Supply Chain Design and Adoption of Indivisible Technology

Liang Lu, Thomas Reardon, and David Zilberman

Abstract

In this paper, we develop a framework to analyze adoption of indivisible technologies by relatively small farms using a threshold diffusion model. It shows that different supply chains may emerge to enable the adoption of indivisible technologies. Independent technology dealers may buy the indivisible equipment and rent it to farmers, when the gain from adoption is not affected by scale or ownership of the technology. Also, larger farmers may buy the technology equipment and rent it (renting the machine per se or providing a set of services that includes use of the machinery for the farmer buying the service) to smaller farmers, especially when there are gains from scale or ownership. The paper derives equilibrium prices and quantities in the output, equipment, and technology rental market. These equilibrium prices and quantities depend on the heterogeneity of farmers and the features of the technology. Introduction of the new indivisible technology will benefit larger adopting farmers and consumers but may hurt non-adopters. We illustrate our conceptual findings with empirical examples.

Keywords: Supply chain, Technology adoption, Threshold model, Agricultural services, Farm mechanization.

JEL Classification Numbers: Q12, Q18.

Introduction

The farm household literature on technology change has focused on the incentives for and capacity of farmers to adopt new inputs. The new inputs were seen as objects that embody technology change. Some of the inputs are divisible, like fertilizer or seed, and some are indivisible or lumpy, like tractors.

A substantial and early literature formed on the diffusion of indivisible input technologies, for example concerning the rapid diffusion of tractors in the US from the mid nineteenth to the mid twentieth centuries, substituting for animal draft power. This diffusion was conceived at first as a threshold investment based on break-even points linked to a critical farm size (David 1966). The analysis of David (1966) was criticized by Olmstead and Rhode (1995) who noted that the threshold literature had ignored the possibility that small and/or capital-poor farms would demand tractor services but not buy tractors, and that large and/or capital-rich farms would buy tractors and use them on their own land and provide tractor services to other farms with the surplus capacity of the machines. Olmstead and Rhode (1995) and Olmstead and Rhode (2001) showed instead that the demand and supply of such services were widespread; the service diffusion explained why many small farms used tractor services without owning, and many farmers with holdings below the break-even farm size threshold to own a tractor actually bought tractors with the aim of service provision. Allen and Lueck (2004) showed that teams of men with tractors moved across American farmland to provide these services to small farms whose owners eventually bought their own tractors. Moreover, Wolf, Just, and Zilberman (2001) showed that provision of services to not be only that of lumpy physical capital, but also of intangible services like information systems.

The survey by Feder, Just, and Zilberman (1985) reviews early case studies in developing countries where adoption of lumpy technologies was feasible through rental arrangements, citing Staub and Blase (1974) and Alviar (1972) for hired tractor services in Thailand and the Philippines. There are recent cases of such arrangements such as for combine rental services in China, Vietnam, and India (Reardon et al. 2014), cross-province mobile combine services for rice in China (Yang et al. 2013), and "sprayer-trader" services for mango in Indonesia (Qanti, Reardon, and Iswariyadi forth-

coming); these recent cases are used as illustrations for theoretical propositions presented in this paper.

The interest and importance of the emerging empirical cases of custom service provision highlight the need for a systematic theoretical model of demand and supply of these services. Despite the "opening of a conceptual door" by Feder, Just, and Zilberman (1985) and Sunding and Zilberman (2001) to modeling custom services, the technology change literature has, however, rarely (with a few empirical exceptions noted above) modeled farmers' demand for agricultural services such as plowing or harvesting services by tractor management firms. Moreover, the farm household and the agricultural enterprise literature have not modeled the supply of agricultural services, to wit, the supply chain of these services. Even the supply chain/value chain literature seldom models the input provision segments, and never the agricultural service provision segments.

To fill that gap in the literature is the purpose of this paper. We argue that the most appropriate model to use as a basis for this is the generalization of the David (1966) model by Sunding and Zilberman (2001). The latter includes three elements: decision criteria of a micro unit (profit maximization, utility maximization, etc.), sources of heterogeneity of the micro unit, and dynamic processes that affects the system (such as learning-by-dong, learning-by-using, change in price). This threshold model results in an S-shaped diffusion curve as a function of time. The generalized threshold model has not yet been applied to model the diffusion of indivisible technology.

The two key messages of the paper are as follows.

First, the emergence of agricultural machinery rental services (either as rental of a machine or as provision of a set of services that include the use of the machine, the lumpy technology) allows the possibility of separation between technology adoption decisions and machinery ownership decisions, which reconciles the differences between threshold model predictions in David (1966) and stylized facts in Olmstead and Rhode (1995).

Second, supply chains (such as the supply chain of provision of services, for example grain combine services, orchard spraying services, land preparation, irrigation management, product processing, and product marketing) can be viewed as mechanisms to address indivisibility of tech-

nology that are embodied in machinery. The size and shape of the supply chain and the evolution of the service provision industry's structure depends on the nature of technology.

In this paper, we develop various models to demonstrate how the features of the technologies involved affect the shape of the supply chain of the provision of custom services. The models in this paper will be applied to model the diffusion of new technologies, and alternative supply chain introduced to distribute these technologies. To our knowledge, this is the first conceptual paper that models the demand and supply of custom agricultural services, and demonstrates the link between the threshold model for technology adoption and the development of supply chains for agricultural services.

This paper proceeds as follows. First, we use the stylized facts of the above arrangements as the foundation to lay out a model of the demand and supply of agricultural services in situations where the technology requires a lumpy investment, and there are heterogeneous farmers in terms of land quality. From individual choices, we develop the threshold condition for service adoption. We show that the set of parameters that leads to adoption includes output price, land rent, and profitability of traditional technology. Then we depict the joint market equilibrium of the markets for the final agricultural product, the machinery rental service, and the equipment itself. We also use comparative statics to show that technological change and policies of various types affect adoption. For instance, if a policy such as a farmers field school improves the utilization of the traditional technology, then there is less use for the modern one (pesticides application by specialized agents for example). On the contrary, if the government extension service increases farmers' awareness of a problem addressed by indivisible technology (awareness of pests of various types for example), then its adoption increases. We also consider other sources of heterogeneity such as farm size. We provide suggested future research and discussion in the conclusion section.

Model

Defining the equilibrium concept

In the model section, we will first discuss the general framework of machinery service supply chain equilibrium. Here, we define the market equilibrium to be a three-way equilibrium. Namely, the three markets clear jointly; those markets are the market for final agricultural output, the market for machine rental services, and the market for machine purchase. These equilibrium conditions implicitly determine the output price, rent for services, and price of the machinery. The framework is addressing the adoption of indivisible technology by either owning or renting. We consider heterogeneity among farmers, which is consistent with the threshold model. Output is a function of technology of technology adoption, ownership decision (adopters could own the machine or renting the machine), farmer attributes as well as farm characteristics, which are sources of heterogeneity (which can be land quality, rainfall, human capital of the farmers, etc). For simplicity, our model does not consider farmers' decision on variables inputs use, but the model can be expanded to consider such inputs following the formulation of Hellegers, Zeng, and Zilberman (2011).[1]

After the introducing the general equilibrium concept, we will provide a series of different specifications on the general framework. In the first case, we consider the most simplified version of the model where output is not affected by scale and the only source of heterogeneity is land quality. For simplicity, in the first case, we only allow third party providers to offer the machine rental service and no farm is big enough to justify purchasing the machine. Using comparative statics, we show the response of adoption decisions, both individual and aggregate, to a series of exogenous shocks. Then, we relax the assumptions in the first model, in case 2, we consider a scenario that output is indeed affected by scale and the source of heterogeneity comes from both farm size and land quality. However, we do not allow for the possibility that productivity is affected by ownership decision. Finally, in case 3, we relax the condition and allow for output production affected by ownership decision. In the latter two cases, we discuss both adoption and ownership patterns of machinery.

Consider a farming area where each farmer is endowed with a vector of attributes and farm characteristics $\boldsymbol{x} = (x_1, x_2, \ldots, x_n, L)$ that are the source of heterogeneity in the threshold model. Each x_i stands for a certain farmer's attribute or farm characteristics and L stands for farm size. The attributes could be the farmer's wealth, human capital, ability to use machinery, and so on. Farm characteristics may include factors such as land quality, rainfall abundance, or pest pressure. The joint density function of these attributes and characteristics is denoted by $f(\boldsymbol{x})$. Following the formulation of Caswell and Zilberman (1986), we use $h_i(\boldsymbol{x}, s)$ to denote the farmer's yield per acre as a function of the attributes $\boldsymbol{x}$, machinery adoption choice i and some productivity shock s, where $i = 0, 1$. $i = 0$ indicates the farmer does not adopt machinery and $i = 1$ means the farmer adopts machinery. In a similar fashion, we can define farmers' ownership decision j, where $j = 0, 1$. $j = 0$ indicates a farmer choose to rent the machine and $j = 1$ means the farmer buys the machine. Clearly, the decision j is only triggered when farmer chooses to adopt the machinery, i.e., $i = 1$. The demand of the agricultural output is $D(p)$ where p is the output price and the supply function for the machine is $S(I, r, M)$ where I is the cost of machine, the capacity of the machine is M acres of land, the per acre cost of the machine is denoted by r. For simplicity, we assume that the maximum farm size $\bar{L}$ is smaller than the capacity of machine M.

For simplicity, we assume profit maximizing behavior for farmers but the analysis can be generalized to include other criteria such as expected utility maximization or safety rule under uncertainty. We use π^d to denote a farmer's profit under decision d where $d = i(j + 1)$. Clearly, $d = 0$ as long as $i = 0$, which means the farmer does not adopt the machinery. $d = 1$ occurs if and only $i = 1, j = 0$, which indicates the farmer uses the machinery through renting-in. $d = 2$ happens if and only if $i = 1, j = 1$, which means that the farmer uses the machinery through buying. The farmer's profit is a function of output price, machine rent, machine cost, and other shocks. i.e., $\pi^d = \pi^d(\boldsymbol{x}, p, r, I, s)$. Under this notation, we can easily define the set of adopters, renters, and buyers. Let X be the set of farmers. The set of adopters A is all the farmers such that using the machinery, either through renting-in or buying, achieves higher profit than not using it: $A = \{\boldsymbol{x} \in X | \pi^1 > \pi^0 \ or \ \pi^2 \geq \pi^0\}$. Then the set of non-adopters is the complement of A: X/A or

A^c. In a similar fashion, one can define the set of renters R: $R = \{x \in X | \pi^1 \geq \max\{\pi^2, \pi^0\}\}$ and the set of buyer B: $B = \{x \in X | \pi^2 \geq \max\{\pi^1, \pi^0\}\}$. Clearly, we have $B \cap R = \emptyset, B \cup R = A$.[2]

Now we are able to define the market equilibrium condition. The total final output, denoted by Q_O^s is all the production under yield function h_1 for adopters and h_0 for non-adopters.

$$(1) \quad Q_O^s(p, r, I, M, s) = \int_{x \in A} h_1(x) f(x) L dx + \int_{x \in A^c} h_0(x) f(x) L dx.$$

It should be noted that Q_O^s is a function of p, r, I, M, s because these variables/parameters could affect the farmer's profit and, consequently, affect the adoption set and the value of the integral. The aggregate demand for machine rental services, denoted by Q_R^d is the integral over the acreages of the renters' set:

$$(2) \quad Q_R^d(p, r, I, M, s) = \int_{x \in R} f(x) L dx.$$

To find the aggregate supply of rental services, we assume that if farmers who are buying the machines have idle machine capacity, i.e. $M > L$, they can rent their machine to renters and charge the per acre rent r. There could also be third party service providers that offer the service with aggregate supply of $T(r, I, M)$. The aggregate supply of rental services from Q_R^s is the sum of services from both machine-buying farmers and third party machine service providers:

$$(3) \quad Q_R^s(p, r, I, M, s) = \int_{x \in B} f(x)(M - L) dx + T(r, I, M).$$

Since the total rental service is measured in acres, Q_R^s / M gives the number of machines being rented out. The number of machine demanded, denoted by Q_M^d are either from machine-buying farmers or third-party service providers:

$$(4) \quad Q_M^d(p, r, I, M, s) = \frac{1}{M} [\int_{x \in B} f(x) L dx + T(r, I, M)].$$

We can now define the joint equilibrium for the three markets.

Definition 1 *The joint supply chain market clearing condition is determined by the following set of conditions:*

1. *Clearing of the output market:* $Q_O^s(p^*, r^*, I^*, M, s) = D(p^*)$.

2. *Clearing of the rental service market:* $Q_R^d(p^*, r^*, I^*, M, s) = Q_R^s(p^*, r^*, I^*, M, s)$.

3. *Clearing of the machine purchase market:* $Q_M^d(p^*, r^*, I^*, M, s) = S(I^*, r^*, M)$.

4. *Linkage between the machine purchase and rental service market:* $r^* = \frac{I^*}{M}$.[3]

This set of conditions simultaneously determines the output quantity, the number of machines being rented, and the number of machines being purchased in equilibrium. At the same time, these conditions implicitly define the equilibrium output price $p^*(M,s)$, the machine rent $r^*(M,s)$, and the price of machines $I^*(M,s)$ as functions of exogenous parameters M and s.

As noted above, in the next three subsections we will examine the market equilibrium under three special cases: 1) heterogeneous land quality and farm size does not affect productivity; 2) heterogeneity in both land quality and farm size, but ownership does not affect productivity; and 3) heterogeneity in both land quality and farm size, and ownership affects productivity.

Case 1. Yield is not affected by scale when land quality is heterogeneous

In this case, yield per unit of land is not affected by farm size. As a consequence, farm size does not affect the technology adoption decision. This allows us to make the assumption that each production unit has 1 acre of land without altering any of the conclusions we can draw from the model. We assume that the land quality is measured by an index α, with α ranging from 0 to 1 where a higher value of the index indicates better land quality. Thus, the vector of farm characteristics and farmer attributes $\boldsymbol{x}$ reduces the single variable α. Consequently, the joint distribution function $f(\boldsymbol{x})$ reduces to $f(\alpha)$. In this model, we assume that all the farmers get access to machinery through renting instead of buying. This assumption is appropriate when all farms are small enough so that buying the machine will incur a high level of idle capacity. This assumption implies that the buyer

set B in the model is empty and adoption set A is nothing but renter set R:

(5) $B = \emptyset, \; A = B \cup R = R.$

Since all the machine rental services are provided by a third party, then the number of machines being supplied in the region is exactly $S(I,M,r)$. If a farmer does not rent-in the machine, his profit is $ph_0(\alpha)$. If the farmer does rent-in the machine, the profit is $ph_1(\alpha) - r$. For either adopter or non-adopter, we assume that $h_i'(\alpha) > 0, h_i''(\alpha) > 0$ to reflect that yield is increasing in land quality and marginal product is also increasing over the range of land quality (Hellegers, Zeng, and Zilberman 2011). Examples of justification for this assumption can be found in cases such as difference in the gain from fertilizer or pesticide is increasing when the soil or water condition is better. Since farmers' decision only consists of renting-in or not adopting, the farmer's decision d reduces to the possibilities of $d = 0, 1$. In sum, the profit maximization problem for the farmer is:

(6) $\max\limits_{d=0,1} \pi_i = ph_i(\alpha) - rd$

Clearly, a farmer would only adopt the machine if the additional revenue coming from using the machinery exceeds the rent, i.e., $p[h_1(\alpha) - h_0(\alpha)] \geq r$. For convenience, we use $\Delta h(\alpha)$ to denote $h_1(\alpha) - h_0(\alpha)$. If the difference of marginal productivity of land between using the machine and not using the machine is increasing in land quality, then there exists a threshold land quality α^c such that all farmers with $\alpha \geq \alpha^c$ will adopt the machine while farmers with land quality lower than α^c will not adopt. In this case, the adoption set and non-adoption set are:

(7) $A = R = \{\alpha \in X | \alpha \geq \alpha^c\}, \; A^c = \{\alpha \in X | \alpha < \alpha^c\}.$

Figure 1a provides an illustration for the threshold. At the threshold land quality level, we have

(8) $p[h_1(\alpha^c) - h_0(\alpha^c)] = r.$

This farmer is indifferent between using the machine or not. Since we assume that the difference in marginal productivity of land between using machinery and not using machinery is increasing in land quality, then Δh is increasing in land quality, we know that any farmer with better land quality has a stronger incentive to use the machinery as it brings about higher revenue. The threshold condition for individual farmers implicitly defines α^c as a function of output price p and rent r. Comparative statics show:

$$(9) \quad \frac{\partial \alpha^c}{\partial p} = -\frac{h_1(\alpha^c) - h_0(\alpha^c)}{p(h'_1(\alpha^c) - h'_0(\alpha^c))} < 0, \frac{\partial \alpha^c}{\partial r} = \frac{1}{p(h'_1(\alpha^c) - h'_0(\alpha^c))} > 0.$$

That is, the critical land quality increases as rent increases and decreases as output price increases. These comparative statics suggest that the aggregate adoption is positively sloped with respect to output price and is negatively sloped w.r.t rent. These properties guarantee the equilibrium in the rental service market. Since any farmer with land quality greater than α^c will adopt the machinery, then the aggregate demand for rental services can be written in the integral form:

$$(10) \quad Q_R^d = \int_A f(\alpha)d\alpha = \int_{\alpha^c(p,r)}^1 f(\alpha)d\alpha.$$

Figure 1b demonstrates the aggregate demand for machine services. Since we assume that no farmer would by the machinery in the case, the machine market equilibrium is obsolete: total number of machine demanded is nothing but the total supply of machinery through third party providers:

$$(11) \quad Q_M^d = \frac{T(r,I,M)}{M} = S(I,r,M)$$

Since $r = I/M$ and the supply of machine is just a function of investment I and machine capacity M: $S(I,M)$, the market equilibrium condition for machine rental services is:

$$(12) \quad Q_R^d(I/M) = MS(I,M)$$

or

(13) $\int_{\alpha^c(p,I/M)}^{1} f(\alpha)d\alpha = MS(I).$

For total output production, as introduced in the general formulation, Q_O^s can be written as:

(14)

$$Q_O^s = \int_A h_1(\alpha)f(\alpha)d\alpha + \int_{A^c} h_0(\alpha)f(\alpha)d\alpha = \int_{\alpha^c(p,r)}^{1} h_1(\alpha)f(\alpha)d\alpha + \int_0^{\alpha^c(p,r)} h_0(\alpha)f(\alpha)d\alpha$$

Thus, the output equilibrium condition can be written as:

(15) $\int_{\alpha^c(p,r)}^{1} h_1(\alpha)f(\alpha)d\alpha + \int_0^{\alpha^c(p,r)} h_0(\alpha)f(\alpha)d\alpha = D(p).$

The equilibrium rent and output price are implicitly determined by the market clearing condition. Comparative statics on the market equilibrium suggest that:

Result 1. As the demand of the agricultural product increases, both market equilibrium rent and number of machine supplied increases. Moreover, the threshold land quality for machine adoption decreases, the change in output price is higher than the increment in rent.

This point is illustrated with a case from Qanti, Reardon, and Iswariyadi (forthcoming) for sprayer-trader service provision in the mango sector of Indonesia. On Javan, there has been a diffusion of "sprayer-trader" firms that use teams if skilled workers, spraying machines and ladders, and select and spray trees, prune, and harvest mangoes for mango farmers. The latter are of two types: smaller farmers in dynamic mango commercial zones, and larger orchard growers who have off-farm employment and thus demand the sprayer-trader expertise and labor provision and coordination of their operations but face their own constraints of human capital (skill and time to do the work due to opportunity costs of their time) and equipment. The sprayer-traders are large mango famers who also have expertise (such as agronomy degrees), holdings of the specialized equipment, ability to manage teams to prune and spray, and vehicles to transport the mangoes.

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Sometimes they have social capital linkages or joint ventures upstream with input retailers and modern food industry firms. In the latter case, quality/safety requirements of the mango buyers are an additional inducement for farmers to seek the specialized skills/asset specificity of the sprayer traders.

Based on the stylized facts of this Indonesian case, we can illustrate the point above by surmising that an increase in the demand for sprayer-trader services can come from several sources: (1) shift from the commodity to the higher quality variety of the product, in particular, from in the Indonesian case from the commodity Harumanis variety to the niche-speciality Gedong Gincu variety, which commands a higher price; (2) given the variety, a shift from lower to higher quality fruit, which requires a specific set of sprayings, fertilizer application, and careful water control to the mango tree; (3) abstracting from quality and variety, and increase in demand for mangoes due to more wholesalers coming to the area, such as when the Jakarta-Bandung highway was built a decade ago and mango demand went up sharply. The increased profitability of mangoes combined with great demand for volume, and for services of spraying and watering and pruning and fertilization to attain consistent quality, and hormonal application to extend the season to meet extended demand. This initially increased from zero the cost of sprayer-trader services (equivalent to machine rent in the model) and then pressed the "rent" of those services up consistently; the rise in price kept ahead of the rent increase, maintaining profitability as product differentiation and quality increased, "climbing the value ladder" from the farmer's perspective. Moreover, the implied increase in fertilization and water control allowed mango production to diffuse beyond an initial set of farmers with higher quality land and the best conditions for orchards, to farmers with somewhat less optimal conditions but whose deficiencies can be countered by water control and chemicals and careful husbandry.

Result 2. As the capacity of machinery increases (one machine could be used on more acres), market equilibrium rent goes down and there is more machine adoption in equilibrium.

The paper by Qanti, Reardon, and Iswariyadi (forthcoming) also provides an example to illustrate this point. After the high quality variety was introduced in Indonesia it increased the demand

for sprayer trader services. The provider of the services, in the second period, has improved their physical capital, human capital, and social capital. This lead to increased scale of the productive capacity of each machine, which allowed service providers to make the service more affordable to farmers (thus creating regular clientele and lower demand side risk for the service). This lead to more adoption of use of the service.

Result 3. A subsidy on the machinery will lead to both higher market equilibrium rent and number of machine supplied. Moreover, the threshold land quality for machine adoption decreases and the subsidy amount is higher than the increment in rent.

Similarly, a subsidy on productive capital can increase the quality and quantity of the service provided. An example of this subsidy to human capital can be government provision of more and better agronomic training to prospective sprayer-trader (Qanti, Reardon, and Iswariyadi forthcoming). This expands their potential range of sub-services included in the service package and allows them to credibly claim that they can reduce risk of poor quality and so on for farmer clients. This training also allows sprayer traders to increase the overall volume of service provided. The threshold quality of land for service adoption decreases for the same reason it did in the earlier part of this illustration.

For the rest discussion of this model, we consider two types of shocks that affect the productivity of land. First, a farmer school program, s_1, that only enhances the productivity of land for non-adopters: $\frac{\partial h_0}{\partial s_1} > 0, \frac{\partial h_1}{\partial s_1} = 0$. This assumption is plausible when the education program allows farmers to gain better knowledge about traditional farming technology such as how to optimally apply fertilizer, but the program has nothing to do with the modern technology embodied in the machinery. Second, a technology enhancement program, s_2 that only enhances the productivity of land for adopters: $\frac{\partial h_1}{\partial s_2} > 0, \frac{\partial h_0}{\partial s_2} = 0$. Using comparative statics, we have the following result:

Result 4. If a farmer school program only enhances the land productivity for non-adopters, then machinery adoption threshold increases. Both market equilibrium rent and machine adoption decrease. If a technology enhancement program only enhances the land productivity for adopters,

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then the machinery adoption threshold decreases. Both market equilibrium rent and machine adoption increase.

The intuition behind this observation is that since the farmer school program increases the productivity of land under traditional technology, a direct consequence is that the extra benefit from modern technology, if any, becomes smaller. Therefore, the threshold of adoption becomes higher after the education program and aggregate demand for machine rental service declines. Since machine service supply is not affected by the program, but aggregate demand shifts down, the rent for machine services under the new market equilibrium is lower than the old equilibrium.

Using a similar argument, the direct effect of a technology enhancement program is that the gap of benefits between the new technology and the old technology becomes even larger. As a consequence, the adoption threshold is lower, which means more farms will adopt the technology and service providers will charge a higher rent for the machine in equilibrium.

There are many real world examples where a competitive farm industry comprised of small farmers will be served by firms that provide custom services. Sharma, Singh, and Panesar (1998), is an analysis of custom hiring in India, concludes that (pp.1) "The custom hiring got a boost with the onset of the green revolution in mid-1960s and establishment of agro-industrial corporations and road networks in rural areas. The custom hiring gained importance mainly due to rise in the cropping intensity and drop in average land holding." They argue that custom services are crucial for improved land preparation, planting and harvesting, and allow smallholders to take advantage of new technologies. For example, laser leveling that enhances water use efficiency leads to increases in yields and better weed control. It requires specialized equipment and thus has been provided by specialized companies. This has been the case in California, as well as in the Pakistani Punjab and Uttar Pradesh in India (Jat et al. 2006).

Case 2: Heterogeneity in both land quality and farm size when productivity is affected by farm size

In this case, we consider another dimension of heterogeneity. Unlike above where we assumed that each farm is endowed with one acre of land, we now allow the possibility that each farm has *L*

acres of land. Under this setting, some farms are big enough to justify the purchase of the machine instead of renting it (or buying services providing it). We use a series of specifications to show the adoption patterns and ownership patterns. In some cases the two choices are independent, while the two are correlated under other cases.

We keep the notations from above, and add farm size L as another exogenously given factor. The farmer now has three choices available: not adopting the machinery, adoption through renting-in, and adoption through buying. Non-adopting farmers earn a profit of $ph_0(\alpha)L$. Renting farmers receive revenue of $ph_1(\alpha)L$ and pay total rent of rL. Farmers that purchase the machine will have the same revenue as renting farmers, but incur a cost of I. It should be noted that, in this model, the extra capacity of the machine of $M - L$ acres is not being utilized. In sum, the farmer's profit maximization problem can be written as:

$$(16) \quad \max_{i,j=0,1} \pi_i = ph_i(\alpha)L - rLi - Ij,$$

where $i = 1$ if the farmer adopts the technology, $j = 1$ if the farmer rents it, and $j = 1$ if the farmer buys the machine. As above, there exists a critical α^c such that, for all farms with land quality higher than α^c, they will adopt the machinery. Moreover, there also exists a critical farm size L^c such that for farms larger than L^c, the cost of machine is smaller than the total rent, which means these farms will choose to purchase rather than rent the machine. The critical α and L are determined by:

$$(17) \quad p\Delta h(\alpha^c) = r,$$

and

$$(18) \quad rL^c = I.$$

Note that in the case that L^c and α^c are independent of each other, the decisions on adoption and ownership are separated. However, under other scenarios, the two decisions might be made jointly. In this case, we discuss the possibility is that productivity under the modern technology is increasing in farm size. This assumption is plausible for utilization of a new technology. Under this assumption, we have h_1 not only as a function of land quality, but as an increasing function of farm size. i.e., $h_1(\alpha, L)_L > 0$. Foster and Rosenzweig (1995) and Foster and Rosenzweig (2010) documented that larger farm sizes allow for the possibility of larger scale of experimentation, which, in turn leads to better utilization of the machinery and higher productivity from the new technology. Under this assumption, it is clear that the critical farm size has not been affected as the revenue from buying or renting is identical. However, the critical land quality is now determined by:

(19) $\quad p[h_1(\alpha^c, L) - h_0(\alpha^c, L)] = r.$

This equation determines the land quality threshold as a function of p, r and L. Comparative statics show that:

(20) $\quad \dfrac{d\alpha^c}{dL} = -\dfrac{h_1(\alpha^c, L)_L}{h_1(\alpha^c, L)_\alpha - h_0(\alpha^c)_\alpha} < 0.$

That is, if productivity under modern technology is increasing in farm size, then the critical land quality is decreasing as farm size increases. Supporting empirical evidence of the comparative statics can be found in Khanna (2001), which suggests that, among four Midwestern states, the adoption of soil testing technology and variable rate technology are positively affected by farm size. With a similar exercise, one can show that $\frac{d\alpha^c}{dp} < 0$ and $\frac{d\alpha^c}{dr} < 0$ still hold as in the previous model. In this case, the adoption set and buyer set are:

(21) $\quad A = \{(\alpha, L) | \alpha > \alpha^c(L, p, r)\}, B = \{(\alpha, L) | L > L^c(p, r)\}$

Note that in this case, the adoption threshold is affected by farm size, but the ownership decision is not affected by land quality.

There is some evidence that that larger farms may have lower land quality and these evidence are related to technology option. Indian literature reviewed in Bhalla and Roy (1988), showed that in this case there is a negative correlation between farm size and productivity. Our model suggests that such studies should control for variation in land quality. Indeed, Bhalla and Roy (1988) added land quality to studies that explain productivity and they did not find a relationship between size and productivity. This evidence implies that there is negative correlation between size and land quality: larger farms are more likely to adopt technologies that allow economic viability in locations with adverse conditions. One example of large farmers adopting practices (including dams) that allow farming in low land qualities is the Tulare Lake in California. In this region large farms (including the largest farm in California , the one belongs to J.G. Boswell) used heavy equipment and labor to drain the lake and grow cotton and other crops (Arax and Wartzman 2005).

The mango case we studied earlier could also be an example of where large farms adopt modern technology on lower quality land. Large mango farmers have in their land holding land of varying quality. They adopt spraying and fertilization and irrigation equipment and detailed agronomic knowledge capital to create consistent yield and quality over plots of heterogeneous land quality and water access. This is analogous to precision farming in the US on large acreages where similar homogenization of yield occurs on land holding heterogeneous subplots. For that matter, this applies to off-farm firms, such as McDonald's, which has production over many countries and many zones in a country but needs always consistent quality and output and has to adopt machines and train staff and impose private quality and safety standards so that the product is homogeneous despite extremely heterogeneous supply situations.

Case 3: Heterogeneous land quality and farm size when ownership affects productivity

Another possibility is that the ownership threshold can be affected by land quality. Suppose that ownership increases productivity because: (1) it allows the owner more flexibility of time, as he or she does not have to wait for the service, flexibility which is valuable at peak season or

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when prices are high; (2) he or she develops skills through learning-by-doing. In this case, the production function h is further modified as: $h_1 = h_1(\alpha, L, \eta)$, where η is the number of machines owned by the farmer where $\frac{\partial h_1}{\partial \eta} > 0$. Moreover, the farmer could provide renters machine services and collect $r(M - L)$ of total rent. In this case, the critical ownership condition is altered as owning the machine provides an extra benefit.

$$(22) \quad p\left(\frac{\partial h_1(L^c)}{\partial \eta} - \frac{\partial h_0(L^c)}{\partial \eta}\right) + r(M - L^c) = I - rL^c.$$

This equation shows that, at critical farm size, the extra benefit of buying the machine equals the additional cost of owning it. The equation will determine the farm size threshold as a function of (p, r, α, I). Comparative statics suggest that $\frac{dL^c}{d\alpha} < 0$, $\frac{dL^c}{dp} < 0$, $\frac{dL^c}{dr} < 0$, $\frac{dL^c}{dI} > 0$. Thus, the farm size threshold is increasing with respect to the cost of the machine, and is decreasing with respect to output price, machine rent, and land quality.

In summary, the discussion above suggests that the adoption decision and ownership decision are independent of each other if land productivity only depends on land quality and whether machinery is being adopted. However, if land productivity is increasing in farm size, then larger farms are more likely to adopt machinery. Moreover, if ownership brings about extra value, then farms with better land quality are more likely to purchase the machinery.

In the latter two cases, the two decisions are no longer independent. Let $f(\alpha, L)$ be the joint density function of α and L, then we can show that the total farm land in the region is:

$$(23) \quad \int_0^{\bar{L}} \int_0^1 L f(\alpha, L) d\alpha dL.$$

The total number of adopters is:

$$(24) \quad \iint_{(\alpha, L) \in A} L f(\alpha, L) d\alpha dL,$$

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where A is the set of adopters, i.e, $A = \{(\alpha, L) | \alpha > \alpha^c(L, p, r)\}$. The set A can be further decomposed into two categories: the set of buyers B and the set of renters R. Here, we have $B = \{(\alpha, L) | \alpha > \alpha^c(L, p, r), L > L^c(\alpha, r, p, I)\}$ and $R = \{(\alpha, L) | \alpha > \alpha^c(L, p, r), L < L^c(\alpha, r, p, I)\}$.

Then the total acreage for which farmers demand rental services is:

$$(25) \quad Q_R^d = \iint\limits_{(\alpha, L) \in R} Lf(\alpha, L) d\alpha dL,$$

and, for farmers that are buying the machine, $M - L$ is the capacity of machine that is available for renting. Thus, the total capacity of rental service supply is:

$$(26) \quad Q_R^s = \iint\limits_{(\alpha, L) \in B} (M - L) f(\alpha, L) d\alpha dL.$$

In equilibrium, the demand for rental services meets the supply of the service:

$$(27) \quad \iint\limits_{(\alpha, L) \in R} Lf(\alpha, L) d\alpha dL = \iint\limits_{(\alpha, L) \in B} (M - L) f(\alpha, L) d\alpha dL.$$

Note that we can rearrange the terms and rewrite the equation as: $\iint\limits_{(\alpha, L) \in R} Lf(\alpha, L) d\alpha dL + \iint\limits_{(\alpha, L) \in B} Lf(\alpha, L) d\alpha dL = \iint\limits_{(\alpha, L) \in B} Mf(\alpha, L) d\alpha dL$, which reduces to the following:

$$(28) \quad \iint\limits_{(\alpha, L) \in A} Lf(\alpha, L) d\alpha dL = \iint\limits_{(\alpha, L) \in B} Mf(\alpha, L) d\alpha dL = S(I),$$

which implies that the total acreage of farmers adopting machine services equals the total capacity of machines that buyers have available. The equation after that means that the total machine demanded equals to machine supply. The output equilibrium is defined by:

$$(29) \quad \iint\limits_{(\alpha, L) \in A} h_1 fLd\alpha dL + \iint\limits_{(\alpha, L) \in A^c} h_0 fLd\alpha dL = S(I).$$

The market equilibrium condition implicitly determines the equilibrium rent r^* and, consequently, the equilibrium threshold α^{c*} and L^{c*}.

Result 5. As the cost of the machine decreases, the set of adopters does not change and some large farms switch from renting to buying. Both equilibrium rental services and the rent go down. As demand for output increases, both the set of adopters and the number of farms buying the machine increases. However, the effect of equilibrium rent is uncertain.

Figure 2 and figure 3 jointly depicts the effect of the change in output demand. After the expansion of demand in output, the equilibrium output price must go up. However, the effect on rent is unclear. The reason is that, after the output price change, there must be more farmers adopting the machine due to a lower adoption threshold; more farmers buying the machine results from a lower ownership threshold. Therefore, the net effect on aggregate rental service demand is unclear. Moreover, even if there is more aggregate rental demand, as Figure 3 suggests, since aggregate rental service supply also increases, and the resulting effect on equilibrium rent remains uncertain, but equilibrium rental services are increased from Q^* to Q^{**}.

We draw from US agricultural history for an illustration of the above proposition. The case is of combine machine services provided by mobile labor teams who went (according to the time in the season) from the north (Dakotas) south, harvesting as they went (Allen and Lueck 2002). In the late 1800s and early 1900s in that area many farmers were too small or capital poor to have their own machines, so they bought the outsource machine services (Cochrane 1979 and Allen and Lueck 2002) . As they expanded their farms and/or capitalized, the upper end of the distribution switched from renting to buying machines. This continued until a substantial reduction of demand for the mobile services occurred.

Another illustration is of produce processing and shipping that requires adoption of indivisible technologies. In this case, larger farms may purchase the processing facilities and shipping equipment, even if their scale of production is below the capacity of the equipment. Then they will contract out with smaller farmers to provide extra output require to meet the capacity constraint. The contracting between the larger, and frequently more efficient grower-shippers and the smaller

producers have various forms, and accommodate other considerations, such as transaction costs and agency considerations (Key and Runsten 1999).

A similar example can be drawn from Miyata, Minot, and Hu (2009) who show that multilevel production supply chains emerge in the production of apple and green onion in China. Large retail buyers (including supermarkets) contract with large farmers who adopt packing and processing equipment and then contract out to small farmers who need that technology to meet quality and volume requirements of the contracting packers.

Conclusions

This paper develops a conceptual framework based on the threshold model of diffusion. It explains how the emergence of agricultural service supply chains enables the diffusion of indivisible technologies in agricultural regions with small farmers. The nature of the technology as well the institutional set up determines the nature of supply changes that may emerge to enable adoption of indivisible technologies.

We consider cases where there are constraints on acquisition of land. If there are not economies of scale in the gains from adoption, if the economy has sufficient financial market and there are financial markets and an entrepreneurial spirit that enables the emergence of supply chains of providers of custom services, then small scale farms will not impede adoption. We found that if ownership provides a gain from adoption, larger farms may have the incentive to establish service supply chains that allow them to adopt indivisible technologies and rent extra capacity to smaller farmers. In these cases, and in cases where the gain from adoption increases with scale, adoption of the technology will benefit the larger farms.

Our analysis should be expanded to address cases where land markets emerge over time. In these cases when the gain from the adoption of new technology is increasing with scale or with ownership, the introduction of the indivisible technology may lead to expansion of farms who may purchase land from farmers who do not adopt the technology or rent the machines. In this case, increasing farm size reduces the provision of the technology by custom services over time.

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Incorporating risk and risk aversion can expand the analysis in this paper. One can incorporate risk reducing marketing practices such as money back guarantees and warranties by technology sellers (Zilberman, Zhao, and Heiman 2012), as well as price and crop insurance to enhance adoption. Furthermore, risk considerations may lead to new forms of supply chains and contracting. Another area of analysis is how adoption patterns and supply chains evolve over time as new technology improves. This should be treated in the research on the co-evolution of agriculture supply chain technology and market structures, a link which has been under-researched. Finally, the model presented in this paper should be applied using simulations as well as economic analysis, following the approach taken for example by Isik and Khanna (2003) in the study of adoption of precision farming.

Our model develops a framework to integrate technology adoption, technology rental markets, and output markets. This framework would allow further welfare analysis. Our results suggest that introduction of technologies may make consumers better off by reducing output prices, but have a negative effect on non-adopters. When the gain from the technology is increasing with scale or with ownership of equipment, then some of the smaller adopters of the technology may be worse off because of low output prices. The analysis also suggests that the nature of the technology will affect its welfare implications. For example, in cases where the technology enhances the value of low quality land, then adopters with low land quality may be gainers from the technology.

We consider cases when technology is biased to benefit farmers with higher land quality. For example, fertilizer benefits farmers that get more rain. But technologies like drip irrigation that augment land quality provide a greater benefit to farms with lower land quality. Under such a model, we will still be able to obtain the adopter set and corresponding equilibrium, the only difference is that the adoption set is farmers with land quality or other source of heterogeneity below a certain threshold. The model can also be expanded to include options such as not participating in farming business, then we may discuss topics such as extensive margin and intensive margin effect.

Another expansion of the model is to introduce variable inputs: adopting an indivisible technology that is also using variable inputs such as fertilizer and pesticides. In such cases, the existing results would not change except that we would have another market for variable inputs. Finally, another expansion of the model is when producing requires minimum fixed cost per acre. In this case, we have three types of land: land that is not in production, land that is using traditional technology, and land that is using modern technology. If the margin benefit is larger with modern technology, then adoption will increase total acreage.

Notes

[1]Adding the decisions on variable input use will not alter the main conclusions of this paper.

[2]Here we make the assumption that if $\pi^1 = \pi^2$, the farmer will buy the machine; if $\pi^1 = \pi^0$, the farmer will rent the machine. The assumption avoids the possibility that the intersection of B and R can be nonempty for farmers with the same profit under different technology adoption and purchase options.

[3]It should be noted that this linkage equation only holds when the rental suppliers do not have market power.

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Figures

Figure 1. Adoption threshold and aggregate demand for machine rental service
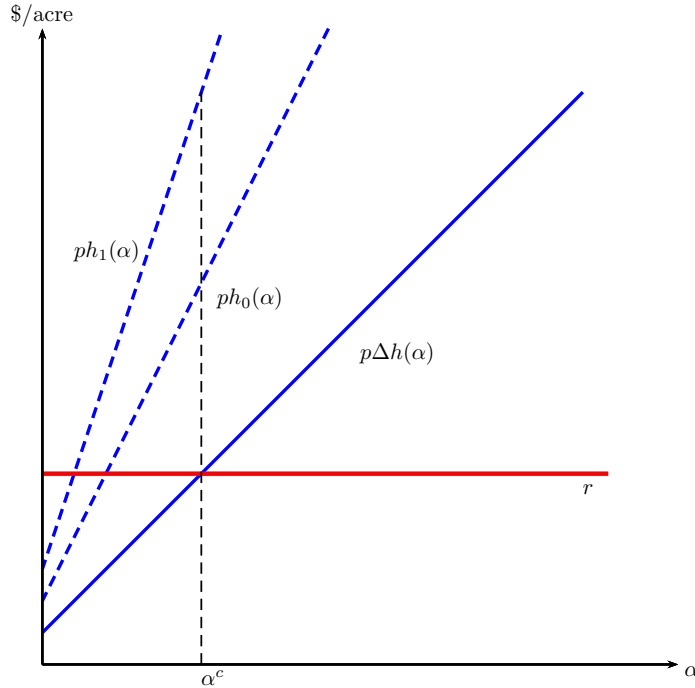

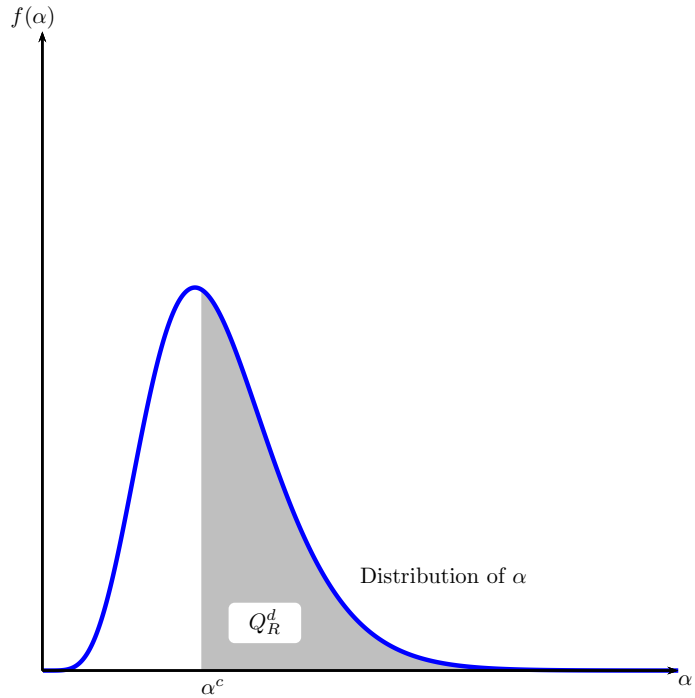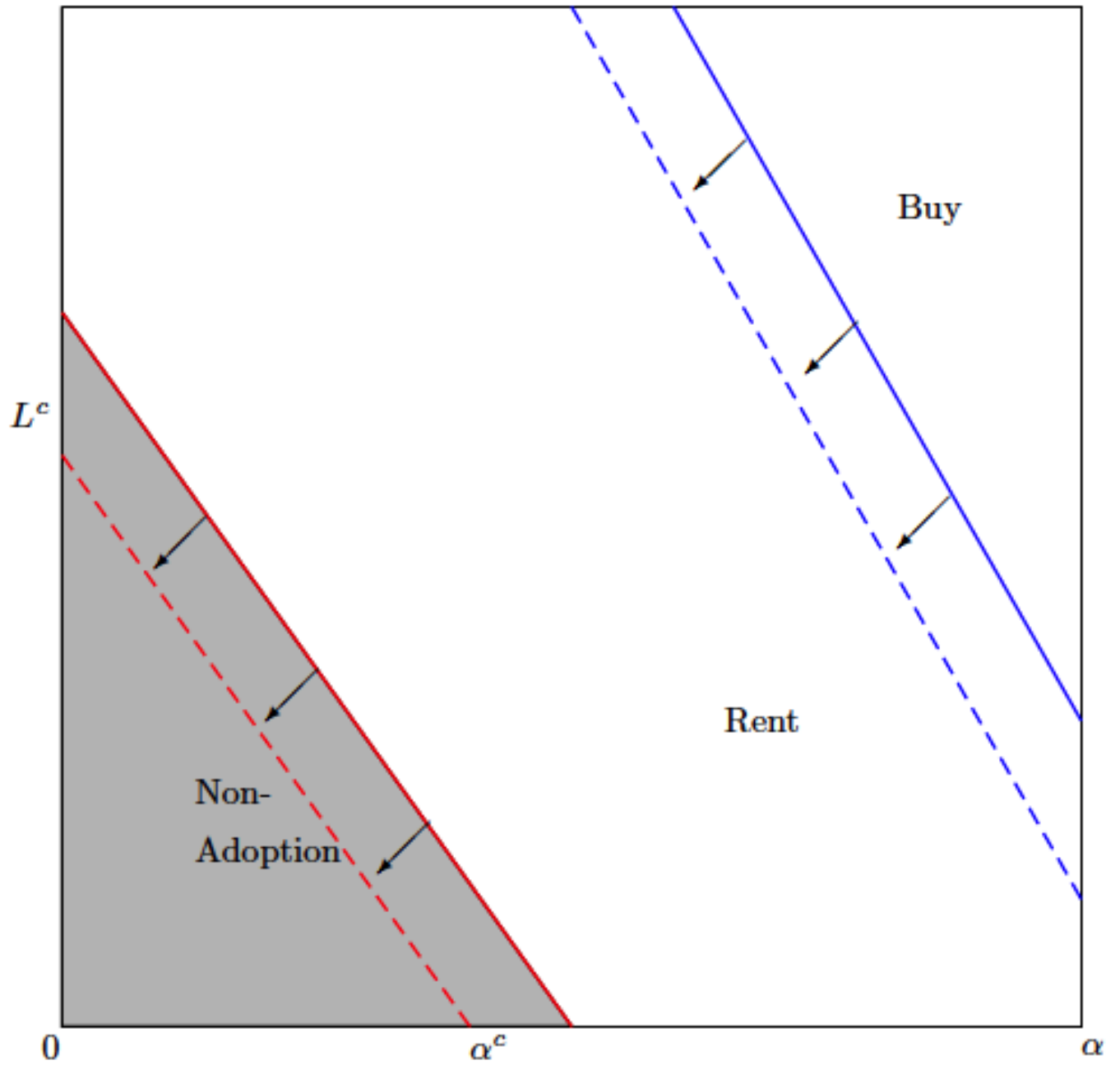Figure 1a. Condition for renting in machine service

Figure 1b. Aggregate rental demand

Figure 2. Adoption and Ownership patterns

Figure 3. Machine rental equilibrium before and after output demand change