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Pay for the option to pay? The impact of improved scientific information on payments for ecosystem services

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Abstract The scientific information to precisely link land use changes to changes in ecosystem service provision is often unavailable, particularly for hydrological ecosystem services. Potential buyers of ecosystem services must weigh the risk of paying to incentive conservation that fails to deliver valuable ecosystem services against the risk that land is developed before its value is known. This paper uses a two period model to assess when expected future improvements in scientific information should substantially impact payments for conservation today. Optimal current payments increase, often substantially, as the quality of expected future information increases, but the gain from increasing payments to account for the expected degree of improved information is small in many cases. Larger values occur when the buyer believes that the land whose private development value is the highest also provides the highest ecosystem service, when the buyer faces relatively more uncertainty about ecosystem service provision than about the cost of inducing conservation, and when the buyer believes land is highly likely to be developed absent incentive payments.

Keywords: ecosystem services; uncertainty; option value; numerical simulation

1 Introduction

There is a growing recognition that undeveloped land provides many ecosystem services. When the benefits of these service are external to private landowners, private land use decisions are not optimal. In this setting, using a payment for ecosystem services (PES) plan to promote conservation represents a potentially important policy tool (Ferraro & Simpson, 2002). An important category of ecosystem services are hydrological or water-related ecosystem services. Brauman et al. (2007) discuss the nature and value of water related ecosystem services and Porras et al. (2008) document numerous examples of PES programs focused on watershed services.

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Despite their promise, PES payment plans come with many challenges (Kinzig et al., 2011). Wunder et al. (2008) and Pattanayak et al. (2010) identify understanding the precise link between land use and ecosystem services as as one of the four critical factors for identifying whether PES programs can provide benefit. In particular, the relationship between ecosystem service provision and land-use is often imprecisely understood so that ecologists are rarely able to provide specific estimates of the service provided by individual parcels. Moreover, even when the biophysical services can be accurately quantified, the economic value of those services is also uncertain (Johnson et al., 2012). As a result, buyers seeking to implement payment for ecosystem service approaches are left uncertain about what they might be purchasing. Wunder et al. (2008) and Wunder & Albán (2008) emphasize that this concern is particularly acute for watershed protection programs. Some of this uncertainty is due to the inherently stochastic nature of ecosystems, but improved scientific understanding in the future may partially reduce this uncertainty and significant efforts to improve understanding are underway.[1] If potential ES buyers wait until they are sure of the services provided by a parcel, it may be too late to avoid development. Instead, buyers may need to provide conservation incentives today to preserve the option to pay for valuable ecosystem services tomorrow.

In this paper, I use a two period model to investigate how expected improvements in knowledge about the link between land use changes and ecosystem service (ES) provision affect optimal payments today. A buyer of ES can offer payment to a landowner today in exchange for an agreement to conserve land for a specified period of time but faces uncertainty about both the payment needed to induce conservation and the ecosystem services provided by the parcel. The buyer weighs the risk of paying for conservation on parcels that in fact provide little to no ES value against the risk that land that does have high ES value will be irreversibly developed before the buyer learns this. I begin by considering the optimal offer the buyer should make once improved information is available. I then step back in time and ask how landowners should respond in the prior period, knowing that if they do not develop their land, buyers will learn more information about conservation value and make more specific offers in the future. I find that under most conditions, the possibility of improved future information does not influence a landowner's choice in the first period. Finally, I step back further and explore what offer a buyer should make today, given the possibility of improved information in the future. The improved information naturally leads to increased offers today and increases the range of parameters for which making positive offers is optimal. At the same time, the increase in the buyer's payoff from responding optimally tends to be quite small unless the land is highly likely to be developed in the absence of a payment today **and** the expected ES value substantially exceeds the expected payment needed to induce conservation.

[1] For example, Quintero et al. (2009) use a hydrological modeling tool called SWAT to provide suggestions for targeting future PES payments in the same programs where such information was identified as lacking in Wunder & Albán (2008). Methods to improve understanding of hydrological ecosystem service provisions are discussed by numerous authors including Keeler et al. (2012), Guswa et al. (2014), Grizzetti et al. (2016), and Trisurat et al. (2016)

Costello & Polasky (2004) emphasize the importance of up front conservation in a model of selecting sites for a conservation reserve. In their model, the buyer faces uncertainty about whether a particular site will be developed. Since the uncertainty cannot be resolved before the buyer either commits to payment or loses the opportunity for conservation, there is no gain from waiting for better information. Newburn et al. (2005) and Newburn et al. (2006) emphasize the importance of considering both the cost of acquiring a particular parcel and the likelihood that a parcel will be developed in the absence of policy since parcels more likely to develop also tend to cost more to conserve. Dissanayake & Önal (2011) consider the dynamic effect of purchasing land over time on equilibrium land prices. My analysis differs from the reserve site selection literature in two important ways. First, the emphasis in the site selection literature is on uncertainty over which sites will be developed. I couple this uncertainty with partially reducible uncertainty about the benefits different sites provide. Second, I focus on temporary payments for delaying conservation rather than permanent payments. Shah & Ando (2016) develop an infinite horizon model to assess the minimum temporary and permanent payments need to induce landowners to conserve their land when landowners face uncertainty about the future (private) benefits from both conservation and development (conversion). They compute the minimum payments needed to induce conservation but do no optimize from the buyer's perspective.

The ES buyer in this paper faces uncertainty about both the cost of inducing conservation and the benefits of conservation. Both sources of uncertainty have been considered previously. Buyer uncertainty about the payment need to induce conservation is a result of asymmetric information between the landowner and buyer. Engel et al. (2008) describe three types of inefficiency that can plague PES programs as a result of this asymmetry: failing to provide a sufficiently high incentive when conservation would be valuable, paying more conservation than it is worth, and paying for non-additional conservation. Ferraro (2008) notes that strategies to reduce the cost of asymmetric information on PES programs generally fall into three categories: (1) acquiring more information, (2) offering a menu of contracts using techniques from the mechanism design literature, or (3) conducting procurement auctions. While the literature has often focused on the second (Parkhurst et al., 2002; Sheriff, 2009; Arguedas & van Soest, 2011) and third (Cason & Gangadharan, 2004; Reeson, 2011; Bardsley & Burfurd, 2013; Polasky et al., 2014; DePiper, 2015; Fooks et al., 2016) approaches, Ferraro emphasizes that no one approach dominates. Moreover, Arnold et al. (2013) emphasize that adverse selection remains an issue with auctions. The buyer in the present analysis implicitly adopts the first strategy, allowing buyers to condition a single take-it-or-leave it offer on only observed information. The emphasis here is on learning more information about the conservation value of a parcel of land; knowledge about the private development is gained only indirectly when correlation between values is present.

Uncertainty about the ES provided by land use practices has also received considerable attention in the literature. Rabotyagov (2010) considers a regulator or purchaser of offsets who wishes to maximize the benefit of services subject to a constraint on the likelihood that a level of service greater than or equal to the claimed level is actually provided and demonstrates that applying a margin of safety discount is optimal for a regulator or aggregator with CARA risk-preferences. Springborn et al. (2013) argue that margin of safety discounts should generally be applied at a high level of aggregation rather than at a parcel level. An important consideration in the literature considering mechanisms to reduce the cost of asymmetric information is the relative performance of input based payments versus output based payments when buyers are risk neutral and landowners are risk-averse but landowners have better information on the services provided by their parcel than buyers do (Derissen & Quaas, 2013). The buyer's level of uncertainty remains fixed in these analyses; in contrast, I consider how reductions in uncertainty could affect payments in a multi-period setting.

The remainder of the paper is organized as follows. Section 2 of the paper develops the multi-period analytical model and provides a preliminary discussion of the impacts of model parameters. Since the model does not have an analytical solution, Sections 3 and 4 use numerical simulations to describe these impacts, with section 3 assuming independence between the uncertainty in public conservation value and private development value and section 4 considering the impact of correlation. Section 5 offers concluding comments.

2 Model

Consider a buyer who wishes to maximize the value of services received by a given parcel of land over two time periods. The land parcel has two possible states (developed and conserved) and the decision to develop a parcel of land is irreversible. Arnold et al. (2013) hypothesize that private landowners receive benefits from their land in both the developed and the conserved state and that landowners can vary along both dimensions. Vedel et al. (2015) use a choice experiment to demonstrate significance variation in landowners' willingness to accept payment for adopting particular forest management strategies based on their current practices also suggesting that private benefits of development may vary across landowners. Instead of explicitly modeling the components of private benefits, I let p represent the private net benefit of development over conservation. Similarly, the buyer could derive benefits from land in either state. I define the buyer's benefit of *conservation* over development as e. From the buyer's perspective, the optimal use of the parcel would be to develop the land if $e < 0$ and to conserve the land if $e \geq 0$, but development decisions are made by the landowner who will choose to develop if $p > 0$ and to conserve if $p \leq 0$.[2]

With perfect information, the buyer would offer the landowner a payment $\phi = p$ if $e \geq p > 0$ and no payment otherwise.[3] However, the buyer has imperfect information about the values of e and p. In

[2] Throughout the model, I assume that indifference is resolved in favor of conservation.

[3] I assume that the buyer views payments as costs rather than redistributive transfers. This is consistent with a buyer representing direct beneficiaries of ecosystem services (e.g. a downstream water utility making payments to upstream

particular, in the first period, the buyer has little information about how much, if anything, the parcel needs to be paid to remain undeveloped or the actual benefit the parcel provides if conserved. Waiting for additional information that is expected to arrive in the future carries a substantial risk that the land will be irreversibly developed before its conservation value is known. The possibility of new information creates an option value of conservation that will increase the buyer's willingness to pay for conservation today. The goal of the model is to describe how this option value influences both offers and social welfare today.

To focus on this possibility, I assume that p is fixed over time. At time 0, the buyer has an initial estimate of the distribution of e. At time T, the buyer observes a signal s that reduces uncertainty about the true conservation value. For analytical tractability, I assume that the variables have a multivariate normal distribution with the form

$$\begin{bmatrix} s \\ p \\ e \end{bmatrix} \sim N_3 \left(\begin{bmatrix} 0 \\ \mu_p \\ \mu_e \end{bmatrix}, \begin{bmatrix} 1 & \rho_{es}\rho_{ep}\sigma_p & \rho_{es}\sigma_e \\ \rho_{es}\rho_{ep}\sigma_p & \sigma_p^2 & \rho_{ep}\sigma_e\sigma_p \\ \rho_{es}\sigma_e & \rho_{ep}\sigma_e\sigma_p & \sigma_e^2 \end{bmatrix} \right). \tag{1}$$

With this structure $\rho_{es} \in (0,1)$ measures the quality of the signal and ρ_{ep} measures the correlation between environmental service value and private development value.[4] Moreover, $\mu_{p|e,s} = \mu_{p|e}$ for all values of s and e, implying that the only information the signal provides about private development value is derived from the information it reveals about conservation value.

The buyer can make an offer to the landowner in both periods in exchange for an agreement to conserve the parcel. Accepting an offer at time 0 requires the landowner to conserve the land until time T, at which point the landowner is free to develop the land or to continue conservation. The parcel provides a per period benefit of p to the landowner in any period in which it is developed. The buyer receives a per period benefit of e from the land when it is conserved, although the value of e is not directly observed.[5] The relative value of payoffs in the second time period (starting at time T) to those in the first time period (from time 0 to time T) is given by δ.[6] Development is irreversible.

landowners). To the extent that the buyer represents a government who views the payments as transfers, the cost of payments in (2) and (7) could be multiplied by a factor ν representing the opportunity cost of funds to pay for the transfers.

[4] In this model, ρ_{ep} refers to correlation between the unknown elements of e and p, not a statement about their expected values. If the buyer knows that a particular parcel is likely to provide high environmental service value, but is also likely to provide high benefits to the landowner if it is developed, this implies that both μ_e and μ_p are high, but does not imply that $\rho_{ep} > 0$. The natural cause for a non-zero value of ρ_{ep} in this model is a difficult to observe or verify land characteristic that influences both development value and ecosystem service value.

[5] Engel et al. (2008) note that in many government-financed PES programs, the buyers of an ecosystem service "have no first-hand information on its value, and generally cannot observe directly whether it is being provided" (pg. 666).

[6] Since the model is designed to capture long time frames, there is no a priori assumption that the two time periods have equal length. As a result, I require $\delta > 0$, but do not impose $\delta < 1$. If the time until information is received is relatively short and the parties expect decisions in the second period to persist for a long time frame, $\delta > 1$ is reasonable. The simulations place equal weight on the two periods.

2.1 Buyer's final period offer

In this section, I describe the optimal payment in the final period, exploring how the well-known issues of non-additionality and overpayment play out in the context of this model. If the parcel remains undeveloped at time T, the buyer will observe a signal s about the conservation value provided by the parcel. This signal could be the result of improved information about the parcel itself or could result from improved information about the processes linking land use decisions or parcel characteristics to ecosystem services. Based on this information, the buyer can offer a payment $\phi > 0$ to the landowner in exchange for conserving the land.[7] Although the buyer does not receive a direct signal about the value of p, some information may be inferred from the landowner's previous action. In particular, under conditions described below, the buyer infers that there is an upper bound $\bar{p} \in [0, \infty]$ for the private development value of the parcel, given that the landowner chose to conserve the land until period T. Since this is the last period, the landowner will accept the offer if $p \leq \phi$. The buyer's goal is to maximize the expected value from conservation less any payments made to the landowner. An offer greater than $\bar{p}$ cannot be optimal because the buyer could lower the offer to $\bar{p}$ and maintain perfect certainty that the parcel will be conserved, while lowering the expected cost. The buyer's expected payoff for a parcel as a function of ϕ, given that $\phi \leq \bar{p}$, is given by

$$W(\phi, s) = \int_{-\infty}^{\phi} \int_{-\infty}^{\infty} (e - \phi) f_{e|s,p}(e|s,p)\, de f_{p|s}(p|s)\, dp \tag{2}$$

Since this expression is independent of $\bar{p}$, the upper bound affects the problem only through the constraint that $\phi \leq \bar{p}$. As shown in the appendix, under the multivariate normal assumption, this expression can be simplified to

$$W(\phi, s) = -\sigma_e \sigma_p \rho_{ep} \left(1 - \rho_{es}^2\right) f_{p|s}(\phi|s) + (\mu_e + \rho_{es}\sigma_e s - \phi) F_{p|s}(\phi|s). \tag{3}$$

The buyer's goal is to identify the value of $\phi \in [0, \bar{p}]$ that maximizes this expression. The following two propositions are proved in the appendix.

Proposition 1 *$W(\phi, s)$ reaches a maximum on $[0, \bar{p}]$ for all values of s and for any $\bar{p} \geq 0$.*

Proposition 2 *There is at most one interior local maximum of $W(\phi, s)$ on $[0, \infty)$.*

An immediate consequence of Propositions 1 and 2 is that the solution could occur at $\phi = 0$, at an interior solution, or at the upper bound $\bar{p}$. If multiple solutions provide the same payoff, I assume the buyer will resolve the indifference in favor of maximizing conservation. At an interior solution, the first

[7] Given the multivariate normal assumption, there is a probability that the buyer might want to set $\phi < 0$ to induce a landowner to develop land the landowner would prefer to conserve. Such payments are outside the typical scope of payment for ecosystem service plans and are not considered in this analysis.

order condition

$$f_{p|s}\left(\phi|s\right)\left[\mu_e+\sigma_e\rho_{es}\left(1-\gamma\rho_{ep}^2\right)s-\frac{\sigma_e\rho_{ep}}{\sigma_p}\gamma\mu_p-\left(1-\gamma\frac{\sigma_e\rho_{ep}}{\sigma_p}\right)\phi\right]=F_{p|s}\left(\phi|s\right) \tag{4}$$

where $\gamma=\frac{1-\rho_{es}^2}{1-\rho_{es}^2\rho_{ep}^2}$ must hold.[8] The right hand side is the marginal cost of increasing the offer: the buyer must make larger payments if the landowner accepts the offer, which happens with probability $F_{p|s}\left(\phi|s\right)$. This cost is illustrated for a specific example by the solid line in Figure 1. The left hand side of (4) is the marginal benefit of increasing the offer, which is the product of two quantities: the probability that increasing the offer changes the landowner's conservation decision and the expected net gain from changing the parcel's choice. The latter term is the expected gain conditional on the parcel being indifferent between conservation and development and is the term in brackets on the the left-hand side of (4). In Figure 1, the dotted line is the probability that increasing the offer changes the parcel's decision (given by $f_{p|s}\left(\phi|s\right)$), while the dashed line is the conditional expected gain. In this example,$\rho_{ep}=0$. Since there is no correlation, knowing that the parcel has accepted the offer reveals nothing about the expected benefit of conserving the parcel and increasing the offer decreases the conditional gain dollar for dollar. The dot-dashed line is the product of the dashed and dotted lines and represents the marginal benefit.

The key benefit of additional information in the second period is that it allows the buyer to customize the offer based on the improved understanding about the conservation value provided by the parcel. Separation of the first order condition into its component parts facilitates discussion of how the observed signal and the possibility of correlation impact the optimal payment. Figure 2 illustrates the impact of correlation and the observed signal on each of the lines from Figure 1. In the middle column, the buyer observes a signal of zero, while the left column and right columns illustrate negative and positive signals respectively and thus correspond to learning that the parcel is likely to provide more or less benefit when conserved than originally expected. The solid black lines show the curves when there is no correlation, the dashed lines illustrate negative correlation between public conservation value and private development value and the dotted lines illustrates positive correlation. From this figure, we observe several effects.

First, as the observed signal increases, the conditional gain rises because we expect the parcel to provide more value. Thus each of the lines in the conditional gain panels on the second row shift up as we move from a negative to zero to positive signal.

Second, when there is no correlation between conservation and development value, the signal reveals no information about development value and thus has no impact on the marginal cost or the probability a parcel is marginal. In this case, increasing the signal unambiguously increases the optimal offer.

Third, when there is correlation, (either negative or positive), the buyer's uncertainty about the *private* value is also reduced through observation of the signal s, leading to changes in the probability

[8] For the derivation of this condition, see Appendix C.

that increasing the offer will change the landowner's choice and to changes in the costs. When the buyer observes a signal of 0 in the middle column, the mean of the subjective distribution remains unchanged but its variance falls as illustrated with the dotted lines. In the left and right columns we see that in addition to reducing the variance of the conditional distribution of p, positive and negative correlation will cause its mean to shift if a non-zero signal is observed. High signals increase the mean with positive correlation and decrease the mean with negative correlation, while low signals do the reverse. The combined effects can be positive or negative depending on whether the optimal offer is above or below the conditional mean private development value.

Fourth, correlation has a substantial impact on the conditional expected gain, shown in the second row of Figure 2. As the offer increases, the expected gain on the marginal parcel falls due to the increase in payment. If $\rho_{ep} = 0$ (e.g. the solid lines), this is the only impact of changing the offer, so the conditional gain has a slope of -1 with respect to the offer, as with the solid lines. With correlation, increasing the offer not only increases the cost at the marginal parcel, it also influences the expected conservation value of the marginal parcel. If $\rho_{ep} < 0$, the negative correlation implies that as we increase the offer, the conditional expected conservation value falls because the highest conservation value parcels are the ones most likely to conserve even with a low offer. As a result, the slope of the conditional gain will be less than -1 and the dashed lines slope down more steeply than the solid lines. The effect is amplified as the negative correlation gets stronger. With positive correlation, the conditional expected conservation value increases as the offer increases, so the slope will increase and can be positive if $\sigma_e > \sigma_p$, especially when the correlation is strong.

Fifth, any correlation dampens the impact of the signal on the conditional gain (because $\gamma\rho_{ep}^2 < 1$), so the dashed and dotted lines shift up and down less as we move across the columns than the solid lines do. Intuitively, since knowing the parcel was induced to change its choice by the change in offer reveals some information about the expected conservation value when there is correlation, there is less remaining uncertainty for the signal to reveal.

Finally, since γ falls as ρ_{es} increases, all of the impacts of changing correlation are dampened as the signal reveals more information about the environmental benefit so the conditional gain cannot vary as much. In contrast, as ρ_{es} increases, the impact of the signal is magnified since it reveals more information.

The combined effect of the changes on the first two rows is shown on the marginal benefit curve in the middle row of Figure 2. For both negative and zero correlation, the marginal benefit first rises, then falls, and eventually rises again, approaching zero asymptotically. This pattern is reversed for positive correlation if $\sigma_p < \sigma_e$ as in the case in this example. The final row illustrates the buyer's payoff function for the different cases and illustrate the different possible solution types described above. With the parameters illustrated here and negative or zero correlation, there is a single local (and thus global) maximum of $W(\phi, s)$, while with positive correlation there are two local maxima of $W(\phi, s)$ in the feasible set: one at zero and one with a positive offer. This reflects an important cost that positive correlation between e and p imposes on the buyer: the land is likely to be ecologically valuable only when it will also require a high payment to induce conservation. Unfortunately, making such a high offer will also induce the landowner to conserve when the land is not ecologically valuable. In this situation, the buyer is better off making no offer than a low offer and must carefully assess whether a zero offer or a high offer is preferable. In the example here, the positive solution is preferred with the mean or high signal, but no offer is preferred with a low signal. Moreover, this implies that the optimal offer may change discontinuously as problem parameters change, if the change induces a shift from preferring a positive offer to preferring a zero offer. With zero or positive correlation, the optimal offer increases with the signal observed, while with negative correlation, it will tend to increase at low signal values when the direct effect on the expected conservation value dominates and will tend to decrease at high signal values when the high signal suggests a low development value and thus a low offer needed to induce conservation. Sections 3 and 4 use numerical simulations to illustrate the size of these effects for specific parameterizations.

2.2 Landowner's prior period decision

The upper bound on p consistent with the landowner conserving the land until time T is found by considering the landowners' decision at time 0. At this time, the landowner must decide whether to develop the land immediately and receive a payoff of p in every period or to accept the buyer's offered conservation payment τ for this period and retain the option to conserve or develop the land at time T. The landowner knows p, which will give private information about the likelihood of possible values of s when $\rho_{es} > 0$ and $\rho_{ep} \neq 0$. In particular, $s|p \sim N\left(\sigma_p \rho_{es} \rho_{ep} \left(p - \mu_p\right), \sigma_p \sqrt{1 - \rho_{es}^2 \rho_{ep}^2}\right)$. This induces a subjective distribution of possible offers with $f_{\phi|p}\left(\phi|p\right) = \sum_{s:\phi^*(s,\bar{p})=\phi} f_{s|p}\left(s|p\right)$. The expected benefit of conservation for the landowner is

$$B\left(p\right) = \tau + \delta\left(\int_{p}^{\infty} \left(\phi - p\right) f_{\phi|p}\left(\phi|p\right) d\phi\right) - p. \tag{5}$$

Consistent with the second period decision, the landowner is assumed to conserve the land when indifferent. Although there is no closed form solution for $\phi^*\left(s\right)$, several conclusions about the landowner's decision can be reached. First, since ϕ is bounded below by zero, the landowner will conserve the land if it was privately optimal to do so without a policy, e.g. if $p \leq 0$. Second, when $\rho_{ep} = 0$, $B\left(0\right) = \tau + \delta\left(\int_p^{\infty} \left(\phi - p\right) f_{\phi|p}\left(\phi|p\right) d\phi\right) \geq 0$ and $f_{\phi|p}\left(\phi|p\right)$ is constant for all values of p, implying that $\frac{dB}{dp} = -1$. In this case, there is a unique threshold $\bar{p}$ such that the landowner will conserve at $t = 0$ if $p \leq \bar{p}$ and will develop immediately otherwise. As the correlation grows stronger, the impact of changes in p on the integral increases. It is possible, although unlikely, that there will be multiple solutions to $B(p) = 0$.

When a unique threshold exists, its value solves the equation $B(\bar{p}) = 0$. If the landowner knows that the parcel is at this threshold, $p = \bar{p}$ and $f_{\phi|p}(\phi|p) = 0$ for any value of $\phi > \bar{p}$ since the landowner knows that the buyer will never make an offer higher than this. As a result, the landowner's second period payoff will be $\bar{p}$ with certainty – either because the buyer offers exactly $\bar{p}$ and the landowner accepts or because the buyer offers $\phi < \bar{p}$ and the landowner chooses to develop. As a result

$$B(\bar{p}) = \tau + \delta\bar{p} - \bar{p}(1+\delta) = 0 \tag{6}$$

implying that the threshold value is $\bar{p} = \tau$. If the private value is below the cutoff the landowner might receive more than the private value in the second period, but if $p = \bar{p}$, the landowner will only conserve today if the payment today exceeds the private development value. As a result, while the value of ρ_{es} may affect the landowner payoff if $p \leq \bar{p}$, the value of ρ_{es} has no impact on the likelihood the parcel will convert or on the value of $\bar{p}(\tau)$ as long as $B(p) = 0$ has a unique solution. The simulations discussed below confirm that this is true under a wide variety of parameter values.

2.2.1 Buyer's initial period offer with unique threshold

At time 0, the buyer knows better information will arrive at time T and must decide how aggressive to be in inducing conservation today. If the buyer makes a large offer today, the parcel is likely to conserve, but the buyer risks both paying for non-additional conservation and conserving land that provides conservation benefits below the cost. On the other hand, if the buyer makes no offer today, any opportunity to alter landowner development decisions is lost since all land with $p > 0$ will be developed immediately. The buyer must balance these concerns in deciding how aggressive to be with payments today. When there is a unique threshold as described in the previous section, the buyer knows that the landowner will develop if $p > \tau$ and will conserve otherwise, implying that $\bar{p} = \tau$. This means that the buyer's full payoff is given by

$$V(\tau) = \int_{-\infty}^{\tau} \left(\mu_{e|p}(p) - \tau\right) f_p(p)\,dp + \delta \int_{-\infty}^{\infty} W^*(s,\tau)\, f_s(s)\,ds, \tag{7}$$

which can be simplified to

$$F_p(\tau)(\mu_e - \tau) - \sigma_e\sigma_p\rho_{ep} f_p(\tau) + \delta \int_{-\infty}^{\infty} W^*(s,\tau)^*(s,\tau)\, f_s(s)\,ds. \tag{8}$$

The first-order condition for an interior solution is

$$f_p(\tau)\left(\mu_e - \tau + \frac{\sigma_e}{\sigma_p}\rho_{ep}(\tau - \mu_p)\right) + \delta \int_{-\infty}^{\infty} \frac{\partial W^*}{\partial \bar{p}}(s, \tau) f_s(s)\, ds = F_p(\tau) \tag{9}$$

This condition mirrors (4) in that the marginal cost of increasing the offer is the probability it will be accepted. The first term of the marginal benefit is the same as in (4): the expected gain in the initial period conditional on the parcel's decision being changed times the probability of its choice is changed. The new element is the benefit of increasing the probability that the parcel will be undeveloped at time T when the signal is observed. By the envelope theorem, $\frac{\partial W^*}{\partial \bar{p}}(s, \tau) = 0$ if the upper bound is not binding in the second period problem and $\frac{\partial W^*}{\partial \bar{p}}(s, \tau) = \frac{\partial W}{\partial \phi}(\bar{p}, s) > 0$ when the upper bound is binding. Therefore, the new term is necessarily non-negative and considering the second period will (weakly) lead to an increase in initial offers.

The impact of improved future information on the buyer's payoff can be decomposed into two effects. First, there is the direct effect: improved information in the future will allow the buyer to target future offers more precisely and will thus increase the buyer's second period payoff. Second, there is the indirect effect through the impact on τ. This is a second order effect that disappears in the comparative statics per the envelope theorem, but measures how much responding to the possibility of improved information impacts the buyer's payoff. The key numerical questions are how much improved information will increase optimal first period offers and how large valuable adopting these optimal offers will be. To answer these questions, I turn to numerical simulation since the model has no analytical solution.

3 Impact of Information without Correlation

To explore the impact of different parameters on the model solution, I begin by normalizing the expected conservation value (μ_e) to 1 and measure all other values relative to this value. Throughout the main results, I also set $\delta = 1$ so the decision makers place equal weight on the time before and after additional information is received.[9] The numerical results presented here proceed in several steps. In this section, I assume $\rho_{ep} = 0$. First, I describe in detail the impact of signal quality on the optimal last period policy for a single example. I then describe the two period solution for that case and how it varies with signal quality. Next, I discuss the impact of the distribution of possible values of p on those solutions, still keeping $\rho_{ep} = 0$. In Section 4, I explore the impact of allowing ρ_{ep} to vary. Throughout the results, the emphasis is on identifying when the possibility of improved information will have the largest impacts on policy today.

[9] Increasing or decreasing the value of δ has the expected impact of increasing or decreasing the impact of improved information on today's outcomes. Also note that as long as $B(p) = 0$ has a unique solution, the value of δ does not influence the landowner's decision.

3.1 Optimal policy with no correlation

For this simulation, I set $\mu_p = 0.5$, $\sigma_p = 0.25$, and $\sigma_e = 0.75$. These parameters imply that the buyer best estimate before observing the signal is that the parcel provides twice as much conservation value to the buyer as it does to the landowner when developed suggesting that a PES offer has a strong chance of being viable. The standard deviations imply that the buyer believes there is a roughly an 84% chance that the parcel will be developed in the absence of a payment and that there is a roughly 91% chance that the net benefit of conservation to the buyer is positive.

Final period policy In the last period, the buyer has a signal of environmental service value that allows some degree of targeting of offers based on the expected environmental service value conditional on the signal observed. Based on the offer received, a parcel will fall into one of four categories: (I) conserved despite a zero offer because it is privately optimal to do so ($\phi = 0$ and $p \leq 0$), (II) paid for non-additional conservation ($\phi > 0$ and $p < 0$) (III) induced to conserve by the program because $0 < p \leq \phi$, and (IV) developed despite the offer because $p > \phi$.[10] As the offer increases, the buyer must weigh the cost of additional losses on parcels in category II against increased gains for moving more parcels from category IV to category III. Figure 3 illustrates the optimal offers and identifies which parcels will fall into each category for three different values of ρ_{es} if all parcels remain undeveloped at the start of the second period. In each panel, the private development value increases along the vertical axis while the signal increases along the horizontal axis. The shaded contours in the background indicate the likelihood that the parcel is located at that point. The solid line corresponding to the shading for the given ρ_{es} value is the optimal second period offer. When $\rho_{es} = 0$, the signal provides no useful information and the buyer will make the same offer to all parcels regardless of signal because the expected conservation value is the same throughout the figure. When $\rho_{es} > 0$, the conditional gain will shift with the signal as illustrated in Figure 2, resulting in different offers. As ρ_{es} increases, the minimum signal that need to induce the buyer to make a positive offer increases. Above this threshold, increasing the signal increases the offer at a decreasing rate, with the rate of decrease falling as the signal quality increases.

The parcel will be developed if it is located above the offer line corresponding to the given ρ_{es} value, since $p > \phi$ in this region. The offer will result in additional conservation if the parcel is located above the y-axis and below the solid line. If the parcel is below the y-axis, it would have conserved regardless. If it is located below the y-axis and to the right of the dashed line corresponding to the given ρ_{es} value, it will be paid for non-additional conservation, while if it lies to the left of this line, it will conserve

[10] These categories are reminiscent of Engel et al.'s (2008) sources of inefficiency from PES programs but do not correspond exactly except in the case of category II – payments for non-additional conservation, which correspond to Engel et. al's case D. Category IV here includes both situations where the value of conservation is less than the cost ($p > e$) so the outcome is efficient and situations where $e > p$ but the buyer's best estimates lead to an offer that was too small to induce conservation (what Engel et. al. term Case B). Moreover, because of the uncertainty, category III may include parcels where the value of conservation ends up being less than the cost so the buyer would have been better off not inducing conservation (what Engel et. al. term Case C).

despite a zero offer. Since all parcels are made a positive offer when $\rho_{es} = 0$, there is no dashed line corresponding to $\rho_{es} = 0$ and all parcels below the y-axis would be paid for non-additional conservation. As the minimum signal needed to induce a positive offer increases with signal quality moving from lighter to darker lines, the area in which the parcel is paid for non-additional conservation shrinks. Moreover, since the offer rises more rapidly as the signal quality increases, the area in which the offer induces the parcel to provide additional conservation also grows.

If the buyer observed the signal before any development occurred, the conclusions of Figure 3 would be straightforward: better information about conservation value would allow the buyer to target purchases more effectively. By limiting offers to parcels that are likely to provide high conservation value, the buyer would limit non-additional payments and increase the expected gain on the parcels in category III. But this figure readily demonstrates that if the parcel has a high value of p, it will eventually develop in period 2, implying its owner will develop at $t = 0$ before the signal is observed unless offered an incentive to conserve. In fact, since $\rho_{ep} = 0$ in this scenario, we know from Section 2.2 that $B(p) = 0$ has a unique solution and therefore any parcel in category III would develop at $t = 0$ unless given an incentive not to. The buyer must pay in the first period to have any option to purchase additional conservation in the second period.

As $\bar{p}$ falls, category III shrinks because if the parcel is in the upper right of this region, it has a high p value and would have developed at $t = 0$. As this region shrinks, the buyer will reduce offers made after observing high signals, thus reducing the expected offer. Figure 4 illustrates the impact of changes in the upper bound remaining undeveloped on the expected second period offer and the buyer's optimized second period payoff for several different signal quality levels. The shading of the lines indicates the signal quality with darker lines representing better information. As expected, lowering the upper bound reduces the mean offer as long as $\rho_{es} > 0$. For most values of $\bar{p}$, increasing the signal quality *lowers* the expected offer as shown in Figure 3. Since the optimal offer is bounded above by $\bar{p}$, the increase in the offer when the signal is high is constrained and the probability of making no offer increases as the minimum signal needed to induce a positive offer increases. These effects combine to lower the expected offer. With a high $\bar{p}$, this effect can be reversed because the offer following a high signal is less constrained. In the second panel, we see that increasing information naturally increases the buyer's optimized payoff, with the impact increasing with the quality of the signal. Moreover, note that increasing the quality of the signal has a much large impact on the buyer's payoff when the upper bound is high.

Initial period policy In the first period, the buyer will weigh the cost of paying to make the parcel more likely to conserve in period 1 against the gain from it being more likely that the parcel will remain undeveloped in the second period, allowing the buyer to achieve the higher payoffs illustrated in Figure 4. In the two period model, a parcel will be in one of five categories: (I) conserved in both periods despite a zero offer at time T because it is privately optimal to do so ($\phi = 0$ and $p \leq 0$), (II) paid for non-additional conservation in both periods ($\phi > 0$ and $p \leq 0$), and (III) induced to conserve in both periods by the program because $0 < p \leq \phi$, (IV) developed at time T because $\phi < p < \tau$, or (V) developed immediately because $p > \tau$.[11]

The right hand column of Figure 5 illustrates the location of these categories in s, p space for $\rho_{es} = (0, 0.5, 1)$ in a manner similar to Figure 3. In each panel, the dashed line is the initial payment offered to all parties, which becomes the upper bound for private development value if the parcel remains undeveloped at the start of the second period. The dot-dashed line is the optimal second period offer. If the buyer does not expect improved information as in the top right panel, the second period is simply a repeat of the first; in this case, there is no chance the parcel will be developed in the second period and no chance the parcel will be made a zero offer in the second period so categories I and IV are empty. The buyer expects half of the uncertainty about e to be resolved in the middle panel and all of the uncertainty to be resolved in the bottom panel. In these figures, the dashed line marking the initial period offer and the dot-dashed line marking the second period offer diverge for low signals. As the signal quality improves, two effects occur. First, the first period offer increases, decreasing the size of category V. Second, the buyer will be able to make a more targeted second period offer, reducing the probability the parcel is in category II and increasing the probability it is in category I. This targeting also shift some (s, p) pairs from category III to category IV. category III may thus increase or decrease with more information.

The right column illustrates the probability and gain for each of these categories. The top right hand panel shows the probability that the parcel is in categories I-IV.[12] The height of the stacked bar gives the probability the parcel will be conserved in period 1. The light purple section at the top of the bar is the probability the parcel will conserve in period 1 but then develop in period 2, so the top of the dark purple bar gives the probability the parcel will remain conserved at the end of the second period. The dark orange bars indicate non-additional conservation that is paid for in both periods, while the light orange bars indicate non-additional conservation that is only paid for in the first period. As the figure demonstrates, improving the quality of the signal increases the offer made initially and thus increases the probability the parcel will conserve initially. In the second period, the better information lowers the probability of conservation because the buyer targets high conservation value parcels only.

The middle panel illustrates the buyer's expected gain across both periods relative to no policy. The height of the stacked bar gives the expected gain from a PES program as a function of the quality of the future information, while the shading indicates the contribution to this gain from each category (e.g. the conditional gain times the probability the parcel will be in that category). Since the buyer will lose if the parcel is in categories I, II, and possibly IV, the bars for these categories are below the axis (representing losses) and the wide purple bars show much of the gain from category III offsets these losses and how much remains. The final row illustrates the portion of the gains from the middle panel that result from

[11] Assuming all parcels remain undeveloped at time T is equivalent to assuming that category V is empty.

[12] The probability the parcel is developed immediately (category V) is the space between the top of the bar and 1.

customizing the first period offer to the level of information expected at time T. As noted in Section 2.2.1, this second order effect of information measures the value of adjusting current policy for the possibility of improved information.

From this figure, we see that information changes the optimal offers and the probability of first period conservation, but does not have a dramatic effect. The expected gain rises modestly from 0.19 to 0.25 (or roughly 19% to 25% of the initial estimated conservation value) as ρ_{es} rises from 0 to 1. But only a small portion of the gain from this increase comes from customizing the first period policy to the level of expected information. Even if the buyer expects to learn e perfectly, adjusting policy today will increase the expected gain by only 1.3% of the expected conservation value.

3.2 Impact of changing the distribution of development value

The values in Figure 5 are specific to the parameterization. Figure 6 illustrates the impact of changing the mean and variance of private development value on the offer made today, the probability of conservation today, the expected payoff across both periods, and the value of customizing the first period offer to the expected improvement in information. The dashed lines in the second and third row represent the outcome if the buyer adopted no policy, while the different color lines indicate the value for various levels of ρ_{es}.

As the mean development value increases along the x-axis in each panel, two effects occur. First, it is less likely that the parcel has a negative private development value and will conserve without payment. This reduction in the probability of paying for non-additional conservation will lead the buyer to increase payments as shown on the top row. Second, the cost of inducing a given probability of conservation increases because the probability of a high private development value increases. This leads to a smaller optimal conservation probability as shown on the second row. Since the probability of conservation falls to zero as μ_p increases, the buyer's payoff (which is measured relative to the value of development) also falls to zero. Changing the variance of private development while holding the mean constant as we move from panel to panel similarly has a number of impacts. It increases the probability of both very high and very low private development values, while decreasing the probability the parcel is close to the mean. This increases the probability the parcel will be paid for non-additional service and thus lowers the optimal offer. For a high standard deviation and low mean, the high probability of paying for non-additional services drives optimal payments to zero and the probability of conservation and the buyer payoff converge to the no PES value.

The effect of improved future information on the outcomes is illustrated by the different lines, with the lightest line representing no improved future information and the darkest line representing the resolution of all uncertainty about e by T.[13] Looking at the top row, we see that the lines diverge more as information

[13] Figure 9 in the appendix plots illustrates the difference between the lines shown in Figure 6.

improves, implying that improving information leads to progressively larger changes in offers as μ_p increases. In other words, the buyer should modify today's policy more in response to the possibility of improved information when the private development value is expected to be high. At the same time, the value of the information, both in terms of the probability that land is conserved and overall payoff first rises and then falls as expected private development value increases. Ultimately, this implies that buyers should pay the most attention to the possibility of improved information when the uncertainty about private development value is smaller than the uncertainty about conservation value and the expected development value is neither too small or too large. When the expected development value is relatively small, the benefit of adopting some conservation payment policy is large because the required payments are low, but adjusting that policy to account for improved future information is less important. When the expected development value is relatively high, the buyer is unlikely to be able to profitably induce conservation whether or not improved information arrives in the future. The buyer could marginally increase her payoff by making a large offer that is still almost certain to be rejected, but the value of doing so is small. This pattern remains similar as the variance increases, with one notable addition. In the top right panel, we see that as the quality of the expected information improves (moving from lighter to darker lines), the minimum value of μ_p that induces the buyer to make an offer falls. Holding the variance fixed, lowering the mean will increase the probability that the landowner finds conservation privately optimal and will thus increase the probability that the buyer will end up paying for non-additional conservation. Information thus plays an important role in determining how large a probability of non-additional payments in period 1 the buyer is willing to tolerate when making an offer.

4 Impact of future information with correlation

The prior section assumes that conditional on the information known at time 0, there is no correlation between e and p. Due to the interpretation of e and p, the zero correlation case covers many of the scenarios often described as correlation between development and conservation value. If the buyer knows a particular parcel is likely to have both a high value to the landowner if developed and a high value to society if conserved, this suggests high values of μ_e and μ_p and relatively low values of σ_e and σ_p, but does not imply correlation. This section considers the possibility of correlation between the deviations of e and p from their means. As described above, this could occur if the parcel of land possesses a difficult to verify or observe characteristic that influences both e and p.

Final Period with Correlation Figure 7 replicates the right hand panels of Figure 5 with negative (left column) and positive (right column) correlation.[14] All else equal, positive correlation makes the buyer worse off in all cases because the parcel is valuable to conserve precisely when it is also the most expensive

[14] See the appendix for a similar figure that replicates the left hand panels of Figure 5 with correlation.

to induce to conserve. Moreover, since the buyer cannot reliably identify when this is the case, attempts to induce conservation of valuable land will require high offers that will also be accepted when the parcel provides low gains. In contrast, negative correlation improves the situation for the buyer. The parcel is most likely to provide high conservation value when it is also most likely to be conserved without payment or to conserve with only a small payment.

At the same time, information is far more valuable when there is positive correlation. With positive correlation and current levels of uncertainty about the conservation value, the buyer will make only a very small offer today. The probability of non-additionality and the likelihood of paying a parcel more than the services it ultimately provides are too high to raise the offer further. As a result, it is highly likely that if the parcel has high conservation value, it will be developed before the buyer learns this. If the buyer knows better information will arrive in the future, it makes sense to increase the offer so that it is more likely the parcel will remain undeveloped long enough to learn its conservation value is high. Moreover, comparing the second and third rows demonstrates that roughly half the value of improved information comes from customizing the first period offer. In contrast with negative correlation, a PES program can be very valuable, but improved future information has little impact on that value.

Figure 7 illustrates two specific cases, with the baseline values of μ_p and σ_p and $\rho_{ep} = (-0.75, 0.75)$. Figure 8 graphs the impact of various degrees of correlation on the value of adjusting first period offers for expected improvements in information.[15] The value is relatively low in all cases, but several important patterns emerge. First, the value tends to increase as correlation increases, at least up to a point. Once correlation becomes too high, the buyer is quite confident that only parcels with very high development value will provide similarly high conservation value. The cost of inducing these parcels to conserve until information arrives is too high for the buyer to find a PES program valuable so the buyer makes no offer in the first period. This point is reached at a lower level of correlation as the mean development value (and thus the expected cost of achieving a given conservation level) increases. When $\mu_p = 0.75$ and $\sigma_p = 0.25$ in the first panel on the third row, the value of information can be as high as 0.16 (which represents 16% of the expected conservation value if the land were conserved with certainty).

When the mean development value is low, the probability of non-additionality is relatively high, making the cost of increasing offers to induce more conservation high. Thus, the value of responding to the possibility of information is lower. As the mean development value increases, lower the probability of making non-additional payments, the value of information increases, until the expected cost of conservation approaches the expected benefit of conservation. Naturally, as uncertainty about development value increases, the costs related to asymmetric information increase, eroding the buyer's ability to profitably respond to improved information so the value of information falls as we move across each row.

[15] Figures illustrating the impact of correlation on the other variables graphed in Figure 6 are provided in the Appendix.

5 Conclusions

In this paper, I developed a two-period model to investigate the impact of expected improvements in knowledge on optimal PES plans today. Ecologists and hydrologists are continually working to improve our understanding of the link between land use decisions and hydrological ecosystem services. Waiting until such relationships are well understood carries a real risk that land will be developed and the associated services lost if buyers wait until they are sure of the science before offering conservation incentives.

The analysis suggests that optimal first period offers increase substantially as the quality of information the buyer expects to receive increases. Despite these often substantial changes in the optimal offer, the difference between the buyer's expected benefit from the optimal offer and the buyer's expected benefit from the optimal no additional information offer is generally small. Three primary situations that can lead to larger gains were identified. First, when the buyer believes that the most valuable land is at the highest risk of immediate development (e.g. the buyer believes there is some postie correlation between conservation and development value), this positive correlation significantly reduces the buyer's expected benefits, but amplifies the importance of preserving as much land as possible until better information arrives. Second, when the buyer has relatively more information about the development value than the conservation value, the costs of asymmetric information in the first period are reduced and the scope for improved information to alter future incentives is increased. Finally, when the buyer believes that most land will be developed in the absence of a policy, the low risk of non-additionality reduces the costs associated with increasing current PES payments to preserve more land and increases the gain from customizing offers to the degree of expected future information.

In addition to the results and conclusion presented here, the model can provide important insights for developing a multi-period model. Solving the two-period model presented here requires solving the final period model with many different levels of current information, the amount of land remaining undeveloped as determined by the upper bound on private development value of land remaining undeveloped, and the correlation between the remaining uncertainty in conservation and private development value under numerous parameteriziations. These results provide insight into how these factors influence the instantaneous benefit a buyer would receive in a multi-period dynamic optimization model.

The model also suggests that landowners are unlikely to conserve their land today if the current incentive offered to do so is less than their private net benefit from development, even if they expect a buyer of services to receive improved information that may lead to higher offers in the future. To the extent that landowners' behavior ***does*** change in response to prospect of better information, the analysis suggests this response must be rooted in either a factor not included in the model, like landowner uncertainty about future development value, or the existence of multiple, disjoint regions of the landowner benefit distribution that prefer conservation. The analysis in subsection 2.2 suggests the latter case will only occur when several conditions are met. First, there must be strong positive correlation between conservation value and private development value, implying that landowners have considerable private information about the offers they are likely to receive in the future. Second, the buyer must currently have a large amount of uncertainty about conservation value, but must expect to receive much better information in the future. Finally, the expected benefit of conservation to the buyer must substantially exceed the expected cost of inducing the landowner to conserve.

The model presented here made several strong assumptions and focused on parcel level analysis to yield a tractable model. There are reasons to believe that landscape scale effects may be critical in understanding the benefit of hydrological ecosystem services, so extending the model to consider the impact of the total amount of development or conservation and possibly its spatial arrangement would be valuable. The key logistical challenge to doing so is specifying a tractable and realistic specification of the relationship between the random conservation and development value across parcels. The present model also assumes that both buyers and sellers know the value of ρ_{es} and ρ_{ep} throughout the time frame. The implications of the model could be different if one or both parties was uncertain about these values.

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Fig. 1 Marginal Benefit and Cost of Increasing the Final Period Offer

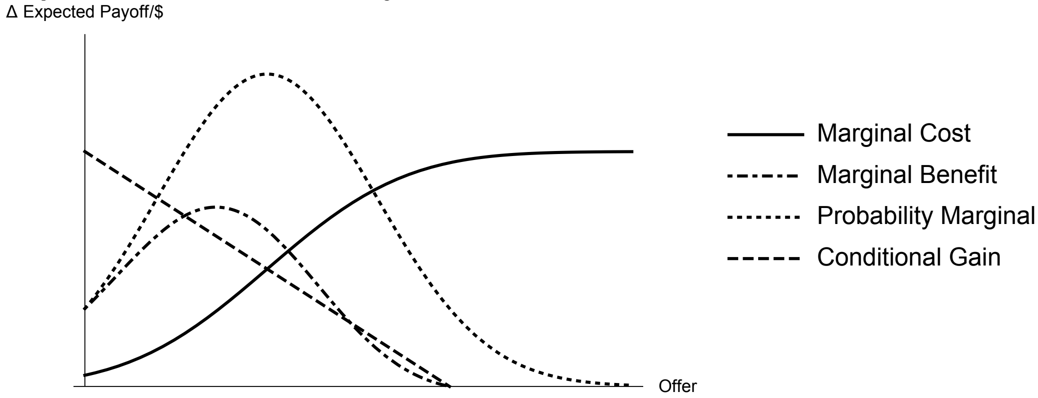


Fig. 2 Impact of Changing Parameters

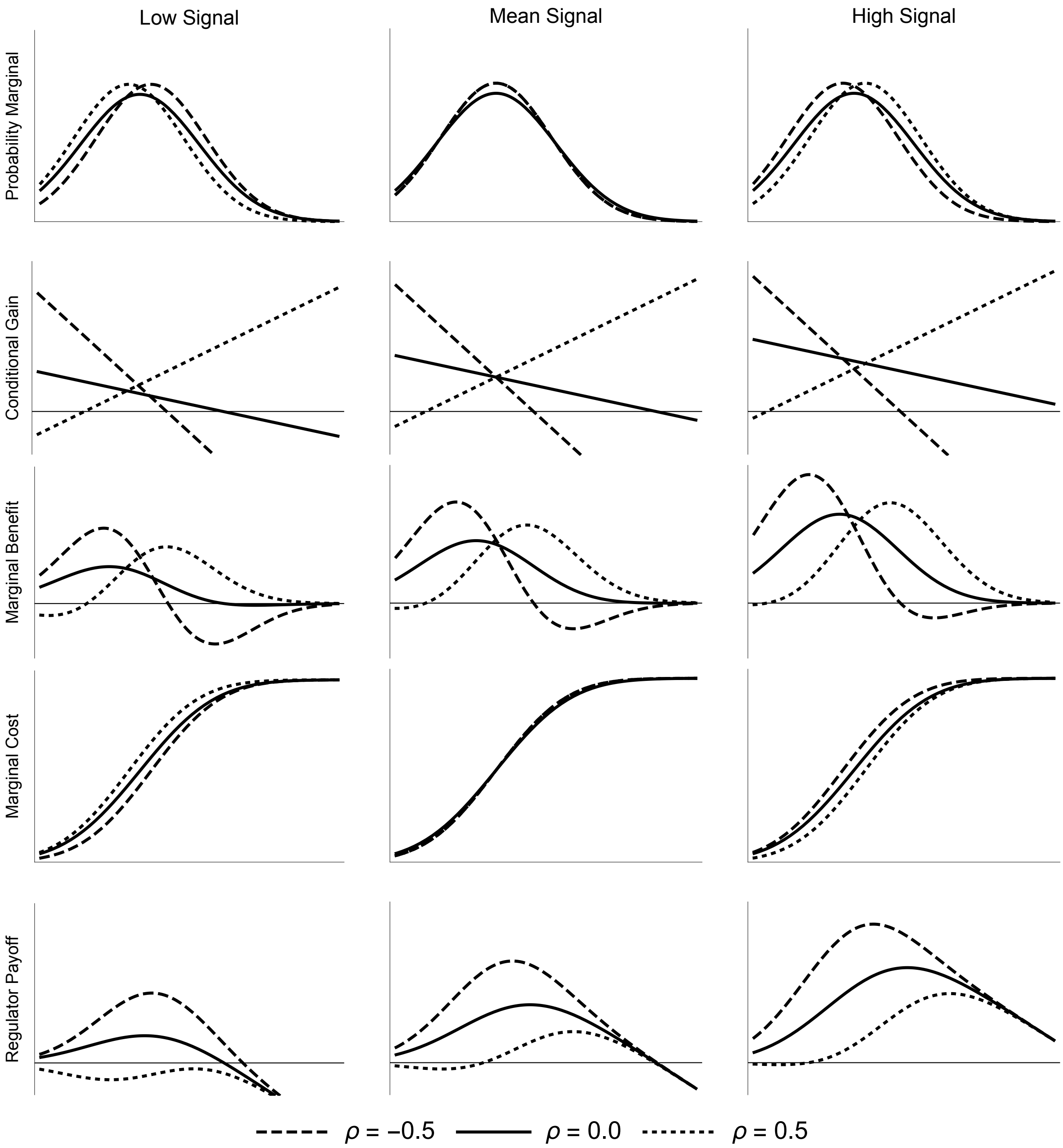


Fig. 3 Optimal offers and parcel categorization (baseline scenario)

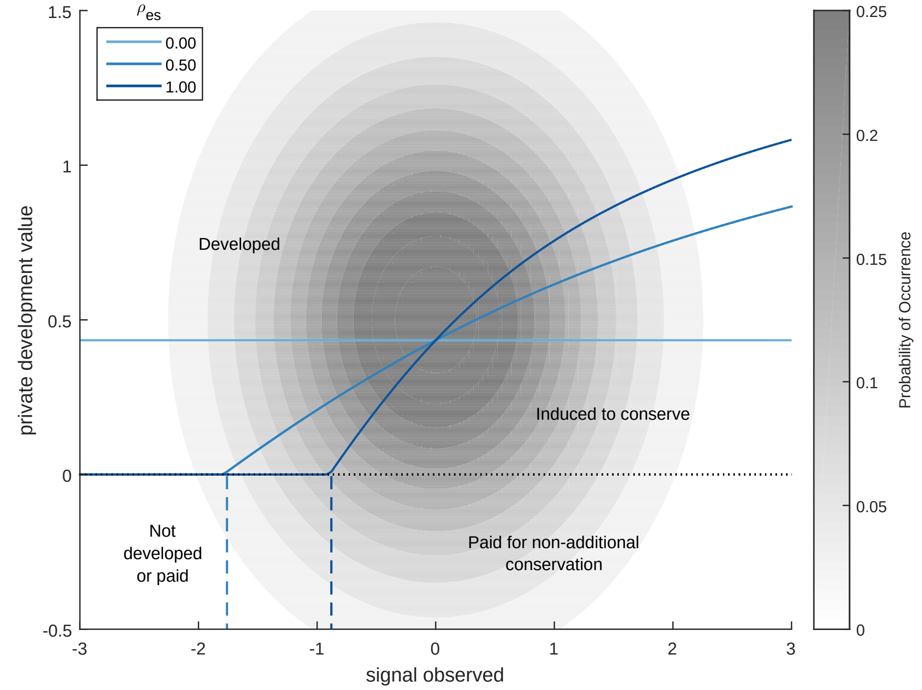


Fig. 4 Expected period 2 outcomes (baseline scenario)

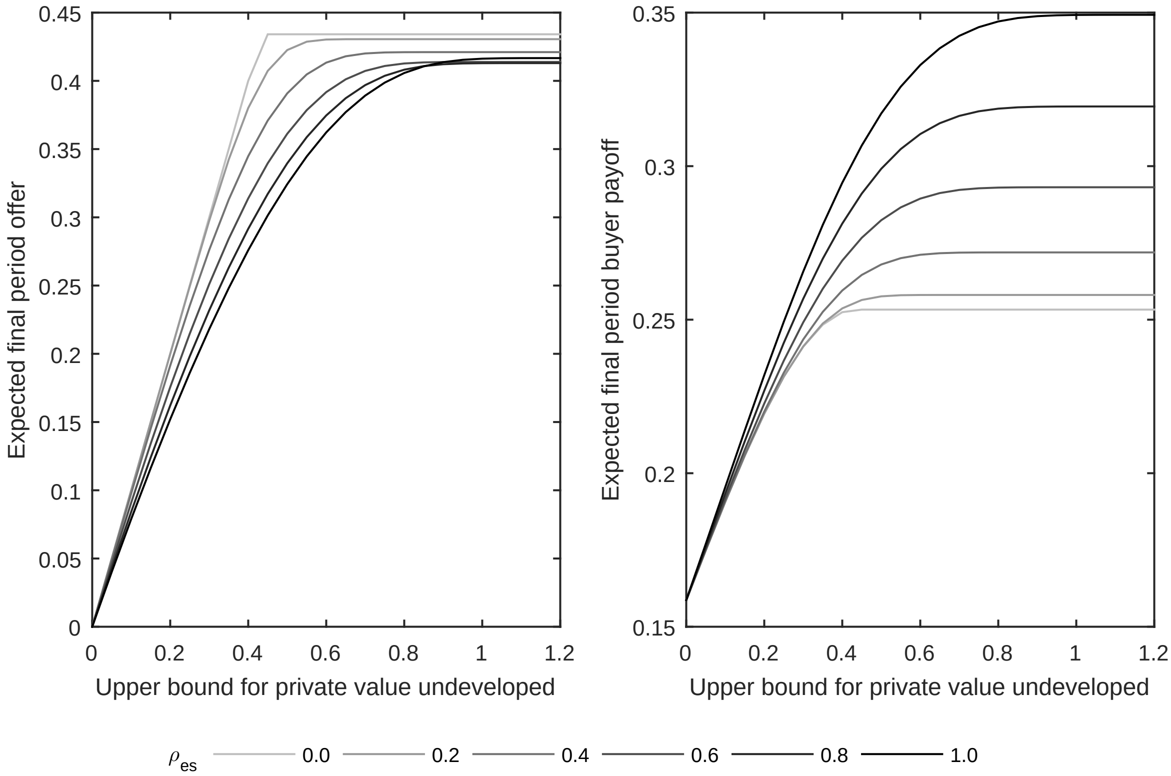


Fig. 5 Optimal outcomes for buyer by signal quality (baseline scenario)

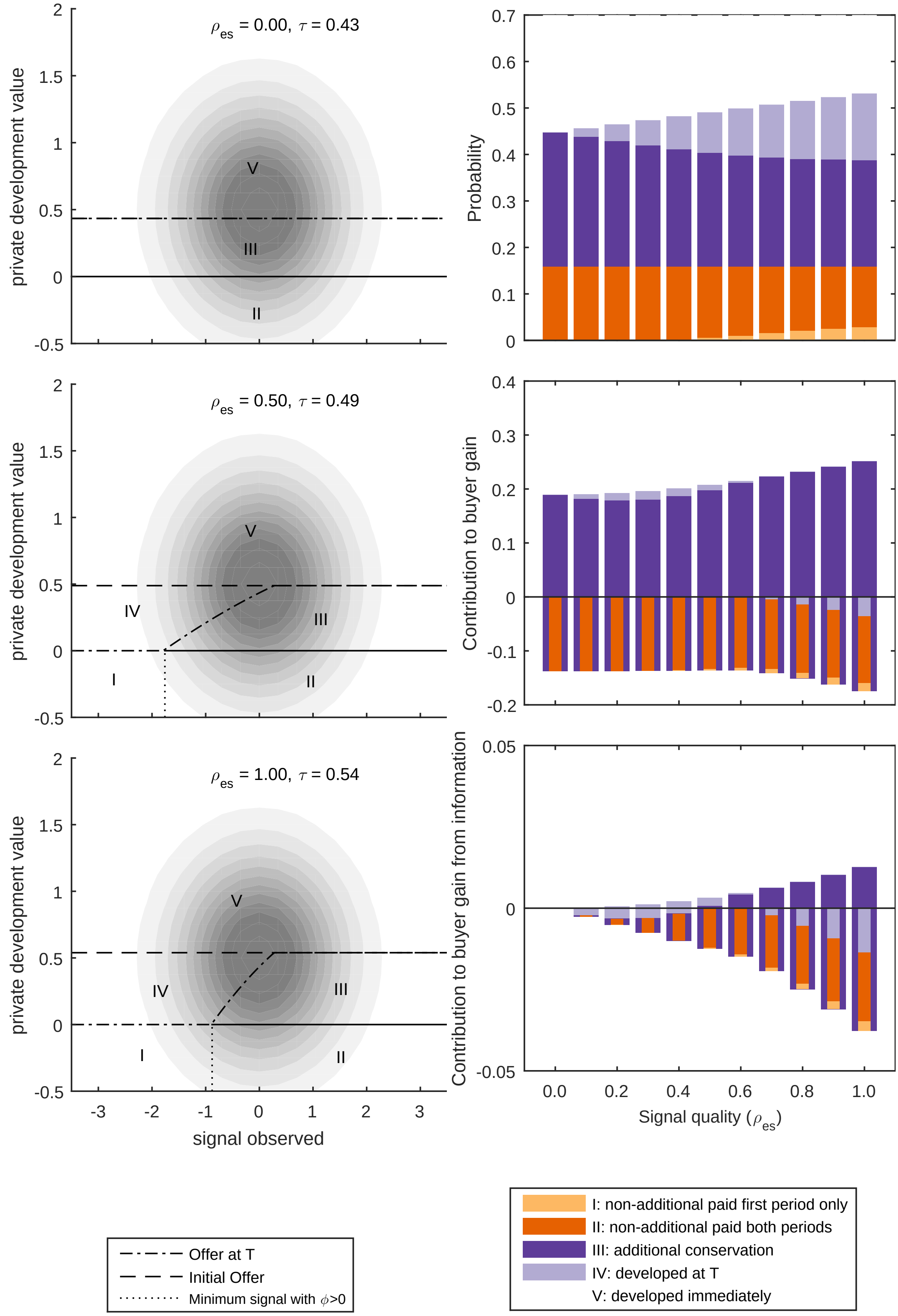


Fig. 6 Impact of mean and variance of private development value

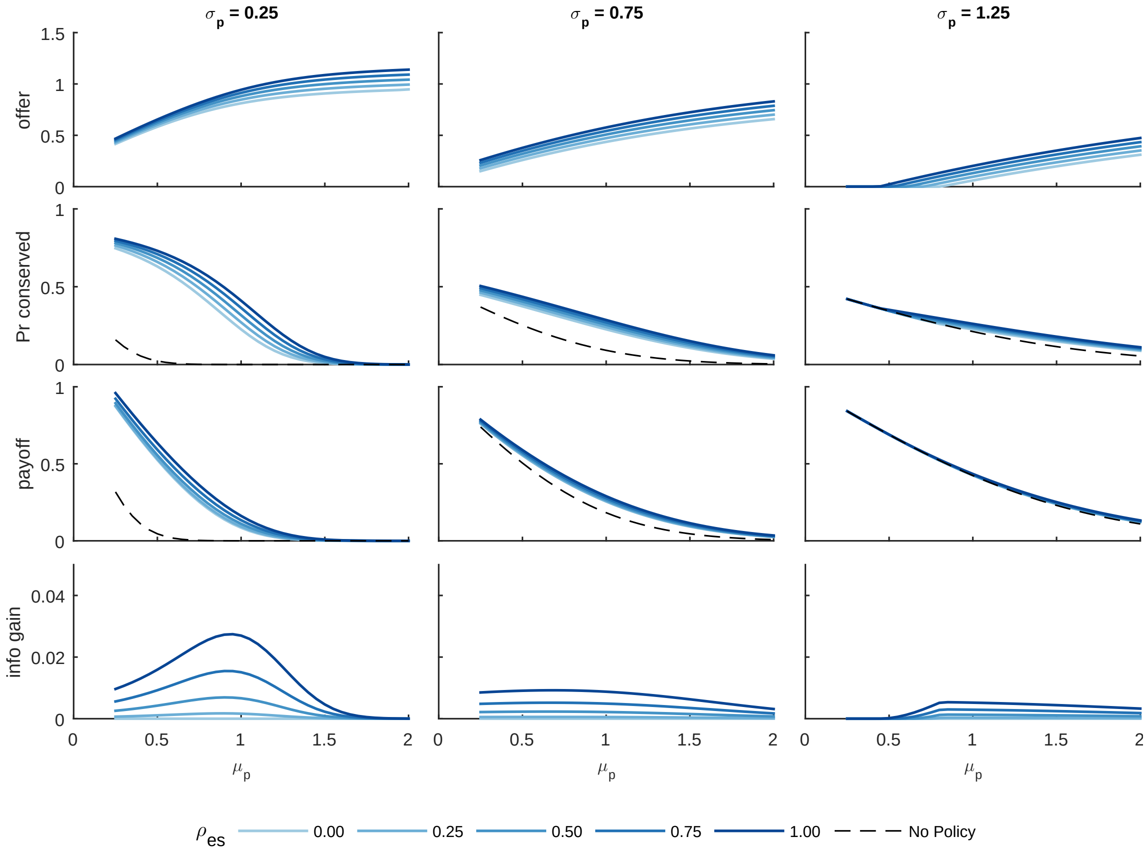


Fig. 7 Parcel Categories with Correlation

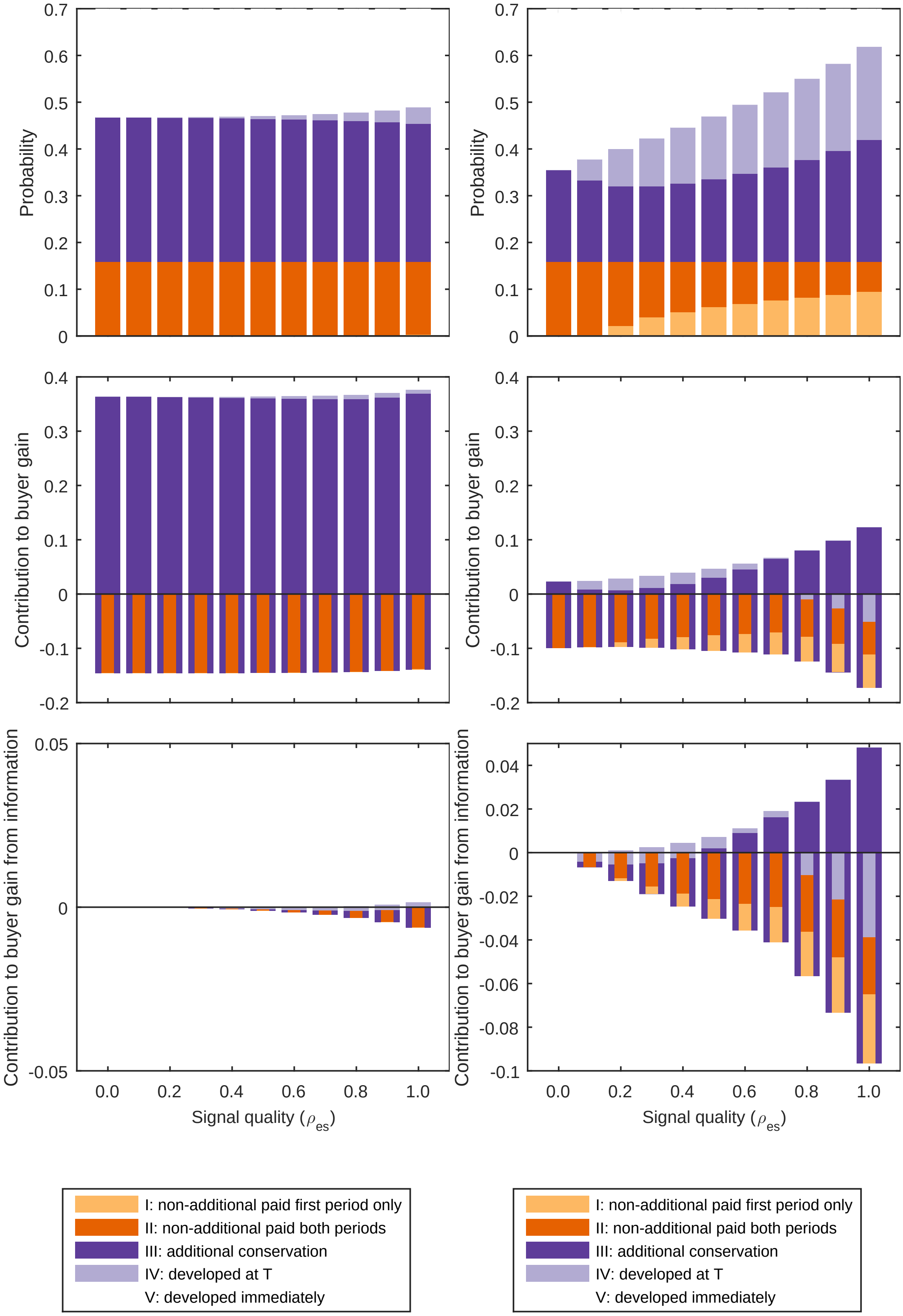
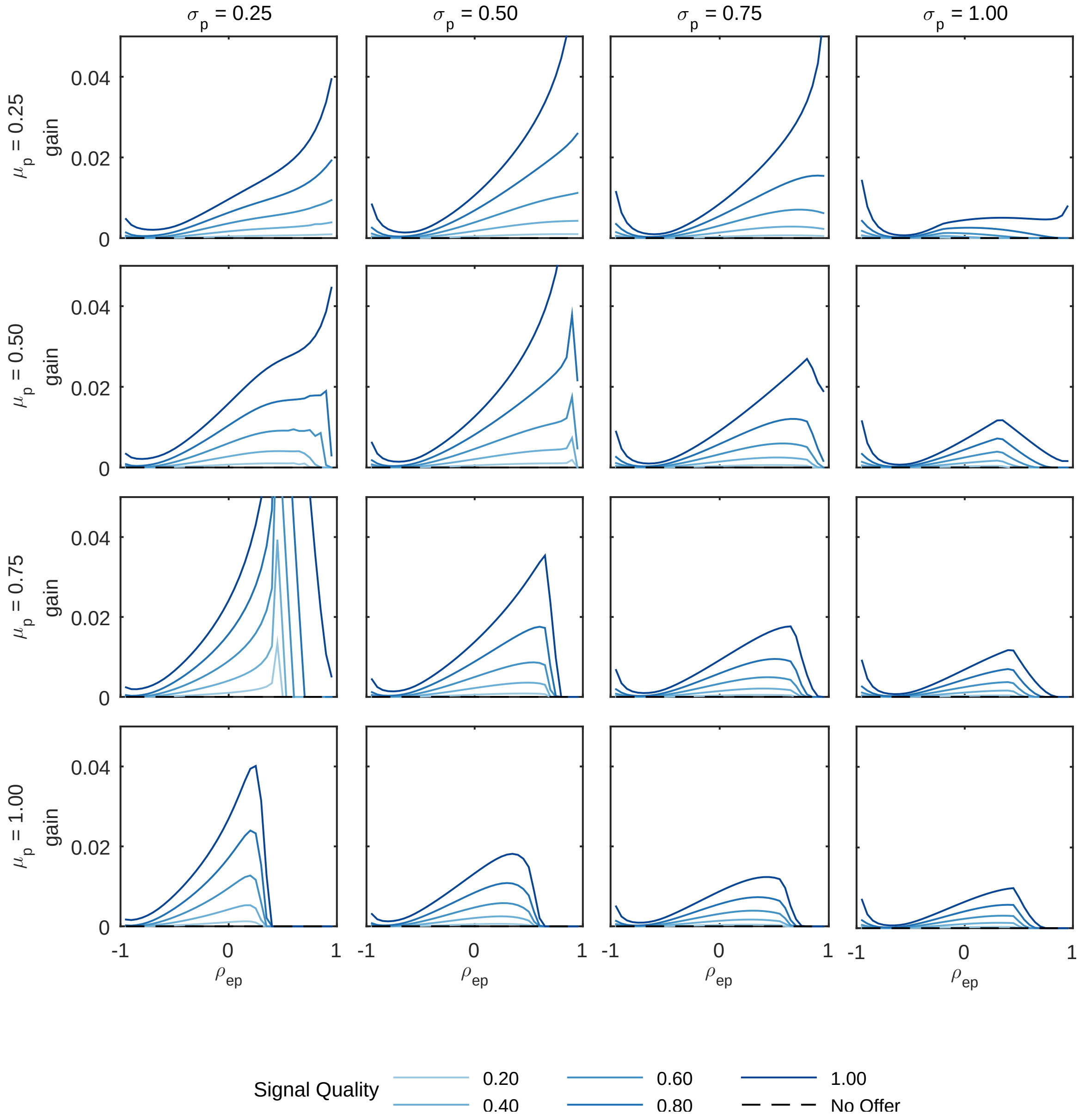


Fig. 8 Value of Improved Information



A Simplification of buyer's payoff

The buyer's single period payoff as a function of the payment offered is given by

$$W(\phi, s) = \int_{-\infty}^{\phi} \int_{-\infty}^{\infty} (e - \phi) f_{e|s,p}(e|s,p)\, de f_{p|s}(p|s)\, dp$$

The multivariate normal assumption allows us to simplify this expression considerably. First, note that

$$\mu_{e|s,p}(s,p) = \frac{\sigma_e(\rho_{ep} - \rho_{ep}\rho_{sp})}{\sigma_p\left(1-\rho_{sp}^2\right)} p + \mu_e + \frac{\sigma_e(\rho_{es} - \rho_{ep}\rho_{sp})}{\left(1-\rho_{sp}^2\right)} s - \frac{\sigma_e(\rho_{ep} - \rho_{ep}\rho_{sp})}{\sigma_p\left(1-\rho_{sp}^2\right)} \mu_p$$

so the inner integral can be rewritten as

$$\begin{aligned}
\int_{-\infty}^{\infty} (e-\phi) f_{e|s,p}(e|s,p)\, de &= \int_{-\infty}^{\infty} e f_{e|s,p}(e|s,p)\, de - \int_{-\infty}^{\infty} \phi f_{e|s,p}(e|s,p)\, de \\
&= \mu_{e|s,p}(s,p) - \phi \\
&= \frac{\sigma_e(\rho_{ep} - \rho_{es}\rho_{sp})}{\sigma_p\left(1-\rho_{es}^2\rho_{ep}^2\right)} p + \mu_e + \frac{\sigma_e(\rho_{es} - \rho_{ep}\rho_{sp})}{\left(1-\rho_{es}^2\rho_{ep}^2\right)} s - \frac{\sigma_e(\rho_{ep} - \rho_{ep}\rho_{sp})}{\sigma_p\left(1-\rho_{es}^2\rho_{ep}^2\right)} \mu_p - \phi
\end{aligned}$$

To simplify derivations, let $\alpha = \mu_e + \frac{\sigma_e(\rho_{es} - \rho_{ep}\rho_{sp})}{\left(1-\rho_{es}^2\rho_{ep}^2\right)} s - \frac{\sigma_e(\rho_{ep} - \rho_{ep}\rho_{sp})}{\sigma_p\left(1-\rho_{es}^2\rho_{ep}^2\right)} \mu_p - \phi$ and let$\beta = \frac{\sigma_e\left(\rho_{ep}\left(1-\rho_{es}^2\right)\right)}{\sigma_p\left(1-\rho_{es}^2\rho_{ep}^2\right)}$. The full first integral is thus

$$\int_{-\infty}^{\phi} (\alpha + \beta p) f_{p|s}(p|s)\, dp$$

or

$$\alpha F_{p|s}(\phi|s) + \beta \int_{-\infty}^{\phi} p f_{p|s}(p|s)\, dp.$$

The latter integral can also be simplified under the normality assumption to

$$\sigma_{p|s}^2\left(-f_{p|s}(\phi|s)\right) + \mu_{p|s} F_{p|s}(\phi|s).$$

Combining elements, we have the full first integral as

$$\alpha F_{p|s}(\phi|s) + \beta\left(\sigma_{p|s}^2\left(-f_{p|s}(\phi|s)\right) + \mu_{p|s} F_{p|s}(\phi|s)\right)$$

or

$$\left(\alpha + \beta\mu_{p|s}\right) F_{p|s}(\phi|s) - \beta\sigma_{p|s}^2 f_{p|s}(\phi|s).$$

We also know that

$$\mu_{p|s} = \mu_p + \sigma_p \rho_{sp} s$$

and

$$\begin{aligned}
\beta\mu_{p|s} &= \frac{\sigma_e\left(\rho_{ep}\left(1-\rho_{es}^2\right)\right)}{\sigma_p\left(1-\rho_{es}^2\rho_{ep}^2\right)} (\mu_p + \sigma_p\rho_{sp} s) \\
&= \frac{\sigma_e\left(\rho_{ep}\left(1-\rho_{es}^2\right)\right)}{\sigma_p\left(1-\rho_{es}^2\rho_{ep}^2\right)} \mu_p + \frac{\rho_{sp}\left(\rho_{ep}\left(1-\rho_{es}^2\right)\right)}{\left(1-\rho_{es}^2\rho_{ep}^2\right)} \sigma_e s
\end{aligned}$$

$$\alpha+\beta\mu_{p|s} = \mu_e + \frac{\sigma_e\rho_{es}\left(1-\rho_{ep}^2\right)}{\left(1-\rho_{es}^2\rho_{ep}^2\right)}s - \frac{\sigma_e\rho_{ep}\left(1-\rho_{es}^2\right)}{\sigma_p\left(1-\rho_{es}^2\rho_{ep}^2\right)}\mu_p - \phi + \frac{\sigma_e\rho_{ep}\left(1-\rho_{es}^2\right)}{\sigma_p\left(1-\rho_{es}^2\rho_{ep}^2\right)}\mu_p + \frac{\rho_{es}\rho_{ep}\rho_{ep}\left(1-\rho_{es}^2\right)}{\left(1-\rho_{es}^2\rho_{ep}^2\right)}\sigma_e s$$
$$= \mu_e + \rho_{es}\sigma_e s - \phi$$

Finally, note that

$$\sigma_{p|s}^2 = \sigma_p^2\left(1-\rho_{es}^2\rho_{ep}^2\right)$$

so

$$\beta\sigma_{p|s}^2 = \sigma_e\sigma_p\rho_{ep}\left(1-\rho_{es}^2\right).$$

Putting all these pieces together, we have

$$W(\phi,s) = -\sigma_e\sigma_p\rho_{ep}\left(1-\rho_{es}^2\right)f_{p|s}(\phi|s) + (\mu_e+\rho_{es}\sigma_e s-\phi)F_{p|s}(\phi|s)$$

B Proof of Proposition 1

Case 1 $\bar{p}$ is finite.

If $\bar{p}$ is finite, then the interval $[0,\bar{p}]$ is closed and bounded and since $W(\phi,s)$ is continuous, it attains a maximum on this interval.

Case 2 $\bar{p}=\infty$

In this case, the buyer believes the landowner will choose to conserve in period 1 regardless of the value of p. The $\lim_{\phi\to\infty} W(\phi,s) = -\infty$ so there exists a value $\hat{\phi}$ such that $W(\phi,s) < W\left(\hat{\phi},s\right)$ for any $\phi > \hat{\phi}$. Again, continuity of $W(\phi,s)$ implies that it attains a maximum on the closed and bounded interval $\left[0,\hat{\phi}\right]$, with the maximized value greater than or equal to $W\left(\hat{\phi},s\right)$. Thus,this value also maximized $W(\phi,s)$ on $\phi\geq 0$.

C Proof of Proposition 2

A local interior maximum requires $\frac{\partial W}{\partial\phi} > 0$ and $\frac{\partial^2 W}{\partial\phi^2} \leq 0$.

$$\frac{\partial W}{\partial\phi}(\phi,s) = -\sigma_e\sigma_p\rho_{ep}\left(1-\rho_{es}^2\right)\frac{df_{p|s}}{dp}(\phi|s) + (\mu_e+\rho_{es}\sigma_e s-\phi)f_{p|s}(\phi|s) - F_{p|s}(\phi|s)$$

Since $p|s \sim N\left(\mu_p+\sigma_p\rho_{es}\rho_{ep}s, \sigma_p^2\left(1-\rho_{es}^2\rho_{ep}^2\right)\right)$, we know that

$$\frac{df_{p|s}}{dp}(\phi|s) = -\frac{\phi-\mu_p-\sigma_p\rho_{es}\rho_{ep}s}{\sigma_p^2\left(1-\rho_{es}^2\rho_{ep}^2\right)}f_{p|s}(\phi|s).$$

giving

$$\frac{\partial W}{\partial\phi}(\phi,s) = f_{p|s}(\phi|s)\left[\left(\gamma\frac{\sigma_e\rho_{ep}}{\sigma_p}-1\right)\phi + \sigma_e\rho_{es}\left(1-\gamma\rho_{ep}^2\right)s + \mu_e - \frac{\sigma_e\rho_{ep}}{\sigma_p}\gamma\mu_p\right] - F_{p|s}(\phi|s) \tag{10}$$

where $\gamma = \frac{1-\rho_{es}^2}{1-\rho_{es}^2\rho_{ep}^2}$. The second derivative is

$$\frac{\partial^2 W}{\partial\phi^2}(\phi,s) = f_{p|s}(\phi|s)\left(\gamma\frac{\sigma_e\rho_{ep}}{\sigma_p}-1\right) + \frac{df_{p|s}}{dp}(\phi|s)\left[\left(\gamma\frac{\sigma_e\rho_{ep}}{\sigma_p}-1\right)\phi + \sigma_e\rho_{es}\left(1-\gamma\rho_{ep}^2\right)s + \mu_e - \frac{\sigma_e\rho_{ep}}{\sigma_p}\gamma\mu_p\right] - f_{p|s}(\phi|s).$$

Using the same substitution as above, we get

$$\frac{\partial^2 W}{\partial \phi^2} = f_{p|s}(\phi|s)\left[\left(\gamma\frac{\sigma_e\rho_{ep}}{\sigma_p} - 1\right) + \left(\frac{\mu_p + \sigma_p\rho_{es}\rho_{ep}s - \phi}{\sigma_p^2\left(1-\rho_{es}^2\rho_{ep}^2\right)}\right)\left[\left(\gamma\frac{\sigma_e\rho_{ep}}{\sigma_p} - 1\right)\phi + \sigma_e\rho_{es}\left(1-\gamma\rho_{ep}^2\right)s + \mu_e - \frac{\sigma_e\rho_{ep}}{\sigma_p}\gamma\mu_p\right] - 1\right].$$

Letting $a = \left(\gamma\frac{\sigma_e\rho_{ep}}{\sigma_p} - 1\right)$, $b = \frac{1}{\sigma_p^2\left(1-\rho_{es}^2\rho_{ep}^2\right)}$, $c = \frac{\mu_p+\sigma_p\rho_{es}\rho_{ep}s}{\sigma_p^2\left(1-\rho_{es}^2\rho_{ep}^2\right)}$, and $d = \sigma_e\rho_{es}\left(1-\gamma\rho_{ep}^2\right)s + \mu_e - \frac{\sigma_e\rho_{ep}}{\sigma_p}\gamma\mu_p$, we have

$$\frac{\partial^2 W}{\partial \phi^2} = f_{p|s}(\phi|s)\left[a + (c - b\phi)(a\phi + d) - 1\right]$$

or

$$\frac{\partial^2 W}{\partial \phi^2} = f_{p|s}(\phi|s)\left[a + \left(ca\phi + dc - ba\phi^2 - bd\phi\right) - 1\right]$$

or

$$\frac{\partial^2 W}{\partial \phi^2} = f_{p|s}(\phi|s)\left[-ba\phi^2 + (ca - bd)\phi + a + dc - 1\right].$$

Since $f_{p|s}(\phi|s) > 0$ for all ϕ, $\frac{\partial^2 W}{\partial \phi^2}(\phi, s) = 0$ only when the term in brackets equals 0. This expression is quadratic in ϕ, implying that $\frac{\partial^2 W}{\partial \phi^2}(\phi, s)$ has at most two zeros. If there are multiple interior local maxima of $W(\phi, s)$, they must both have $\frac{\partial^2 W}{\partial \phi^2}(\phi, s) \leq 0$ and be separated by an interior minimum where $\frac{\partial^2 W}{\partial \phi^2}(\phi, s) \geq 0$. This implies that there must be two zeros of $\frac{\partial^2 W}{\partial \phi^2}(\phi, s)$ between the local maxima. Since $\frac{\partial^2 W}{\partial \phi^2}(\phi, s)$ has at most two zeros, this requires that the sign of $\frac{\partial^2 W}{\partial \phi^2}(\phi, s)$ is the same for any value of ϕ above the largest value of ϕ that results in a local maximum. Since we must have $\frac{\partial^2 W}{\partial \phi^2}(\phi, s) < 0$ and $\frac{\partial W}{\partial \phi}(\phi, s) = 0$ at the largest local maximum, this requires that $\frac{\partial^2 W}{\partial \phi^2}(\phi, s) < 0$ and $\frac{\partial W}{\partial \phi}(\phi, s) = 0$ for any value of ϕ above the largest value of ϕ that results in a local maximum. Moreover, it requires that $\frac{\partial^2 W}{\partial \phi^2}(\phi, s) < 0$ and $\frac{\partial W}{\partial \phi}(\phi, s) > 0$ for any value of ϕ below the smallest value of ϕ that results in a local maximum. Note that the $\lim_{\phi\to\infty} -ba\phi^2 + (ca - bd)\phi + a + dc - 1 = -ba(\infty)$ and $b > 0$, suggesting that the sign of $\frac{\partial^2 W}{\partial \phi^2}(\phi, s)$ at very high values of ϕ is the opposite of the sign of a. Since we must have $\frac{\partial^2 W}{\partial \phi^2}(\phi, s) < 0$ at high values of ϕ, we can only have two local maxima of $W(\phi, s)$ if $a > 0$. The $\lim_{\phi\to-\infty}\frac{\partial W}{\partial \phi}(\phi, s) = \left(1 - \gamma\frac{\sigma_e\rho_{ep}}{\sigma_p}\right)\infty = -a\infty$. Thus, at very low values of ϕ, the sign of $\frac{\partial W}{\partial \phi}(\phi, s)$ is opposite the sign of a. So if $a > 0$, then $\frac{\partial W}{\partial \phi}(\phi, s) < 0$ at very low values of ϕ, which contradicts the requirement that $\frac{\partial W}{\partial \phi}(\phi, s) > 0$ for values of ϕ below the smallest value of ϕ that results in a local maximum. Since $W(\phi, s)$ has at most one interior local maxima on $(-\infty, \infty)$, it has at most one interior local maximum on $[0, \bar{p}]$.

D Supplemental Graphs

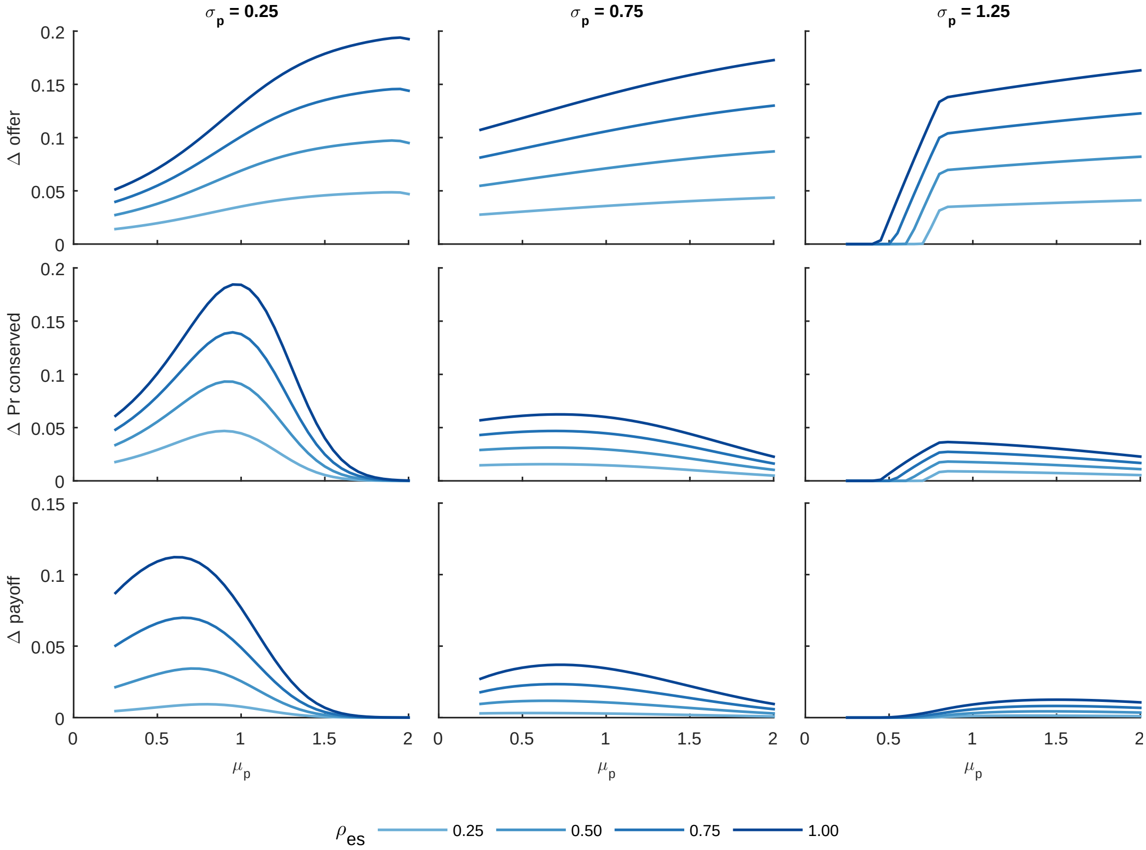
D.1 Benefit of improved information

In Figure 6, the impact of information on optimal values is shown by the different lines. It can be difficult to see how the size of these differences varies from this figure. Figure emphasizes these difference by plotting subtracting the value for $\rho_{es} = 0$ (e.g. the lightest line in Figure 6) from the lines for each remaining value of ρ_{es}.

D.2 Impact of correlation

Figure 10 replicates the left-hand columns of Figure 5 with negative and positive correlation. Two effects are apparent from this figure. First, in the left hand column, we see that with negative correlation, the optimal offer first increases and then decreases as the observed signal of conservation value rises. At low signal value values, the increase in the expected conservation value dominates and leads to higher offers. When a high signal is observed, this causes the buyer to believe the development is likely to be low, suggesting that the parcel can be induced to conserve with a lower offer. Second, we

Fig. 9 Change in optimal outcomes due to improved information



see that when there is correlation, the signal reveals information about the expected development value, so the probability the parcel is in each location in the figure changes as the signal increases. With negative correlation, the probability of observing high p and low s or low s and high p increases, while with negative correlation, the probability of observing a high p and a high s or a low p and a low s increases.

Figures 11, 12, and 13 illustrate the impact of correlation on optimal offers, the probability of first period conservation, and the optimized expected buyer payoff.

Fig. 10 Optimal Policies with Correlation

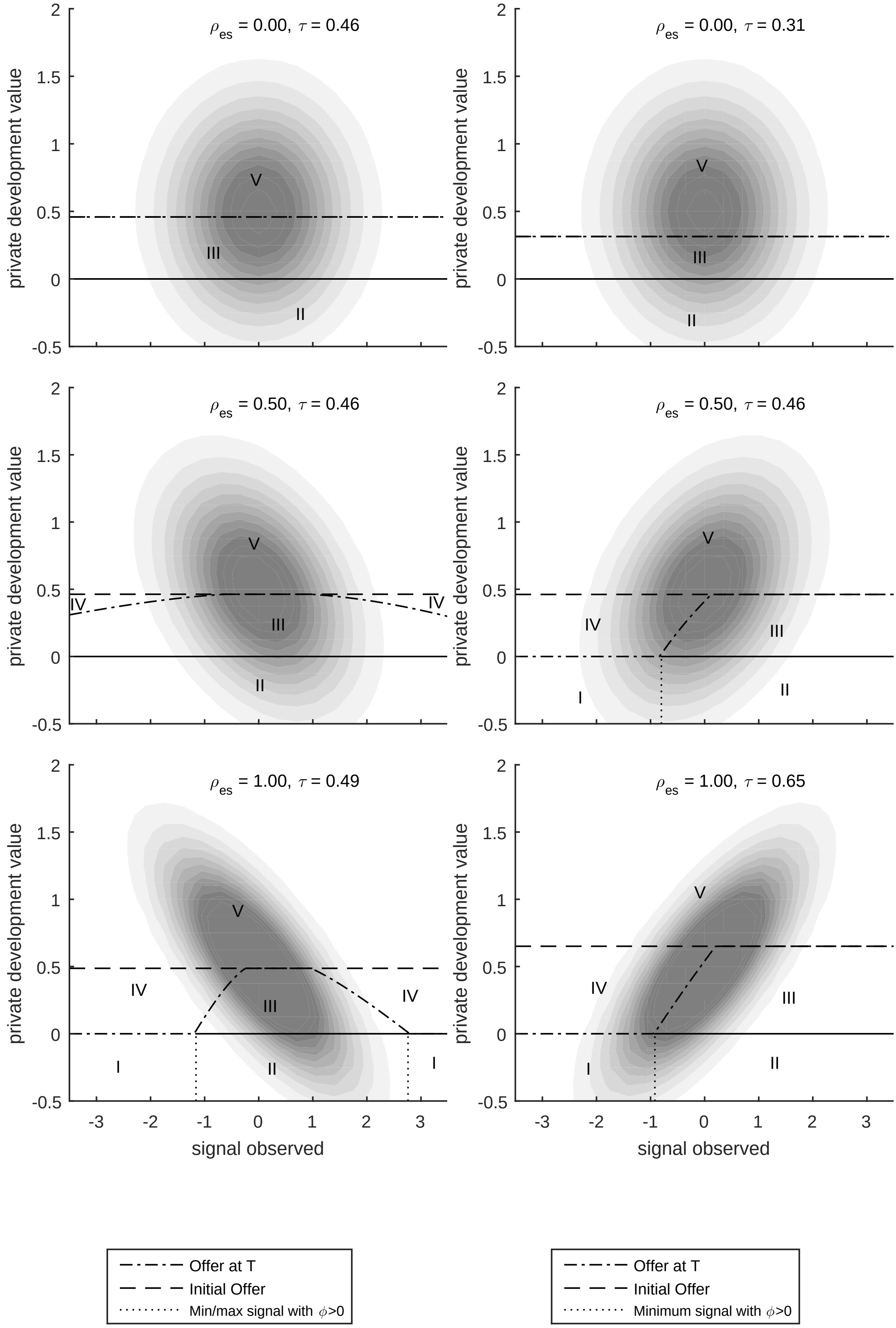


Fig. 11 Impact of correlation on optimal first period offers

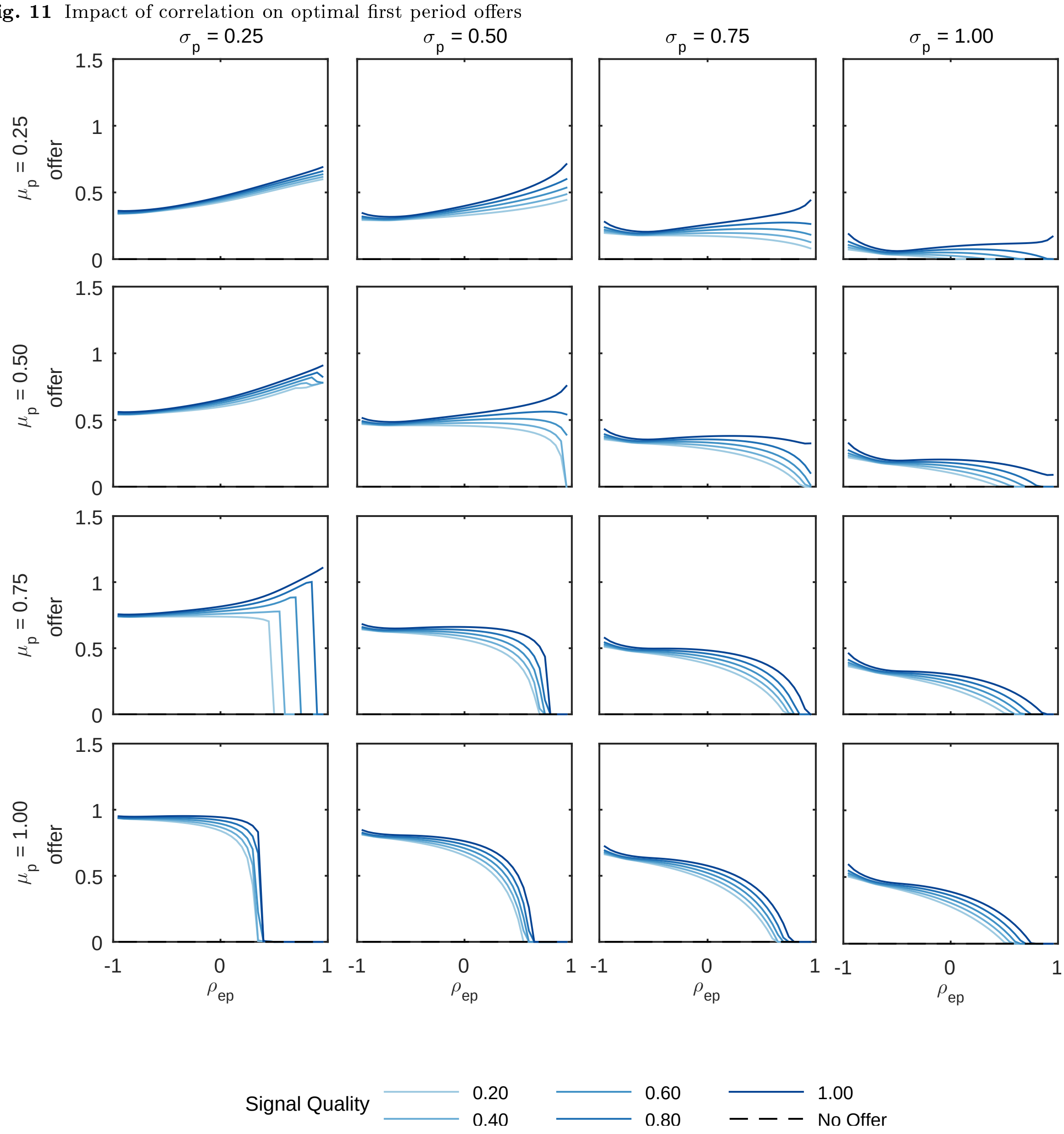


Fig. 12 Impact of correlation on probability of first period conservation

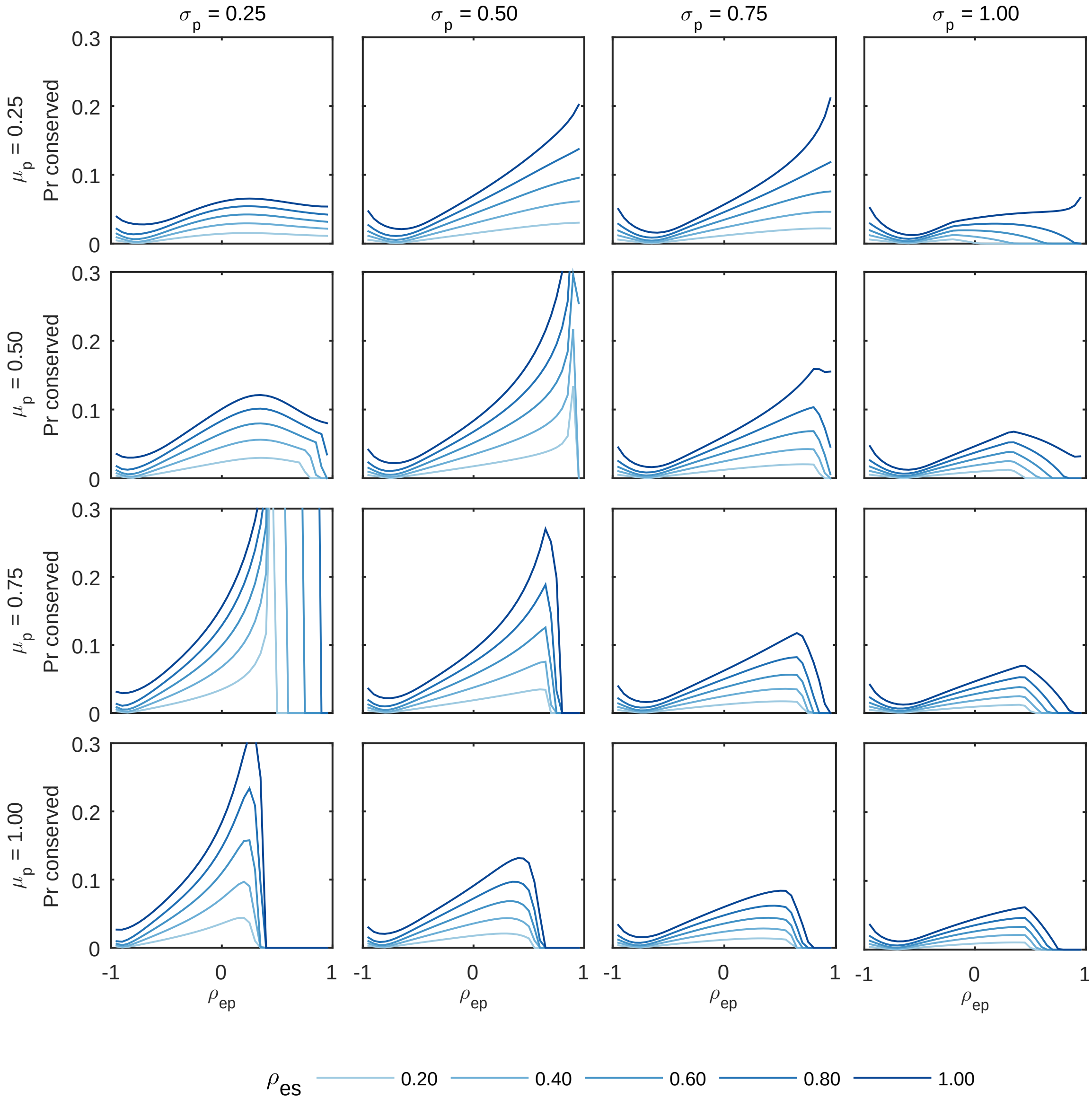


Fig. 13 Total impact of correlation on buyers optimized payoff