Economics of Agricultural Supply Chain Design: A Portfolio Selection Approach

Xiaoxue Du, Liang Lu, Thomas Reardon, and David Zilberman

Agrifood firms in a globalizing and competitive market, both in developing and developed countries, often undertake innovations in products and technologies. Innovators such as firms and other agents develop supply chains to accommodate the nature of the innovations. In this article we analyze an innovator's supply chain design problem. The design of the supply chain involves three sets of decisions. The first is how much to produce. The second involves how to undertake production, and how many resources to allocate to the production of feedstock (agricultural products that are inputs for processing), processing, and marketing. The third set involves deciding on the amount of feedstock to be obtained through contracts with farmers. We show that the innovator determines its overall level of production by taking advantage of its monopoly power, derived from the innovation in the output market, and behaves as a monopsony in buying feedstock from contractors. These decisions are constrained by the marginal cost of capital and the properties of production and marketing technologies. When the innovator is risk averse, risks in farm production, processing, and marketing will affect both processed output and the share of feedstock bought through contracts.

Key words: Agricultural contracts, innovation, supply chain.

JEL codes: Q12, Q16.

There has been rapid evolution of agribusiness in developed countries (Boehlje and Schrader 1998) and in developing regions (Reardon and Timmer 2012). Agrifood firms in these globalizing and competitive markets often undertake innovations in products and in technologies. Innovations by firms are induced both by technological development in the firm's environment, and by structural and behavioral change on the demand side. Innovation by a firm includes a technical aspect (such as a new or altered type of product, or a new technology), as well as managerial and intra-firm institutional aspects. The firm then commercializes the innovation via a supply chain for the product or technology.

Compared with the supply chain the firm was using before the innovation, after the innovation the firm or other agent typically has to adjust its supply chain design in order to produce and commercialize the innovation. The differentiated product or new technology brings a new set of needs and challenges and opportunities. The adjustment takes place upstream in the firm's input procurement arrangements and production technology, midstream in its processing technology, and downstream in its marketing arrangements based on the nature of the innovation in product or technology it undertakes. These adjustments also occasion tensions that need to be resolved for the innovation to succeed. Sources of tension include capital constraints, risks from its feedstock suppliers or own feedstock production, and risks from wholesalers and retailers. Moreover, the choice of supply chain design does not occur in a vacuum. Rather, the choice is affected by government policies as well as evolving demand and supply forces. As these two sets of conditioners evolve, this will set in motion dynamic

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patterns of output and prices determined by the supply chain.

The problem that we study and the contribution made by the model we present can be situated among several bodies of literature that our work is related to.

The first strand of literature is Coase's theory of the firm (Coase 1937). Coase examined the determinants of the boundary of the firm, including what activities will be done within the firm and what will be bought in the market. He used minimization of transaction costs as a criterion for resource allocation. Evolving from Coase, transaction cost theory holds that firms use different governance strategies (market, intermediate, or hierarchical) to deal with different kinds of exchanges so that the threat of opportunism is minimized, such as vertical coordination (Allen and Lueck 1995; Hennessy and Lawrence 1999; and Franken, Pennings, and Garcia 2009).

The second strand of literature relevant to our modeling is Zusman's work on the importance and evolution of contracts in agricultural economics (Bell and Zusman 1976; Zusman 1982). He emphasized the importance of relationships between parties and analyzed how contracts are established. For example, Knoeber and Thurman (1995), Goodhue (2000), and Hueth and Ligon (2002) analyze the contractual relationship between processors and farmers. Relating contracting and product innovation, Boehlje and Schrader (1998) note that modern industrial agriculture is associated with the use of contract farming by agribusiness firms that introduce differentiated products and secure residual feedstock (beyond their in-house production) through contract farming. These forms of organization were associated with the introduction of new models of agribusiness like the production and processing of broilers, swine, or biofuel, as well as rubber and palm oil in Africa (Ruf 2009).

The above two strands of literature set the stage for but do not formally and fully address the economic problem we are addressing: what is the optimal supply chain choice of the innovator. This question can be furthered decomposed to six detailed choices: (1) how much to produce of the processed product, given capital constraints; (2) looking upstream, whether and how much a firm should grow its own feedstock or buy it from farmers; looking downstream, whether and how much a firm should grow its own marketing services for processed output; (3) if the innovating processor decides to buy feedstock from farmers (or buy marketing services from distribution firms), whether to contract with the farmers (or distribution firms) or buy the feedstock (or services) from them in a spot arrangement; (4) if the processor decides to grow its own its feedstock or marketing services, what technology to use for this; (5) if the processor decides to contract, what design (terms) the contract should have; and (6) how the degree of monopsony and monopoly, as well as government regulation that affects market power, changes or conditions the answers to the first four questions. Coase essentially considered question (2), that is, whether the firm makes or buys, but not the volume. Further, Coase considered whether to contract for the bought input but not the design of the contract. The contract literature considered the design of the contract (question [5]), but not in tandem with whether to contract or even whether to buy input.

These important prior works addressed these component questions but not the overall problem of the innovating firm simply because they were not addressing the innovation firm's meta-question, which is how it will design its overall supply chain to source input, make, and deliver the innovation to market. We thus proceed in this article to formally model the meta-question by linking three essential questions in one systematic treatment. In particular, we answer questions (1), (2), and (6), and our results can hold for any solution for (3), (4), or (5). We expand the analysis to address the situation where the outcome of production both in-house or by contractors is subject to risk.

Static Model

Consider a firm that introduces an innovative product that requires feedstock processing. Let x be final output. To model the innovator's processing investment problem, we follow Spence (1977). We assume the innovator uses capital, k, to construct the processing capacity. We assume for simplicity that one unit of processing capacity requires one unit of capital. Hence, capital and processing capacity are the same thing as long as all capital is used to build processing capacity. Moreover, k, measured in x, must at least match the output level, that is, $k \geq x$.

The innovator can produce the feedstock in-house, x_1, or buy it from farmers, x_2. Note that $x = x_1 + x_2$. $r(k)$ and $C(x_2)$ denote the functions of the cost of capital and the cost of feedstock bought from farmers. We assume $r' > 0, C' > 0$, and allow for the marginal cost of capital and inputs to be increasing. Hence, $r'' \geq 0, C'' \geq 0$. Increasing the marginal cost of capital not only comes from an imperfect physical capital market; here, capital includes physical, human, and managerial capital. Limited access to any kind of capital justifies assuming increasing r'. An innovator with monopsony power over farmers faces an increasing marginal cost of feedstock. We assume the capital used for feedstock production is k_1 with the production function $x_1 = f(k_1)$. $g(x_1)$, the inverse of the production function f, is used to capture the capital requirement for producing x_1. Finally, the revenue function is $R(x)$.

The innovator's decision problem is a two-stage optimization procedure: first, the innovator chooses the optimal "make and buy" combination given the production level; second, the innovator chooses the optimal production level.

The first-stage problem is

$$(1) \quad \min_{x_1, x_2 \geq 0} r(x_1 + x_2 + g(x_1)) + C(x_2), \quad s.t.\ x_1 + x_2 = x.$$

The second-stage problem is

$$(2) \quad \max_x R(x) - V(x)$$

where $V(x) = r(x_1^*(x) + x_2^*(x) + g(x_1^*(x))) + C(x_2^*(x))$ is the minimum cost derived from the first stage.

We begin by analyzing the first stage. A first question is whether the innovator will choose to only grow its own feedstock or to buy it from farmers, or a mix. Lemma 1 provides the conditions under which a mix is not preferred.

Lemma 1. *(Condition for interior solution) If, for all $x > 0$, $g'(x) < \frac{C'(x)}{r'(x)}$, then the innovator will choose to only grow its own feedstock; If, for all $x > 0$, $g'(x) > \frac{C'(x)}{r'(x+g(x))}$, then the innovator will choose to buy from farmers only.*

See supplementary online appendix A.1 for the proof.

Figure 1 illustrates cases limited to corner solutions, that is, the innovator only grows or only buys feedstock but does not mix the two. The dashed curve r_1 is the case where $g'(x) < \frac{C'(x)}{r'(x)}$, and the curve r_2 is the case where $g'(x) > \frac{C'(x)}{r'(x)}$. The two cases are when the innovator either has an absolute cost advantage or disadvantage of growing its own feedstock, with the cost of growing always being above or below mixing, that is, the $c + r$ curve. But when the two curves intersect, as in r_3, an interior solution is possible.

Given that an interior solution is possible, the optimality conditions are:

$$(3) \quad r'(x + g(x_1))(1 + g') = \lambda; \quad r'(x + g(x_1)) + C'(x_2) = \lambda$$

where λ is the Lagrange multiplier for the capacity constraint. Combining the two equations, we have $r'(x + g(x_1))(1 + g') = r'(x + g(x_1)) + C'(x_2)$. We can further rewrite it as:

$$(4) \quad g'(x_1) = \frac{C'(x_2)}{r'(x + g(x_1))}.$$

The first-order conditions imply that, at the optimal feedstock production point, the marginal input requirement for in-house production of feedstock equals the ratio of the marginal cost of feedstock bought from farms to the marginal cost of capital. The intuition for the condition is as follows: if $g'(x_1) < \frac{C'(x_2)}{r'(x+g(x_1))}$, then the innovator could reach the feedstock goal of x by allocating one less unit of feedstock bought from farmers and one more unit of feedstock grown by itself. By doing so, the production plan requires $r' + C'$ less of the cost of purchasing from farms and processing the product, and needs $r'(1 + g')$ of the cost of capital if the innovator produces the one extra unit. Therefore, as long as $g'(x_1) < \frac{C'(x_2)}{r'(x+g(x_1))}$, the original output is still feasible and requires lower cost. If $g'(x_1) > \frac{C'(x_2)}{r'(x+g(x_1))}$, by the same logic, it is efficient to allocate one more unit of x to buy feedstock from farms and one less unit of x to growing it. Thus, when the production plan is optimized, we have $g'(x_1) = \frac{C'(x_2)}{r'(x+g(x_1))}$.

Figure 2 illustrates the input cost minimization problem and the output expansion path. The first quadrant shows in-house feedstock

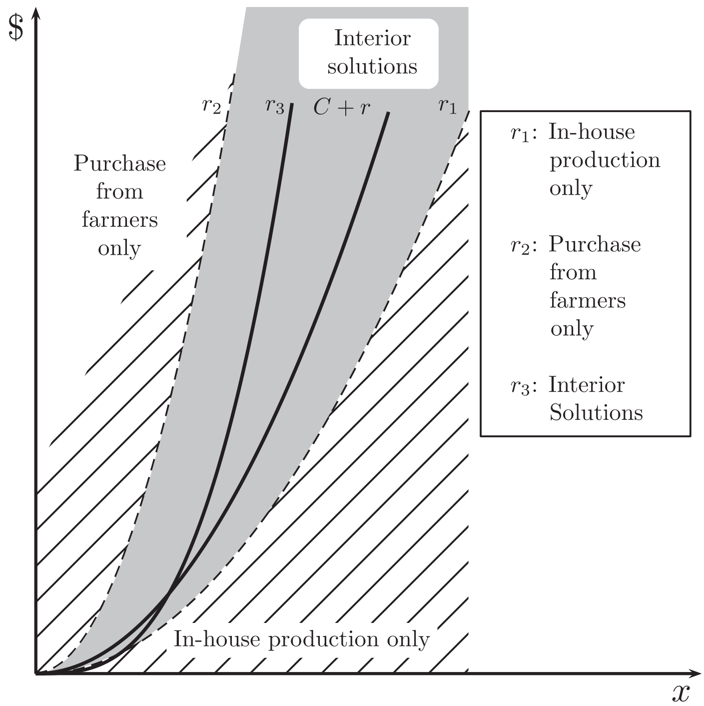

Figure 1 Illustration for buy-only and make-only

production against purchasing feedstock from farmers. For any level of x, the dotted lines determine the isoquants: $x_1 + x_2 = x$. The black dashed curves are isocosts. In the second quadrant, we plot the in-house feedstock production total cost curve $r(x + g(x))$, where the x axis is the dollar amount. Using a 45-degree line, we map this dollar amount to the y-axis in the third quadrant. Finally, in the fourth quadrant, we plot the total cost for the innovator if it is solely relying on farmers for the feedstock. One can easily see how many units of x can be produced if the same amount were not invested in the innovator growing its own feedstock. The following lemma determines the shape of the isocost curves.

Lemma 2. *The isocost curves are concave.*

See supplementary online appendix A.2 for the proof.

The isocost curves are concave because r' and c' are increasing. Thus, on any isocost curve, a mix of the firm's growing feedstock and buying it from farmers incurs a higher cost than doing only one or the other.

Once the isocost shapes are determined, the tangency between isocosts and isoquants yields the optimal input mix.[1] The black solid curve shows the output expansion path.

Recall that the first stage solves the innovator's cost minimizing "make and buy" combination given output. The comparative statics of an exogenous shock on processing capacity is addressed in Proposition 1.

Proposition 1. *As processed output increases, the innovator will buy more feedstock from farmers unless $r'' = g'' = 0$; the innovator will make more if $\epsilon_{C'} > \epsilon_{r'}$, where $\epsilon_{C'}$ is the elasticity of marginal cost of buying feedstock from farmers and $\epsilon_{r'}$ is the elasticity of the marginal cost of capital.*

See supplementary online appendix A.3 for the proof.

Proposition 1 says that as long as the marginal cost of the firm's growing its own feedstock is increasing, either due to increasing marginal cost of capital or decreasing marginal product, processed output expansion

[1] Note that when the isocost and isoquant curves are tangent, the slope of the isocost curve is $-\frac{C'+r'}{r'(1+g')}$, as we know from the proof of lemma 2. The slope of the isoquant line is –1. Therefore, when the two slopes equal, we have $\frac{C'+r'}{r'(1+g')} = 1$, which is the first-order condition of the input cost minimization problem.

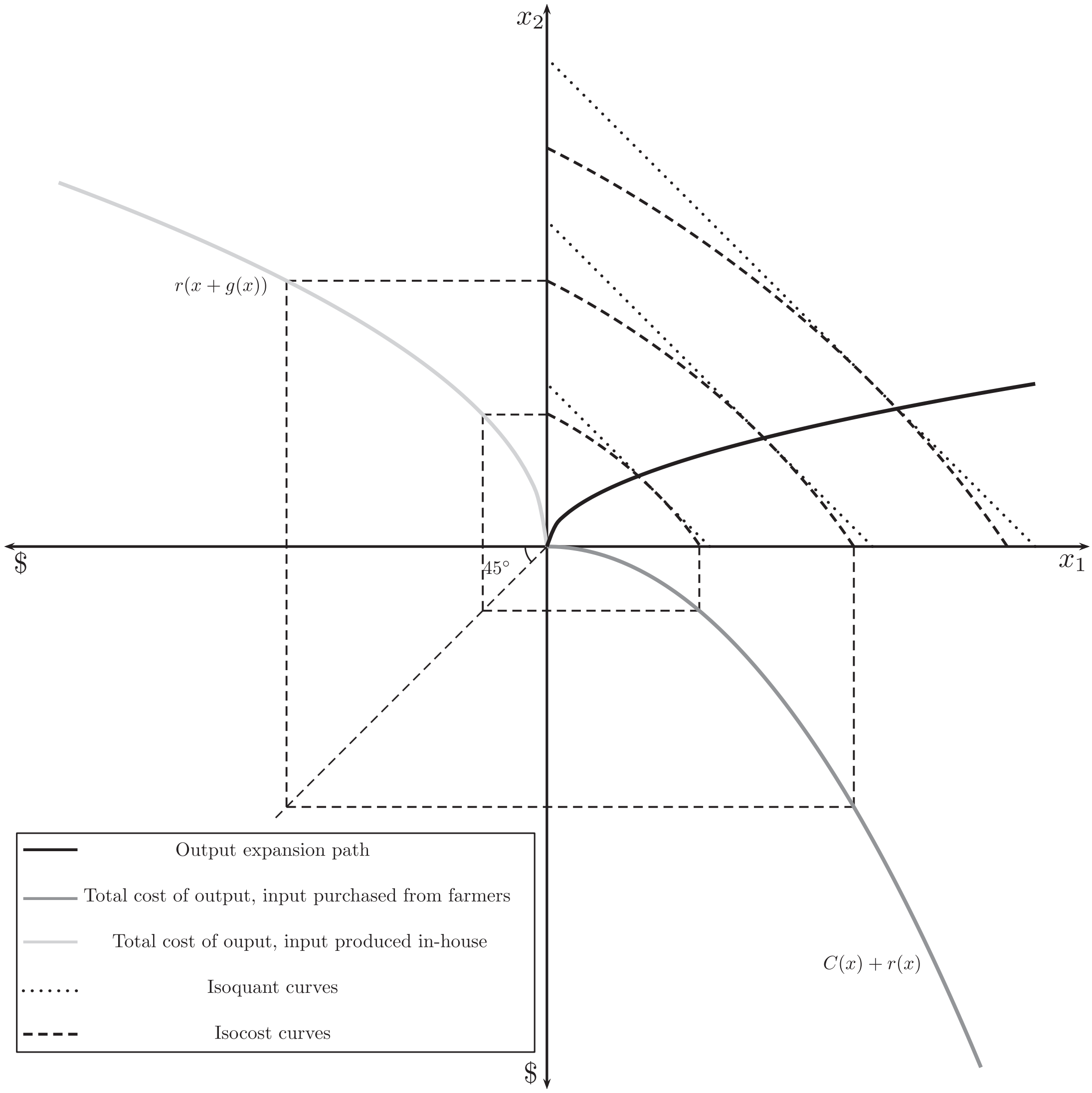

Figure 2 Output expansion path

involves more feedstock bought from farmers.[2] Moreover, whether the innovator grows more of its own feedstock depends on whether this has a cost advantage. In other words, when $\epsilon_{C'} > \epsilon_{r'}$, the cost of buying the feedstock from farmers is increasing faster than the cost of feedstock grown by the innovator, giving the innovator a cost advantage in producing feedstock in-house as processing capacity increases. This implies a relative cost advantage, as opposed to absolute advantage wherein the innovator could produce the feedstock at a lower cost for any capacity level. For an extra unit of processed output, the marginal cost of feedstock from farmers is C'', but the marginal cost from own-production of feedstock is $r''g'$. Thus, the $\epsilon_{C'} > \epsilon_{r'}$ condition indicates that although the innovator does not have an absolute cost advantage to produce its own feedstock, own-production becomes more plausible after processed output reaches some critical level as C' increases more rapidly than r'. Again, from figure 2, we can see that x_1 might increase as x increases.

Proposition 1 implies that contracting with farmers allows an innovating processor to overcome capital scarcity. The case of Tyson

[2] Note that $g'' > 0$ is equivalent to $f'' < 0$, that is, a decreasing marginal product.

Foods illustrates this. Tyson conceived of a new way of processing chicken, to sell parts rather than sell the whole frozen chicken. Tyson wanted to increase market share and needed to produce more chicken parts. They faced the issue of how many resources to put into building processing facilities versus growing its own feedstock. Tyson had the constraint of fixed resources: the Bank of America only approved them for a 1 billion dollar loan. Tyson decided to invest most of that in marketing and processing and buy chicken from farmers rather than producing their own chicken, so that they could capture a larger market. Our proposition implies that the elasticity of the marginal cost of capital was relatively large for Tyson.

The motivation and arrangements of contracting farmers as reflected in the Tyson case are common for firms in developing countries as well. Deb and Suri (2013) shows that in the 1990s, pineapple exporters in Ghana found sea shipments to be cheaper than air shipments. That induced shippers to contract farmers to get large volumes of fruit. Suzuki, Jarvis, and Sexton (2011) found that these exporters partly grew their own pineapples and partly bought them from contracted farmers. Here, the new shipping technology reduces $\epsilon_{C'}$, and we thus observe the emergence of contracts as the proposition predicts.

In the second stage, the innovator solves

$$(5) \quad \max_x \; R(x) - V(x).$$

The first-order condition yields: $R' - V' = 0$. Using the envelope theorem, $V' = \lambda^*$, where λ^* is the shadow price of output x at the optimal production portfolio. To explore how a demand shifter would change the equilibrium, let θ be a demand shifter such that $R = R(x, \theta)$ and $R_\theta > 0$. We have the following proposition to characterize the comparative statics:

Proposition 2. *(Innovator's market power over upstream or downstream)*

a) If the processor-innovator does not have monopsony power over farmers, then the innovator will grow less of its own feedstock as processing capacity increases. If the innovator faces a constant marginal cost of capital, then the innovator will always produce more of its own feedstock as processing capacity increases.

b) If the innovator has monopoly power over downstream buyers, it will buy more feedstock from farmers and will produce more (less) feedstock in-house if $\epsilon_{C'} - \epsilon_{r'} > 0 (< 0)$.

See supplementary online appendix A.4 for the proof.

The standard monopsony model shows that a firm that has monopsony power over input providers will reduce input use to gain monopsony profit from a lower input price. In our model, when an innovator has market power over farmers, it would acquire less feedstock from farmers to exploit its market power. But the innovator faces the constraint of obtaining adequate feedstock. The innovator will then rely more on its own production of feedstock. Therefore, when market power is eliminated, the optimal business model would involve buying more feedstock from farmers. Moreover, when the marginal cost of capital is not increasing, the innovator could grow more of its own feedstock without facing higher additional costs. Thus, the innovator would make more in-house when $r'' = 0$.

An example of diminishing market power is the case of Shuanghui, the largest pork processor in China.[3] Shuanghui is seeking greater market share for high-end pork products. Although Shuanghui has substantial market power over farmers for commodity hogs, it has little monopsony power over farmers for the high-quality variety of hogs. Thus, Shuanghui eschews raising pigs and instead sought a partner for high-quality pig production, leading to its acquisition of Smithfield Foods in 2013.

Figure 3 provides an illustration for part (b) of proposition 2. As demand shifts from D to D', the innovator expands its processed output. From proposition 1, we know that the innovator will buy more feedstock from farmers. In figure 3, the optimal production expansion $x_1^*(x)$ and $x_2^*(x)$ are illustrated by the black and gray curves. The figure shows that the innovator buys from farmers and grows less of its own feedstock as $\epsilon_{C'} < \epsilon_{r'}$.

Proposition 2 is especially pertinent to "make or buy" decisions when a new product is increasingly adopted by consumers. The innovator has to increase processing capacity. If the marginal cost of capital is increasing, the marginal cost of producing its own feedstock must increase as well. This means that $\epsilon_{C'} < \epsilon_{r'}$

[3] This example is from Zhang, Y., X. Rao, and H.H. Wang. 2016. Organization and Technology Innovations through Acquisition in China's Pork Value Chains: A Retrospective Examination of the Smithfield Acquisition by Shuanghui. Unpublished, Zhejiang University.

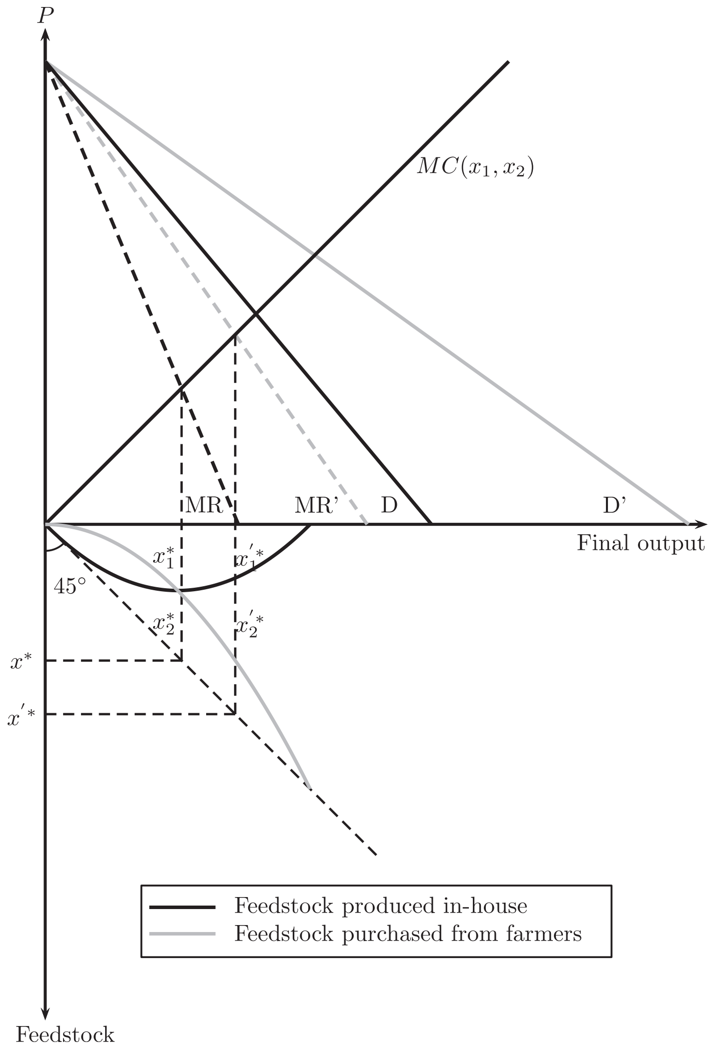

Figure 3 Optimal production plan as demand expands

is more likely and less production of feedstock in-house by the processor would occur.

If the processor-innovator has market power over farmers, $\epsilon_{C'}$ is larger. The innovator is then a middleman in the market. The concept of middlemen is discussed in Lerner (1934), Just, Schmitz, and Zilberman (1979), and Vercammen (2011). The middleman model shows that when a firm has both monopoly and monopsony power in the market, production is reduced even further and the profit margin is higher than where the firm has only one form of market power. In our model, when the innovator has monopsony power over farmers and the marginal cost of capital is not rising too rapidly, we will observe more production by the innovator of its own feedstock as the innovator reduces the purchase of feedstock from farmers to exercise its monopsony power. Overall, proposition 2 suggests that the innovator responds to a demand shock by changing how it sources feedstock. In our deterministic setting, the key factors that drive the decision are the firm's capital access and whether it has monopsony power over its suppliers. When the innovator faces both of the factors, then the relative magnitudes of $\epsilon_{C'}$ and $\epsilon_{r'}$ matter.

This proposition may help to explain different supply chain governance structures (organization and institutions) over firms in the U.S. broiler industry. Tyson and Perdue tend to use contracts with poultry farmers while Foster Farms is vertically integrated (producing feedstock and processing). Tyson tends to use contracts in the United States but it uses vertical integration, producing birds and processing in China. A plausible explanation is that Foster Farms was started by turkey farmers, while Tyson was started by truckers, and Perdue was from the beginning specialized in selling genetic material to farmers. Foster Farms emphasized bird quality and it appears it did not want to risk compromising that quality by contracting out bird production. They thus operate at a relatively small scale in the United States but use vertical integration. For Perdue and Tyson, expansion was important, and therefore they moved to contract farming. Here, the difference between Tyson and Foster Farms can be mainly explained by $\epsilon_{r'}$: when a firm emphasizes expansion, the elasticity of marginal cost of capital is higher.

When Tyson introduced the innovation of modern chicken processing technology in China, although vertical integration reduced its expansion rate, the benefit from the consumer perception of higher quality offset the cost of limiting the rate of expansion. But to deliver higher-quality chicken, $\epsilon_{C'}$ is higher. Again, our proposition predicts what is happening: Tyson relies more on vertical integration in China. In both cases, introducing a new technology together with the processor's core competence shaped the final structure of governance.

Uncertainty

We now consider an innovator's decision under uncertainty. The uncertainty may come from several sources: (i) demand uncertainty is often associated with new product introduction; (ii) processing uncertainty is most pertinent when a new processing technology is invented, such as new biofuel refining technology; (iii) feedstock production uncertainty such as stochastic weather is faced in both in-house production of feedstock and purchase from farmers; (iv) contract uncertainties may occur due to asymmetric information—the innovator may not observe the ability of and effort being devoted by the contracted supplier.

Let θ_1 be a random disturbance term that affects demand. We assume that the revenue function is of the form $\theta_1 R(x)$. To keep the solution tractable, we add the assumption that the function $r(x+g(x))$ is additive separable, that is,

$$(6) \quad r(x+g(x_1)) = r(x) + r(g(x_1)).$$

We use $C_1(x_1)$ to denote $r(g(x_1))$, which is the total cost of producing x_1. The assumption is essentially saying that the total in-house cost is the sum of the processing cost and the in-house feedstock production cost. We use the random variable θ_2 to denote the random fluctuation of the processing cost, and θ_3 the randomness of in-house feedstock production costs. The total in-house cost is thus $\theta_2 r(x) + \theta_3 C_1(x_1)$. Finally, θ_4 is the stochastic variation of the outsourced (bought from farmers) feedstock production cost. In sum, the innovator's profit can be written as

$$(7) \quad \pi = \theta_1 R(x) - \theta_2 r(x) - \theta_3 C_1(x_1) - \theta_4 C_2(x - x_1).$$

For all $i = 1,2,3,4$, θ_i are such that $E\theta_i = 1$, $Var\theta_i = \sigma_i^2$. The correlation coefficient between θ_i and θ_j is ρ_{ij}. To write the summation more tightly, we redefine $f^1(x) \equiv R(x)$, $f^2(x) \equiv -r(x)$, $f^3(x_1) \equiv -C_1(x_1)$, $f^4(x,x_1) \equiv -C_2(x-x_1)$. Then we can rewrite $\pi(x,x_1) = \sum_i \theta_i f_i$, where the expected profit is

$$(8) \quad E\pi(x,x_1) = \sum_i f^i$$

and the variance of profit is

$$(9) \quad \sigma^2(\pi(x,x_1)) = \sum_{i=1}^{4}\sum_{j=1}^{4} f^i f^j \sigma_i \sigma_j \rho_{ij}.$$

In the general case, the innovator has a risk preference over the random events. We use $U(\pi)$ to denote the innovator's utility of profit with $U'(\pi) > 0, U''(\pi) < 0$. Assuming $U(\pi)$ has Constant absolute risk aversion (CARA) with an absolute risk aversion parameter, r, the maximization of expected utility, is equivalent to the following problem:

$$(10) \quad \max_{x,x_1} \; E\pi(x,x_1) - \frac{r}{2}\sigma^2(\pi(x,x_1)) \; s.t \quad 0 \le x_1 \le x$$

where the constraint comes from the fact that both in-house (by the innovator) feedstock production and contract production $x_1, x - x_1$ are non-negative and cannot exceed the processing capacity x.

In the deterministic case, there is a well-established equivalence between the two-stage problem we set up and the simultaneous decision problem where the innovator chooses processing capacity and the feedstock sourcing plan at the same time. However, in the uncertainty case, the equivalence does not apply due to the potential correlation between cost-side uncertainty and demand-side uncertainty. The Lagrangian for the problem is

$$(11) \quad \ell = E\pi(x, x_1) - \frac{r}{2}\sigma^2(\pi(x, x_1)) + \mu_1 x_1 + \mu_2(x - x_1).$$

Our formulation is closely related to Just and Zilberman (1983), in which the theoretic framework considers decisions under two sources of uncertainty with a capacity constraint. In our model, the capacity is endogenously determined, and as we take a supply chain approach, we also consider possible correlation between the demand-side and cost-side uncertainty. The Just and Zilberman (1983) model can be viewed as the innovator's first-stage problem.

The First order condition (FOC) gives

$$(12) \quad \sum_i f_x^i = \frac{r}{2}\sum_{i=1}^{4}\sum_{j=1}^{4}(f_x^i f^j + f^i f_x^j)\sigma_i\sigma_j\rho_{ij} - \mu_2$$

and

$$(13) \quad \sum_i f_{x_1}^i = \frac{r}{2}\sum_{i=1}^{4}\sum_{j=1}^{4}(f_{x_1}^i f^j + f^i f_{x_1}^j)\sigma_i\sigma_j\rho_{ij} - (\mu_1 - \mu_2).$$

In general, this framework still allows the possibility to discuss the discrete choice of whether the innovator solely relies on vertical integration, adding own-production, or outsourcing to secure its feedstock. Further, $\mu_1 = 0, \mu_2 > 0$ indicates vertical integration, while $\mu_1 > 0, \mu_2 = 0$ implies all feedstock production comes from farmers. Finally, $\mu_1 = \mu_2 = 0$ indicates a mix of "make and buy" sourcing of feedstock. However, the general framework needs further simplification for meaningful discussion. Here, we consider several special cases of the general model.

Case 1. No correlation among the random variables. ($\rho_{ij} = 0$ for all i, j)

In this case, the general conclusions of Sandmo (1971) apply. Under either demand uncertainty, or processing or feedstock production uncertainties, expected feedstock production is less than in the case of certainty. However, whether the decline in feedstock production only happens for feedstock production by the innovator, or for contracted feedstock production by farmers, or total production decreases, depends on the source of the uncertainty. In particular, if demand or processing technology are uncertain, then both in-house and contracted feedstock production will be below the production level when there is no uncertainty present. But if the uncertainty comes only from feedstock production, then contracted production will decrease and own-production of feedstock may be above or below the certainty case. The intuition behind this scenario is that the firm may choose to diversify its production sourcing under certainty. However, when there is uncertainty due to asymmetric information, the consequence is two-fold: the innovator will reduce total production; but it may choose to use only own-production of feedstock if the uncertainty is too high.

The key notion from case 1 is that, when we apply Sandmo's model to supply-chain design, the type and source of uncertainty matters. It is not hard to imagine that, for example in the winery sector, feedstock production risk due to weather fluctuations is relatively high but the processing technology is more or less established. In the case of second-generation biofuel, the processing technology is uncertain and the contracting cost with farmers is uncertain as well. It should also be noted that a well-designed contract will reduce or even eliminate the uncertainty that comes from asymmetric information, which we discuss in case 2.

Case 2. θ_3 and θ_4 significant, θ_1 and θ_2 negligible.

In this case, θ_3 is production uncertainty, and θ_4 includes both production and contract uncertainty. We assume that the uncertainty in feedstock production from farmers, θ_4, is a mean-preserving spread of θ_3: let θ_5 be a random variable, which can be interpreted as the randomness in contracting itself, with zero mean such that

$$(14) \quad \theta_4 = \theta_3 + z\theta_5$$

where z is an arbitrary given parameter. We assume that as optimal contract design is being implemented, the influence of θ_5 on total risk from purchasing feedstock is reduced, that is, $z \to 0$. Thus, one must have $\sigma_4^2 \to \sigma_3^2$, $\sigma_{34} \to \sigma_3^2$.

We hypothesize that optimal contract design will increase total feedstock production. As the latter expands, more (less) feedstock will be produced in-house if $\sigma_4^2 - \sigma_3\sigma_4\rho_{34} > (<) 0$. This result is closely related to Just and Zilberman (1983), wherein, under a capacity constraint on fixed feedstock use, the correlation between different sources of uncertainties matters and may have an impact on the firm's choice. In our model, we extend the model of Just and Zilberman (1983) by allowing for endogenously determined optimal capacity. One way to look at our model is that it is a combination of Just and Zilberman (1983) and Sandmo (1971) where the conclusions of the Just and Zilberman (1983) model apply to the portfolio selection of feedstock production sources, which is the first stage of the firm's problem, and the propositions in Sandmo (1971) apply to the firm's second-stage problem.

The first part of our hypothesis above, that optimal contract design increases total feedstock production, requires the assumption that better contract design reduces contract uncertainty. This assumption is relatively mild and is well-established in the contract design literature. For instance, in a signaling game where the principal does not observe the agents' abilities, optimal contract design allows for a separating equilibrium where agents will truthfully report their types. As a consequence, σ_4^2 becomes smaller. However, it does not necessarily mean more feedstock will be produced through contracts, as better contract design also increases ρ_{34}.

The second part of the hypothesis above shows that risk affects whether an innovator would choose to produce in-house or contract: it affects the share of contracting. At the same time, not only do different types of risks matter as we have shown in case 1, but as insights from Just and Zilberman (1983) suggest, the correlation between the two disturbances matters. Namely, the sign of $\sigma_4^2 - \sigma_3\sigma_4\rho_{34}$ governs whether more feedstock will be produced in-house as total production expands.

Case 3. θ_2 and θ_3 are significant, θ_1 and ρ_{34} are negligible.

A motivating example comes from biofuel refining. The refining technology is uncertain. Rubber producers in Africa and Malaysia face decisions on how to allocate resources between processing facilities versus farming (Wang, Wang, and Delgado 2014). They can produce more rubber if they rely on contracted farmers; but then the rubber company must face uncertainty about supply reliability. Thus, the decision about the magnitude of the purchase from contracted farmers is important. Another case comes from palm oil in Africa: again, to what extent should an investor allocate resources to processing or to secure feedstock supply by investing in own production of feedstock? Large fruit and vegetable export operations face similar decisions: how much processing capacity to build and how much to invest in own-production.

Conclusions

Implementing new agricultural innovations frequently requires the establishment of a supply chain that includes the production of feedstock, which is then processed to obtain the final product. This article analyzes the optimal supply chain design problem, in particular the volume of the final output produced and the extent to which the feedstock is purchased from suppliers versus produced in-house. We model the supply chain design problem as a constrained profit-maximizing or expected utility maximization problem, where the constraints can be interpreted as credit or capital constraints, as well as human capital constraints. The innovator frequently has significant monopoly power in the final output market and monopsony power in the feedstock market. We find that stricter constraints lead to reduced overall operation, and may lead to increased reliance on contract farming rather than in-house production. The volume of output and the extent of reliance on purchased inputs are also dependent on the market power in the final product market and the feedstock market.

We also analyze how risks affect an innovator's decision. Understanding the source of risks and correlation among those risks are important in shaping the supply chain. For example, both the final output and the extent of reliance on external feedstock suppliers are likely to decline the more risky is sourcing from these farmers, and the more risk averse the innovator. Our analysis develops testable hypotheses about important choices of agribusiness firms. In addition, our analysis can be applied to case studies such as the evolution of the poultry industry and the constraints that led companies like Tyson to establish contract-farming arrangements.

There are several future directions in which our model can be extended. First, it can be expanded to address the development of more complex supply chains. An example would be where the entrepreneur has to decide about overall production of a product, allocation of feedstock production among different sources, and allocation of the output among different marketing channels. The latter involves understanding the choice of the appropriate channel to market the processed product: for example, how much of it would be sold direct to supermarket chains, to wholesalers, or direct to traditional retailers.

Finally, our modeling framework could be used to analyze the evolution of agricultural and agribusiness sectors in various locations over time, as new innovations give rise to new markets and supply chains, and lead to the transformation of existing practices and resource allocation patterns.

Supplementary material

Supplementary material is available online at http://oxfordjournals.org/our_journals/ajae/.

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