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Agricultural contracts, adverse selection, and multiple inputs

Rachael Goodhue[1]* and Leo Simon[2,3]

*Correspondence: goodhue@primal.ucdavis.edu
[1]Department of Agricultural and Resource Economics, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA
Full list of author information is available at the end of the article

Abstract

A significant and growing share of US agricultural output is produced under a production or marketing contract. An important controversy regarding agricultural production contracts is the control of non-labor inputs. Over time, contracts have tended to place more inputs under the buyer's control and fewer under the farmer's. This analysis examines the welfare effects of this trend. In the framework considered here, returns are reduced for some farmers and left unaffected for others. Returns to the buyer increase. The net effect on total surplus has two components. Output is higher when the buyer controls the input, due to lower information rents accruing to more productive farmers. However, this reduction distorts input use away from the production cost-minimizing level, which is costly. The net effect on total surplus depends primarily on the elasticity of substitution between inputs. Given the limited substitutability between labor and non-labor inputs in many agricultural activities, the analysis suggests that greater control of non-labor inputs by the buyer increases total surplus. The increase in returns to the buyer is consistent with the growing share of output produced under vertical coordination and the tendency to specify a greater number of production activities rather than allowing farmers to make their own decisions. The reduction in the returns obtained by some farmers is consistent with farmers' opposition to such requirements.

Keywords: Adverse selection, Agricultural contracts, Asymmetric information, Principal-agent theory, Production contracts, Vertical coordination

Background

Worldwide, many agricultural markets cannot be characterized as spot markets. A tremendous variety of forms of vertical coordination govern relationships between farmers and their buyers. One type of coordination is a production contract. Production contracts between farmers and buyers specify allowable fertilizers, seedstock, production practices, and other inputs. Under some contracts the buyer may retain ownership of a key input, such as chickens in broiler chicken contracts and the seed and output in crop contracts. In others, such as processing tomato contracts, the buyer may restrict the set of permissible pesticides. Our analysis focuses on US production contracts as defined by the National Agricultural Statistics Service (2014) for the Census of Agriculture: ones which set "terms, conditions, and fees to be paid by the contractor to the operation for the production of crops, livestock, or poultry." Production contracts account for a significant share of the value of agricultural output in the USA (16.8 % in 2008). Farmers may choose

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to enter a production contract for a variety of reasons, such as a lower need for operating capital because the buyer provides some inputs, access to technical assistance provided by the buyer, or risk management. Often, the farmer's contracting decision may have more than one reason. We examine one motivation for buyers, such as meatpackers, seed companies, and processors, to use production contracts when coordinating production with farmers.

While there are a number of reasons why a buyer may choose to control inputs that could just as easily be chosen by the farmer, this paper focuses on an information-driven motivation: the reduction of information rents arising from adverse selection and the resulting increase in profits. Information rents are the rents which are captured by a high ability farmer because his ability (type) is his private information. We examine the effects of who controls inputs in a framework in which output is a function of the farmer's type and the levels of inputs he uses. The farmer's type, his private information, affects the productivity of his effort, which is not observable, and of a non-labor input which the buyer observes only if she provides or specifies it as part of a production contract. We compare output and input levels, farmer compensation, buyer profits and total surplus under a contract which specifies that the buyer controls the input ("restrictive contract") with one in which the farmer controls it ("basic contract"). We then identify how the effects depend on the nature of the production process as characterized by the elasticity of substitution between non-labor inputs and the farmer's effort.

The use of contracts differs across commodities. Some commodities use primarily production contracts, some use marketing contracts and others have little use of contracts of any type.[1] With the exception of dairy production, for which contracts are mostly marketing contracts, the majority of contracts in livestock production are production contracts. A smaller share of crops are under contract, and most contracts are marketing contracts (O'Donoghue et al. 2011). The use of contracts also varies by farm size; large commercial farms are more likely to use production and/or marketing contracts and to use contracts for a larger share of their production (MacDonald and Korb 2011; MacDonald et al. 2004).

Within livestock production, the use of production contracts varies. The two sectors with the most intensive use of contracts are broiler chickens and hogs. In 2011, 97 % of broilers were produced under contract, and 94 % of these contracts used contained provisions linking compensation to grower performance (MacDonald 2014).[2] Generally, buyers, known as integrators, provide chicks, feed, veterinary services, transportation services, and technical advice to growers. Additionally, they include specific requirements regarding housing in the contracts. Requirements are not limited to initial construction; 29 % of respondents to the 2011 USDA Agricultural Resources Management Survey reported incurring capital expenditures required by their integrators in 2009–2011 (MacDonald 2014).

Over the past 25 to 30 years, the use of production contracts in hog production has increased substantially. During the same period, operations have become larger and more specialized; the number and production share of farrow-to-finish operations has declined, while the shares of operations that are farrow-to-wean, wean-to-feeder, and feeder-to-finish have increased (McBride and Key 2013). On average, in 2009, larger, more specialized operations were especially likely to use contracts (McBride and Key 2013). Hog contracts generally involve the contractor maintaining ownership of animals, providing inputs and technical advice to farmers. The farmer provides labor and facilities.

The farmer receives a fee and the contractor receives the residual returns. The farmer's return includes a payment based on the number of hogs or capacity. It may include incentive clauses regarding feed efficiency (MacDonald and McBride 2009). Key and McBride (2003) find that production contracts notably increase the productivity of US feeder-pig-to-finish hog operations. Key and McBride (2008) find that there was a substantial increase in total factor productivity in the U.S. hog industry between 1992 and 2004, due mostly to technical progress and increased scale efficiencies. This finding is consistent with contract use and contract provisions influencing productivity due to which farmers contract and the design of these contracts.

Variations in the use of contracts across commodities and regions suggest that there are many factors which influence contract choice. Here, we provide a few examples. Consider the case of a supermarket chain entering a developing country and deciding how to procure fresh produce. It may elect to use a production contract with local farmers or farmers' organizations in order to provide seed, fertilizer, and technical education because local producers cannot deliver produce of the chain's desired quality with local inputs or, perhaps due to credit constraints, cannot purchase sufficient inputs. On the other hand, a supermarket chain in a developed country may elect to use a marketing contract because its domestic producers can deliver produce of the requisite quality. Although the contracting parties and the output are the same in these cases, in one case a farmer cannot produce that output without input provision by the buyer. In this example, an off-setting consideration might be differences in contract enforcement due to differences in the strength of the legal system.

Alternative means of providing information may reduce the need for contracts. For example, public or third-party grading standards that evaluate all verifiable product characteristics of value to buyers at the time of delivery can substitute for a marketing contract that specifies these same requirements. In instances in which grading standards address all relevant characteristics, there is less of an incentive to use marketing contracts rather than the spot market.

Product perishability is another consideration. When a product is highly perishable, then a contract with a buyer ensures the farmer that he can place his output while it still has market value. Subject to the vagaries of weather, contracting also ensures the buyer that she will have a consistent stream of deliveries. This is an important consideration for retailers and for processors. Whether or not these considerations indicate that a production contract should be selected rather than a marketing contract will in turn be influenced by other factors, such as those discussed above. When a product is storable, timing and consistent deliveries are less important factors.

Clearly, no single factor motivates all contract choices. This analysis focuses on one motivation for using production contracts: the buyer can reduce the information rents obtained by high ability farmers by designing a production contract menu for farmers of different abilities that specifies or provides non-labor inputs, as well as output, for farmers of each type.

Within the literature on agricultural contracts there is a small subset of analyses which directly address the question of input control. We focus on these analyses and do not offer a comprehensive review of the literature on agricultural contracts.[3] Relatively few articles address the role of non-labor inputs in agricultural contract design in a theoretical model. Goodhue (2000) and Just et al. (2005) are the closest to the analysis presented here. Goodhue (2000) demonstrates that when there is an adverse selection problem, the buyer can reduce information rents by controlling non-labor inputs used in the restrictive case of a Cobb-Douglas production function. Unlike the analysis here, she compares the two conventional cases of complete information and "pure" asymmetric information where the buyer has zero information regarding the farmer's use of the non-labor input unless the buyer controls the input. In contrast, by introducing a continuous degree of asymmetric information we can use comparative statics to examine the properties of the buyer's profit-maximizing solution. Just et al. (2005) focus on the effect of sharing technologies when firms may choose to integrate horizontally. Unlike the non-cooperative solution concept considered here, they consider a cooperative solution. Using the Nash bargaining solution, they find that the gains from horizontal integration increase with the degree of differences in firms' production technologies and endowments.

There is a fairly small empirical literature regarding the use of input control by the buyer in agricultural contracts. Within this literature, the four articles which address questions most closely related to our analysis are Knoeber and Thurman (1995), Martin (1997), Thomsen et al. (2004), and Goodhue et al. (2003). Knoeber and Thurman (1995) examine how provisions in broiler contracts alter the per-flock risks borne by farmers and by processors (commonly known as integrators in this industry) compared to the spot market, using spot market prices and a dataset on broiler contract outcomes. They find that the majority of risk is transferred from farmers to integrators, including price risk and relative production risk. Price risk accounts for the majority of risk transferred. Martin (1997) performs a similar analysis of hog contracts. Thomsen et al. (2004) consider the effect of placement risk, defined as how often flocks are placed with growers, on grower returns. Goodhue et al. (2003) examine the determinants of the use of input control provisions in California winegrape contracts and find that these provisions are more commonly used in regions which produce higher quality winegrapes. Fraser (2005) finds similar results for contracts in the Australian wine industry.

Our analysis is also related to work regarding contracting outside of agriculture, including Maskin and Riley (1985), Khalil and Lawaree (1995), Laffont and Tirole (1986), and Lewis and Sappington (1991) although it differs from these analyses in terms of assumptions regarding input substitutability and/or the timing of critical contract decisions relative to the timing of production. Maskin and Riley (1985) and Khalil and Lawaree (1995) assume that there is no substitutability between effort and other inputs that may be exploited by the principal. Others model agent effort as a perfect substitute for other inputs (Laffont and Tirole 1986; Lewis and Sappington 1991). Khalil and Lawarree (2001) and Dewatripont and Maskin (1995) assume that the principal can choose what she monitors after the agent has made his production decisions. Dewatripont and Maskin (1995) address the principal's optimal monitoring choice when monitoring is costless and agent effort is an imperfect substitute for purchased inputs. They compare a number of monitoring possibilities: monitoring only capital, labor (purchased by the agent), or total cost savings, monitoring both inputs, or monitoring cost savings and capital. They find that monitoring total cost savings after production has occurred dominates monitoring either purchased input for the principal, and dominates monitoring both total cost savings and capital. This second result is the opposite of our finding that the buyer always increases profits with the restrictive contract in which she observes both output and the non-labor input. The difference is due to two assumptions that differ from ours: (a) the principal always has the possibility to choose to observe inputs purchased by the agent; and (b) the timing of their model, especially the possibility of renegotiation after the agent chooses capital but before production occurs. We assume that capital and effort are chosen simultaneously, and that production is realized without an opportunity for renegotiation.

Of course, the model developed here is only one possible explanation for buyers' adoption of input control provisions. There are many other reasons why buyers may choose to adopt input control provisions in agricultural contracts (Goodhue 1999; Hueth et al. 1999). Some, but not all, involve asymmetric information. Some instances of asymmetric information may arise in a buyer-farmer relationship involving multiple inputs. For example, the buyer may be less informed than the farmer regarding the precise nature of the production function. When information is asymmetric in this sense, it may be costly for the buyer to determine the input mix: she may select a combination that the farmer could improve upon. There may be a moral hazard problem if the farmer's effort is unobservable in terms of its effects on quantity or product quality and the effect is dependent on the use of other inputs (Sexton 2013). Other motivations for input provision based on the farmer's characteristics include relaxing a liquidity constraint if he is credit constrained or redistributing risk if he is risk averse. Quality considerations, including but not limited to ones involving asymmetric information, are also important. Contracts, including ones with input control provisions, can aid planning of the production process for the buyer in terms of obtaining sufficient product with the desired quality attributes to ensure consistency, as well as simply in terms of timing deliveries to manage throughput, even in the absence of asymmetric information (Jang and Olson 2010; Wilson and Dahl 1999; Worley and McCluskey 2000).

Under an agricultural contract, the change in which party controls key inputs and/or other production decisions alters the distribution of risks and returns to the farmer and buyer relative to those associated with the spot market. We focus on the change in the distribution of returns and total surplus due to differences in who controls non-labor inputs. In order to do so, we introduce a theoretical construction which continuously varies the degree of asymmetric information in the buyer's maximization problem.

Our approach is similar in some technical respects to the use of marginal analysis of the share of informed farmers as a measure of the asymmetric information facing market makers in the market microstructure literature examining bid-ask spreads, e.g. Copeland and Galai (1983), Glosten and Milgrom (1985), and Kyle (1985). However, our approach differs from Khalil and Lawarree (2001) and these studies conceptually due to our different context and research question; because we are interested in the total cost of a specific degree of asymmetric information, not just its marginal cost, we integrate the results of our marginal analysis over specified intervals in order to analyze the total impacts of a given degree of asymmetric information.

Using this approach, we show that the buyer can reduce information rents by controlling the non-labor input. Furthermore, the buyer's optimal contract menu always results in higher profits under the restrictive contract than the basic contract, even though she always chooses an input mix which is sub-optimal from a pure production standpoint. Additionally, output is less distorted relative to the first-best level under the restrictive contract than under the basic contract, which also increases her profits.

The net effect of these differences between the contract types for society as a whole is less clear. We establish that if the elasticity of substitution between effort and the other input is sufficiently small, the restrictive contract will result in higher total surplus than the basic contract. If the elasticity of substitution is large, the welfare comparison depends on the relative importance of the output and the input mix distortions. These findings contribute to the property rights literature regarding how the boundaries and the allocation of decision rights affect the ex post-efficiency of production (Coase 1937; Tirole 1999; Williamson 1985). The analysis has a specific implication in our context; because there is limited substitutability between labor and inputs such as seed animals, or facilities in agricultural production, it is most likely the case that higher total surplus results when buyers, rather than farmers, control non-labor inputs in agricultural contracts.

These findings provide a strong motivation for the buyer to increase the degree of integration; that is, one must look outside our framework to justify a decision by the buyer to allow the farmer to make input allocation decisions rather than controlling them herself. Moreover, the model provides one explanation of why buyers are choosing to source an increasing share of their purchases through integrated production and contracts specifying non-labor inputs: by doing so, buyers can reduce the information rents that they need to pay. Conversely, it suggests a reason for the widespread opposition by farmers to increased coordination (Vavra 2009): highly productive farmers do not want the information rents they can command to be reduced by greater buyer control over production.

Methods

We begin with a standard principal-agent model. The farmer, who is the agent, may be one of two types; each type has access to a distinct production function, and one type's function is more productive than the other. Both the buyer (principal) and farmer are perfectly informed about the specification of these functions and the probability distribution over types. The farmer's realized type, however, is unknown to the buyer. The buyer's goal is to maximize her profits from production, which depend on the farmer's production possibilities. To induce the farmer to reveal his true type, she must offer him a menu of two contracts, one designed for each type, that provides him with adequate incentives to do so. We assume that the buyer cannot observe the level of effort supplied by the farmer. We compare two cases: one in which capital is non-observable and non-verifiable and one in which it is observable and verifiable. For expository convenience, we refer to non-observable capital as capital supplied by the farmer and observable capital as capital supplied by the buyer. We assume that capital is homogeneous, so that only the level of capital and the production set available to the farmer who uses it are relevant to production.

The production function: Production depends on capital (k), effort (e), and the farmer's type (θ). There are two types, "low" and "high," denoted by ℓ and h. The farmer's true type is $\theta \in \{\theta^\ell, \theta^h\}$. Let $\Theta = \frac{\theta^\ell}{\theta^h} < 1$, reflecting the fact that ℓ is less efficient than h. For $i = \ell, h$, let ϕ^i denote the probability that a farmer's type is i. (Obviously, $\phi^\ell + \phi^h = 1$).

We impose the following additional assumptions on the production function, $f(e, k; \theta)$.

A1: There exists a twice continuously differentiable function, $g : \mathbb{R}^2 \rightarrow \mathbb{R}$, such that for $\theta \in \{\theta^\ell, \theta^h\}, f(\cdot, \cdot, \theta) = \theta g$;

A2: The function g is homogeneous of degree $\alpha < 1$ in e and k;

A3: The marginal products of effort and capital, g_e and g_k, are positive, and g is strictly concave in (e, k), (i.e., $g_{ee}, g_{kk} < 0$ and $g_{ee}, g_{kk} > (g_{ek})^2$).

For $i = \{\ell, h\}$, we shall usually write f^i rather than $f(\cdot, \cdot, \theta^i)$. For convenience, we will normalize by setting $\theta^\ell = 1$, so that $f^\ell \equiv g$. Assumption A1 implies that θ is "technologically neutral," in the sense that for each e and k, $\frac{f_e^\ell(e,k)}{f_k^\ell(e,k)} = \frac{f_e^h(e,k)}{f_k^h(e,k)}$.[4]

Farmer's decision: The farmer receives a lump-sum transfer payment from the buyer and in return delivers a specified level of output, contributing effort and, in one of our two cases, capital. The farmer's outside alternative is to provide his effort at the given wage rate $w > 0$ per unit effort supplied. The wage rate exactly compensates for the farmer's constant marginal disutility of effort, so that his reservation utility when he does not supply effort is zero. The price of capital is constant at $r > 0$ per unit. In order to induce the farmer to supply effort level e and capital level k, the buyer's transfer payment must at least cover the farmer's cost, $we + rk$.

Input levels: If a farmer of type θ chooses input levels to produce a given q—i.e., if the buyer cannot observe and verify capital levels—he will solve the (neo-classical) cost minimization problem $\min_{e,k} \; we + rk$ s.t. $f(e, k, \theta) = q$. Let $\left(\tilde{e}(q,\theta), \tilde{k}(q,\theta)\right)$ denote the solution to this problem.

We will refer to this input vector as the *neoclassical input mix for q*. The solution to the farmer's problem exhibits the following, well-known properties:

Remark 1 *The neoclassical input mix is uniquely defined by the first-order condition:*

$$0 = wf_k\left(\tilde{e}(q,\theta), \tilde{k}(q,\theta), \theta\right) - rf_e\left(\tilde{e}(q,\theta), \tilde{k}(q,\theta), \theta\right). \tag{1}$$

Moreover, there exists a constant $\tilde{\beta}$ *such that for all* q, $\frac{\tilde{k}(\cdot,\theta^\ell)}{\tilde{e}(\cdot,\theta^\ell)} = \tilde{\beta}$. *Finally, for all* q, $\left(\tilde{e}(q,\theta^\ell), \tilde{k}(q,\theta^\ell)\right) = \Theta^{1/\alpha}\left(\tilde{e}(q,\theta^h), \tilde{k}(q,\theta^h)\right)$.

Uniqueness follows from the strict concavity of g (A3). Linearity of farmer ℓ's expansion path follows from homogeneity (A2) and the fact that r and w are constants. The proportionality relationship between different types' input vectors follows from A1 and A2.

Let $\tilde{C}^P(q,\theta)$ denote type θ's *production cost* of delivering output q with the neoclassical input mix:

$$\tilde{C}^P(q,\theta) = w\tilde{e}(q,\theta) + r\tilde{k}(q,\theta). \tag{2}$$

An immediate consequence of Remark 1 is that when the farmer chooses inputs, there is an equivalent, *single-input* characterization of technology, $\ddot{f}(\ddot{e},\theta) = \ddot{e}^\alpha f(1,\tilde{\beta},\theta)$, and of production costs, $\ddot{C}^P(q,\theta) = \ddot{v}\ddot{e}(q,\theta)$, where each unit of the *composite* input $\ddot{e}$ is composed of one unit of e and $\tilde{\beta}$ units of k, and $\ddot{v} = (v + \tilde{\beta}r)$ denotes the unit cost of $\ddot{e}$. Provided that the input mix is always neo-classical, this alternative characterization is equivalent to the original one in the following sense:

Remark 2 *For each* q *and* θ, $\ddot{f}(\ddot{e}(q,\theta),\theta) = f\left(\tilde{e}(q,\theta), \tilde{k}(q,\theta), \theta\right)$ *and* $\ddot{C}^P(q,\theta) = \tilde{C}^P(q,\theta)$.[5]

The significance of Remark 2 is that when the farmer chooses inputs, the buyer's problem in our two-input model is formally equivalent to the corresponding, and routine, textbook problem, in which technology is given by the single-input production function $\ddot{f}$ with constant unit cost $\ddot{v}$.

Now assume instead that the buyer chooses the level of capital, let $\bar{e}$ denote the level of effort required to produce q given k and θ, and let $\bar{C}^P(q,k,\theta)$ denote θ's production cost of delivering q using k:

$$\bar{C}^P(q,k,\theta) \quad = \quad w\bar{e}(q,k,\theta) \quad + \quad rk. \tag{3}$$

The cost to farmer-type ℓ of producing any level of output is strictly larger than the cost to type h.

Contracts: A *basic contract* is one in which the farmer chooses both inputs. A menu of basic contracts assigns to each announced type θ^i, $i \in \{\ell, h\}$, an output level and transfer, $\left(\tilde{q}(\theta^i), \tilde{t}(\theta^i)\right)$. We will sometimes write the contract menu $\left\{\left(\tilde{q}(\theta^i), \tilde{t}(\theta^i)\right)\right\}_{i=\ell,h}$ as $(\tilde{\mathbf{q}}, \tilde{\mathbf{t}}) = \left((\tilde{q}^\ell, \tilde{t}^\ell), (\tilde{q}^h, \tilde{t}^h)\right)$. A *restrictive contract* is one in which the buyer specifies capital and the farmer chooses labor. A menu of restrictive contracts assigns to each θ^i an output level, capital level, and transfer. We will similarly sometimes write $\left\{\left(\bar{q}(\theta^i), \bar{k}(\theta^i), \bar{t}(\theta^i)\right)\right\}_{i=\ell,h}$ as $(\bar{\mathbf{q}}, \bar{\mathbf{k}}, \bar{\mathbf{t}}) = \left((\bar{q}^\ell, \bar{k}^\ell, \bar{t}^\ell), (\bar{q}^h, \bar{k}^h, \bar{t}^h)\right)$. Invoking the revelation principle (Myerson 1979), we restrict our analysis to truth-telling contracts in which each farmer chooses to announce his true type by selecting the contract for his type from the menu of two contracts offered by the buyer.

Timing and information: Regardless of contract type, the timing of the game is as follows: The buyer offers a contract menu to the farmer on a take-it-or-leave-it basis. At the time the contract menu is offered, the farmer's type is his private information. The probability of each type occurring is common knowledge. We assume that if the farmer is indifferent between accepting and not accepting a contract then he will accept the contract. Similarly, we assume if he is indifferent between the two contracts, he will choose the contract intended for his true type. Production and transfers are then implemented according to contract specifications. The buyer then sells her output on a competitive market.

Symmetric information benchmark: We assume throughout that output is sold on a perfectly competitive market at a price of p. For $\theta \in \{\theta^\ell, \theta^h\}$, let $q^\star(\theta)$ denote the level of output satisfying $\frac{d\tilde{C}^P(q^\star(\theta),\theta)}{dq} = p$. Also, let $(e^\star(\theta), k^\star(\theta)) = (\tilde{e}(q^\star(\theta),\theta), \tilde{k}(q^\star(\theta),\theta))$ denote the neoclassical input mix for $q^\star(\theta)$. If the buyer *were* able to observe the farmer's type, the solution to the buyer's profit maximization problem would be to specify the output pair $q^\star(\cdot)$, whether or not she chose capital levels. Regardless of who chose the level of capital, the farmer of type θ would then produce $q^\star(\theta)$ with inputs $(e^\star(\theta), k^\star(\theta))$. We shall refer to $(q^\star, e^\star, k^\star)$ as the *symmetric information benchmark solution*. Assumptions A1–A3 ensure that in the benchmark solution both types produce a positive quantity.

Results and discussion

We first evaluate the effect of production contracts on information rents, the buyer's profits, and the total surplus obtained by the farmer and the buyer by comparing the profit-maximizing basic and restrictive contract menus under the standard treatment of asymmetric information. Then, in order to better understand the role of information in driving differences in outcomes under the two contracts, we conduct a marginal analysis by continuously varying the degree of asymmetric information between symmetric information and the standard model. The marginal analysis identifies the factors which influence profits and total surplus as the degree of information asymmetry increases. In the context of production contracts, it identifies the value to the buyer of reducing asymmetric information by imposing additional constraints on production decisions.

Buyer's profit-maximizing basic and restrictive contracts

This subsection develops the buyer's profit-maximizing basic and restrictive contracts and then compares output, information rents, production costs, and profits under the two contracts.

Buyer's profit-maximizing basic contract

Given a menu of basic contracts $(\tilde{\mathbf{q}}, \tilde{\mathbf{t}})$, the buyer's profit when the farmer declares a type of $\hat{\theta}$ is $p\tilde{q}(\hat{\theta}) - \tilde{t}(\hat{\theta})$. Thus, the buyer's problem is to choose the contract menu $(\tilde{\mathbf{q}}, \tilde{\mathbf{t}})$ that maximizes $\sum_{i\in\{\ell,h\}} \left\{\phi^i \left(p\tilde{q}(\theta^i) - \tilde{t}(\theta^i)\right)\right\}$ subject to incentive and participation constraints. Because the principal's problem when there is a basic contract is the same as one with a single composite input, we can characterize the optimal basic contract menu by drawing on standard results from the mechanism design literature in which production is a function of the farmer's effort: the constraints that are binding on the buyer are type h's incentive compatibility constraint and type ℓ's individual rationality constraint. Consequently, h and ℓ produce, respectively, at and below the symmetric information benchmark solution levels for their types. Moreover, the difference between the transfer offered to ℓ and ℓ's production cost of delivering the designated output level will just equal ℓ's reservation utility, which in our model is zero. On the other hand, the transfer offered to h includes a premium, referred to as his *information rent*, which in the optimal contract will just offset the increment in utility that h would derive by adopting ℓ's contract rather than the one intended for him. Remark 3 summarizes the textbook treatment of this class of contract (see, e.g., Varian 1992, pp. 457–463).

Remark 3 *The optimal basic contract menu has the following properties:*

1. *farmer ℓ produces less than he does in the symmetric information benchmark, $\tilde{q}^\ell < q^\star(\theta^\ell)$, and receives a transfer equal to his production costs:*

$$\tilde{t}^\ell = \tilde{C}^P_\ell(\tilde{q}^\ell). \tag{4a}$$

2. *farmer h produces the same quantity as in the symmetric information benchmark, $\tilde{q}^h = q^\star(\theta^h)$, and receives a transfer greater than his production costs:*

$$\tilde{t}^h = \tilde{C}^P_h(\tilde{q}^h) + \left(\tilde{C}^P_\ell(\tilde{q}^\ell) - \tilde{C}^P_h(\tilde{q}^\ell)\right). \tag{4b}$$

h's transfer compensates him for his own production costs (the first term) plus pays him the difference between the transfer he would obtain for producing $\tilde{q}^\ell$ and his cost of producing it (the difference between the second and third terms).

In what follows, we sometimes use the terminology *production costs* and *information costs* to distinguish between costs incurred through production and costs paid to ensure truthful revelation by the buyer.[6] The terms "marginal production" and "marginal information" costs will then have the obvious interpretation.

Profit-maximizing restrictive contract

Given a restrictive contract menu $(\bar{\mathbf{q}}, \bar{\mathbf{k}}, \bar{\mathbf{t}})$, the buyer's profit from a farmer declaring a type of $\hat{\theta}$ is $p\bar{q}(\hat{\theta})-\bar{t}(\hat{\theta})$. Thus, her problem is to choose the contract menu $(\bar{\mathbf{q}}, \bar{\mathbf{k}}, \bar{\mathbf{t}})$ that maximizes $\sum_{i\in\{\ell,h\}}\left\{\phi^i\left(p\bar{q}(\theta^i)-\bar{t}(\theta^i)\right)\right\}$ subject to incentive and participation constraints.

Under a restrictive contract, the input mix is no longer exogenous to the buyer's decision. Consequently, the textbook single-input model can no longer be used to characterize the optimal restrictive contract menu. Instead, Lemma 1 below establishes that the principal's constrained profit maximization problem is equivalent to an unconstrained profit maximization problem which substitutes into the principal's expression for profits the two binding contraints: the low ability farmer's reservation utility constraint and the high ability farmer's incentive compatibility constraint.

Lemma 1 *The problem of choosing the optimal restrictive contract menu is equivalent to the following problem:*

$$\max_{(\bar{\mathbf{q}},\bar{\mathbf{k}})} \sum_{i\in\{\ell,h\}} \left\{\phi^i\left(p\bar{q}(\theta^i) - \bar{t}(\theta^i)\right)\right\} \tag{5}$$

$$\textit{where}\quad \bar{t}^h = \bar{C}^P_h(\bar{q}^h,\bar{k}^h) + \left(\bar{C}^P_\ell(\bar{q}^\ell,\bar{k}^\ell) - \bar{C}^P_h(\bar{q}^\ell,\bar{k}^\ell)\right)$$

$$\bar{t}^\ell = \bar{C}^P_\ell(\bar{q}^\ell,\bar{k}^\ell).$$

That is, any solution to (5) *is a solution to the buyer's restrictive problem and vice versa.*

The proofs, and all subsequent ones, are deferred until the "Appendix". Equipped with Lemma 1, we establish that the restrictive contract problem shares many of the properties of the single-input problem. Formally,

Proposition 1 *The optimal restrictive contract menu has the following properties:*

1. *farmer ℓ produces less than he does in the symmetric information benchmark, $\bar{q}^\ell < q^\star(\theta^\ell)$, with capital level $\bar{k}^\ell$ and receives a transfer equal to his production costs:*

$$\bar{t}^\ell = \bar{C}^P_\ell\left(\bar{q}^\ell,\bar{k}^\ell\right); \tag{6a}$$

2. *farmer h produces the same quantity as in the symmetric information benchmark, $\bar{q}^h = q^\star(\theta^h)$, using the neo-classical input vector $\left(e^\star(\theta^h), k^\star(\theta^h)\right)$, and receives a transfer greater than his production costs:*

$$\bar{t}^h = \bar{C}^P_h\left(\bar{q}^h\right) + \left(\bar{C}^P_\ell\left(\bar{q}^\ell,\bar{k}^\ell\right) - \bar{C}^P_h\left(\bar{q}^\ell,\bar{k}^\ell\right)\right). \tag{6b}$$

   h's transfer compensates him for his own production costs (the first term) plus pays him the difference between the transfer he would obtain for producing $\bar{q}^\ell$ and his cost of producing it (the difference between the second and third terms).

3. *farmer ℓ's capital-effort ratio exceeds the neo-classical ratio $\tilde{\beta}$.*

Let $\bar{C}^I(q,k) = \bar{C}^P_\ell(q,k) - \bar{C}^P_h(q,k)$ denote the information cost of contracting with type ℓ to produce q with capital level k under a restrictive contract. It follows from Lemma 1 that the task of choosing the optimal restrictive contract menu can be reformulated as the following (unconstrained) maximization problem:

$$\max_{(\bar{\mathbf{q}},\bar{\mathbf{k}})} \sum_{i\in\{\ell,h\}} \phi^i \left(p\bar{q}(\theta^i) - \bar{C}^P(\bar{q}(\theta^i),\bar{k}(\theta^i),\theta^i)\right) \quad + \quad \phi^h \bar{C}^I(\bar{q}(\theta^\ell),\bar{k}(\theta^\ell)). \tag{7a}$$

Similarly, from Proposition 3, the task of choosing the optimal basic contract can be reformulated as

$$\max_{\tilde{\mathbf{q}}} \sum_{i\in\{\ell,h\}} \phi^i \left(p\tilde{q}\left(\theta^i\right) - \tilde{C}^P\left(\tilde{q}\left(\theta^i\right),\theta^i\right)\right) \quad + \quad \phi^h \tilde{C}^I\left(\tilde{q}\left(\theta^\ell\right)\right) \tag{7b}$$

where $\tilde{C}^I(q) = \tilde{C}^P_\ell(q) - \tilde{C}^P_h(q)$ denotes the information cost of contracting with type ℓ to produce q under a basic contract.

Because information costs are independent of type h's contractual variables, the presence of information asymmetry has no impact on h's choice of inputs or output, and hence cost of production, under either type of contract. Hence, all these values coincide with their symmetric information benchmark values. For this reason, we shall ignore this aspect of the buyer's problem for the remainder of the paper and focus our attention on the contract targeted for type ℓ. Because information costs depend on the difference in productivity between the two types, h will continue to be in the discussion.

To streamline notation,[7] we divide by ϕ^ℓ and write ϕ^h/ϕ^ℓ as Φ .

$$\textbf{Basic:} \qquad \max_{\tilde{q}} \left(p\tilde{q} - \tilde{C}^P\left(\tilde{q},\theta^\ell\right)\right) \quad - \quad \Phi\,\tilde{C}^I(\tilde{q}). \tag{7c}$$

$$\textbf{Restrictive:} \qquad \max_{(\bar{q},\bar{k})} \left(p\bar{q} - \bar{C}^P\left(\bar{q},\bar{k},\theta^\ell\right)\right) \quad - \quad \Phi\,\bar{C}^I(\bar{q}). \tag{7d}$$

Given q, let $\tilde{C}^I(q) = \tilde{C}^P_\ell(q) - \tilde{C}^P_h(q)$ denote the information cost of having q produced under a basic contract, when both types use the neo-classical input mix. For given k, let $\bar{C}^I(q,k) = \bar{C}^P_\ell(q,k) - \bar{C}^P_h(q,k)$ denote the information cost of having q produced under a restrictive contract requiring the use of the capital level k. The results which follow are consequences of the following inequality:[8]

$$\text{for all positive } q, \text{and all } k \ge \tilde{k}\left(q,\theta^\ell\right), \quad \tilde{C}^I(q) > \bar{C}^I(q,k). \tag{8}$$

That is, the information cost associated with the profit-maximizing basic contract is always greater than the information cost associated with the profit-maximizing restrictive contract (which requires type ℓ to utilize a super-optimal level of capital).

Figure 1 illustrates (8) by comparing a basic contract in which the farmer is required to produce an arbitrary output level q against a restrictive contract in which the farmer is required to produce q using the neo-classical input mix for his type. The purpose of the figure is to show that the latter contract will be more profitable than the former. It is not, however, the *most* profitable way for the buyer to obtain q: from part 3 of Proposition 1, the buyer can do even better than the illustrated restrictive contract if she requires ℓ to choose a super-optimal capital-labor mix.

The two isoquants in each panel of the figure, labeled $\mathrm{IQ}_\ell(q)$ and $\mathrm{IQ}_h(q)$, indicate the input combinations with which ℓ and h can produce q. The parallel lines represent iso-cost curves. The brace in the left panel indicates the cost differential when farmer type i

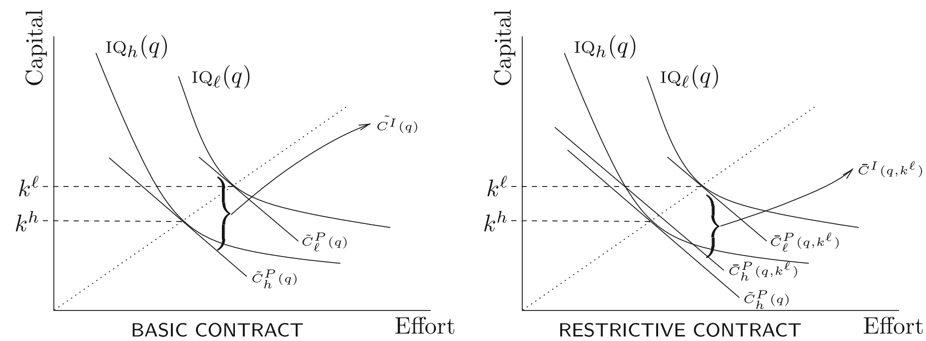

Fig. 1 Information cost of producing q under a basic contract vs. a restrictive contract

produces q using the neo-classical input mix for his type (including k^i). The brace in the right panel indicates the reduced cost differential when the contract designed for type ℓ specifically requires that q must be produced using the capital level k^ℓ that is optimal for type ℓ; because of this restriction, if type h chose the contract for type ℓ, he would be obliged to use an excessive amount of capital. (A sufficient condition for the cost differential to be smaller in the right panel than the left is that effort and capital are not perfectly substitutable.) The braces in the two panel also represent the respective information rents that the buyer must pay farmer h to produce q, under either a basic and restrictive contract: the input-mix penalty built into the restrictive contract lowers the incentive for h to "cheat" and pretend to be ℓ and hence also the incentive payment required to induce truthful revelation.

Figure 1 also demonstrates how the buyer can construct a restrictive contract which exactly mimics any basic contract, except for the added restriction on the input mix that h must use if she deviates from truthful behavior. The buyer's revenues are the same under both contracts because outputs are the same. Production costs are also the same because, provided the farmer of type i chooses the contract designed for type i, the input mix he selects will be identical under the two contracts. But information rents are lower under the restrictive contract, and so profits associated with q are higher. Since q and k were chosen arbitrarily, this argument applies in particular to $\tilde{q}(\theta^\ell)$, the output assigned to ℓ in the optimal basic contract. It follows that profits under this contract must be strictly less than profits he obtains by "mimicking" ℓ and choosing ℓ's restrictive contract described above, and hence lower by an even greater margin than profits under the *optimal* restrictive contract. The preceding remarks are summarized in Proposition 2.

Proposition 2 *The buyer's profits under the optimal restrictive contract strictly exceed her profits under the optimal basic contract.*

Marginal analysis of the basic and restrictive contracts

We use marginal analysis to study the relationship between the two kinds of contracts. Specifically, we vary continuously the amount of uncertainty faced by buyers in a situation of asymmetric information, starting with symmetric information and ending with the incomplete information model described in the "Methods" section. Let $\Phi = \phi^h/\phi^\ell$ denote the ratio of the probabilities that the farmer is of either type. We will now, for each $\gamma \in [0, \Phi]$, solve for the optimal basic and restrictive contracts, when Φ in each problem is replaced with γ. When $\gamma = 0$, the asymmetric information component of the buyer's problem is eliminated, since the farmer is known to be of type ℓ. Now, we can use calculus techniques to examine the impact of a small "increase in buyer uncertainty," $d\gamma$. For each agent type, the symmetric information benchmark solution (p. 8) is independent of the type-probability ratio γ; consequently, the rates at which, *conditional on each type*, output, the buyer's profits, etc. decline as γ increases are pure measures of the *marginal* impacts of buyer uncertainty. We then integrate these marginal impacts over the interval $[0, \Phi]$ to recover and compare the *total* impacts of buyer uncertainty on the solutions to the buyer's original problems (7c) and (7d).

Marginal analysis of the restrictive contract

We begin by determining the minimum cost to the buyer of having type ℓ produce at least q under a restrictive contract for a given γ, while ensuring that type h does not have an incentive to pretend to be type ℓ. This cost minimization problem requires picking the nonnegative vector $(\mathbf{e}, k)$, $\mathbf{e} = \left(e^\ell, e^h\right)$, which minimizes the *production cost* $(we^\ell + rk)$ plus the *expected information cost* $\gamma w\left(e^\ell - e^h\right)$ of producing q under the restrictive contract, subject to the constraints that (a) farmer ℓ produces q using $\left(k, e^\ell\right)$ and (b) if farmer h selects the contract designed for ℓ, he produces q using $\left(k, e^h\right)$. Summarizing, the principal's problem is

$$\min_{(\mathbf{e},k)} \underbrace{\left\{w\left((1+\gamma)e^\ell - \gamma e^h\right) + rk\right\}}_{\text{Term A}} \text{ s.t. } f^\ell(e^\ell, k) = q, f^h(e^h, k) = q \text{ and } (\mathbf{e}, k) \geq 0. \quad (9)$$

As a consequence of a restriction, we shall later impose (see (15) below), the solution values $(\mathbf{e}, k)$ for (9) are necessarily positive. Because of this, we will omit the nonnegativity constraints from our specification of the Lagrangian, which is

$$\bar{L}(\mathbf{e}, k, \boldsymbol{\lambda}; q, \gamma) = w\left((1+\gamma)e^\ell - \gamma e^h\right) + rk + \lambda^\ell(q - f^\ell(e^\ell, k)) + \lambda^h(f^h(e^h, k) - q)). \quad (10)$$

where $\boldsymbol{\lambda} = (\lambda^\ell, \lambda^h)$ is the vector of multipliers for the restricted problem. Let $\left(\bar{\bar{e}}(q,\gamma), , \bar{k}q,\gamma), \bar{\boldsymbol{\lambda}}q,\gamma)\right)$ denote the solution to (9). Inserting these values into Term A of (9), we obtain the *restrictive cost function*, $\bar{C}(q,\gamma) = \bar{C}^P(q,\gamma) + \bar{C}^i(q,\gamma)$, where $\bar{C}^P(q,\gamma) = (w\bar{e}^\ell(q,\gamma) + r\bar{k}(q,\gamma))$ is the production cost, and $\bar{C}^i(q,\gamma) = \gamma w(\bar{e}^\ell(q,\gamma) - \bar{e}^h(q,\gamma))$ is the information cost of producing q under the restrictive contract.

The first-order condition for $\bar{L}$ has five equations in five unknowns:

$$\triangledown\bar{L} = \begin{bmatrix} \bar{L}_{e^\ell} \\ \bar{L}_{e^h} \\ \bar{L}_k \\ \bar{L}_{\bar{\lambda}^\ell} \\ \bar{L}_{\bar{\lambda}^h} \end{bmatrix} = \begin{bmatrix} (1+\gamma)w - \bar{\lambda}^\ell f_{e^\ell} \\ -\gamma w + \bar{\lambda}^h f_{e^h} \\ r - \bar{\lambda}^\ell f_k^\ell + \bar{\lambda}^h f_k^h \\ q - f^\ell(e^\ell, k) \\ f^h(e^h, k) - q \end{bmatrix} = 0. \quad (11)$$

At the solution to (11), $\left(\bar{\mathbf{e}}(q,\gamma), \bar{k}(q,\gamma), \bar{\boldsymbol{\lambda}}(q,\gamma)\right)$, the constraints are identically zero so that the *restrictive cost function* $\bar{C}(q,\gamma)$—defined as the minimum attainable value of total cost under the restrictive contract for each (q, γ) pair—is identically equal to the minimized value of $\bar{L}$, henceforth denoted by $\bar{L}(\cdot\,; q, \gamma)$.

Note that because $\bar{L}_{e^\ell}$, $\bar{L}_{e^h}$, and $\bar{L}_k$ are all zero, we have

$$\bar{\lambda}^\ell = \frac{(1+\gamma)w}{f_e^\ell} > \bar{\lambda}^h = \frac{\gamma w}{f_e^h}. \tag{12}$$

Substituting the expressions for the λ's (Eq. (12)) into the expression for $\bar{L}_k$ (eq. (11)) yields:

$$\frac{r}{w} = \frac{\bar{f}_k^\ell}{\bar{f}_e^\ell} + \gamma \left(\frac{\bar{f}_k^\ell}{\bar{f}_e^\ell} - \frac{\bar{f}_k^h}{\bar{f}_e^h} \right). \tag{13}$$

Because h is more efficient than ℓ and both use the same level of capital to produce q, h's effort level under the restrictive contract must be less than ℓ's. That is, $\frac{\bar{k}}{\bar{e}^\ell} > \frac{\bar{k}}{\bar{e}^h}$ which in turn implies $\frac{\bar{f}_k^\ell}{\bar{f}_e^\ell} > \frac{\bar{f}_k^h}{\bar{f}_e^h}$. Hence, the term in parentheses in (13) is positive, implying $\frac{\bar{f}_k^\ell}{\bar{f}_e^\ell} < \frac{r}{w}$. Proposition 3 follows immediately.

Proposition 3 *In a restrictive contract for a given $(q, \gamma) \gg 0$, the prescribed capital-effort ratio for the low ability farmer is greater than the neoclassical ratio $\tilde{\beta}$.*

(For a vector $\mathbf{x} \in \mathbb{R}^n$, we write $\mathbf{x} \gg 0$ if $x_i > 0$, for $i = 1, ...n$). Note that Proposition 3 is more general than, and hence implies, property 3 of Proposition 1. Figure 2 provides intuition for Proposition 3. Its top panel reproduces Fig. 1 above. Consider the effect on the buyer's problem of increasing γ from zero, for the moment holding the output level constant at an arbitrary output level q. When $\gamma = 0$, the type ℓ farmer is required to use the neo-classical input mix. By the envelope theorem, a small increase in capital intensity above the neoclassical level has only a second-order impact on the production costs of farmer ℓ (see the bottom panel of Fig. 2). On the other hand, because the neo-classical k level for farmer ℓ is super-optimal for farmer h, the given increase in capital intensity would result in a *first*-order increase in farmer h's production cost if he chose the contract designed for ℓ. Thus, a small increase in capital intensity beyond the neoclassical level for ℓ results in a first-order reduction in information costs, and a second-order increase in production costs. It follows that whenever $\gamma > 0$, the prescribed level of capital for farmer ℓ will exceed the neoclassical level for her prescribed level of output.[9]

The *restrictive marginal cost function*, denoted by $\overline{MC}$, is identically equal to $\frac{d\bar{L}(\cdot\,;q,\gamma)}{dq}$ which, by the envelope theorem, equals $\frac{\partial \bar{L}(\cdot\,;q,\gamma)}{\partial q}$. This partial derivative in turn equals the difference between the two Lagrangians, $\bar{\lambda}^\ell$ and $\bar{\lambda}^h$, so that $\overline{MC}(q, \gamma) = \bar{\lambda}^\ell(q, \gamma) - \bar{\lambda}^h(q, \gamma)$. Moreover, at the buyer's optimum, $\overline{MC}(\bar{q}(\gamma), \gamma) = p$, where $\bar{q}(\gamma)$ is the profit maximizing level of output produced by the farmer of type ℓ at price p under the restrictive contract.

Our strategy for studying the properties of the restrictive contract is to apply the implicit function theorem to the first-order conditions (11), along the path $\{(\bar{q}(\gamma), \gamma) : \gamma \in [0, \Phi]\}$. This requires, of course, that the determinant of the Hessian of $\bar{L}(\cdot\,; \bar{q}(\gamma), \gamma)$, denoted $\Delta^{\overline{HL}}(\gamma)$, is non-zero along this path. It is easy to verify that $\Delta^{\overline{HL}}(0)$ is positive. By continuity, the previous requirement is then equivalent to requiring that $\Delta^{\overline{HL}}(\cdot)$ is positive on $[0, \Phi]$.

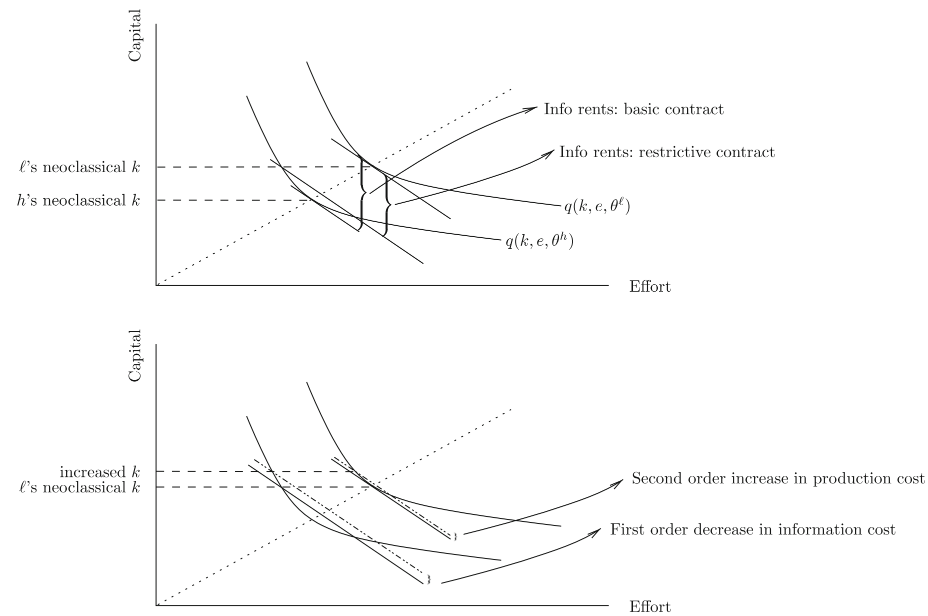

Fig. 2 Effects on production and information cost of increasing capital: basic vs. restrictive contract

Consider the case in which the production function g is CES in addition to satisfying A1–A3. In this case, the expression for the determinant reduces to

$$\Delta^{\overline{HL}}(\gamma) = -\tau \times \left\{ \frac{\gamma}{f_e^h(e^h,k)} \frac{e^\ell f_e^\ell(e^\ell,k)}{k f_k^\ell(e^\ell,k)} - \frac{1+\gamma}{f_e^\ell(e^\ell,k)} \frac{e^h f_e^h(e^h,k)}{k f_k^h(e^h,k)} \right\}. \tag{14}$$

where $\tau > 0$ depends only on parameters of the model. Clearly, expression (14) will be positive in a neighborhood of $\gamma = 0$. For large γ, however, positivity is difficult to guarantee when inputs are close substitutes and h is much more efficient than ℓ. Figure 3 illustrates the problem. When isoquants have minimal curvature, the difference between $f_e^\ell(e^\ell, k)$ and $f_e^h(e^h, k)$ depends on the efficiency gap, but only minimally on the input ratio, while the ratios $\frac{e^\ell f_e^\ell(e^\ell,k)}{k f_k^\ell(e^\ell,k)}$ and $\frac{e^h f_e^h(e^h,k)}{k f_k^h(e^h,k)}$ are very similar. Given all other parameters, therefore, we can construct an example in which e^h is arbitrarily close to zero (as in Fig. 3), ensuring that (14) will be positive except when γ is very small. Lemma 2 establishes that this problem does not arise when the elasticity of substitution between effort and labor is bounded above by unity. [10]

Lemma 2 *If g is CES in effort and capital, with constant elasticity of substitution parameter $\bar{\sigma}_{ke} \leq 1$, then $\Delta^{\overline{HL}}(\cdot)$ will be positive on* $[0, \Phi]$.

Because the sufficient condition in Lemma 2 is far from necessary for the property we need, we will hold the condition in reserve for the moment and, in Propositions 4 and 6 below, simply *assume* that $\Delta^{\overline{HL}}(\cdot) > 0$. A convenient implication of this assumption—which we invoked when we specified the Lagragian (10)—is

$$\text{For all } \gamma > 0, \text{if } \Delta^{\overline{HL}}(\gamma) \text{is positive then}$$
$$e^h(\bar{q}(\gamma), \gamma) \text{ and hence } e^\ell(\bar{q}(\gamma), \gamma) \text{ and } \bar{q}(\gamma) \text{ are also positive.} \tag{15}$$

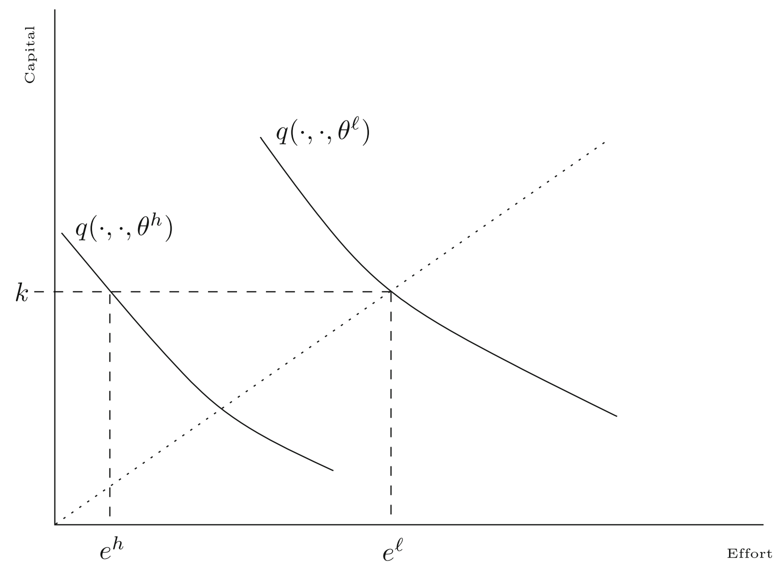

Fig. 3 Signing $\Delta^{\overline{HL}}(\cdot)$

To see this, note that if $e^h(\bar{q}(\gamma),\gamma)$=0, the first term in (14) would be positive and the second term zero.

Proposition 4 *A sufficient condition for the restrictive marginal cost function* $\overline{MC}(\cdot,\gamma)$ *to be increasing in q, and for* $\bar{q}(\cdot)$ *to be a continuously differentiable function of* γ*, for all* $\gamma \in [0,\Phi]$*, is that the determinant of the Hessian of the Lagrangian* (10) *is positive on* $[0,\Phi]$*. Moreover,*

$$\bar{q}'(\cdot) = \frac{w\left(\bar{e}^\ell - \bar{e}^h\right)}{(\alpha-1)(\bar{\lambda}^\ell - \bar{\lambda}^h)} < 0. \tag{16}$$

It is straightforward to verify, from (12) and (29), that if the ratio, γ, of high types to low types is sufficiently small, the determinant of the Hessian of the Lagrangian will indeed be positive.

Marginal analysis of the basic contract

In order to compare outcomes under the two contracts, we must obtain an expression for $\frac{d\tilde{q}(\gamma)}{d\gamma}$. Remark 2, established that it is sufficient to analyze the equivalent single-input formulation of the buyer's problem under the basic contract.

Let $\ddot{g}$ denote the single-input production function corresponding to f^ℓ. Let $\ddot{e}^i(q)$ denote the level of composite input required for type i to produce q.[11] From Remark 1, $\ddot{e}^h(\cdot) = \Theta^{1/\alpha}\ddot{e}^\ell(\cdot)$ (recall from page 7 that $\Theta = \frac{\theta^\ell}{\theta^h}$), so that the information cost of producing q under a basic contract is $\ddot{C}^i(q) = \ddot{v}\left(1-\Theta^{1/\alpha}\right)\ddot{e}^\ell(q)$. Thus, the *basic cost function* is

$$\tilde{C}(q,\gamma) \quad = \quad \ddot{C}^P\left(q,\theta^\ell\right) \quad + \quad \gamma\ddot{C}^i(q) \quad = \quad \ddot{v}\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}\ddot{e}^\ell(q). \tag{17}$$

Because $\frac{d\ddot{e}^\ell(q)}{dq} = \left(\ddot{g}'(\ddot{e}^\ell(q))\right)^{-1}$, the *basic marginal cost function* is

$$\widetilde{MC}(q,\gamma) \quad = \quad \ddot{v}\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}\left(\ddot{g}'(\ddot{e}^\ell(q))\right)^{-1}. \tag{18}$$

The profit maximizing level of output, $\tilde{q}(\gamma)$, produced by the farmer ℓ at price p under the basic contract is defined by the condition $\widetilde{MC}(\tilde{q}(\gamma),\gamma) = p$. Applying the implicit function theorem,

$$\begin{aligned}\frac{d\tilde{q}(\gamma)}{d\gamma} &= -\frac{\partial \widetilde{MC}(\tilde{q}(\gamma),\gamma)}{\partial \gamma} \Bigg/ \frac{\partial \widetilde{MC}(\tilde{q}(\gamma),\gamma)}{\partial q} \\ &= \ddot{v}\left(1-\Theta^{1/\alpha}\right)/\ddot{g}'\frac{\ddot{v}\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}}{(\ddot{g}')^2}\frac{\ddot{g}''}{\ddot{g}'}.\end{aligned}$$

Euler's theorem implies that $\ddot{g}'' = (\alpha-1)\ddot{g}'/\ddot{e}^{\ell}(q)$. because $\ddot{g}'$ is homogeneous of degree $\alpha-1$. By profit maximization, $\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\} = p\ddot{g}'/\ddot{v}$. Using these two equalities, the expression becomes

$$\frac{d\tilde{q}(\gamma)}{d\gamma} = \frac{\ddot{v}\ddot{e}^{\ell}(q)\left(1-\Theta^{1/\alpha}\right)}{(\alpha-1)p} = \frac{(w\tilde{e}^{\ell}(q)+r\tilde{k}^{\ell}(q))\left(1-\Theta^{1/\alpha}\right)}{(\alpha-1)p} < 0. \tag{19}$$

Comparing the marginal effects of the restrictive and basic contracts

This subsection establishes two factors that contribute to the dominance, from the buyer's perspective, of the restrictive over the basic contract. Inequality (8) above established that information costs are lower under the the optimal restrictive contract than under the optimal basic contract; Proposition 3 established that *production* costs are higher. Proposition 5 demonstrates that the former inequality dominates.

Proposition 5 *For any given* $(q,\gamma) \gg 0$, *the buyer's total cost of optimally obtaining q under a restrictive contract is less than the corresponding costs under a basic contract. That is,*

$$\textit{for all} q \textit{and all} \gamma > 0, \quad \bar{C}(q,\gamma) < \tilde{C}(q,\gamma). \tag{20}$$

The proof of Proposition 5 is immediate: the neoclassical input mix is feasible under the restrictive contract, but, by Proposition 3, violates the first-order condition (13). The proposition reflects the fact, illustrated in Fig. 2, that the first-order reduction in information costs obtained by moving away from the neoclassical input mix necessarily offsets the resulting, second-order increase in production costs.

Our next result is less immediate. It establishes that relative to the symmetric information benchmark, output is less distorted under the restrictive contract than under the basic contract.

Proposition 6 *If the determinant of the Hessian of the Lagrangian (10) is positive on* $[0,\Phi]$, *then output produced by farmer* ℓ *is higher under the optimal restrictive contract than under the optimal basic contract.*

An interpretation of Proposition 6 is that the restrictive marginal cost curve (including both production and information rent costs) is strictly lower under the restrictive contract than under the basic contract. Intuitively, this holds because under the restrictive contract, the buyer can limit the extent to which farmer h could substitute between effort and capital if he were to select the contract designed for ℓ.

The social cost of information asymmetry

As we have seen, the buyer's profits are higher under the optimal restrictive contract than under the optimal basic contract. This does not imply, however, that restrictive contracts are preferable to basic contracts from a *social* perspective. While the buyer's objective is to minimize the sum of production and information costs, only production costs matter for total surplus. Information costs are simply a transfer from the buyer to farmer h. Our task in this section is to compare total surplus under the two types of contracts.

In the present model with perfectly elastic demand, total surplus is equal to the buyer's total revenue minus *production* costs because the information rent obtained by h is a cost to the buyer. Although information rents are lower under the optimal restrictive contract, average production costs are higher because the input mix is sub-optimal from a pure production standpoint. We refer to this distortion as the *input mix effect*. The second factor which affects total surplus is the level of production. Proposition 6 establishes that production is always higher under the optimal restrictive contract. We refer to this difference as the *output effect*. The difference between total surplus under the two contracts is the sum of the two effects. Whether the positive output effect or the negative input mix effect dominates depends on a number of considerations, including the elasticity of substition, the relative importance of the two inputs in the production process, and the productive efficiency gap between the two types.

We find that if the elasticity of substitution is sufficiently small, then total surplus is higher under the restrictive contract than under the basic contract. To obtain this result, we need certain parameters to be bounded away from their natural boundaries. Specifically, the ratio of types' efficiency factors (Θ), the probability of type ℓ (ϕ^ℓ), and the homogeneity factor (α) must all belong to compact subsets of $(0, 1)$, and the neoclassical input ratio ($\tilde{\beta}$) and the level of output associated with input vector $(1, \tilde{\beta})$ must belong to compact subsets of $(0, \infty)$. Since any compact sets will do, we define them all in terms of an arbitrarily small scalar, $\check{\omega} \in (0, 0.5)$. Let

$$G = \left\{ g \text{ satisfying A1–A3} : \Theta, \phi^\ell, \alpha \in [\check{\omega}, 1 - \check{\omega}], \& \ \tilde{\beta}, g(1, \tilde{\beta}) \in [\check{\omega}, 1/\check{\omega}] \right\}. \tag{21}$$

Given a production function g, let $\sigma(e, k|g)$ denote the elasticity of substitution of capital for effort for the function g at (k, e) and let $\bar{\sigma}(g) = \sup \left\{ \sigma(e, k|g) : (e, k) \in \mathbb{R}^2_+ \right\}$.

Obviously, for the special case in which g is CES, $\bar{\sigma}(g)$ is just the familiar constant measure. Significantly, the fact that g belongs to G does not impose any restriction on $\bar{\sigma}(g)$.

Proposition 7 *There exists $n \in \mathbb{N}$ such that for all $g \in G$ with $\bar{\sigma}(g) \leq 1/n$, social surplus with technology g is higher under the restrictive contract than under the basic contract.*

The intuition for this result is straightforward.

As the elasticity of substitution declines, the buyer can obtain a larger and larger "bang for the buck" in terms of information rents. That is, a small distortion in the capital-effort ratio away from the optimal ratio results in a larger and larger decrease in information rents. Figure 4 illustrates the effect of the elasticitiy of substitution. The two panels display the effect of a given increase in ℓ's k away from its neoclassical value for a given quantity. The top panel illustrates that the reduction in information rents is relatively small when

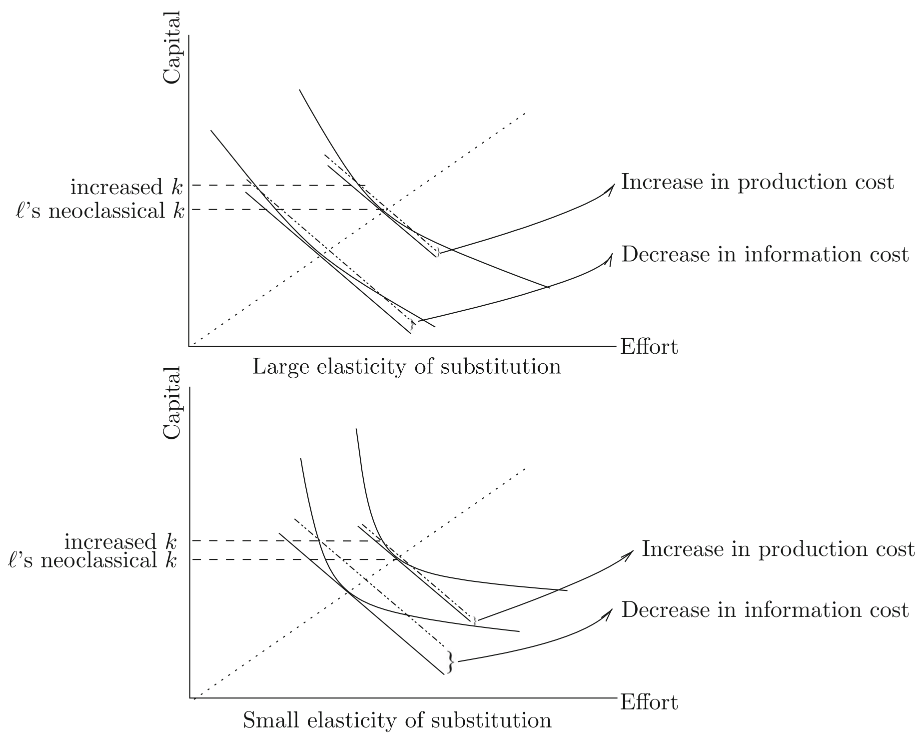

Fig. 4 Input mix distortions and information rents as functions of the elasticity of substitution

the elasticity of substitution is large. In the bottom panel, the reduction in information rents is large when the elasticity of substitution is small. As a consequence of this relationship, as the elasticity of substitution approaches zero, the quantity produced under the optimal restrictive contract approaches the first-best quantity, while the distortion in the capital-effort ratio goes to zero. It follows that for n sufficiently large, the optimal restrictive contract will generate greater total surplus than the optimal basic contract.

Matters are less straightforward when the two inputs are close substitutes. First (as in Fig. 3), an interior solution may exist but the determinant of the Hessian of the Lagrangian may be negative for sufficiently large γ (see (14)). In this case, none of the machinery on which Proposition 7 is based can be applied. Second, suppose, for a sequence (g^n) satisfying A1–A3 with $\bar{\sigma}(g^n)$ increasing without bound, that an interior solution does exist and the determinant of the Hessian of the Lagrangian is positive on $[0, \Phi]$. In this case, both the input mix and output effects will converge to zero and there is no guarantee that the latter effect will dominate the former. Hence, it is possible that when the two inputs are close substitutes, the optimal basic contract yields a higher level of total surplus than the optimal restrictive contract. Finally, an interior solution for the restrictive contract may not exist. Specifically, if θ^h was slightly higher than the value represented in Fig. 3, then type h would be able to imitate ℓ without utilizing any effort at all.

Conclusions

Production contracts include clauses specifying one or more inputs or production practices. While there are a number of possible reasons for these clauses, one possibility is asymmetric information. Farmers' private information regarding their productivity allows some farmers to collect information rents at the expense of the buyer. Restricting farmers' scope for making production decisions can reduce those information rents and increase the buyer's returns. The net effect on total surplus is indeterminate. Output is higher when the buyer controls the input, due to lower information rents accruing to more productive farmers. However, this reduction distorts input use away from the production cost-minimizing level, which is costly. The net effect on total surplus depends primarily on the elasticity of substitution between inputs. The less substitutability between labor and other inputs, the smaller the profit-maximizing distortion in the input ratio, and the smaller the reduction in the output specified in the contract for the low-ability agent. Both of these effects increase total surplus. Given the limited substitutability between labor and non-labor inputs in many agricultural activities, the analysis suggests that greater control of non-labor inputs by the buyer increases total surplus.

These findings have important implications relating to the design and welfare effects of agricultural contracts. Natural illustrations of inputs for which labor has limited substitutability are seeds supplied for the production of specialty crops and animals supplied by the buyer. In such cases, when the elasticity of substitution is low, our analysis implies that buyer control of inputs increases total surplus, even though it decreases the information rents obtained by some farmers.

Of course, there are other cases in which the elasticity of substitution may be high; for example, labor may substitute reasonably well for specific production techniques. In such instances, it is unclear whether total surplus is higher when the buyer requires specific production techniques or when the farmer chooses them. Importantly, regardless of the effect on total surplus, in either case the information rents accruing to some farmers will decline and returns to the buyer will increase. Consequently, our analysis contributes to the property rights literature by providing a strong argument for integration; the buyer's profits are higher when she controls material inputs than when she does not in this framework.

Oftentimes in agricultural markets, buyers who contract with farmers have oligopoly power in their output markets. The effect identified in our model is not eliminated when oligopoly power is introduced by allowing the buyer to face a downward-sloping demand curve rather than a constant output price. The logic is simple. First, consider a buyer who is a monopolist in her output market. She will maximize expected profits, recognizing that marginal revenue is less than price. Exercising market power, her contract menu will specify lower outputs for farmers of each type. As a result, production and information costs will be correspondingly lower. The high ability farmer will still obtain information rents—i.e., the buyer will incur information costs—although these will be smaller in magnitude than in the perfectly competitive case. Moreover, the high ability farmer will still obtain a lower information rent under the restrictive contract than under the basic one. In summary, the presence of monopoly power does not eliminate the problem analyzed in this paper.

Now consider an oligopolistic buyer. Our model structure—one farmer and one buyer who holds all bargaining power—limits the strategic considerations that can come into play. First, in contrast to Von Schlippenbach and Teichmann (2012), the farmer does not have the opportunity to increase his reservation utility by contracting with a different buyer. Second, unlike in Helper and Levine (1992), there is no scope for the farmer to negotiate a share of the buyer's rents from the output market. Third, in contrast to Krattenmaker and Salop (1986), our buyer does not have the opportunity to increase her input purchases and output sales by contracting with additional farmers. This eliminates another motivation—raising competitors' costs —for contracting in an oligopoly. Once again, quantity is the only strategic variable available to the buyer in the context of our model structure, and the presence of market power will affect contract menu design only through its effect on this variable. Thus, the insights of the analysis can be applied to questions regarding agricultural contracts even in markets where buyers have market power.

The results of the analysis provide a way of evaluating the effects of government policies regarding agricultural production contracts. Under pressure from farmers, Iowa and other US states enacted laws that banned meatpacker ownership or control of cattle and hogs intended for slaughter. While contracting per se was not outlawed under these measures, contracts where the meatpacker controls major production decisions were. In our context, the laws outlawed restrictive contracts in which the meatpacker specifies non-labor inputs but did not outlaw basic contracts in which the farmer chooses the means of production (McEowen et al. 2002). Clearly, the reduced information rents farmers receive under integration and input control contracts provided them with an incentive to lobby for these laws. Our framework allows us to assess the social desirability of such laws. Because labor has a limited ability to substitute for animals in meat production, this type of contract provisions almost certainly do not increase total surplus in our framework. They can only promote efficiency if another market failure exists and its effects are mitigated by replacing the spot market with contracted and integrated production. On the other hand, the substitutability of labor for specific production techniques may be somewhat higher, so that the efficiency implications of such contract provisions are less clear.

In Iowa, major processors sued the state government, arguing that the ban was unconstitutional. The state settled with the companies starting in 2005 and continuing through 2013. The settlement agreements addressed concerns outside our modeling framework that could affect returns to farmers, including retaliation against contracting farmers who formed or joined a contract grower's association and transparency regarding the data used to calculate compensation, among other considerations. It also allowed the processors to continue to use contracts (Iowa Department of Justice 2013). Our analysis suggests that the settlements will promote efficiency, provided that the elasticity of substitution between farmers' labor and inputs specified in the production contracts is sufficiently low.

Endnotes

[1] Unlike production contracts, marketing contracts only address the product at the time of delivery, including the pricing mechanism, delivery time and location, and verifiable product characteristics.

[2] In turn, most of these provisions (94 %) linked compensation to the grower's performance relative to his peers. Relative compensation provisions are the subject of many studies, some of which focus on the broiler industry, e.g., Knoeber (1989), Knoeber and Thurman (1994), Knoeber and Thurman (1995), Goodhue (2000), Tsoulouhas and Vukina (2001), Levy and Vukina (2004), and Wu and Roe (2005), among others.

[3] Recent discussions of other aspects of the contracting literature and of issues related to analyzing agricultural contracts include Goodhue (2011), Sexton (2013), and Wu (2014).

[4] Assumptions A1 and A2 are much stronger than we need, but the computational convenience that these assumptions provide amply compensates for the loss of generality.

[5] Because f is homogeneous of degree α (A2), $\ddot{f}\left(\ddot{e}(q,\theta),\theta\right) = \ddot{e}(q,\theta)^{\alpha} f(1,\tilde{\beta},\theta) = \ddot{e}(q,\theta)^{\alpha}\left[\tilde{e}(q,\theta)^{-\alpha} f\left(\tilde{e}(q,\theta),\tilde{k}(q,\theta)\right)\right] = f\left(\tilde{e}(q,\theta),\tilde{k}(q,\theta)\right)$.

[6] From the buyer's perspective, the farmer's information rents are a cost.

[7] For reasons that will become clear, type h is in the numerator of Φ but the denominator of $\Theta = \frac{\theta^{\ell}}{\theta^{h}}$ (p. 6).

[8] To see why inequality (8) holds, suppose first that $k = \tilde{k}(q,\theta^{\ell})$. In this case, $\bar{C}^{I}(q,k)=\bar{C}^{P}_{\ell}(q,k)-\bar{C}^{P}_{h}(q,k)$ is the difference between the two type's production costs, when type h is constrained to use the same level of capital as type ℓ. But since this level is super-optimal for h for producing q, the cost difference $\tilde{C}^{I}(q)=\tilde{C}^{P}_{\ell}(q)-\tilde{C}^{P}_{h}(q)$, when h is permitted to substitute labor for capital, is even greater. If $k > \tilde{k}(q,\theta^{\ell})$, then k would be even more super-optimal for h for producing q, and hence the gain to h from replacing surplus capital with labor would be even higher. Figure 1 illustrates this argument graphically.

[9] Figure 2 makes clear that neither A1 or A2 is required for this result to hold. A sufficient but still far from necessary condition is that the difference between types be technologically neutral, in the sense that for any q, the isoquants associated with that q for the two types be parallel to each other.

[10] The elasticity of substitution of f at (e,k) is denoted by (see Silberberg (1990))

$$\sigma_{ke}(e,k) = -\frac{\partial \ln(k/e)}{\partial \ln(f_k/f_e)}\Big|_{f(e,k)=\text{constant}} = -\frac{d(f_k/f_e)}{f_k/f_e}\Big/\frac{d(k/e)}{k/e}\Big|_{f(e,k)=\text{constant}}$$
$$= -\frac{f_e f_k (f_e e + f_k k)}{ek\left[(f_k)^2 f_e e - 2 f_e f_k f_{ek} + (f_e)^2 f_{kk}\right]}.$$

[11] Because the buyer has only one choice variable under a basic contract, there is no need to set up a Lagrangian corresponding to (10) to determine the cost function.

Appendix

Proof of Lemma 1:

The optimal restrictive contract is the solution to the following program:

$$\max_{(\bar{\mathbf{q}},\bar{\mathbf{k}},\bar{\mathbf{t}})} \sum_{i\in\{\ell,h\}} \left\{\phi^{i}\left(p\bar{q}(\theta^{i}) - \bar{t}(\theta^{i})\right)\right\} \tag{22a}$$

$$\text{subject to} \quad \bar{t}(\theta^{\ell}) \geq \bar{C}^{P}(\bar{q}(\theta^{\ell}),\bar{k}(\theta^{\ell}),\theta^{\ell}) \tag{22b}$$
$$\bar{t}(\theta^{h}) \geq \bar{C}^{P}(\bar{q}(\theta^{h}),\bar{k}(\theta^{h}),\theta^{h}) \tag{22c}$$
$$\bar{t}(\theta^{\ell}) - \bar{C}^{P}(\bar{q}(\theta^{\ell}),\bar{k}(\theta^{\ell}),\theta^{\ell}) \geq \bar{t}(\theta^{h}) - \bar{C}^{P}(\bar{q}(\theta^{h}),\bar{k}(\theta^{h}),\theta^{\ell}) \tag{22d}$$
$$\bar{t}(\theta^{h}) - \bar{C}^{P}(\bar{q}(\theta^{h}),\bar{k}(\theta^{h}),\theta^{h}) \geq \bar{t}(\theta^{\ell}) - \bar{C}^{P}(\bar{q}(\theta^{\ell}),\bar{k}(\theta^{\ell}),\theta^{h}). \tag{22e}$$

Now, given $(\bar{\mathbf{q}},\bar{\mathbf{k}},\bar{\mathbf{t}})$ define the *information rent* vector $\bar{\mathbf{dt}}$ by for $\theta \in \left\{\theta^{\ell},\theta^{h}\right\}$, $\bar{dt}(\theta) = \bar{t}(\theta) - \bar{C}^{P}(\bar{q}(\theta),\bar{k}(\theta),\theta)$. The principal's problem can now be rewritten in terms of $(\bar{\mathbf{q}},\bar{\mathbf{k}},\bar{\mathbf{dt}})$ as

$$\max_{(\bar{\mathbf{q}},\bar{\mathbf{k}},\bar{\mathbf{t}})} \sum_{i\in\{\ell,h\}} \left\{\phi^i \left(p\bar{q}(\theta^i) - \bar{t}(\theta^i)\right)\right\} \tag{23a}$$

$$\text{subject to} \quad \bar{d}t(\theta^\ell) \geq 0 \tag{23b}$$

$$\bar{d}t(\theta^h) \geq 0 \tag{23c}$$

$$\bar{d}t(\theta^\ell) \geq \bar{d}t(\theta^h) - \left(\bar{C}^P(\bar{q}(\theta^h), \bar{k}(\theta^h), \theta^\ell) - \bar{C}^P(\bar{q}(\theta^h), \bar{k}(\theta^h), \theta^h)\right) \tag{23d}$$

$$dt(\theta^h) \geq dt(\theta^\ell) + \left(\bar{C}^P(\bar{q}(\theta^\ell), \bar{k}(\theta^\ell), \theta^\ell) - \bar{C}^P(\bar{q}(\theta^\ell), \bar{k}(\theta^\ell), \theta^h)\right). \tag{23e}$$

Clearly, given any solution $(\bar{\mathbf{q}}, \bar{\mathbf{k}}, \bar{\mathbf{t}})$ of (22a), if $\bar{d}t(\theta^\ell) = 0$ and $\bar{d}t(\theta^h) = \left(\bar{C}^P(\bar{q}(\theta^\ell), \bar{k}(\theta^\ell), \theta^\ell) - \bar{C}^P(\bar{q}(\theta^\ell), \bar{k}(\theta^\ell), \theta^h)\right)$, then $(\bar{\mathbf{q}}, \bar{\mathbf{k}})$ must be a solution to (5), since the set of instruments available to the principal in the latter problem is a strict subset of the set of instruments available to her in the former. To prove the lemma, therefore, we need only show that if $(\bar{\mathbf{q}}, \bar{\mathbf{k}}, \bar{\mathbf{t}})$ is a solution to (22a), then

$$\bar{d}t(\theta^\ell) = 0 \quad \text{and} \quad \bar{d}t(\theta^h) = \left(\bar{C}^P(\bar{q}(\theta^\ell), \bar{k}(\theta^\ell), \theta^\ell) - \bar{C}^P(\bar{q}(\theta^\ell), \bar{k}(\theta^\ell), \theta^h)\right) \tag{24}$$

so that $(\bar{\mathbf{q}}, \bar{\mathbf{k}})$ is also a solution to (5).

First note that if $\bar{d}t(\theta^\ell) = 0$, then (23e) must hold with equality, so that (24) holds. Otherwise, $\bar{d}t(\theta^h)$ could be reduced without violating either (23e) or (23c), resulting in a higher payoff to the principal. In order to complete the proof, therefore, it is sufficient to prove that $\bar{d}t(\theta^\ell) = 0$. Suppose that $\bar{d}t(\theta^\ell) = \epsilon > 0$. Then by (23e), $\bar{d}t(\theta^h) \geq \epsilon$, since $\left(\bar{C}^P(\bar{q}(\theta^\ell), \bar{k}(\theta^\ell), \theta^\ell) - \bar{C}^P(\bar{q}(\theta^\ell), \bar{k}(\theta^\ell), \theta^h)\right)$ is obviously positive. In this case, we can subtract ϵ from both $\bar{d}t(\theta^h)$ and $\bar{d}t(\theta^\ell)$, all four inequalities will remain satisfied, and the principal's payoff will be higher. ∎

Because the proof of Proposition 1 relies on Proposition 4, we postpone it until after Proposition 4 has been proved.

Proof of Proposition 2:

Let $(\tilde{\mathbf{q}}, \tilde{\mathbf{t}}) = \left((\tilde{q}^\ell, \tilde{t}^\ell), (\tilde{q}^h, \tilde{t}^h)\right)$ denote the optimal basic contract. Construct the restrictive contract $(\check{\mathbf{q}}, \check{\mathbf{k}}, \check{\mathbf{t}}) = \left((\check{q}^\ell, \check{k}^\ell, \check{t}^\ell), (\check{q}^h, \check{k}^h, \check{t}^h)\right)$, where $\check{\mathbf{q}} = \tilde{\mathbf{q}}$ and for $\theta \in \left\{\theta^\ell, \theta^h\right\}$, $\check{k}(\theta) = \tilde{k}(\tilde{q}, \theta)$. That is, under this constructed restrictive contract, the outputs that were produced under the original basic contract are once again produced using the (neoclassical) input mix that was endogenously selected under the original basic contract. Thus, for each θ, the production cost of $\check{q}(\theta)$ is identical under both contracts. On the other hand, the *information cost* associated with $(\check{\mathbf{q}}, \check{\mathbf{k}}, \check{\mathbf{t}})$ is lower than the information cost associated with $(\tilde{\mathbf{q}}, \tilde{\mathbf{t}})$. To see this, note that since $\theta^\ell < \theta^h$, $\check{k}^\ell = \tilde{k}(\check{q}^\ell, \theta^\ell)$ is distinct from the unique solution $\tilde{k}(\check{q}^\ell, \theta^h)$ to the first-order condition (1) for type h. Hence, we have $\bar{C}^P_h(\check{q}^\ell, \check{k}^\ell) > \bar{C}^P_h(\check{q}^\ell, \tilde{k}(\check{q}^\ell)) = \tilde{C}^P_h(\check{q}^\ell)$. Therefore,

$$\begin{aligned}
\tilde{C}^I(\check{q}^\ell) =& \tilde{C}^P_\ell(\tilde{q}^\ell) - \tilde{C}^P_h(\tilde{q}^\ell) \\
>& \tilde{C}^P_\ell(\tilde{q}^\ell) - \bar{C}^P_h(\check{q}^\ell, \check{k}^\ell) \\
=& \bar{C}^P_\ell(\check{q}^\ell, \check{k}^\ell) - \bar{C}^P_h(\check{q}^\ell, \check{k}^\ell) = \bar{C}^I(\check{q}^\ell, \check{k}^\ell).
\end{aligned} \tag{25}$$

The restrictive contract we constructed thus delivers the same output at strictly less cost to the buyer, and hence achieves strictly higher profits for the buyer than the optimal basic contract. Since this constructed contract is feasible, the optimal restrictive contract must also achieve strictly higher profits. ∎

Proof of Lemma 2:

The lemma follows immediately from an inspection of (14). Because h is more efficient than ℓ and $e^h < e^\ell$, we have $f_e^h(e^h,k) > f_e^h(e^\ell,k)$ so that $\frac{1+\gamma}{f_e^\ell}(e^\ell,k) > \frac{\gamma}{f_e^h(e^h,k)}$. (14) will therefore be positive if

$$\frac{e^h\ f_e^h(e^h,k)}{k\ \ f_k^h(e^h,k)} > \frac{e^\ell\ f_e^\ell(e^\ell,k)}{k\ \ f_k^\ell(e^\ell,k)} \quad \text{or, more conveniently,} \quad \frac{k\ \ f_k^\ell(e^\ell,k)}{e^\ell\ f_e^\ell(e^\ell,k)} > \frac{k\ \ f_k^h(e^h,k)}{e^h\ f_e^h(e^h,k)}. \tag{26}$$

Now $e^h < e^\ell$; moreover since $\bar{\sigma}_{ke} \le 1$, a given change $|\frac{d(k/e)}{k/e}|$ induces a weakly smaller change $|\frac{d(f_k/f_e)}{f_k/f_e}|$ (see fn. 10), i.e., we have $\frac{k/e^\ell}{k/e^h} \ge \frac{f_k^h(e^h,k)/f_e^h(e^h,k)}{f_k^h(e^h,k)/f_e^h(e^h,k)} > 1$. Hence (26) is satisfied. ∎

Proof of Proposition 4:

The Hessian of $\bar{L}(\cdot\,;\bar{q}(\gamma),\gamma)$ (expression (11)) is

$$\overline{HL}(\gamma) = \begin{bmatrix} -\bar{\lambda}^\ell f_{ee}^\ell & 0 & -\bar{\lambda}^\ell f_{ek}^\ell & -f_e^\ell & 0 \\ 0 & \bar{\lambda}^h f_{ee}^h & \bar{\lambda}^h f_{ek}^h & 0 & f_e^h \\ -\bar{\lambda}^\ell f_{ek}^\ell & \bar{\lambda}^h f_{ek}^h & (\bar{\lambda}^h f_{kk}^h - \bar{\lambda}^\ell f_{kk}^\ell) & -f_k^\ell & f_k^h \\ -f_e^\ell & 0 & -f_k^\ell & 0 & 0 \\ 0 & f_e^h & f_k^h & 0 & 0 \end{bmatrix}.$$

By assumption, $\Delta^{\overline{HL}}(\gamma)$ is positive for all γ. Hence we can obtain the derivatives of the $\bar{\lambda}^i$'s w.r.t. q and γ by applying the implicit function theorem to the first-order condition (11). Because the inverse of $\overline{HL}(\gamma)$ is complex, we replace terms that we do not need to evaluate in the expression below by ⊛'s:

$$\begin{bmatrix} \partial\bar{e}^\ell/\partial\gamma & \partial\bar{e}^\ell/\partial q \\ \partial\bar{e}^h/\partial\gamma & \partial\bar{e}^h/\partial q \\ \partial\bar{k}/\partial\gamma & \partial\bar{k}/\partial q \\ \partial\bar{\lambda}^\ell/\partial\gamma & \partial\bar{\lambda}^\ell/\partial q \\ \partial\bar{\lambda}^h/\partial\gamma & \partial\bar{\lambda}^h/\partial q \end{bmatrix} = -\overline{HL}(\gamma)^{-1} \begin{bmatrix} \partial\bar{L}_{\bar{e}^\ell}/\partial\gamma & \partial\bar{L}_{\bar{e}^\ell}/\partial q \\ \partial\bar{L}_{\bar{e}^h}/\partial\gamma & \partial\bar{L}_{\bar{e}^h}/\partial q \\ \partial\bar{L}_{\bar{k}}/\partial\gamma & \partial\bar{L}_{\bar{k}}/\partial q \\ \partial\bar{L}_{\bar{\lambda}^\ell}/\partial\gamma & \partial\bar{L}_{\bar{\lambda}^\ell}/\partial q \\ \partial\bar{L}_{\bar{\lambda}^h}/\partial\gamma & \partial\bar{L}_{\bar{\lambda}^h}/\partial q \end{bmatrix} = \frac{\bar{\lambda}^\ell\bar{\lambda}^h}{\Delta^{\overline{HL}}(\gamma)} \times \cdots \tag{27}$$

$$\begin{bmatrix} \frac{(f_e^h)^2(f_k^\ell)^2}{\bar{\lambda}^\ell\bar{\lambda}^h} & \frac{f_e^h f_k^\ell f_k^h f_e^\ell}{\bar{\lambda}^\ell\bar{\lambda}^h} & \circledast & \frac{(f_e^h)^2\beta^\ell\mu(\ell)}{\bar{\lambda}^h} - \frac{f_e^\ell\xi^h}{\bar{\lambda}^\ell} & -\frac{f_e^\ell f_k^\ell\mu(h)}{\bar{\lambda}^\ell} \\ \frac{f_e^h f_k^\ell f_k^h f_e^\ell}{\bar{\lambda}^\ell\bar{\lambda}^h} & \frac{(f_e^\ell)^2(f_k^h)^2}{\bar{\lambda}^\ell\bar{\lambda}^h} & \circledast & -\frac{f_e^h f_k^h\mu(\ell)}{\bar{\lambda}^h} & \frac{(f_e^\ell)^2\beta^h\mu(h)}{\bar{\lambda}^\ell} - \frac{f_e^h\xi^\ell}{\bar{\lambda}^h} \\ \frac{-(f_e^h)^2 f_k^\ell f_e^\ell}{\bar{\lambda}^\ell\bar{\lambda}^h} & \frac{-(f_e^\ell)^2 f_k^h f_e^h}{\bar{\lambda}^\ell\bar{\lambda}^h} & \circledast & \frac{(f_e^h)^2\mu(\ell)}{\bar{\lambda}^h} & \frac{(f_e^\ell)^2\mu(h)}{\bar{\lambda}^\ell} \\ \frac{(f_e^h)^2\beta^\ell\mu(\ell)}{\bar{\lambda}^h} - \frac{f_e^\ell\xi^h}{\bar{\lambda}^\ell} & -\frac{f_e^h f_k^h\mu(\ell)}{\bar{\lambda}^h} & \circledast & f_e e^\ell\xi^h - \frac{\bar{\lambda}^\ell(f_e^h)^2\psi(f,\ell)}{\bar{\lambda}^h} & \mu(\ell)\mu(h) \\ -\frac{f_e^\ell f_k^\ell\mu(h)}{\bar{\lambda}^\ell} & \frac{(f_e^\ell)^2\beta^h\mu(h)}{\bar{\lambda}^\ell} - \frac{f_e^h\xi^\ell}{\bar{\lambda}^h} & \circledast & \mu(\ell)\mu(h) & f_{ee}^h\xi^\ell - \frac{\bar{\lambda}^h(f_e^\ell)^2\bar{\lambda}^\ell}{\psi(f,h)} \end{bmatrix} \begin{bmatrix} w & 0 \\ -w & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & -1 \end{bmatrix}.$$

Where for $i = h, \ell$:

$$\begin{aligned}
\mu(i) &= f^i_{ee} f^i_k - f^i_{ek} f^i_e \\
\bar{\beta}^i &= \bar{k}/\bar{e}^i \\
\xi^i &= f^i_{ee}(f^i_k)^2 + f^i_{kk}(f^i_e)^2 - 2f^i_{ek} f^i_k f^i_e \quad = \quad \mu(i)(\bar{e}^i f^i_e + \bar{k} f^i_k)/\bar{k} && (28)\\
\psi(f,i) &= f^i_{kk} f^i_{ee} - (f^i_{ek})^2 \\
\Delta^{\overline{HL}}(\gamma) &= \bar{\lambda}^h (f^\ell_e)^2 \xi^h \quad - \quad \bar{\lambda}^\ell (f^h_e)^2 \xi^\ell . && (29)
\end{aligned}$$

We can now compute the partial derivatives of the marginal cost function at q, γ:

$$\begin{aligned}
\frac{\partial \overline{MC}(q,\gamma)}{\partial \gamma} &= \left(\frac{\partial \bar{\lambda}^\ell(q,\gamma)}{\partial \gamma} - \frac{\partial \bar{\lambda}^h(q,\gamma)}{\partial \gamma} \right) \text{ which, after much tedious manipulation} \\
&= \frac{w(\bar{e}^h - \bar{e}^\ell)}{\bar{k}\Delta^{\overline{HL}}(\gamma)} \left(\bar{\lambda}^\ell (f^h_e)^2 \mu(\ell) - \bar{\lambda}^h (f^\ell_e)^2 \mu(h) \right) \\
&\quad \text{which, since } \mu(i) = \frac{\bar{k}\xi^i}{\bar{e}^i f^i_e + \bar{k} f^i_k} \text{ (expression 28)} \\
&= \frac{w(\bar{e}^h - \bar{e}^\ell)}{\Delta^{\overline{HL}}(\gamma)} \left(\frac{\bar{\lambda}^\ell (f^h_e)^2 \xi^\ell}{e^\ell f^\ell_e + \bar{k} f^\ell_k} - \frac{\bar{\lambda}^h (f^\ell_e)^2 \xi^h}{e^h f^h_e + \bar{k} f^h_k} \right) \\
&\quad \text{which, since } f \text{ is homogenous of degree } \alpha \\
&= \frac{w(\bar{e}^h - \bar{e}^\ell)}{\alpha q(\gamma)\Delta^{\overline{HL}}(\gamma)} \left(\bar{\lambda}^\ell (f^h_e)^2 \xi^\ell - \bar{\lambda}^h (f^\ell_e)^2 \xi^h \right) \text{ which, from (29)} \\
&= \frac{w(\bar{e}^\ell - \bar{e}^h)}{\alpha q(\gamma)} \quad > \quad 0.
\end{aligned}$$

Similarly, we have

$$\begin{aligned}
\frac{\partial \overline{MC}(q,\gamma)}{\partial q} &= \left(\frac{\partial \bar{\lambda}^\ell(q,\gamma)}{\partial q} - \frac{\partial \bar{\lambda}^h(q,\gamma)}{\partial q} \right) \qquad \text{which, after similar manipulation} \\
&= \frac{(\bar{\lambda}^\ell - \bar{\lambda}^h)(1-\alpha)}{k\Delta^{\overline{HL}}(\gamma)} \left(\bar{\lambda}^\ell (f^h_e)^2 \mu(\ell) \quad - \quad \bar{\lambda}^h (f^\ell_e)^2 \mu(h) \right) \\
&= \frac{(\bar{\lambda}^\ell - \bar{\lambda}^h)(1-\alpha)}{\alpha q} \quad > \quad 0,
\end{aligned}$$

proving the first sentence of the proposition. Now, for all γ, at the profit maximizing level of q, we have $\overline{MC}(q,\gamma) = p$. Moroever, since $\frac{\partial \overline{MC}(\bar{q}(\gamma),\gamma)}{\partial q}$ is nonzero for all $\gamma \in [0,1]$,the implicit function theorem now implies the existence of neighborhoods U^γ of γ, U^q of $\bar{q}(\gamma)$ and a continuously differentiable function$\bar{q} : U^\gamma \to U^q$ such that $\overline{MC}(\bar{q}(\gamma),\gamma) = p$ on U^γ. It follows that $\bar{q}(\cdot)$ is continuously differentiable on $[0,1]$, with

$$\frac{d\bar{q}(\gamma)}{d\gamma} = -\frac{\partial \overline{MC}(\bar{q}(\gamma),\gamma)}{\partial \gamma} \Bigg/ \frac{\partial \overline{MC}(\bar{q}(\gamma),\gamma)}{\partial q} = \frac{w(\bar{e}^\ell - \bar{e}^h)}{(\alpha - 1)(\bar{\lambda}^\ell - \bar{\lambda}^h)}. \qquad (30)$$

Expression (30), which is identical to expression (16) in the text, is negative because $\bar{e}^\ell > \bar{e}^h$, $\bar{\lambda}^\ell > \bar{\lambda}^h$ & $\alpha < 1$, proving the second sentence of the proposition. ∎

Proof of Proposition 1:
(6a) and (6b) follow immediately from Lemma 1. $\bar{q}^{\ell} < q^{\star}(\theta^{\ell})$ is an immediate implication of Proposition 4 (specifically, $\frac{d\bar{q}(\gamma)}{d\gamma} < 0$ for all γ and $\bar{q}^{\ell} = q^{\star}(\theta^{\ell}) + \int_0^1 \frac{d\bar{q}(\gamma')}{d\gamma} d\gamma'$.) Part 3 is a special case of Proposition 3, for $\gamma = 1$. ■

Proof of Proposition 6:
We begin by comparing (16) for the optimal restrictive contract to the corresponding expression, (19), for the optimal basic contract:

$$\frac{d\bar{q}(\gamma)}{d\gamma} - \frac{d\tilde{q}(\gamma)}{d\gamma} = \frac{1}{1-\alpha}\left(\frac{(w\tilde{e}^{\ell} + r\tilde{k}^{\ell})\left(1 - \vartheta^{1/\alpha}\right)}{p} - \frac{w(\bar{e}^{\ell} - \bar{e}^{h})}{\bar{\lambda}^{\ell} - \bar{\lambda}^{h}}\right). \tag{31a}$$

As we observed on page 14, $(\bar{\lambda}^{\ell} - \bar{\lambda}^{h}) = p$ at the optimal restrictive contract. Hence, for all $\gamma \geq 0$, (38) reduces to

$$\frac{d\bar{q}(\gamma)}{d\gamma} - \frac{d\tilde{q}(\gamma)}{d\gamma} = \frac{1}{p(1-\alpha)}\left(\tilde{C}^{I}(\tilde{q}(\gamma),\gamma) - \bar{C}^{i}(\bar{q}(\gamma),\gamma)\right). \tag{31b}$$

We use this result to show that $\bar{q}(\Phi) > \tilde{q}(\Phi)$. First note that because $\bar{C}^{i}(\cdot,\gamma)$ increases with q, and $\bar{q}(\cdot)$ is a continuous function of γ (Proposition 4), inequality (20) implies the existence of a continuous, positive function $\epsilon(\cdot)$ of γ such that

$$\forall \gamma \geq 0, \frac{d\bar{q}(\gamma)}{d\gamma} - \frac{d\tilde{q}(\gamma)}{d\gamma} > 0 \text{ if } \bar{q}(\gamma) \leq \tilde{q}(\gamma) + \epsilon(\gamma). \tag{32}$$

Now, suppose that there exists $\gamma \in [0,\Phi]$ such that $\bar{q}(\gamma) \leq \tilde{q}(\gamma)$ and let $\gamma^{\star}$ be the infimum of such γ's. Since $\bar{q}(\cdot) - \tilde{q}(\cdot)$ is continuous with respect to γ, $\bar{q}(\gamma^{\star}) = \tilde{q}(\gamma^{\star})$. We will now establish a contradiction.

Since $\tilde{q}(0) = \bar{q}(0)$, property (32) plus continuity implies the existence of $\underline{\gamma} > 0$ such that for all $\gamma \in (0,\underline{\gamma}]$, $\tilde{q}(\gamma) = \int_0^{\gamma} \frac{d\tilde{q}(\gamma')}{d\gamma} d\gamma' < \int_0^{\gamma} \frac{d\bar{q}(\gamma')}{d\gamma} d\gamma' = \bar{q}(\gamma)$. Therefore, $\gamma^{\star} > \underline{\gamma} > 0$. Now by assumption $\bar{q}(\cdot) > \tilde{q}(\cdot)$ on $[0,\gamma^{\star})$ and $\bar{q}(\cdot) - \tilde{q}(\cdot)$ is continuous with respect to γ, there exists $\bar{\gamma} < \gamma^{\star}$ such that $\bar{q}(\cdot) - \epsilon(\cdot) < \tilde{q}(\cdot) < \bar{q}(\cdot)$ on $[\bar{\gamma},\gamma^{\star})$. Therefore, from (32),

$$\left(\bar{q}(\gamma^{\star}) - \tilde{q}(\gamma^{\star})\right) = (\bar{q}(\bar{\gamma}) - \tilde{q}(\bar{\gamma})) + \int_{\bar{\gamma}}^{\gamma^{\star}} \left(\frac{d\bar{q}(\gamma')}{d\gamma} - \frac{d\tilde{q}(\gamma')}{d\gamma}\right) d\gamma' > 0$$

contradicting the existence of $\gamma \in [0,\Phi]$ such that $\bar{q}(\gamma^{\star}) = \tilde{q}(\gamma^{\star})$. ■

Proof of Proposition 7:
While the proof of Proposition 7 is conceptually very simple, it requires a massive amount of detail. The details arise because we need to find a bound on the elasticity of substitution that implies our result *for all* production functions in the set G. This task would be much easier if the set G were compact. We cannot, however, impose this restriction because we need to include in G functions with arbitrarily small, but positive, elasticities of substitution. The proof is organized into five steps. Step 1 establishes lower and upper bounds on

the level of inputs used in any optimal contract and on the rates at which certain variables change with γ. Steps 2 and 3 are convergence results as the upper bound on the elasticity of substitution goes to zero: step 2 proves that the divergence from the neoclassical input mix of the mix that is optimal for type ℓ in the restrictive contract goes to zero also; step 3 proves that while type h's capital usage in the restrictive contract is bounded away from h's use in the basic contract, the difference between the levels of labor that h uses in the two contracts goes to zero. Step 4 extends Proposition 6 by establishing a lower bound on the gap between optimal outputs under the two kinds of contract that holds uniformly for all technologies in G with sufficiently small elasticities of substitution. Step 5 now completes the proof, by identifying a lower bound on the (positive) output effect, and showing that the (negative) input mix effect can be made arbitrarily small by shrinking the upper bound on the elasticity of substitution.

As usual, all symbols with bars (tildes) over them are part of the solution to the restrictive (basic) contract. The proof involves five steps:

Step 1: Preliminaries: bounding key variables.

Pick $g \in G$, let $\tilde{\beta}$ denote the neoclassical input mix (see Remark 1) for $f^\ell \equiv g$, let $\ddot{g}$ denote the composite input function corresponding to g and let $\ddot{e}^i(q)$ denote the level of composite input required to produce q with $\ddot{g}$. Rewriting (18) (p. 16), the *basic marginal cost function* for $\ddot{g}$ is

$$\widetilde{MC}(q,\gamma) \quad = \quad \ddot{v}\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}\left(\ddot{g}'(\ddot{e}^\ell(q))\right)^{-1}. \tag{33}$$

As noted on page 17, $\widetilde{MC}(\tilde{q}(\gamma),\gamma)=p$ at the buyer's optimum, where $\tilde{q}(\gamma)$ is the profit maximizing level of output produced by the farmer ℓ at price p under the basic contract. In this proof, we shall abbreviate $\ddot{e}^i(\tilde{q}(\gamma))$ to $\ddot{e}^i(\gamma)$. Similarly, let $\bar{e}^i(\gamma)=\bar{e}^i(\bar{q}(\gamma))$ and $\bar{k}(\gamma)=\bar{k}(\bar{q}(\gamma))$. Manipulating (33), which is the same as (18) in the text, we obtain

$$\ddot{g}'(\ddot{e}^\ell(\gamma)) \quad = \quad \frac{\ddot{v}}{p}\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}.$$

Since $\ddot{g}'$ is homogenous of degree $\alpha-1$, we have

$$\ddot{e}^\ell(\gamma)^{\alpha-1}\ddot{g}'(1) \quad = \quad \frac{\ddot{v}}{p}\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}$$

Since $\ddot{g}$ is homogeneous of degree α, $\ddot{g}'(1)=\alpha\ddot{g}(1)$ and hence

$$\ddot{e}^\ell(\gamma)^{\alpha-1}\alpha\ddot{g}(1) \quad = \quad \frac{\ddot{v}}{p}\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}. \qquad \text{so that}$$

$$\ddot{e}^\ell(\gamma) \quad = \quad \left[\frac{\ddot{v}}{p\alpha\ddot{g}(1)}\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}\right]^{1/(\alpha-1)}. \tag{34}$$

Since $g \in G$, the right hand side of (34) is bounded below by $\check{e}=\left(\frac{w\check{\omega}+r}{p\check{\omega}^4}\right)^{-1/\check{\omega}}$ and above by $\hat{e}=\min[1,\left(p/w\check{\omega}\right)^{1/\check{\omega}}]$. To verify the lower bound, note that $\gamma<\frac{1-\check{\omega}}{\check{\omega}}$ and $\left(1-\Theta^{1/\alpha}\right)<1$. Hence $\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}<1+\frac{1-\check{\omega}}{\check{\omega}}=1/\check{\omega}$. Moreover, since $\alpha,\ddot{g}(1)\geq\check{\omega}$, and $\ddot{v}\leq w+r/\check{\omega}$, we have a lower bound of $\left(\frac{w\check{\omega}+r}{p\check{\omega}^4}\right)^{-1/\check{\omega}}$. To verify the upper bound, note that since y is negative, the coefficient $\left(\frac{\ddot{v}}{p\alpha\ddot{g}(1)}\right)^y$ is maximized when $\frac{\ddot{v}}{p\alpha\ddot{g}(1)}$ is minimized and y is maximized in absolute value. Moreover, we have $\left(\frac{\ddot{v}}{p\alpha\ddot{g}(1)}\right)^y\geq\left(\frac{w\check{\omega}}{p(1-\check{\omega})}\right)^y\geq$

$\left(\frac{w\breve{\omega}}{p}\right)^{-1/\breve{\omega}}$. On the other hand $\left\{1+\gamma\left(1-\Theta^{1/\alpha}\right)\right\}^{1/(\alpha-1)} \leq 1$. Hence, we have an upper bound of $\left(\frac{w\breve{\omega}}{p}\right)^{-1/\breve{\omega}}$. Moreover, $\frac{d\ddot{e}^{\ell}(\gamma)}{d\gamma}$ is bounded above by $\hat{d}_e = \frac{1}{\breve{\omega}}\left(p/\, w\breve{\omega}\right)^{1/\breve{\omega}}$. To verify this, note that $\frac{d\ddot{e}^{\ell}(\gamma)}{d\gamma} = \left(\frac{\ddot{v}}{p\alpha\ddot{g}(1)}\right)^{y}(1+\gamma x)^{y}$ where, $x = \left(1-\Theta^{1/\alpha}\right)$ and $y = 1/(\alpha-1) < -1$. The argument we used to construct $\hat{e}$ shows that the upper bound on the coefficient is $\left(\frac{w\breve{\omega}}{p}\right)^{-1/\breve{\omega}}$. Next, note that $|\frac{d(1+\gamma x)^{y}}{d\gamma}| = |yx(1+\gamma x)^{y-1}| \leq |yx| \leq |y| \leq 1/\breve{\omega}$. Hence, we have $|\frac{d\ddot{e}^{\ell}(\gamma)}{d\gamma}| \leq \frac{1}{\breve{\omega}}\left(\frac{w\breve{\omega}}{p}\right)^{-1/\breve{\omega}}$.

Finally, from (19), $|\frac{d\tilde{q}(\gamma)}{d\gamma}|$ is bounded below by $\check{d}_q = \breve{e}(w+r\breve{\omega})\breve{\omega}/p$. To verify this bound, note from (19) that

$$|\frac{d\tilde{q}(\gamma)}{d\gamma}| = |\frac{\dddot{v}\ddot{e}^{\ell}(q)\left(1-\Theta^{1/\alpha}\right)}{(\alpha-1)p}| \geq |\frac{\breve{e}(w+\breve{\omega}r)\left(1-(1-\breve{\omega})^{1/\alpha}\right)}{(\alpha-1)p}| \geq \frac{\breve{e}\breve{\omega}(w+\breve{\omega}r)}{p}.$$

Step 2: Given $\epsilon \in (0,1]$, $q \in \mathbb{R}$, and $g \in G$, let $(\tilde{e}^{\ell}, \tilde{k}^{\ell})$ denote the cost-minimal vector for producing q with technology g. There exists $n, N \in \mathbb{N}$ such that if $\bar{\sigma}(g) < 1/n$ and farmer ℓ uses the input vector $(\bar{e}^{\ell}, \bar{k}^{\ell})$ in the solution to the restrictive FOC (11) for some $\gamma \in (0, \Phi\,]$, then (a) $(\tilde{e}^{\ell} - \bar{e}^{\ell}) < \epsilon$ and (b) $\bar{k}^{\ell} < N$.

Proof of step 2:

Fix $\epsilon \in (0,1]$, $q \in \mathbb{R}$, and $g \in G$. For $i = \ell, h$, let $\mathsf{mrs}^{i}(e,k)$ denote the marginal rate of substitution $\frac{f^{i}_{k}(e,k)}{f^{i}_{e}(e,k)}$. Observe first that substituting the expressions for the λ's obtained in (12) into the expression for $\bar{L}_k$ obtained in (11) yields

$$1 - \frac{w}{r}\mathsf{mrs}^{\ell}(\bar{e}^{\ell},\bar{k}^{\ell}) = \frac{\gamma w}{r}\left(\mathsf{mrs}^{\ell}(\bar{e}^{\ell},\bar{k}^{\ell}) - \mathsf{mrs}^{h}(\bar{e}^{\ell},\bar{k}^{\ell})\right) \text{ or, rearranging}$$

$$1 + \frac{\gamma w}{r}\mathsf{mrs}^{h}(\bar{e}^{\ell},\bar{k}^{\ell}) = (1+\gamma)\,\frac{w}{r}\mathsf{mrs}^{\ell}(\bar{e}^{\ell},\bar{k}^{\ell}). \tag{35}$$

Since the left hand side of (35) is bounded below by unity, and $1+\gamma \leq 1+\Phi \leq (1+\breve{\omega})/\breve{\omega}$, the expression $\mathsf{mrs}^{\ell}(\bar{e}^{\ell},\bar{k}^{\ell})$ is bounded below by $\frac{r\breve{\omega}}{w(1+\breve{\omega})}$. Moreover, $\mathsf{mrs}^{\ell}(\tilde{e}^{\ell},\tilde{k}^{\ell}) = \frac{r}{w}$. Pick n, N sufficiently large that $\frac{\hat{e}}{n\breve{\omega}} < \epsilon$ (where $\hat{e}$ was defined on p. 27) while $\frac{\hat{e}}{\breve{\omega}}\left(1-\frac{\epsilon}{\hat{e}}\right)^{-1} < N$. For all (e,k) such that $g(e,k) = q$, we have $-\frac{d(k/e)}{d(\mathsf{mrs}^{\ell}(e,k))}\frac{\mathsf{mrs}^{\ell}(e,k)}{k/e}\Big|_{g\text{ const}} \leq \frac{1}{n}$ so that $\frac{d(k/e)}{d(\mathsf{mrs}^{\ell}(e,k))}\Big|_{g\text{ const}} \geq -\frac{1}{n}\frac{k/e}{\mathsf{mrs}^{\ell}(e,k)}$ and hence

$$\begin{aligned}
\frac{\tilde{k}^{\ell}}{\tilde{e}^{\ell}} - \frac{\bar{k}^{\ell}}{\bar{e}^{\ell}} &\geq -\frac{1}{n}\int_{\mathsf{mrs}^{\ell}(\bar{e}^{\ell},\bar{k}^{\ell})}^{\mathsf{mrs}^{\ell}(\tilde{e}^{\ell},\tilde{k}^{\ell})}\left(\frac{k'/\,e'}{\mathsf{mrs}^{\ell}(e',k')}\right)d\left(\mathsf{mrs}^{\ell}(e',k')\right)\\
&\geq -\frac{1}{n}\frac{\bar{k}^{\ell}\big/\bar{e}^{\ell}}{\mathsf{mrs}^{\ell}(\bar{e}^{\ell},\bar{k}^{\ell})}\left(\mathsf{mrs}^{\ell}(\tilde{e}^{\ell},\tilde{k}^{\ell}) - \mathsf{mrs}^{\ell}(\bar{e}^{\ell},\bar{k}^{\ell})\right)\\
&\geq -\frac{1}{n}\frac{w}{r}\frac{\bar{k}^{\ell}\big/\bar{e}^{\ell}}{\breve{\omega}/\,(1+\breve{\omega})}\frac{r}{w}\left(1-\frac{\breve{\omega}}{1+\breve{\omega}}\right) = -\frac{1}{n}\frac{\bar{k}^{\ell}\big/\bar{e}^{\ell}}{\breve{\omega}} \text{ or}\\
\frac{\tilde{k}^{\ell}}{\tilde{e}^{\ell}} &\geq \left(1-\frac{1}{n\breve{\omega}}\right)\frac{\bar{k}^{\ell}}{\bar{e}^{\ell}} \qquad \text{so that}\\
\tilde{k}^{\ell}\bar{e}^{\ell} &\geq \left(1-\frac{1}{n\breve{\omega}}\right)\bar{k}^{\ell}\tilde{e}^{\ell}.
\end{aligned} \tag{36}$$

Since $\bar{k}^\ell \geq \tilde{k}^\ell$, (36) implies that

$$\tilde{k}^\ell \bar{e}^\ell \geq \left(1 - \tfrac{1}{n\check{\omega}}\right) \tilde{k}^\ell \tilde{e}^\ell \quad \text{so that} \quad \bar{e}^\ell \geq \left(1 - \tfrac{1}{n\check{\omega}}\right) \tilde{e}^\ell \quad \text{and hence}$$

$$\tilde{e}^\ell - \bar{e}^\ell \leq \tfrac{1}{n\check{\omega}} \tilde{e}^\ell \leq \tfrac{1}{n\check{\omega}} \hat{e} \leq \epsilon.$$

Inequality (36), together with the facts that $\bar{e}^\ell < \tilde{e}^\ell$, $\tilde{k}^\ell \leq \frac{\hat{e}}{\check{\omega}}$, and $\frac{1}{n\check{\omega}} < \frac{\epsilon}{\hat{e}}$ imply that

$$\bar{k}^\ell \leq \tilde{k}^\ell \frac{\tilde{e}^\ell}{\bar{e}^\ell} \left(1 - \frac{1}{n\check{\omega}}\right)^{-1} \leq \frac{\hat{e}}{\check{\omega}} \left(1 - \frac{1}{n\check{\omega}}\right)^{-1} \leq \frac{\hat{e}}{\check{\omega}} \left(1 - \frac{\epsilon}{\hat{e}}\right)^{-1} \leq N. \tag{37}$$

■

Step 3: Fix $\epsilon, \delta, \eta > 0$. There exists $n \in \mathbb{N}$ such that if $g \in G$ with $\bar{\sigma}(g) \leq \frac{1}{n}$ and $\mathsf{mrs}^\ell(e^0, k^0) = \eta$, if $k^1 \leq k^0 + \delta$ and if $g(e^1, k^1) \geq g(e^0, k^0)$, then $e^1 > e^0 - \epsilon$.

Intuition for the proof of step 3 is provided by Fig. 5.

1. From the starting point (e, k), move northwest along the budget line to $(e - 0.5\epsilon, k + 0.5\epsilon/\eta)$, labeled as A in the figure
2. Because A lies on the same iso-cost line as (e, k) and $g \in G$ we know that the level set thru (e, k) intersects the ray thru the origin and A at a point to the north east of A. Call this point B.
3. Figure out what $\bar{\sigma}$ has to be to ensure that the gradient vector thru B is proportional to $[2\delta, \epsilon]$, so that as drawn, the tangent plane thru B has slope $\frac{2\delta}{\epsilon}$.
4. Now by the now familiar argument, if we go out along the tangent plane to B, it has to intersect the horizontal line starting at $k + \delta$ at a point to the right of $e - \epsilon$. Call this intersection point C.

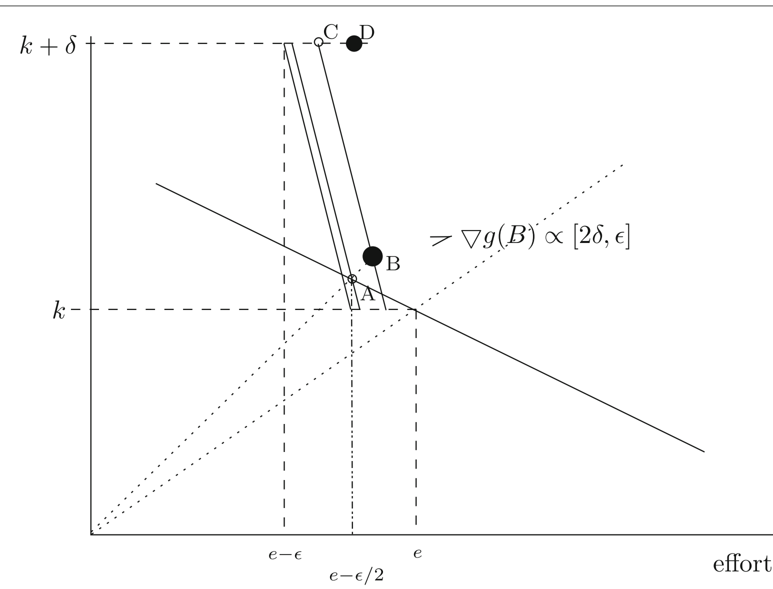

Fig. 5 Intuition for step 3

5. By strict quasi-concavity, the the level set thru (e, k) has to intersect the horizontal line starting at $k + \delta$ to the right of C. Call this point D. Hence, D is a point $k + \delta, e - \omega$, where $\omega < \epsilon$, proving the step.

Proof of step 3:
Given $\epsilon, \delta, \eta > 0$, fix $(e^0, k^0) \gg 0$. Let $\mu^0 = \frac{k^0}{e^0}$ and $\mu^\dagger = \frac{k^0+\epsilon/2\eta}{e^0-\epsilon/2}$. Now, pick $n \in \mathbb{N}$ such that $\frac{\mu^\dagger \eta}{\mu^\dagger + n(\mu^\dagger - \mu^0)} < \frac{\epsilon}{2\delta}$ and a production function $g \in G$ with $\bar{\sigma}(g) \le \frac{1}{n}$ and $\text{mrs}^\ell(e^0, k^0) = \eta$. By construction, the vector $(k^0 + \epsilon/2\eta, e^0 - \epsilon/2)$—which we used to define $\mu^\dagger$—belongs to the line perpendicular to the gradient of g through (e^0, k^0), so that, since g is strictly quasi-concave, $g(e^0 - \epsilon/2, k^0 + \epsilon/2\eta) < g(e^0, k^0)$. Define $(e^\dagger, k^\dagger)$ by the following: $\frac{k^\dagger}{e^\dagger} = \mu^\dagger$ and $g(e^\dagger, k^\dagger) = g(e^0, k^0)$, so that $(e^\dagger, k^\dagger) \gg (e^0 - \epsilon/2, k^0 + \epsilon/2\eta)$. Let $\nu = \text{mrs}^\ell(e^0 - \epsilon/2, k^0 + \epsilon/2\delta)$. Since g is homothetic, $\nu = \text{mrs}^\ell(e^\dagger, k^\dagger)$. Now, for all e, k, we have $\frac{-d(k/e)}{d(\text{mrs}^\ell(e,k))} \frac{\text{mrs}^\ell(e,k)}{k/e}\Big|_{g\text{ const}} \le \frac{1}{n}$ so that $\frac{d(\text{mrs}^\ell(e,k))}{d(k/e)}\Big|_{g\text{ const}} \le -n\frac{\text{mrs}^\ell(e,k)}{k/e}$, and hence

$$
\begin{aligned}
\nu - \eta &= \int_{\mu^0}^{\mu^\dagger} \left(\frac{d\left(\text{mrs}^\ell(e',k')\right)}{d\left(k'/e'\right)}\Big|_{g\text{ const}} \right) d\left(k'/e'\right) \\
&\le -n \int_{\mu^0}^{\mu^\dagger} \left(\frac{\text{mrs}^\ell(e',k')}{k'/e'}\Big|_{g\text{ const}} \right) d\left(k'/e'\right) \\
&\le -n(\mu^\dagger - \mu^0) \frac{\min\left\{ \text{mrs}^\ell(e',k') : \frac{k'}{e'} \in [\mu^0, \mu^\dagger], g(e',k') = q \right\}}{\max\left\{ (k'/e') : \frac{k'}{e'} \in [\mu^0, \mu^\dagger], g(e',k') = q \right\}} \\
&= -n\frac{\nu(\mu^\dagger - \mu^0)}{\mu^\dagger} \qquad \text{so that} \\
\nu &\le \frac{\mu^\dagger \eta}{\mu^\dagger + n(\mu^\dagger - \mu^0)} \quad \text{which is, by assumption} \quad \le \frac{\epsilon}{2\delta}.
\end{aligned}
$$

Now, pick $dk > 0$ such that $[dk, -\epsilon/2]'[g_k(e^\dagger, k^\dagger), g_e(e^\dagger, k^\dagger)] = 0$ so that $dk = \epsilon/(2\nu) \ge \delta$. Since g is strictly quasi-concave, $g(e^\dagger - \epsilon/2, k^\dagger + dk) < g(e^\dagger, k^\dagger)$. But since $e^\dagger > e^0 - \epsilon/2$ and $k^\dagger > k^0$, it follows that $(e^0 - \epsilon, k^0 + \delta) \ll (e^\dagger - \epsilon/2, k^\dagger + dk)$ and hence $g(e^0 - \epsilon, k^0 + \delta) < g(e^\dagger, k^\dagger)$. Conclude that for (e^1, k^1) with $k^1 \le k^0 + \delta, g(e^1, k^1) \ge g(e^0, k^0)$ implies that $e^1 > e^0 - \epsilon$. ■

Step 4: There exists $\delta \in \mathbb{N}$ and $n \in \mathbb{N}$ such that for all $g \in G$ with $\bar{\sigma}(g) \le 1/n$, the level of output under the restrictive contract, using this technology, exceeds by at least δ the level of output under the basic contract.

Proof of step 4:
Let $\delta = \frac{r\check{\omega}\check{e}}{4} \min\left[\frac{\check{d}_q}{w\hat{d}_e}, \frac{\check{\omega}^2}{p}\right]$, where $\check{e}$, $\check{d}_q$ and $\hat{d}_e$ were constructed on p. 27. Invoking steps 2 and 3, pick n sufficiently large that for $i = \ell, h$ and all $g \in G$ with $\bar{\sigma}(g) < 1/n$, $(\tilde{e}^i - \bar{e}^i) < r\check{\omega}^2\check{e}/4\nu$, where $\check{e}$ was constructed on p. 27. Note from Proposition 6 that $(\tilde{q}(\cdot) - \bar{q}(\cdot))$ is negative and continuous on $(0, \Phi]$. Hence, there exists a continuous function $\upsilon : [0, \Phi] \rightarrow [0, \Phi]$, with $\upsilon(\gamma) < \gamma$ on $(0, \Phi]$, such that for all γ, $\tilde{q}(\upsilon(\gamma)) = \bar{q}(\gamma)$. Subtracting (19) from (16), we now obtain

$$\frac{d\bar{q}(\gamma)}{d\gamma} - \frac{d\tilde{q}(\gamma)}{d\gamma} = \frac{1}{p(1-\alpha)}\Big((w\tilde{e}^{\ell}(\gamma) + r\tilde{k}^{\ell}(\gamma))\big(1-\Theta^{1/\alpha}\big) - w(\bar{e}^{\ell}(\gamma) - \bar{e}^{h}(\gamma))\Big)$$
$$= \frac{1}{p(1-\alpha)}\left(\big(1-\Theta^{1/\alpha}\big)\left[r\tilde{k}^{\ell}(\gamma) + \underbrace{w(\tilde{e}^{\ell}(\gamma) - \tilde{e}^{\ell}(\upsilon(\gamma)))}_{\text{Term 1}}\right] - w\left[\underbrace{(\bar{e}^{\ell}(\gamma) - \tilde{e}^{\ell}(\upsilon(\gamma)))}_{\text{Term 2}} + \underbrace{(\bar{e}^{h}(\gamma) - \tilde{e}^{h}(\upsilon(\gamma)))}_{\text{Term 3}}\right]\right). \tag{38}$$

Since $\tilde{\beta}$ is bounded below by $\breve{\omega}$, $r\tilde{k}^{\ell}(\gamma)$ is bounded below by $r\breve{\omega}\breve{e}$. There are now two possibilities to consider:

1. Suppose that $\gamma - \upsilon(\gamma) \geq r\breve{\omega}\breve{e}/(4v\hat{d}_e)$ for some $\gamma^* \in [0, \Phi]$. In this case, since $\upsilon(\cdot)$ is continuous and $\left(\frac{d\bar{q}(\gamma)}{d\gamma} - \frac{d\tilde{q}(\gamma)}{d\gamma}\right)$ is positive whenever $\gamma - \upsilon(\gamma) < r\breve{\omega}\breve{e}/(4v\hat{d}_e)$, it follows that $\gamma - \upsilon(\gamma) \geq r\breve{\omega}\breve{e}/(4v\hat{d}_e)$ for all $\gamma \in [\gamma^*, \Phi]$. But since $|\frac{d\tilde{q}(\gamma)}{d\gamma}| \geq \breve{d}_q$, we have

$$\Phi - \upsilon(\Phi) \geq \frac{r\breve{\omega}\breve{e}}{4v\hat{d}_e} \implies \bar{q} - \tilde{q} = \tilde{q}(\upsilon(\Phi)) - \tilde{q}(\Phi) = -\int_{\upsilon(\Phi)}^{\Phi} \frac{d\tilde{q}(\gamma')}{d\gamma} d\gamma' \geq \frac{r\breve{\omega}\breve{e}\breve{d}_q}{4v\hat{d}_e}.$$

2. Suppose that $\gamma - \upsilon(\gamma) < r\breve{\omega}\breve{e}/(4v\hat{d}_e)$ on $[0, \Phi]$. Since $\left|\frac{d\ddot{e}^{\ell}(\gamma)}{d\gamma}\right| \leq \hat{d}_e$, the absolute value of term 1 is bounded above by $r\breve{\omega}\breve{e}/4v$ whenever $\gamma - \upsilon(\gamma) < r\breve{\omega}\breve{e}/(4v\hat{d}_e)$. Moreover, we have chosen n sufficiently large that terms 2 and 3 are both bounded above by $(r\breve{\omega}^2\breve{e}/4v)$. It now follows from (38) that whenever $\gamma - \upsilon(\gamma) < r\breve{\omega}\breve{e}/(4v\hat{d}_e)$,

$$\frac{d\bar{q}(\gamma)}{d\gamma} - \frac{d\bar{q}(\gamma)}{d\gamma} \geq \frac{r}{p(1-\alpha)}\left(\big(1-\Theta^{1/\alpha}\big)\left[\breve{\omega}\breve{e} - \breve{\omega}\breve{e}/4\right] - \breve{\omega}\left[\breve{\omega}\breve{e}/4 + \breve{\omega}\breve{e}/4\right]\right)$$

but since $\Theta \leq 1 - \breve{\omega}$ and $\alpha < 1$, $\big(1-\Theta^{1/\alpha}\big) \geq \breve{\omega}$, so that

$$\frac{d\bar{q}(\gamma)}{d\gamma} - \frac{d\tilde{q}(\gamma)}{d\gamma} \geq \frac{r\breve{e}\breve{\omega}^2}{4p(1-\alpha)} \geq \frac{r\breve{e}\breve{\omega}^2}{4p}. \tag{39}$$

Since $\Phi \geq \breve{\omega}$, it now follows from (39) that

$$\bar{q} - \tilde{q} \geq \int_0^{\Phi}\Big(\frac{d\bar{q}(\gamma')}{d\gamma} - \frac{d\tilde{q}(\gamma')}{d\gamma}\Big)d\gamma' \geq \frac{r\breve{e}\breve{\omega}^3}{4p}.$$

We have established, therefore, that for all $g \in G$ with $\bar{\sigma}(g) < 1/n$,

$$\bar{q} - \tilde{q} \geq \delta = \frac{r\breve{\omega}\breve{e}}{4}\min\left[\frac{\breve{d}_q}{w\hat{d}_e}, \frac{\breve{\omega}^2}{p}\right].$$

■

Step 5: Proof of the proposition.

From step 4, we can pick $N \in \mathbb{N}$ and $\delta > 0$, such that for all $g \in G$ with $\bar{\sigma}(g) < 1/N$. $(\bar{q} - \tilde{q}) \geq \delta$. From step 2, we can pick $n \geq N$ such that for all $g \in G$ with $\bar{\sigma}(g) < 1/n$, $\bar{e}^{\ell} - \tilde{e}^{\ell} < p\delta\breve{\omega}/w$. We now have

$$\begin{aligned}\Delta\text{SS} &= (p\bar{q} - \bar{C}^P(\bar{q})) - (p\tilde{q} - \tilde{C}^P(\tilde{q}))\\ &= \underbrace{(p\bar{q} - \tilde{C}^P(\bar{q})) \quad - \quad (p\tilde{q} - \tilde{C}^P(\tilde{q}))}_{\text{output effect}} \quad - \quad \underbrace{(\bar{C}^P(\bar{q}) - \tilde{C}^P(\bar{q}))}_{\text{input mix effect}}\\ &= p(\bar{q} - \tilde{q})(1-\alpha) \quad - \quad \left(w(\bar{e}^\ell - \tilde{e}^\ell) + r(\bar{k}^\ell - \tilde{k}^\ell)\right)\\ &\geq p\delta\check{\omega} \quad - \quad w(\bar{e}^\ell - \tilde{e}^\ell) \quad > \quad 0.\end{aligned}$$

■

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Author details
[1]Department of Agricultural and Resource Economics, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA. [2]Department of Agricultural and Resource Economics, University of California, Berkeley, 207 Giannini Hall, Berkeley, CA 94720-3310, USA. [3]Department of Economics, Monash University, Melbourne, Australia.

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