.

Using the first-order conditions of utility maximization with respect to x, we find that the farmer's optimal choice of action is

$$x^\star = \frac{a + p\,\phi}{c}. \tag{10}$$

As one could expect, the optimal action is increasing in both action-based and performance-based payments, and decreasing in the cost parameter c. For a given

[6] Ill-defined objectives may favor action-based payments compared to performance-payments (Zabel and Roe 2009).

performance-based payment p, it is also increasing in the marginal productivity ϕ of the action.

Using the result (10) in (1), we find that the (uncertain) provision of the environmental good under payment scheme (b, a, p) is given by

$$y^* = \phi \, \frac{a + p\,\phi}{c} + \varepsilon_e. \tag{11}$$

For a given marginal productivity ϕ of the farmer's action, and a given payment scheme (b, a, p), the expected benefit of environmental good provision thus is

$$\begin{aligned} E_\varepsilon\left[v(y^*)\right] &= E_\varepsilon\left[\phi \, \frac{a + p\,\phi}{c} + \varepsilon_e - \frac{\rho}{2}\left(\phi \, \frac{a + p\,\phi}{c} + \varepsilon_e\right)^2\right] \\ &= \phi \, \frac{a + p\,\phi}{c} - \frac{\rho}{2}\left(\phi \, \frac{a + p\,\phi}{c}\right)^2 - \frac{\rho}{2}\,\sigma_e^2. \end{aligned} \tag{12}$$

To obtain this result, we have used that the expected value of ε_e is zero. Environmental uncertainty thus decreases the benefit of a risk-averse regulator, but this effect is independent of the payment scheme. This means that, in the absence of asymmetric information, risk aversion on the regulator's side has no influence on the optimal payment scheme. Put differently, we have the following lemma (which we need to derive result 3):

Lemma 1. *Environmental uncertainty does not directly affect the optimal payment scheme for a risk-averse regulator.*

Environmental uncertainty affects the optimal payment scheme indirectly, however, because the farmer is risk-averse, as we will show below.

To meet the participation constraint, the regulator has to set the base payment b such that reservation utility is reached. The certainty equivalent of participating in the PES is obtained by using (10) in (9). Equating this to the certainty equivalent of not participating, which is equivalent to an income of zero, we obtain the minimal base payment b of

$$b^\star = \frac{\eta}{2}\,p^2\,\sigma_e^2 - \frac{(a + p\,\phi)^2}{2\,c}. \tag{13}$$

With a risk-averse farmer, environmental uncertainty increases the base payment. As the performance-based payment p may either be positive (in case of favorable environmental conditions) or negative (in case of very unfavorable environmental conditions), the effect of p on the based payment is ambiguous. The action-based payment a, by contrast, unambiguously decreases the base payment.

Overall, the base payment is likely to be negative, because the expected value of action-based and performance-based payments is positive. This means that a farmer will have to make a payment to the regulator in order to benefit from the participation in the PES scheme. However, the base payment may also be positive, if environmental uncertainty is large and the farmer is very risk-averse.

Using (10), (11), and (13) in (3), the expected payment can be expressed as

$$E_{\varepsilon}[\omega] = \frac{(a + p\,\phi)^2}{2\,c} + \frac{\eta}{2}\,p^2\,\sigma_e^2. \tag{14}$$

As the farmer is risk-averse, and the performance-based payment is affected by environmental uncertainty, the optimal payment rate p depends on environmental uncertainty. Using (12), (13), and (14) in (7), and employing Lemma 1, the regulator's optimization problem can be written as

$$\max_{a,p} E_{\phi}\left\{\phi\,\frac{a + p\,\phi}{c} - \frac{\rho}{2}\left(\phi\,\frac{a + p\,\phi}{c}\right)^2 - \frac{(a + p\,\phi)^2}{2\,c} - \frac{\eta}{2}\,p^2\,\sigma_e^2\right\}. \tag{15}$$

In appendix A we show that the optimal action-based and performance-based payments are

$$a^{\star} = \frac{\bar{\phi}}{\Omega}\left(c\,\eta\,\sigma_e^2 + 2\,\frac{\rho}{c}\,\bar{\phi}^2\,\sigma_{\phi}^2\right) \tag{16a}$$

$$p^{\star} = \frac{\sigma_{\phi}^2}{\Omega}\left(1 - \frac{\rho}{c}\,\left(\bar{\phi}^2 - \sigma_{\phi}^2\right)\right) \tag{16b}$$

with

$$\Omega \equiv \sigma_{\phi}^2 + c\,\eta\,\sigma_e^2 + \frac{\rho}{c}\,\left(2\,\sigma_{\phi}^2\,\left(\bar{\phi}^2 + 2\,\sigma_{\phi}^2\right) + c\,\eta\,\left(\bar{\phi}^2 + \sigma_{\phi}^2\right)\,\sigma_e^2\right) + \frac{\rho^2}{c^2}\,\sigma_{\phi}^2\,\left(\bar{\phi}^4 + 3\,\sigma_{\phi}^4\right) > 0. \tag{17}$$

To analyze the optimal payment scheme, we first focus on the case of a risk-neutral regulator, assuming $\rho = 0$. In this case, the optimal payments are given by the following, much simpler expressions.

$$a^\star|_{\rho=0} = \bar{\phi}\,\frac{c\,\eta\,\sigma_e^2}{\sigma_\phi^2 + c\,\eta\,\sigma_e^2} \tag{18a}$$

$$p^\star|_{\rho=0} = \frac{\sigma_\phi^2}{\sigma_\phi^2 + c\,\eta\,\sigma_e^2} \tag{18b}$$

The following result is obtained immediately.

Result 1. *For a risk-neutral regulator ($\rho = 0$), the optimal PES scheme includes both an action-based and a performance-based component, except for the following cases*

- *If the farmer is risk-neutral ($\eta = 0$) or if there is no environmental uncertainty ($\sigma_e^2 = 0$), the action-based component of the optimal payment scheme is zero.*
- *If there is no asymmetric information, $\sigma_\phi^2 = 0$, the performance-based component of the optimal payment scheme is zero.*

This result shows that an optimal PES scheme should combine both an action-based and a performance-based payment. The only exceptions are extreme cases where either environmental uncertainty plays no role or the regulator has perfect information about the productivity of the farmer's actions. Furthermore, the relative shares of the action-based and the performance-based component of the optimal PES scheme depends on environmental uncertainty and information asymmetry in a very intuitive way, as stated in the following result.

Result 2. *a) For a risk-neutral regulator ($\rho = 0$), the optimal action-based payment increases and the optimal performance-based payment decreases with the farmer's degree of risk aversion, η, and with environmental uncertainty, σ_e.*

b) For a risk-neutral regulator ($\rho = 0$), the optimal action-based payment decreases and the optimal performance-based payment increases with the degree of asymmetric information, σ_ϕ.

We now turn to the case of a risk-averse regulator, assuming $\rho > 0$, and focus on the question how the optimal payment scheme compares to the case of a risk-neutral regulator. The optimal payment scheme is much more complicated than in the case of a risk-neutral regulator. We show in appendix B that the optimal action-based payment depends in an ambiguous way on the degree of risk aversion. For low levels of risk aversion for both the regulator and the farmer, the optimal action-based payment increases with the regulator's degree of risk aversion. We find that even for a risk-neutral farmer the optimal action-based payment for a risk-averse regulator is positive, which is different from the case of a risk-neutral regulator. For very high levels of risk aversion of regulator and farmer, however, the optimal action-based payment will decrease again with the regulator's risk aversion. The performance-based payment, by contrast, decreases with the regulator's degree of risk aversion whenever it is positive at all.

Result 3. *a) For a risk-averse regulator, the optimal action-based payment is positive even when the farmer is risk-neutral.*

b) The optimal performance-based payment decreases with the regulator's degree of risk aversion,

$$\frac{\partial p^\star}{\partial \rho} < 0 \quad \text{for all } p^\star > 0. \tag{19}$$

The intuition behind this result is as follows. The farmer will choose his action $x^\star$ in response to the payment according to (10). An increase in the action-based payment will increase the farmer's action independently of the marginal productivity, while an increase in the performance-based payment will lead to a lower (higher) increase in the level of his action if marginal productivity is low (high). Relative to the action-based payment, the performance-based payment thus amplifies the effect of the regulator's uncertainty on marginal productivity on the provision of the environmental good. The more risk-averse the regulator, the relatively less attractive becomes the performance-based payment compared to the action-based payment.

In the extreme, the performance-based payment may even become negative. This is the case if

$$\rho > \frac{c}{\bar{\phi}^2 - \sigma_\phi^2}. \tag{20}$$

A second effect is that the presence of informational asymmetry and the associated risk premium make the payment for environmental services overall less attractive for the risk-averse regulator. If this effect is sufficiently strong – which is the case for high environmental uncertainty – also the optimal action-based payment is lower for a risk-averse compared to a risk-neutral regulator.

As a final step of the analysis we study how high is the welfare gain, measured by the regulator's objective function, for the combined payment scheme compared to either a pure action-based or a pure performance-based payment scheme. The pure action-based, or performance-based, schemes are obtained by setting $p \equiv 0$, or $a \equiv 0$, in the regulator's optimization problem (15).

In appendix C we derive the welfare levels for all three payment schemes, assuming a risk-averse regulator. We find that the combined payment scheme outperforms the pure action-based scheme except for the case when the regulator has full information, i.e. $\sigma_\phi^2 = 0$. The combined scheme outperforms the pure performance-based scheme except for the case when there is no environmental uncertainty, $\sigma_e^2 = 0$, *and* when the regulator is risk-neutral, $\rho = 0$. For a risk-averse regulator, the pure performance-based scheme is worse than the combined scheme even in the absence of environmental uncertainty (see also result 3a).

For a risk-neutral regulator, the comparisons for the welfare levels is as follows. The welfare gain of the combined payment scheme over the pure action-based scheme is given by

$$E\left[v(y) - \omega\right] - E\left[v(y) - \omega\right]\big|_{p\equiv 0}\Big|_{\rho=0} = \frac{1}{2\,c}\,\frac{\sigma_\phi^4}{\sigma_\phi^2 + c\,\eta\,\sigma_e^2}, \tag{21a}$$

and the welfare gain of the combined payment scheme over the pure performance-based scheme is given by

$$E\left[v(y)-\omega\right] - E\left[v(y)-\omega\right]\big|_{a\equiv 0}\Big|_{\rho=0} = \frac{1}{2\,c}\,\frac{\left(\bar{\phi}\,c\,\eta\,\sigma_e^2\right)^2}{\left(\sigma_\phi^2 + c\,\eta\,\sigma_e^2\right)\left(\bar{\phi}^2 + \sigma_\phi^2 + c\,\eta\,\sigma_e^2\right)}. \tag{21b}$$

Finally, the welfare difference between the pure performance-based PES scheme and the pure action-based one is given by

$$E\left[v(y)-\omega\right]\big|_{a\equiv 0} - E\left[v(y)-\omega\right]\big|_{p\equiv 0}\Big|_{\rho=0} = \frac{1}{2\,c}\,\frac{\sigma_\phi^4 + \bar{\phi}^2\left(\sigma_\phi^2 - c\,\eta\,\sigma_e^2\right)}{\bar{\phi}^2 + \sigma_\phi^2 + c\,\eta\,\sigma_e^2}. \tag{21c}$$

Using these relationships, we obtain the following result:

Result 4. *For a risk-neutral regulator ($\rho = 0$),*

a) The welfare gain of the combined PES scheme over the pure action-based scheme increases with information asymmetry σ_ϕ^2 and decreases with both the farmer's degree of risk aversion η and environmental uncertainty, σ_e^2.

b) The welfare gain of the combined PES scheme over the pure performance-based scheme decreases with information asymmetry σ_ϕ^2 and increases with both the farmer's degree of risk aversion η and environmental uncertainty, σ_e^2.

c) The pure performance-based PES scheme is better than the pure action-based one if and only if

$$c\,\eta\,\sigma_e^2 < \sigma_\phi^2\left(1 + \frac{\sigma_\phi^2}{\bar{\phi}^2}\right). \tag{22}$$

In order to quantify these effects, we apply our analysis to the case of butterfly protection.

4 Quantitative application: Optimal payment scheme for butterfly protection

We base our quantitative application on published ecological-economic studies on the conservation of the Scarce Large Blue (*Maculinea teleius*) in the region of

Landau, Germany (Drechsler et al. 2007, Wätzold et al. 2008). Within European nature conservation, butterflies of the *Maculinea* genus are considered as important flagship species (Dierks and Fischer 2009, Thomas and Settele 2004) and have suffered substantial population declines with local extinctions in recent years (Wynhoff 1998). *Maculinea teleius* is therefore considered as a threatened species in Europe (Swaay and Warren 1999). The butterfly is characterized by a complex life cycle whereby the early instars of this species first feed on the blossoms of *Sanguisorba officinalis* (Great Burnet). Late instars are carried by ants (e.g. *Myrmica rubra*) into their nests where the larvae actively preys on ant brood. Especially the blooming of *Sanguisorba officinalis* and therefore the egg deposition and stage of development of the early instars of *Maculinea teleius* are determined by the mowing regime (Dierks and Fischer 2009). Conservation measures for different mowing regimes have been applied for the enlargement and enhancement of *Maculinea teleius*.

Environmental benefit y is measured in monetary terms. Wätzold et al. (2008, Table 1) provide modeling results of how many butterflies can be conserved with the three projects of applying conservation measures (alternative mowing regimes) to 4, 16, or 64 hectares. The results of a Contingent Valuation published in Wätzold et al. (2008, Table 3), indicate societal conservation benefits of 260, 297, and 426 thousand euros for the three projects. Taking the number of hectares with conservation measures as the farmer's action x, a simple OLS regression shows that the expected marginal productivity of applying conservation measures is $\bar{\phi} = 2.74$ thousand euros per hectare. According to Drechsler et al. (2007, page 183), the coefficient of variation of marginal productivity is about $\sigma_\phi/\bar{\phi} = 0.25$. Hence, $\sigma^2_\phi = 0.47$.

Wätzold et al. (2008) use a linear cost function with constant marginal costs of 0.123 thousand euros per hectare. However, Figure 7b in Drechsler et al. (2007) shows that it is plausible to assume an overall convex cost function. A quadratic cost function with cost parameter $c = 0.015$ [1000 euros/ha] gives the best fit for the range of hectares (4, 16, 64) considered by Wätzold et al. (2008), assuming log-normal errors.

We assume a coefficient of relative risk aversion for farmers of $\rho = 0.74$, which is consistent with experimental evidence for Western Europeans (Andersen et al. 2008). The mean income for German farmers in 2011 was 24.6 thousand euros per year. This leads to an estimate for the degree of absolute risk aversion of about $\eta = 0.74/24.6 = 0.03$/thousand euros.

Since we have no information on the degree of environmental uncertainty, we vary the standard deviation of environmental noise, σ_e. Furthermore, we also vary the regulator's coefficient of risk aversion to obtain an insight of how this parameter influences the quantitative results. These are shown in Figure 1. The left-hand panel in this figure shows the optimal performance-based payment, and the right-hand side the optimal action-based payment for varying environmental stochasticity σ_e. As indicated in *Result 2.* and *3.* the optimal performance-based payment decreases with environmental uncertainty and the action-based payment increases respectively. With a risk-averse regulator ($\rho > 0$), the effect corresponds to the findings as discussed in *Result 4.*: With increasing risk aversion, the performance-based fraction of the combined scheme becomes less attractive for the regulator. The optimal action-based fraction is even higher than the performance-based fraction under circumstances with low environmental stochasticity and increases slightly with increasing σ_e while the performance-based fraction decreases respectively.

Turning to a risk-neutral regulator again we quantify the overall welfare gains of the different payment schemes for the case of the protection of the Scarce Large Blue (*Maculinea teleius*) in Landau. The results shown in Figure 2 correspond to the theoretical findings of *Result 5.*: For low environmental uncertainty the pure performance-based PES may do substantially better than the pure action-based PES, while for high environmental uncertainty, the pure action-based PES would be preferred. However, the combined payment scheme leads always to a

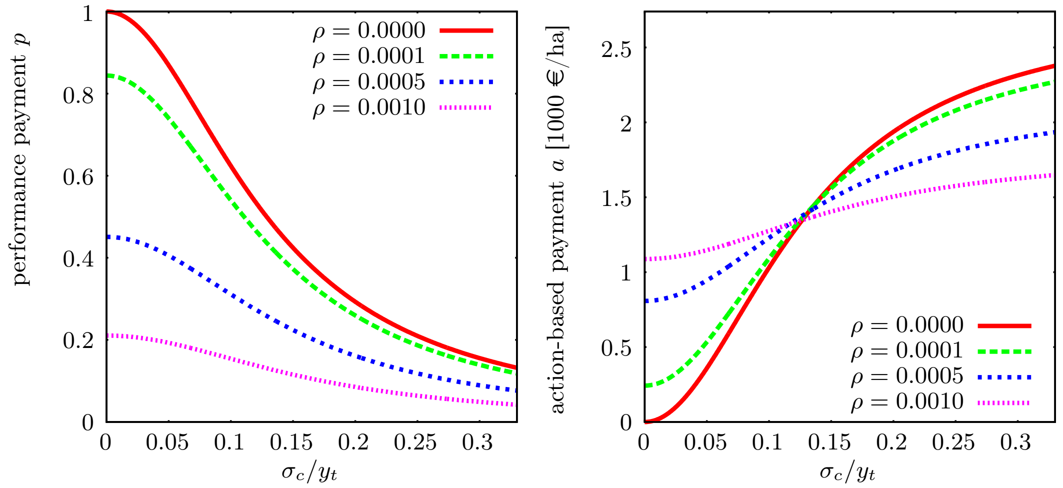

Figure 1: Optimal performance and action-based payments for protection of the Scarce Large Blue (*Maculinea teleius*) in Landau, Germany. The model is calibrated using data from Drechsler et al. (2007) and Wätzold et al. (2008).

higher welfare than either the pure action-based or the pure performance-based scheme. The welfare gain of the combined payment over the pure action-based PES decreases with environmental uncertainty. Furthermore, the welfare gain of the combined scheme over the pure performance-based PES is zero in the absence of environmental uncertainty, in which case the pure performance-based payment is optimal, as shown in *Result 1.*, but is positive when environmental uncertainty matters. Overall the welfare gain of the combined scheme over the pure schemes may sum up to several thousand euros per hectare.

5 Conclusion

In the ongoing discussion on new policy instruments for the provision of environmental goods, performance-based payments gain significant support. In contrast to action-based payment schemes, which are bound to a predefined action or measure, performance-based payments are directly bound to the outcome of the desired environmental or ecosystem service. Even though in the literature performance-based

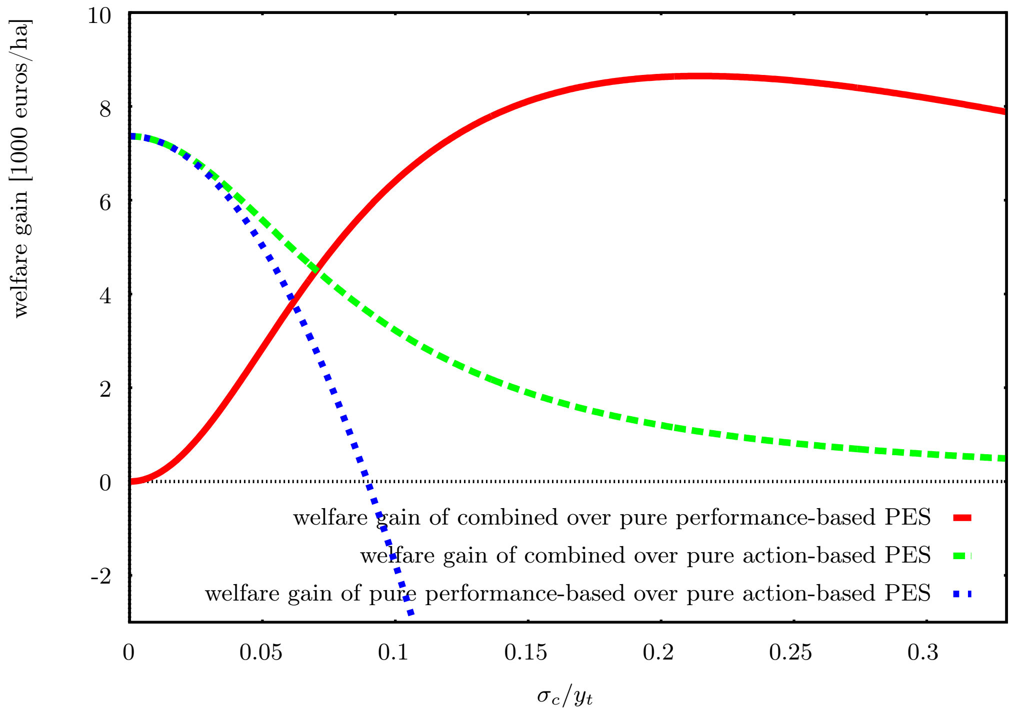

Figure 2: Welfare gains of combined payment scheme over pure performance-based or pure action-based payment schemes, and of pure performance-based payment scheme over pure action-based payment scheme for protection of the Scarce Large Blue (*Maculinea teleius*) in Landau, Germany. Data as in figure 1.

payments occur as the preferred concept in many ways, examples of action-based payments still predominate in practical application. Although it is acknowledged that an action-based payment scheme is not optimal under information asymmetry, a performance-based payment scheme may not be the preferred option either if the performance is risky. Therefore, in this paper we have studied how both types of payment schemes could be optimally combined, because typically both information asymmetry and environmental uncertainty matter in a real-world context.

Based on a principal-agent model we have shown that an exclusively performance-based payment is optimal only if there is no environmental uncertainty or if both the farmer and the regulator are risk-neutral. An exclusively action-based payment is optimal, if the regulator has full information about the productivity of the action i.e. if there is no information asymmetry. In every other case the offering of a combination of performance-based and action-based payments (with different weighting) is optimal. Accordingly, the welfare gain of the combined scheme over the pure action-based scheme increases with information asymmetry, while the welfare gain of the combined scheme over the pure performance-based scheme increases with environmental uncertainty.

With a risk-averse regulator the situation changes as follows. The regulator is not directly affected through environmental uncertainty, but indirectly through the farmer's choice of action, since the farmer chooses his actions considering environmental uncertainty. Under information asymmetry a performance-based payment would amplify the effect of the regulators uncertainty about the action's productivity compared to the action-based payment. Thus, for a risk-averse regulator, the performance-based payment in comparison to the action-based payment pays out worse.

In a quantitative application to the case study of butterfly conservation we have shown that the benefit of the combined scheme over the pure action-based or performance-based schemes may be substantial, reaching several thousand euros per hectare. As a result we can conclude that the pure action-based or pure performance-based schemes perform equally well only in the special cases of either no information asymmetry or no environmental uncertainty.

Appendix

A Optimal payment scheme

Taking expectation over ϕ according to the regulator's assumed distribution with mean $\bar{\phi}$ and variance σ_ϕ^2, the optimization problem can be written as

$$\max_{a,p} \Bigg\{ \frac{a\,\bar{\phi} + p\,(\bar{\phi}^2 + \sigma_\phi^2)}{c} \\ - \frac{\rho}{2}\, \frac{a^2\,(\bar{\phi}^2 + \sigma_\phi^2) + 2\,a\,p\,(\bar{\phi}^3 + 3\,\bar{\phi}\,\sigma_\phi^2) + p^2\,(\bar{\phi}^4 + 6\,\bar{\phi}^2\,\sigma_\phi^2 + 3\,\sigma_\phi^4)}{c^2} \\ - \frac{a^2 + 2\,a\,p\,\bar{\phi} + p^2\,\bar{\phi}^2 + p^2\,\sigma_\phi^2}{2\,c} - \frac{\eta}{2}\,p^2\,\sigma_e^2 \Bigg\}. \quad \text{(A.23)}$$

After few steps of simplification, the first-order conditions with respect to a and p can be written as

$$c\,\left(a^\star + \bar{\phi}\,p^\star - \bar{\phi}\right) + \rho\,\left(a^\star\,(\bar{\phi}^2 + \sigma_\phi^2) + \bar{\phi}\,p^\star\,(\bar{\phi}^2 + 3\,\sigma_\phi^2)\right) = 0 \quad \text{(A.24)}$$

$$\frac{\bar{\phi}^2 + \sigma_\phi^2}{c}\,(1 - p^\star) - \frac{a^\star\,\bar{\phi}}{c} - \eta\,p^\star\,\sigma_e^2 \\ - \rho\,\frac{a^\star\,(\bar{\phi}^3 + 3\,\bar{\phi}\,\sigma_\phi^2) + p^\star\,(\bar{\phi}^4 + 6\,\bar{\phi}^2\,\sigma_\phi^2 + 3\,\sigma_\phi^4)}{c^2} = 0 \quad \text{(A.25)}$$

Solving for $a^\star$ and $p^\star$, we obtain

$$a^\star = \frac{2c\bar{\phi}^3\rho\sigma_\phi^2 + c^3\eta\bar{\phi}\sigma_e^2}{\left(c + \bar{\phi}^2\rho\right)^2\sigma_\phi^2 + 4c\rho\sigma_\phi^4 + 3\rho^2\sigma_\phi^6 + c^2\eta\left(c + \rho\left(\bar{\phi}^2 + \sigma_\phi^2\right)\right)\sigma_e^2} \quad \text{(A.26a)}$$

$$p^\star = \frac{c\,\sigma_\phi^2\left(c - \rho\left(\bar{\phi}^2 - \sigma_\phi^2\right)\right)}{\left(c + \bar{\phi}^2\rho\right)^2\sigma_\phi^2 + 4c\rho\sigma_\phi^4 + 3\rho^2\sigma_\phi^6 + c^2\eta\left(c + \rho\left(\bar{\phi}^2 + \sigma_\phi^2\right)\right)\sigma_e^2} \quad \text{(A.26b)}$$

The denominator of these expressions is

$$\left(c + \bar{\phi}^2\rho\right)^2\sigma_\phi^2 + 4c\rho\sigma_\phi^4 + 3\rho^2\sigma_\phi^6 + c^2\eta\left(c + \rho\left(\bar{\phi}^2 + \sigma_\phi^2\right)\right)\sigma_e^2 \\ = \left(c^2 + 2\,c\,\bar{\phi}^2\rho + \bar{\phi}^4\rho^2\right)\sigma_\phi^2 + 4c\rho\sigma_\phi^4 + 3\rho^2\sigma_\phi^6 + c^2\eta\left(c + \rho\left(\bar{\phi}^2 + \sigma_\phi^2\right)\right)\sigma_e^2 \\ = c^2\,\left(\sigma_\phi^2 + c\,\eta\,\sigma_e^2\right) \\ + \rho\,c\,\left(2\,\sigma_\phi^2\,\left(\bar{\phi}^2 + 2\,\sigma_\phi^2\right) + c\,\eta\,\left(\bar{\phi}^2 + \sigma_\phi^2\right)\,\sigma_e^2\right) \\ + \rho^2\,\sigma_\phi^2\,\left(\bar{\phi}^4 + 3\,\sigma_\phi^4\right). \quad \text{(A.27)}$$

Simplifying and dividing by c^2 leads to (17). Plugging into (A.26), we obtain (16).

B Proof of result 3

Differentiating (16b) with respect to ρ yields

$$
\begin{aligned}
\frac{\partial p^\star}{\partial \rho} = \frac{\sigma_\phi^2}{\Omega^2} \Big[&-\frac{1}{c}\,(\bar\phi^2-\sigma_\phi^2)\,\Big(\sigma_\phi^2+c\,\eta\,\sigma_e^2 \\
&+\frac{\rho}{c}\,\big(2\,\sigma_\phi^2\,(\bar\phi^2+2\,\sigma_\phi^2)+c\,\eta\,(\bar\phi^2+\sigma_\phi^2)\,\sigma_e^2\big)+\frac{\rho^2}{c^2}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big) \\
&-\Big(1-\frac{\rho}{c}\,(\bar\phi^2-\sigma_\phi^2)\Big)\,\Big(\frac{1}{c}\,\big(2\,\sigma_\phi^2\,(\bar\phi^2+2\,\sigma_\phi^2)+c\,\eta\,(\bar\phi^2+\sigma_\phi^2)\,\sigma_e^2\big) \\
&\qquad +\frac{2\,\rho}{c^2}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big)\Big] \\
=\frac{\sigma_\phi^2}{c\,\Omega^2}\Big[&-(\bar\phi^2-\sigma_\phi^2)\,\Big(\sigma_\phi^2+c\,\eta\,\sigma_e^2-\frac{\rho^2}{c^2}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big) \\
&-\Big(2\,\sigma_\phi^2\,(\bar\phi^2+2\,\sigma_\phi^2)+c\,\eta\,(\bar\phi^2+\sigma_\phi^2)\,\sigma_e^2+\frac{2\,\rho}{c}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big)\Big] \\
=-\frac{\sigma_\phi^2}{c\,\Omega^2}\Big[&3\,\sigma_\phi^2\,(\bar\phi^2+2\,\sigma_\phi^2)+2\,c\,\eta\,\bar\phi^2\,\sigma_e^2+\Big(2-\frac{\rho}{c}\,(\bar\phi^2-\sigma_\phi^2)\Big)\,\frac{\rho}{c}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big]
\end{aligned}
\tag{B.28}
$$

Differentiating (16b) with respect to ρ yields

$$
\begin{aligned}
\frac{\partial a^\star}{\partial \rho} = \frac{\bar\phi}{c\,\Omega^2} \Big[&2\,\bar\phi^2\,\sigma_\phi^2\,\Big(\sigma_\phi^2+c\,\eta\,\sigma_e^2 \\
&+\frac{\rho}{c}\,\big(2\,\sigma_\phi^2\,(\bar\phi^2+2\,\sigma_\phi^2)+c\,\eta\,(\bar\phi^2+\sigma_\phi^2)\,\sigma_e^2\big)+\frac{\rho^2}{c^2}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big) \\
&-\Big(c\,\eta\,\sigma_e^2+2\,\frac{\rho}{c}\,\bar\phi^2\,\sigma_\phi^2\Big)\,\Big(2\,\sigma_\phi^2\,(\bar\phi^2+2\,\sigma_\phi^2)+c\,\eta\,(\bar\phi^2+\sigma_\phi^2)\,\sigma_e^2 \\
&\qquad +\frac{2\,\rho}{c}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big)\Big] \\
=\frac{\bar\phi}{c\,\Omega^2}\Big[&2\,\bar\phi^2\,\sigma_\phi^2\,\Big(\sigma_\phi^2+c\,\eta\,\sigma_e^2-\frac{\rho^2}{c^2}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big) \\
&-c\,\eta\,\sigma_e^2\,\Big(2\,\sigma_\phi^2\,(\bar\phi^2+2\,\sigma_\phi^2)+c\,\eta\,(\bar\phi^2+\sigma_\phi^2)\,\sigma_e^2+\frac{2\,\rho}{c}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big)\Big] \\
=\frac{\bar\phi}{c\,\Omega^2}\Big[&2\,\bar\phi^2\,\sigma_\phi^4\,\Big(1-\frac{\rho^2}{c^2}\,(\bar\phi^4+3\,\sigma_\phi^4)\Big) \\
&-c\,\eta\,\sigma_e^2\,\Big(4\,\sigma_\phi^4+c\,\eta\,(\bar\phi^2+\sigma_\phi^2)\,\sigma_e^2+\frac{2\,\rho}{c}\,\sigma_\phi^2\,(\bar\phi^4+3\,\sigma_\phi^4)\Big)\Big]
\end{aligned}
\tag{B.29}
$$

C Proof of result 4

Using (16) in the regulator's objective function that is given in (A.23), we obtain after few steps of rearrangement

$$E\left[v(y)-\omega\right] \\ = \frac{1}{2\,c}\,\frac{\sigma_\phi^2\,(\bar{\phi}^2+\sigma_\phi^2)+\frac{\varrho}{c}\,\sigma_\phi^2\,(\bar{\phi}^4+\sigma_\phi^4)+c\,\eta\,\bar{\phi}^2\,\sigma_e^2}{\sigma_\phi^2+2\,\frac{\varrho}{c}\,\sigma_\phi^2\,(\bar{\phi}^2+2\,\sigma_\phi^2)+\frac{\varrho^2}{c^2}\,\sigma_\phi^2\,(\bar{\phi}^4+3\,\sigma_\phi^4)+c\,\eta\,\sigma_e^2\,\Big(1+\frac{\varrho}{c}\,\sigma_\phi^2\,(\bar{\phi}^2+\sigma_\phi^2)\Big)} \tag{C.30}$$

for the combined PES.

It is straightforward to verify that the optimal pure action-based payment would be

$$a^\star|_{p\equiv 0} = \frac{\bar{\phi}}{1+\frac{\varrho}{c}\,(\bar{\phi}^2+\sigma_\phi^2)}. \tag{C.31}$$

Using this, together with $p \equiv 0$, in the regulator's objective function yields a welfare level of

$$E\left[v(y)-\omega\right]|_{p\equiv 0} = \frac{1}{2\,c}\,\frac{\bar{\phi}^2}{1+\frac{\varrho}{c}\,(\bar{\phi}^2+\sigma_\phi^2)} \tag{C.32}$$

for the pure action-based PES. Finally, the optimal pure performance-based payment would be

$$p^\star|_{p\equiv 0} = \frac{\bar{\phi}^2+\sigma_\phi^2}{\bar{\phi}^2+\sigma_\phi^2+\frac{\varrho}{c}\,(\bar{\phi}^4+6\,\bar{\phi}^2\,\sigma_\phi^2+3\,\sigma_\phi^4)+c\,\eta\,\sigma_e^2}. \tag{C.33}$$

With this, the welfare level is

$$E\left[v(y)-\omega\right]|_{a\equiv 0} = \frac{1}{2\,c}\,\frac{(\bar{\phi}^2+\sigma_\phi^2)^2}{\bar{\phi}^2+\sigma_\phi^2+\frac{\varrho}{c}\,(\bar{\phi}^4+6\,\bar{\phi}^2\,\sigma_\phi^2+3\,\sigma_\phi^4)+c\,\eta\,\sigma_e^2} \tag{C.34}$$

for the pure performance-based PES.

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