

# QUALITY MEASUREMENT AND CONTRACT DESIGN: AN EXAMPLE FROM AGRICULTURE

BRENT HUETH<sup>†</sup> AND TIGRAN MELKONYAN<sup>‡</sup>

**ABSTRACT.** We examine contracts used by growers and processors in the US sugarbeet industry. Though quite similar in most respects, the markets we study exhibit enough variation to represent a sort of natural experiment. One set of growing regions differs from the rest in the farm-level production technology available to growers, and in the set of performance measures used to condition contracts. The second of these differences is somewhat surprising given that the informational content and cost of employing the various performance are likely similar across all production regions. Using agency theory, we provide one plausible explanation for the observed difference in contract structure that relies on nitrogen and irrigation being complementary in sugarbeet production.

## 1. INTRODUCTION

Principal-agent theory has become somewhat of a workhorse for studying information-constrained Pareto optimal allocations. Unfortunately, recent empirical evidence seems to suggest that, for a variety of institutional contexts, the model is misspecified on some important dimension. For example, Prendergast (1999) notes that a significant number of empirical studies have identified a direct relationship between risk (usually taken to be some measure of dispersion for performance measurement) and the power of incentives, while in at least one widely employed specification of the principal-agent model (Holmström and Milgrom (1991)), agency theory predicts an inverse relationship.

Though empirical evidence of this sort can be interpreted as a failure of the principal-agent model in particular institutional contexts, this failure doesn't preclude the possibility that the model may do quite

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<sup>†</sup>Department of Economics, Iowa State University. <sup>‡</sup>Department of Agricultural and Natural Resource Economics, University of Maryland. Prepared for the meetings of the American Agricultural Economics Association, Chicago, IL., August 5-8, 2001. This paper is preliminary and should not be cited without the authors' permission. Copyright 2001 by Brent Hueth and Tigran Melkonyan. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

well in other contexts.<sup>1</sup> Agriculture ought to be one such context. Indeed, sharecropping is often used as a stylized example to motivate textbook treatments of principal-agent theory. There are ample opportunities for information asymmetry between landlords and their tenant farmers (or more generally, between various types of agricultural intermediaries and farmers), and, given the stochastic nature of production, risk sharing is likely an important element of contract design. Moreover, agricultural markets are typically characterized by autonomous producing agents where there are well defined performance measures for growers' output (e.g., yield, and various quality measures). As a result, many of the complications that are present when considering, for example, the design of incentives within firms (peer affects, subjective performance evaluation, team production, etc.), are typically less important in the context of agricultural contracts. Agricultural markets thus represent a convenient laboratory for testing off-the-shelf principal agent theory.

In this paper, we examine contracts used by growers and processors in the US sugar beet industry. Participants in all major beet growing regions are engaged in roughly the same activity, and yet we observe substantial differences in the types of contracts that are employed. In what follows, we examine whether principal-agent theory can explain this variation.

Sugar beets are grown and processed in five major production regions: the Red River Valley (North Dakota), the Great Lakes area (Michigan and Ohio), the Great Plains (Montana and Colorado), the Northwest (Idaho and Oregon), and the Southwest (primarily California) (U.S. Department of Agriculture 1999). For the purposes of this paper, there are two important differences with respect to production practices and contracting activities across these regions. First, the Red River Valley and Great Lakes regions are the only areas where production is nonirrigated. Second, in these same two regions, processors use what seems to be a more efficient contract. Growers' beets are measured both for

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<sup>1</sup>Moreover, rather than interpret these apparent contradictions as a failure of the principal-agent model, one might consider them a consequence of the assumptions (constant absolute risk aversion, linear contracts, and normally distributed noise in performance measurement) employed in the Holmström and Milgrom (1991) model. Though extremely tractable and empirically convenient, this model may simply be misspecified for the relevant contracting environments. For more general specifications of the principal-agent model, the predictions of agency theory are not so straightforward. Indeed, without explicitly specifying some aspect of the model, very little can be predicted. Thus, in order to more fully assess the power of agency theory to predict actual contracts structures, there seems to be a need for more detailed (e.g., structural) empirical work.

their sugar content, and the for the percentage of *extractable* sugar they contain, with both measures used to condition growers' contracts. In all other production regions, extractable sugar is not measured. We elaborate in more detail below, but in short, sugar impurities are extracted during processing, and extractable sugar represents the pure sugar in a beet.

From an agency perspective, this second difference is puzzling. Standard results suggests that any costless and informative signal of farmer effort can Pareto improve contract design (e.g., Holmström (1979)), yet there's little reason to expect either the cost of measuring extractable sugar or its informational content to vary substantially across the various regions. Balbach (1998) argues that the organizational structure of processors can influence the type of contract that's employed. Processors in the Red River Valley are all cooperative organizations.<sup>2</sup> Her claim is that the incentive to participate in an "extractable sugar contract" is greater for cooperative members, because they share in the cost savings from more efficient processing. However, this argument is incomplete, since if it's efficient to use such a contract, there's no reason that private processors can't pass along associated cost savings in their contracts with growers.

We argue instead that the nonirrigated nature of production in the Red River Valley and Great Lakes regions is key to understanding why different contracts are observed. Briefly, growers influence the sugar content in their beets with the amount of nitrogen applied to their crops (Cattanach et al. 1993). Reduced nitrogen use increases the sugar content of a given size beet (total sugar content goes up and there are fewer impurities), but cutting back on nitrogen also reduces the size of each beet (yields). Achieving high levels of sugar production therefore requires managing a tradeoff between beet yield (quantity) and sugar content (quality). If irrigation affects the stochastic relationship that governs total sugar production (and agronomic evidence that we present later in this paper suggests it does), then we'd expect contracts to be designed differently in irrigated and nonirrigated regions.

Thus, one explanation for the observed difference in contract structures is that the use of irrigation in sugar beet production changes the nature of the tradeoff between nitrogen use, beet yield, and the sugar content of beets. In this way, we can use variation in contract structures as "data" to infer something about the primitives of our model. As we explain below, observed differences suggest that nitrogen use and

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<sup>2</sup>In the Great Plains region, a number of private processors have recently been purchased by groups of local growers, and have become cooperative organizations (Raabe 2000). It remains to be seen whether these organizations will adopt the extractable sugar contract.

irrigation are complementary in the sense that irrigation increases the expected marginal *yield* of nitrogen (irrigation may increase or decrease expected marginal *sugar* content, for given yield).

In what follows, we examine this hypothesis more closely by first considering whether the standard principal-agent model can deliver a prediction that’s consistent with the heuristic argument we present below. For a particular specification of our model, we then evaluate whether the magnitude of the effect we identify is sufficiently large to justify the observed variation in contract structure. We evaluate this magnitude using Grossman and Hart’s (1983) algorithm to compute optimal contracts for a calibrated version of our model. Before introducing our model, we first provide a more complete description of the variation in contract structure that’s observed, and more carefully explain how a complementarity between irrigation and nitrogen use can affect contract design.

## 2. QUALITY MEASUREMENT AND CONTRACT DESIGN IN THE US SUGAR BEET INDUSTRY

Balbach (1998) notes that there are three distinct types of contracts in the US sugar beet industry. Processors in the western states use a “participation contract”. In this contract, revenue from sales of refined sugar, net of marketing costs, are split between processors. Growers are apportioned shares of their collective revenue according to the estimated tons of sugar that each grower delivers, with the sugar content of a grower’s beets determined by first measuring the percent of sugar in a sample of beets from each of his deliveries, and then by adjusting for a fixed, factory level “extraction rate” (purity level).<sup>3</sup> Growing costs are born entirely by growers, and processing costs entirely by processors. For concreteness and future reference, it’s useful to characterize this contract algebraically. For simplicity assume there is just a single grower, ignore processing and growing costs, and normalize the per-ton net revenue from marketing raw sugar (price less marketing costs) to one. If a grower delivers  $q$  tons of beets with  $\alpha$  percent sugar, then he receives a payment that depends on  $\alpha\bar{r}q$ . Under this contract, the processor bears the cost of converting  $q$  to pure sugar.

The contract used by processors in Michigan and Ohio—the “sliding-scale contract”—is quite similar to the participation contract, with one

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<sup>3</sup>As mentioned in the introduction, not all the sugar in a sugar beet can be converted into refined sugar. The extraction rate is an approximate measure of the percentage of beet sugar that *can* be converted (for details, see Hobbis (1977))

difference. In addition to measuring sugar content, a factory level extraction rate is assigned to each grower's delivery, with this rate determined *ex post*, after all growers' beets have been processed. Denoting  $\tilde{r}$  as the factory-level extraction rate, a grower's payment under a sliding scale contract depends on  $\alpha\beta\tilde{r}q$ . Under this contract, growers have incentive (though quite limited) to achieve a high extraction rate, and are therefore induced to bear a portion of the cost associated with purifying the sugar in their beets.

The contract used by processors in the Red River Valley conditions payment on a load-specific extraction rate. Total sugar content of a load of sugar beets is computed as  $\alpha r q$ , where  $r$  is an extraction rate specific to each load a grower delivers. If growers can influence extraction rates with their growing and cultivation practices, using this measure would seem to offer an efficiency not found in the other contracts.

As alluded to in the previous section, we argue that the reason only one set of regions chooses to contract in some way on extractable sugar is a direct consequence of the nonirrigated nature of production in those regions. Heuristically, if irrigation increases the expected marginal yield of nitrogen (holding expected marginal sugar production constant) then an optimal contract should implement a relatively high level nitrogen use. If contracts are monotonic in net sugar production, one way to implement a relatively high level of nitrogen use is to *not* contract on extractable sugar (recall that expected extractable sugar content decreases with increased nitrogen use). Alternatively, consider two types of incentive contracts: one based on total sugar production, and another based on net sugar production (total sugar less impurities). If the cost of measuring net sugar is zero and sugar impurity is an informative signal with respect nitrogen use, the second contract will always be preferred. Thus, presuming that measurement costs are similar across the various regions, the benefit from contracting on sugar purity must be relatively high in those areas where it's measured. If one consequence of contracting on purity is reduced nitrogen use (e.g., because contracts are monotonic in net sugar production), then the benefit of such a contract should be relatively high in areas where reducing nitrogen use generates a large net benefit. Positive contributions to this net benefit come from reduced application of a costly input, and from higher expected total sugar production for a given yield. These must be weighed against expected reductions in total yield, which will be high when the expected marginal yield of nitrogen is high. Thus, if irrigation increases the expected marginal yield of nitrogen, the net benefits of contracting on sugar purity will be relatively low.

In the next section we present a simple principal-agent model that allows us to demonstrate this point formally.

## 3. SUGAR BEET CONTRACTS: THEORY

We model sugarbeet contracting between a processor and a single grower, and for simplicity assume the contract governs exchange of a single acre's production. Realized production from this acre is represented by its yield  $y \in Y \equiv \{y_1, \dots, y_{n_y}\}$  and the fraction of yield that is sugar,  $r \in R \equiv \{r_1, \dots, r_{n_r}\}$ .<sup>4</sup> We let  $s \equiv (r, y)$  denote the full vector of signals, and define  $S \equiv \{(r, y) | r \in R, y \in Y\}$  to be the set of all possible realizations of  $s$ . The notation  $s \geq s'$  has the usual componentwise meaning.

The grower conditions the joint distribution of  $s$  with the amount of nitrogen  $a \in A \equiv \{a_1, \dots, a_{n_a}\}$  applied to his crops, assumed non-contractible, and other production inputs that for notational simplicity we suppress. We let  $a$  represent the dollar value of nitrogen use. The probability of outcome  $s$  is denoted by  $\pi(s|a) > 0$  with  $\sum_S \pi(s|a) = 1$  for all  $a \in A$ . For nitrogen level  $a$  and compensation  $w$ , grower utility is given by some von Neumann-Morgenstern utility function  $H(w, a) = G(a) + K(a)U(w)$ , satisfying Assumption 1 in Grossman and Hart (1983). Because we interpret  $a$  as the dollar cost of nitrogen use, it's also natural to assume:

**Assumption 1.** *For all  $w$ ,  $G(a) + K(a)U(w) \geq G(a') + K(a')U(w)$  for  $a' \geq a$ .*

Reservation utility for the grower is denoted by  $\underline{U}$ . The processor is assumed risk neutral, with the value of an acre's production given by  $V(r, y)$ , assumed increasing in both arguments.

Denote compensation given a particular outcome  $s$  by  $w(s)$ , and let  $u(s) = U(w(s))$ . Grossman and Hart (1983) show that the processor's contract design problem can be solved in two stages. In the first stage, the processor chooses  $u(s)$  to minimize the cost of implementing a given action, and in the second stage chooses the action that yields the highest expected net benefit. The optimal compensation schedule is computed as  $w(s) = U^{-1}(u(s))$ . Let  $C(a)$  denote the minimum cost of implementing action  $a$ . If for some  $a$ , there is no feasible solution, then we set  $C(a) = \infty$ ; such an  $a$  is not implementable. The Pareto optimal level of nitrogen use is the one that solves

$$V_s \equiv \max_a \sum_S \pi(s|a) V(r, y) - C(a).$$

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<sup>4</sup>As described above, there are actually three signals used in sugarbeet contracts: beet yield, percent sugar content, "extraction rate" (i.e., sugar purity). Thus, in our model,  $r$  represents percent sugar multiplied by the extraction rate. Explicitly modeling all three signals unnecessarily complicates presentation, without adding any additional insight.

Now suppose there is some strictly positive cost  $K$  that must be incurred to measure  $r$ . The benefit associated with this measurement is given by the expected increase in profits to the principal from conditioning  $w$  on  $s$ , relative to a contract that is conditioned only on  $y$ . Define  $V_y$  as maximum expected profits to the principal from a contract conditioned only on  $y$ . Then it's optimal to condition compensation on  $s$  when  $\Delta \equiv V_s - K - V_y > 0$ .

Based on the discussion in our introduction, we'd like to evaluate how a change in the structure of  $\pi(s|a)$  affects the value of measuring  $r$ , given by  $\Delta$ . To do this, we consider an example where there are only two possible outcomes for each signal, and where the grower selects from three possible levels of nitrogen use.

**3.1. An Example.** Let  $y_L$  and  $y_H$ , with  $y_L < y_H$ , and  $r_L$  and  $r_H$ , with  $r_L < r_H$  denote the possible values of yield and sugar content, respectively. Then, the full vector of signals  $s \equiv (r, y)$  has four possible realizations,  $S \equiv \{(r_L, y_L), (r_L, y_H), (r_H, y_L), (r_H, y_H)\}$ . Let  $s_1 \equiv (r_L, y_L)$ ,  $s_2 \equiv (r_L, y_H)$ ,  $s_3 \equiv (r_H, y_L)$  and  $s_4 \equiv (r_H, y_H)$ ,  $v_i = V(s_i)$ , and  $u_i = u(s_i)$ . We assume that  $v_1 < v_2 < v_3 < v_4$ . That is, the processor's payoff is an increasing function of yield and sugar content, and sugar content is more important in contributing to the processor's payoff than yield ( $v_3 > v_2$ ). Since the processor's payoffs are distinct under all four realizations of the signal  $s$ , the ability of the two parties to contract on  $s$  is equivalent to contracting on the realization of  $v$ .

The grower has a choice over three levels of nitrogen,  $A \equiv \{a_1, a_2, a_3\}$ , where  $a_1 < a_2 < a_3$ . The probability distribution over the  $v_i$ 's induced by action  $a_i$  is given in the following table, where the parameter  $\sigma > 0$  determines how much the action  $a_3$  increases the probability of high  $y$ , relative to action  $a_2$ , and the parameters  $\delta > 0$  and  $\phi \in [0, 1]$  govern the affect of action  $a_3$  on the probability of high  $r$ . We assume  $l_i \in (0, 1)$

	$\pi(v_i a_1)$	$\pi(v_i a_2)$	$\pi(v_i a_3)$
$v_1$	$l_1$	$p_1$	$p_1 - \sigma$
$v_2$	$l_2$	$p_2$	$p_2 + \phi\sigma + \delta$
$v_3$	$l_3$	$p_3$	$p_3 - \delta$
$v_4$	$l_4$	$p_4$	$p_4 + (1 - \phi)\sigma$

TABLE 1. Probability of  $v_i$  given  $a_i$

and  $\sum_i l_i = 1$ , and similarly for  $p_i$ . Also, we assume that  $\sigma < p_1$ ,  $\delta < p_3$ , and  $\delta > (1 - \phi)\sigma$ . The first two of these conditions ensure that the distribution induced by action  $a_3$  places strictly positive weight on all four outcomes, and the last condition ensures that choosing  $a_3$  reduces the probability of high  $r$ , relative to action  $a_2$ .

This specification captures the essential features of the problem outlined in our introduction. When the grower switches from action  $a_2$  to action  $a_3$  the probability of high yield increases from  $p_2 + p_4$  to  $p_2 + p_4 + \sigma + \delta$ , and the probability of high sugar content falls from  $p_3 + p_4$  to  $p_3 + p_4 + (1 - \phi)\sigma - \delta$ . Moreover, we can represent a complementarity between nitrogen use and irrigation by considering an increase in  $\sigma$ , or a reduction in either  $\delta$  or  $\phi$ . For a fixed price of total sugar ( $ry$ ), each of these changes increase the expected marginal benefit of selecting action  $a_3$  over action  $a_2$ . To evaluate how such changes affect the benefit of measuring  $r$ , we need to separately consider how  $V_s$  and  $V_y$  change.

Under full information the processor can observe and verify the level of nitrogen applied by the grower. Let  $C_{FB}(a) \equiv h\left(\frac{U - G(a)}{K(a)}\right)$ .  $C_{FB}(a)$  is the first-best cost of getting the grower to choose action  $a$ . When action  $a$  is contractible, the processor will offer the following contract to induce action  $a$ : the processor pays the grower  $C_{FB}(a)$  if the grower chooses  $a$ , otherwise, the grower pays the processor a high penalty. Note also that the cost of implementing action  $a_1$  is given by  $C_{FB}(a_1)$ , because incentive constraints are irrelevant for this action. From Assumption 1, it follows that  $C_{FB}(a_1) \leq C_{FB}(a_2) \leq C_{FB}(a_3)$ . We let  $B(a_i) = \sum_j \pi(v_j|a_i)v_j$  denote the expected payoff to the processor if the grower picks action  $a_i$ . The first-best optimal action maximizes  $B(a) - C_{FB}(a)$  on  $A$ . To make our problem interesting, we assume that  $a_1$  is never a second-best action, and that action  $a_2$  is first-best.

When nitrogen use is noncontractible, it will be optimal to condition the grower's compensation on  $s$  only if doing so increases expected net benefits by an amount greater than the cost of measuring  $r$ . Thus, it's necessary to compare expected net benefits when  $s$  is contractible and when only  $y$  is contractible. We do this in the next two subsections.

**3.1.1. Two Signals.** We start by supposing the two parties contract on both signals of the grower's action. The processor faces three constraints for implementing action  $a_2$ : the grower's participation constraint, given action  $a_2$ ,

$$(1) \quad G(a_2) + K(a_2) \sum_{j=1}^4 p_j u_j \geq \underline{U},$$

incentive compatibility for action  $a_2$  with respect to action  $a_1$ ,

$$(2) \quad G(a_2) + K(a_2) \sum_{j=1}^4 p_j u_j \geq G(a_1) + K(a_1) \sum_{j=1}^4 l_j u_j,$$



and incentive compatibility for action  $a_2$  with respect to action  $a_3$ ,

$$(3) \quad G(a_2) + K(a_2) \sum_{j=1}^4 p_j u_j \geq G(a_3) + K(a_3) E[u|a_3],$$

where  $E[u|a_3] = (p_1 - \sigma)u_1 + (p_2 + \phi\sigma + \delta)u_2 + (p_3 - \delta)u_3 + (p_4 + (1 - \phi)\sigma)u_4$ . The cost of implementing action  $a_2$  is then given by

$$C_s(a_2) = \min_{u_1, \dots, u_4} \left\{ \sum_j p_j h(u_j) \mid (1), (2), (3) \right\},$$

where  $h \equiv U^{-1}$ .

Similarly, to implement action  $a_3$  the processor faces the constraints

$$(4) \quad G(a_3) + K(a_3) E[u|a_3] \geq \underline{U},$$

$$(5) \quad G(a_3) + K(a_3) E[u|a_3] \geq G(a_1) + K(a_1) \sum_{j=1}^4 l_j u_j$$

$$(6) \quad G(a_3) + K(a_3) E[u|a_3] \geq G(a_2) + K(a_2) \sum_{j=1}^4 p_j u_j,$$

and the cost of implementing  $a_3$  is given by

$$C_s(a_3) = \min_{u_1, \dots, u_4} \{ E[h(u)|a_3] \mid (1), (2), (3) \},$$

where  $E[h(u)|a_3] = (p_1 - \sigma)h(u_1) + (p_2 + \phi\sigma + \delta)h(u_2) + (p_3 - \delta)h(u_3) + (p_4 + (1 - \phi)\sigma)h(u_4)$ . We assume that both actions are implementable:  $C_s(a_2) < \infty$  and  $C_s(a_3) < \infty$ .

Without further parameterizing our model, we cannot determine which action maximizes the net benefit to the principal. However, we can determine how changes in the parameters  $\sigma$ ,  $\delta$ , and  $\phi$  affect the second-best action. Similar to the two-stage algorithm used to solve our principal-agent problem, we perform comparative statics by separately considering the effect of parameters on the expected payoff to the principal  $B(a)$  and the cost  $C(a)$  of implementing a given action  $a$ . For example, if change in a parameter positively affects the net payoff  $B(a) - C(a)$  for action  $a$  while net payoff for other actions decreases or remains unchanged then it is now more likely that action  $a$  is the second-best action. This type of unambiguous result is not feasible if a change in some parameter has a similar effect on net payoffs for different actions.

Consider first an increase in parameter  $\sigma$ . The benefit  $B(a_2)$  is unaffected by increase in  $\sigma$ , while, if the optimal contract is monotonic ( $u_i$  is increasing in  $i$ ),  $C(a_2)$  is nondecreasing. This is easily verified by observing that an increase in  $\sigma$  results in a smaller constraint set since the right-hand-side of the inequality in (3) increases. Thus, the net

payoff  $B(a_2) - C(a_2)$  decreases as a result of an increase in  $\sigma$ . Analogously, one can show that an increase in  $\sigma$  leads to an increase in the net payoff  $B(a_3) - C(a_3)$ . Expected benefits  $B(a_3)$  increase, while  $C(a_3)$  decreases. Thus, as  $\sigma$  increases the expected net benefit from action  $a_3$  relative to action  $a_2$  also increases (the difference between  $B(a_3) - C(a_3)$  and  $B(a_2) - C(a_2)$  increases). For  $\sigma$  sufficiently large,  $a_3$  will be the optimal action. Similar reasoning can be employed to show that a decrease in  $\delta$  and a decrease in  $\phi$  both increase the expected net benefit of action  $a_3$  relative to action  $a_2$ .

Intuitively, an increase in  $\sigma$  raises the cost of implementing action  $a_2$  because choosing this action reduces the probability of a good yield, relative to action  $a_3$ . If the optimal contract is monotonic, then for either realization of  $r$ , the grower receives a higher payment when  $y_H$  is realized, and thus has some incentive to choose  $a_3$ . This incentive increases with  $\sigma$ . Similar intuition applies when considering a decrease in either  $\delta$  or  $\phi$ .

**3.1.2. One Signal.** Now we consider the scenario where the two parties contract only on yield. There are two possible outcome states,  $y_L$  and  $y_H$ , on which compensation can be conditioned. Note that  $\Pr[y_L|a_3] = (p_1 + p_3 - \sigma - \delta)$ , and  $\Pr[y_H|a_3] = (p_2 + p_4 + \sigma + \delta)$ . To implement action  $a_2$ , the following participation and incentive compatibility constraints must be satisfied:

$$(7) \quad G(a_2) + K(a_2)[(p_1 + p_3)u_L + (p_2 + p_4)u_H] \geq \underline{U},$$

$$(8) \quad G(a_2) + K(a_2)[(p_1 + p_3)u_L + (p_2 + p_4)u_H] \geq G(a_1) + K(a_1)[(l_1 + l_3)u_L + (l_2 + l_4)u_H],$$

and

$$(9) \quad G(a_2) + K(a_2)[(p_1 + p_3)u_L + (p_2 + p_4)u_H] \geq G(a_3) + K(a_3)[\Pr[y_L|a_3]u_L + \Pr[y_H|a_3]u_H].$$

The minimum cost of implementing action  $a_2$  with a contract conditioned only on yield is then given by

$$C_y(a_2) = \min_{u_L, u_H} \{(p_1 + p_3)h(u_L) + (p_2 + p_4)h(u_H) \mid (7), (8), (9)\}.$$

Similarly, to implement action  $a_3$ , the processor must satisfy

$$(10) \quad G(a_3) + K(a_3)[\Pr[y_L|a_3]u_L + \Pr[y_H|a_3]u_H] \geq \underline{U},$$

$$(11) \quad G(a_3) + K(a_3)[\Pr[y_L|a_3]u_L + \Pr[y_H|a_3]u_H] \geq G(a_1) + K(a_1)[(l_1 + l_3)u_L + (l_2 + l_4)u_H],$$

and

$$(12) \quad G(a_3) + K(a_3)[\Pr[y_L|a_3]u_L + \Pr[y_H|a_3]u_H] \geq \\ G(a_2) + K(a_2)[(p_1 + p_3)u_L + (p_2 + p_4)u_H].$$

The minimum cost of implementing action  $a_3$  with a contract conditioned only on yield is then given by

$$C_y(a_3) = \min_{u_L, u_H} \{ \Pr[y_L|a_3]h(u_L) + \Pr[y_H|a_3]h(u_H) \mid (10), (11), (12) \}.$$

As in the previous subsection, we consider how parameters  $\sigma$ ,  $\phi$  and  $\delta$  affect the optimal second-best action. Since  $\phi$  does not enter any constraint, it only affects the processor's objective function. An increase in  $\phi$  therefore reduces the expected net benefit of action  $a_3$ , relative to  $a_2$ . One can also show that an increase in  $\sigma$  leads to an increase in the difference between  $B(a_3) - C(a_3)$  and  $B(a_2) - C(a_2)$ , while the effect of an increase in  $\delta$  is ambiguous.

**3.2. Comparative Static Results.** The comparative static results from the previous two subsections are summarized in Table 2.

	$B(a_2)$	$B(a_3)$	$C_s(a_2)$	$C_s(a_3)$	$C_y(a_2)$	$C_y(a_3)$
$\sigma$	0	+	+	-	+	-
$\delta$	0	-	-	+	+	-
$\phi$	0	-	-	+	0	0

TABLE 2. Comparative static results.

Ultimately, we're not interested these comparative statics per se, but rather in the effect of each parameter on  $\Delta$ , which is the *difference* between expected net benefits under each information regime. From Table 2, and if we assume that the optimal actions are the same under each regime, an increase in  $\sigma$  has an ambiguous affect on  $\Delta$ . When  $a_2$  is the second-best action for each regime, then an increase in  $\sigma$  leaves expected benefits unchanged, while implementation costs go up in both cases. Similarly, when  $a_3$  is the second-best action for each regime, expected benefits go up under both regimes, but so do expected implementation costs.

An increase in  $\delta$  unambiguously increases  $\Delta$  when  $a_2$  is the second-best action. Intuitively, when  $a_2$  is the optimal action and  $\delta$  increases, distinguishing between outcomes  $(r_L, y_H)$  and  $(r_H, r_H)$  becomes more valuable, because the former outcome more strongly signals that action  $a_3$  was chosen. This increases the value of measuring  $r$ . Similarly, when action  $a_3$  is optimal an increase in  $\delta$  unambiguously reduces  $\Delta$ : if the grower's contract is conditioned on  $r$  (and assuming the contract

is monotonic), he will have some incentive to choose  $a_2$  since doing so increases the probability of  $r_H$ . Increasing  $\delta$  strengthens this incentive leading to higher implementation costs. When the contract is not conditioned on  $r$ , increasing  $\delta$  reduces implementation costs because the grower maximizes the probability of  $y_H$  by choosing  $a_3$ . An increase in  $\phi$  has the same affect on  $\Delta$  as  $\delta$  and similar intuition applies.

We summarize the comparative static affects of  $(\sigma, \delta, \phi)$  on the expected value of quality measurement  $\Delta$  in the following result:

**Result 1.** *If action  $a_2$  ( $a_3$ ) is second-best under both information regimes:*

- (i) *An increase in  $\sigma$  has an ambiguous affect on  $\Delta$ .*
- (ii) *An increase in  $\delta$  increases (decreases)  $\Delta$ .*
- (iii) *An increase in  $\phi$  increases (decreases)  $\Delta$ .*

Now suppose that action  $a_2$  is not implementable when contracting only on  $y$  (or that the cost of implementing  $a_2$  is very high). This can easily occur because the principal must use two instruments ( $u_L$  and  $u_H$ ) to satisfy three constraints. Suppose also that action  $a_3$  is always optimal when contracting on  $y$ . Then we must also consider the case where the second-best actions are different under the two information regimes. Inspection of Table 2 yields the following result:

**Result 2.** *If action  $a_2$  is second-best when contracting on  $s$ , and action  $a_3$  is second-best when contracting on  $y$ ,*

- (i) *An increase in  $\sigma$  reduces  $\Delta$ .*
- (ii) *An increase in  $\delta$  has an ambiguous affect on  $\Delta$ .*
- (iii) *An increase in  $\phi$  increases  $\Delta$ .*

Increasing  $\sigma$  reduces the expected net benefit of contracting on  $s$  because implementation costs rise. It's becomes harder to induce growers to reduce their use of nitrogen, when doing so substantially reduces expected yield. When contracting on  $y$ , increasing  $\sigma$  increases expected benefits, and reduces implementation costs. Thus, the expected benefit that comes from contracting on  $r$  unambiguously falls. In other words, a strong complementarity between nitrogen use and irrigation (high  $\sigma$ ) reduces the expected benefit that comes from quality measurement, if contracting on  $s$  provides the only means of implementing moderate nitrogen use.

Thus, there are three different scenarios to consider when trying to answer the question, how does a complementarity between nitrogen use and irrigation affect the value of quality measurement? The scenarios are defined by which set of actions are second-best under each regime.<sup>5</sup>

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<sup>5</sup>If  $a_2$  is optimal when contracting on  $y$ , then it's also optimal when contracting on  $s$  because expected benefits remain unchanged and implementation costs (weakly) fall.

When the actions implemented under the two information regimes are the same, the affect of a complementarity between nitrogen use and irrigation is ambiguous. If the first-best action  $a_2$  is implemented when contracting on  $s$ , but the high action  $a_3$  is implemented when contracting on  $y$ , then the complementarity reduces the value of quality measurement.

However, it's important to recognize that the comparative static results in Table 2 that were used to generate these results depend on the optimal contract being monotonic. It's fairly straightforward to verify that the specification for  $\pi(s|a)$  in Table 1 does not satisfy the monotone likelihood ratio property (nor is its distribution function convex). As a result, we cannot be assured that the optimal contract is monotonic. Thus, in the next section we parameterize our model further by specifying a particular set of preferences for the processor and grower, and evaluate these same comparative statics computationally. In addition to confirming the analytic comparative statics results derived in this section, computation also allows to get some sense for how large the benefit from quality measurement can be under the various scenarios.

**3.3. Computations.** We suppose that the processor values total sugar production  $(r, y)$  according to  $V(r, y) = y[p_s r - c(r)]$ , where  $p_s$  represents the price of refined sugar, and

$$c(r) = \begin{cases} \bar{c} & \text{if } r = r_L \\ 0 & \text{if } r = r_H \end{cases}$$

where  $\bar{c}$  is the per-unit cost of a low extraction rate. The grower is assumed constant absolute risk averse with  $G(a) = 0$ ,  $U(w) = -e^{-\rho w}$ , and  $K(a) = e^{\rho a}$ , where  $\rho$  is the grower's measure of constant absolute risk aversion. We let  $p_s = 1$ ,  $r_L = .15$ ,  $r_H = .17$ ,  $y_L = 24$ ,  $y_H = 26$ , and  $\bar{c} = 0.01$  (roughly 7 percent of average per-unit revenue). Nitrogen use can be either .2, .3, or .4 (these numbers are in units of 100 dollars per acre).

Table 3 summarizes comparative static results for the parameters  $\sigma$  and  $\delta$ .

The column labeled  $\Delta/w_F$  represents the expected benefit from quality measurement as a percentage of first-best compensation. Since we don't have good information about processing costs, it's hard to evaluate the magnitude of  $\Delta$  by itself. The columns labeled  $a_y$   $a_s$  ( $w_y$  and  $w_s$ ), represent second-best actions (compensation schedules) when only  $y$  is contractible and when  $s$  is contractible. Note that the compensation schedules are monotonic for this particular specification. Because  $a = .4$  is optimal when contracting on  $y$  and  $a = .3$  is optimal when

$\delta = .1$		$\phi = .9$		$\rho = .8$	
$\sigma$	$a_y$	$a_s$	$\Delta/w_F$	$w_y$	$w_s$
.05	.4	.3	.35	.28,.96	.36,.55,.68,.76
.125	.4	.3	.26	.32,.84	.36,.55,.68,.76
.20	.4	.3	.19	.34,.78	.36,.55,.68,.76
$\sigma = .1$		$\phi = .9$		$\rho = .8$	
$\delta$	$a_y$	$a_s$	$\Delta/w_F$	$w_y$	$w_s$
.01	.3	.3	.07	.27,.99	.36,.55,.68,.76
.11	.4	.3	.29	.31,.87	.36,.55,.68,.76
.20	.4	.3	.41	.34,.78	.36,.55,.68,.76

TABLE 3. Computed comparative static results:  $\sigma$  and  $\delta$ .

contracting on  $s$ , the expected benefit from quality measurement decreases with an increase in  $\sigma$ . Similarly, an increase in  $\delta$  raises the expected benefit from quality measurement.

Table 4 summarizes comparative static results for the parameters  $\phi$  and  $\rho$ .

$\sigma = .1$		$\delta = .9$		$\rho = .8$	
$\phi$	$a_y$	$a_s$	$\Delta/w_F$	$w_y$	$w_s$
.65	.4	.3	.23	.31,.88	.36,.55,.68,.76
.80	.4	.3	.27	.31,.88	.36,.55,.68,.76
.95	.4	.3	.30	.31,.88	.36,.55,.68,.76
$\sigma = .1$		$\delta = .1$		$\phi = .9$	
$\rho$	$a_y$	$a_s$	$\Delta/w_F$	$w_y$	$w_s$
.30	.4	.3	.15	.75,1.33	.82,1.01,1.13,1.22
.90	.4	.3	.16	.28,.85	.33,.52,.65,.73
1.5	.4	.3	.18	.20,.79	.23,.44,.56,.63

TABLE 4. Computed comparative static results:  $\phi$  and  $\rho$ .

As expected, an increase in  $\phi$  raises the expected value of quality measurement. Increased risk aversion also makes quality measurement more valuable. Intuitively, when there are more signals of the grower's action, the processor can achieve similar incentives with less risk in the compensation schedule. This makes quality measurement more valuable when the grower is more risk averse.

#### 4. EVIDENCE AND DISCUSSION

Results from the previous section can be summarized in the following statement: the value of quality measurement falls when it becomes

relatively difficult to implement a moderate level of nitrogen use, and when a high level of nitrogen use is not too costly to the processor. This can occur when a relatively high level of nitrogen use substantially increases expected yields, without reducing expected sugar content too much.

In our introduction we noted that quality measurement is used only in irrigated production regions. It is also the case that average levels of nitrogen use and yields are substantially lower in these regions. In 1999, fertilizer use by growers in the Red River Valley and Great Lakes regions averaged only 50 percent of the average amount used by growers in other regions, and yields averaged 30 percent lower (U.S. Department of Agriculture 1999). Moreover, agronomic evidence suggests that irrigation increases the expected marginal yield of fertilizer (Tisdale et al. 1985). Both pieces of evidence seem to support the hypothesis that quality is not measured in irrigated production regions because doing so would not generate much benefit. It would be difficult to induce growers to lower their nitrogen use, and doing so would reduce expected yields substantially.

## 5. CONCLUSION

We use principal-agent theory to explain variation in the structure of contracts used in the US sugarbeet industry. This particular industry is interesting to study because in it we observe a remarkably straightforward natural experiment. One set of production regions differs from the rest in both the production technology available to growers, and in the set of performance measures used to condition contracts. Given this experiment, it's natural to ask whether existing contract design theory can explain the variation that's observed. We develop a simple principal-agent model that shows how the observed variation can indeed be rationalized, and present agronomic and other evidence that seems to support our explanation.

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IOWA STATE UNIVERSITY

E-mail address: [bhueth@iastate.edu](mailto:bhueth@iastate.edu)

UNIVERSITY OF MARYLAND

E-mail address: [tmelkonyan@arec.umd.edu](mailto:tmelkonyan@arec.umd.edu)