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Technology valuation distributions with heterogeneous adopters

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Abstract: This paper examines technology benefit allocation between an innovating firm and heterogeneous technology adopters. Using a triangular distribution of adopter innovation value, we find that as the upper bound increases, optimal innovation price increases, but at a slower rate. Similarly, as the lower bound decreases, price decreases and producer benefits increase. Finally, greater producer heterogeneity leads to greater producer benefits from innovation in non-competitive markets. An empirical application of the model is considered, bovine somatotropin adoption on dairy farms. The model generates an intuitive explanation of the common finding that average adopters are making zero or negative profits.

Technology valuation distributions with heterogeneous adopters

With a rapidly evolving structure from the retailer to the farmer to the input supplier, structural change and its implications are some of the most pressing issues in the economy today. Technology adoption and diffusion is viewed as jointly determined with industry structural change. That is, technology is both driving structural changes and enabled by these same structural changes in farm size, income, and management practices.

Technologies yield benefits to innovating firms, producers (adopters) and consumers with the benefits distribution depending on the market and technology characteristics. Most research assumes that producers are homogeneous or deals with benefits as aggregate producer surplus ignoring heterogeneity across producers and the resulting distribution of technology value and benefits. In contrast, this paper presents a model to examine the allocation of benefits between the innovating firm and the technology adopters as the technology valuation distribution changes.

We assume that technology purchasers are heterogeneous, with the value of any innovation differing across potential adopters, and that the innovating firm acts as a monopolist in the sense of having at least some degree of price-setting power in the output market. These assumptions are consistent with a variety of innovations that are protected intellectual property, such as most agricultural biotechnology innovations and patented brand-name pharmaceuticals. To illustrate the utility of the model it is applied to recominant bovine somatotropin (bST) using parameters from previous adoption studies. The Michigan dairy industry size and income distribution yields the benefit distribution.

A formal model is developed in the next section. The model is considered first in general terms and then using a triangular distribution of technology adopters to generate specific results.

The specific case of bST is then discussed and estimated using Michigan data. We find that Monsanto is leaving a substantial portion of the profits for the bST adopters at the upper end of the technology valuation distribution but that in the absence of the ability to price discriminate this is a desirable pricing policy.

Model

Standard analysis of technology benefits considers a monopolist who sells to a group of homogeneous adopters. In this case, the monopolist sets price equal to marginal cost and draws all of the rents out of the market for the technology in question. While this model yields straight-forward theoretical results, it is not necessarily consistent with actual market behavior. Several studies have established that a distribution of technology values exists across potential adopters with some adopters realizing profits from the technology and others rationally choosing not to adopt the technology. With heterogeneous adopters, the monopolist pricing problem changes (unless he can perfectly price discriminate) to picking the appropriate price to achieve the sales/profit objective. In this case, the monopolist understands that some of the rents will be captured by the adopters at the top end of the technology value distribution.

This relationship between monopolist and heterogeneous adopters can be further complicated by a changing market structure—in this case a changing distribution of technology adopters. This change could be driven by exogenous forces and/or by the introduction of the technology in question. We show that as the lower end of the tail disappears, or the upper end increases, the monopolist pricing decision and the distribution of benefits is modified in important ways.

General Results

There are two critical assumptions in the model. The first is the idea that technology purchasers are heterogeneous, with the value of any innovation differs across potential adopters. Moreover, in later sections we will assume that there is a systematic relationship between (heterogeneous) characteristics of the potential adopters and their valuations of the innovation. The second critical assumption is that the innovating firm acts as a monopolist in the sense of having at least some degree of price-setting power in the output market. This assumption is consistent with a variety of innovations that are protected intellectual property, such as most agricultural biotechnology innovations and patented brand-name pharmaceuticals.

We are interested in the pricing and the allocation of benefits between the innovating firm and the adopters as the valuation distribution changes over time. To formalize these considerations, let x denote the value of the innovation to a potential adopter, let F(x) denote the cumulative distribution function for these values, and let dF(x) denote the density function. The innovating firm's objective is to maximize profits from sale of the innovation by determining an optimal price. For any price, p, we assume that those individuals with x>p adopt, while those with x<=p do not. The number of adopters is 1-F(p). Firm profits are

(1) $$\Pi(p) = (p - c)(1 - F(p)),$$

where c is the constant unit cost of production. The firm chooses p to maximize profits, leading to the first-order condition

(2) $$1 - F(p) = (p - c)dF(p).$$

The left side of this equation represents the marginal revenue from charging adopters a higher price, the right side represents the marginal cost (loss in revenue) of losing customers due to the higher price.

At a particular price, p, the benefits to adopters can be measured by the consumer surplus, defined to be the difference between each adopter's valuation and the price, aggregated across adopters:

(3) $$CS = \int_p^{\infty} x\,dF(x) - p(1 - F(p)).$$

The integral represents the willingness to pay, aggregated across adopters. The remaining term represents the aggregate amount paid.

Parameterizing the distribution allows us to conduct traditional comparative static exercises. For example, suppose that the distribution is characterized by the mean, m, and standard deviation, s. Rearranging the first-order condition and applying the implicit function theorem yields

(4) $$dp/dm = -\frac{-F_m + (c-p)\,dF_m}{-F_p - dF - p\,dF_p},$$

where subscript notation denotes differentiation. Signing the derivative dp/dm requires additional assumptions. For example, suppose that dF is unimodal with concave tails, and that p lies on the concave portion of the lower tail. Then the denominator in equation (4) is unambiguously negative and the numerator becomes positive as $c \to 0$. Thus, $dp/dm > 0$ for small c (by assuming that p is on the lower end of the tail, and since c<p by profit maximization, we have already implicitly assumed that c is not too large). That is, as the average valuation increases, so does the price which the innovator charges.

The effect of a change in variance is determined by

(5) $$dp/ds = -\frac{-F_s + (c-p)dF_s}{-F_p - dF - p dF_p}$$

Under assumptions similar to those above, this derivative will be negative. This means that as the variance of the value distribution increases the innovating firm drops the price in order to maintain its customer base.

The change in profits as the mean of the distribution increases is given by

$$(6) \qquad d\Pi/dm = \frac{dp}{dm}\left(1-F(p)\right)+(p-c)\left(1-\left(F_m(p)+dF(p)\frac{dp}{dm}\right)\right).$$

Note that since m does not enter the profit function directly, an increase in m affects profits only through the firm's optimal price, p. The first term on the right side represents the partial effect of the price change with no change in sales; the second term represents the indirect effect of the price change via a change in the number of units sold. If $dp/dm > 0$ and $1 > F_m(p) + dF(p)\,dp/dm$, then $d\Pi/dm > 0$; that is, profits will be increasing in the distribution mean.

The effect of an increase in variance is less clear.

$$(7) \qquad d\Pi/ds = \frac{dp}{ds}\left(1-F(p)\right)+(p-c)\left(1-\left(F_s(p)+dF(p)\frac{dp}{ds}\right)\right).$$

Analogously to the change in mean, the first term on the right side of equation (7) represents the partial effect of the price change due to the variance increase, with no change in sales; the second term represents the effect of the price change via the number of adopters. When $dp/ds < 0$, the first term is unambiguously negative, and a sufficient condition for the second term to be positive is $F_s(p) < 1$, which is quite possible since F(p) < 1 for all p. However, this means that the first and second terms have opposite signs, and so the effect on profits is ambiguous. Similarly, the effects of changes in the mean and standard deviation on consumer surplus are unclear without further distributional assumptions.

Results From a Triangular Density

In order to obtain more definitive results, we specify that the density function dF(x) is triangular. For ease in exposition, we define the density in terms of the mode, x_1, and the distances between the mode and the lower and upper endpoints, d_1 and d_2, respectively. Since this is a density function, the density at the mode is $y_1=2/(d_1+d_2)$.

The firm that charges a price, p, will have sales equal to

$$(8) \qquad 1-F(p) \quad = \quad 1-\frac{1}{2}\left(p-\left(x_1-d_1\right)\right)dF(p) \quad = \quad 1-\frac{\left(d_1+p-x_1\right)^2}{d_1\left(d_1+d_2\right)}.$$

For simplicity, we will follow Chamberlin, inter alia, and assume that production costs for the innovation are zero. This does not affect the generality of the results obtained. Firm profit is thus sales times price.

$$(8) \qquad \Pi(p; x_1, d_1, d_2) \quad = \quad p\left(1-\frac{\left(d_1+p-x_1\right)^2}{d_1\left(d_1+d_2\right)}\right).$$

The first order condition is obtained by differentiating the profit function with respect to price, p:

$$(9) \qquad 1 - \frac{\left(d_1+p-x_1\right)^2}{d_1\left(d_1+d_2\right)} \quad = \quad \frac{2p\left(d_1+p-x_1\right)^2}{d_1\left(d_1+d_2\right)}.$$

The left side of the first-order condition (9) represents the partial effect on revenues from raising price, holding sales constant (marginal benefit). The right side represents the loss in revenue from lower sales volume as price rises (marginal cost). At a maximum, the marginal benefit equals the marginal cost.

Solving for the optimal p results in

$$(10) \qquad p \quad = \quad \tfrac{1}{3}\left(2\left(x_1-d_1\right)+\sqrt{4d_1^2+3d_1d_2-2d_1x_1+x_1^2}\right).$$

A check of the various derivatives suffices to show that this is an interior maximum solution whenever $d_2 < 2x_1$.

It is useful to conduct comparative static exercises with respect to p. Assuming that $d_2<2x_1$, which implies an interior solution, then the following hold:

(11) $\partial p / \partial x_1 > 0; \quad \partial p / \partial d_1 < 0 \text{ if } d_1 \leq x_1; \quad \partial p / \partial d_2 > 0.$

These results say that p is increasing in the mode, x_1, and in distance from the mode to the upper bound of the distribution, d_2. That is, as more adopters are willing to pay a higher price for the innovation, the firm raises price. Price will fall if the distance from the mode to the lower bound of the density, d_1 falls, as long as the density lies entirely in the positive quadrant. This restriction is sufficient but not necessary, and numerically we find a negative derivative over a wide range of values. Heuristically, if the lower bound of the distribution shifts to the left, then the firm's optimal response is to lower price to maintain customers.

Comparative static exercises also show that:

(12) $\partial \Pi / \partial x_1 > 0; \quad \partial \Pi / \partial d_1 < 0; \quad \partial \Pi / \partial d_2 > 0.$

These results are easily interpretable in light of the results on optimal price: whenever the distribution shifts so that the firm increases price, then the firm makes more money. Whenever the firm's optimal price falls, so too do firm profits.

To obtain a measure of the farmers' benefit from the innovation, we define the benefit per sale to be the adopter's valuation of the innovation less the price paid. This is the usual definition of consumer's surplus. Assuming that $p < x_1$, (we examine this assumption shortly), aggregating benefits across adopters yields the total farmer benefit:

(13) $$\frac{1}{81d_1(d_1+d_2)}\left(\begin{array}{l} 40d_1^3 + d_1^2\left(63d_2 + 6x_1 - 20\sqrt{4d_1^2+3d_1d_2-2d_1x_1+x_1^2}\right) + 4x_1^2\left(\sqrt{4d_1^2+3d_1d_2-2d_1x_1+x_1^2} - x_1\right) \\ + d_1\left(27d_2^2 + 4x_1\left(3x_1 - 2\sqrt{4d_1^2+3d_1d_2-2d_1x_1+x_1^2}\right) - 6d_2\left(4\sqrt{4d_1^2+3d_1d_2-2d_1x_1+x_1^2} - 3x_1\right)\right) \end{array}\right)$$

This equation is too messy to interpret easily, or to generate definitive comparative static results. Consequently we generate a numerical example to show the effects of changes in the distribution of values on farmer welfare.

Figure 1 shows the farmer benefits for a range of distributions. For each distribution, the mode is set at 100. The left axis measures the lower bound of the distribution, and is set so that this bound ranges from 90 to 99.9. The upper bound is on the right axis, and ranges from 100.1 to 110. The foremost corner represents the triangular distribution with mode 100 and support (99.9, 100.1), the least disperse of the distributions we examine. Not surprisingly, this distribution generates the lowest farmer benefits. Because farmers are close to homogeneous, the firm can set price to extract most of the benefits from the farmers.

As the lower bound decreases, farmers become more heterogeneous, and the firm is unable to extract as much surplus from each farmer. In addition, the firm lowers price as the lower bound decreases, so that adopting farmers gain that way as well.

As the upper bound increases, the density is more disperse, and farmer benefits increase. However, as the upper bound increases, the firm raises the price, so that farmer benefits do not grow as rapidly as when the lower bound decreases. This can be seen by comparing the height of the blue corner on the left, representing the effect of a decreased lower bound, with the green corner on the right, representing the effect of a higher upper bound.

Finally, as both bounds diverge away from the mode, the farmer benefits are greatest. This is because the firm has to keep price low so that farmers in the lower portion will adopt the innovation, leaving a wide gap between price and valuation for most farmers. The relatively high farmer benefits from this heterogeneity are represented by the height of the purple corner in the back of Figure 1.

Application: bST

One of the earliest and most studied biotechnologies is recombinant bovine somatotropin (bST) a hormone that encourages milk production in cattle. While four companies developed and patented versions of bST, only Monsanto has viably commercialized the product, Posilac, in the United States. Approved for sale in 1993, rbST has been examined for consumer reaction, human and animal health concerns, tested for producer adoption and dis-adoption, blamed for generating production surpluses, and tested for scale neutrality among other activities. However, it seems to be an established product that is largely off of the American consumer radar screen and is common in all milk producing regions of the country. While we are not concerned with the bulk of these previous studies, the existence of them, especially the adoption studies, makes bST a prime candidate on which to apply our model.

To apply the model, some explicit description of technology value is required and we use previous studies to guide selection of these parameters. Tauer (2001) examined the profit impact of rbST on a panel data set of New York dairy herds. He found that while bST had an unambiguously positive output impact, the average farm was losing about $100 per cow. Tauer concluded that while the output response was easily observed, it was difficult for farmers to determine whether that increased milk production translated to profit. Stefanides and Tauer (1999) examined a panel data set of 211 New York dairy farms from 1993-95. Farm size, productivity, and education of the principal operator were the most important explanatory variables influencing adoption. Barham, Jackson-Smith, and Moon (2000) examined the adoption of bST on Wisconsin dairy farms. They note that while the per-unit cost of injecting cows with bST tended to be constant over different herd sizes, the actual distribution of adoption was extremely sized biased. Further, the size bias appeared to be growing over time for the

Wisconsin dairy farms examined. The average 1999 herd size of bST adopters was 149 cows compared to 58 cows for non-adopters. Foltz and Chang (2002) examined the adoption, and dis-adoption, of bST across Connecticut dairy farms. While also finding that bST use was associated with significantly less profit per cow, Foltz and Chang found that younger and more educated farmers, as well as larger herds, were significantly more likely to be adopters.

Past research clearly establishes a basis for heterogeneity influencing the farm value of bST. The findings indicate that farm size, productivity, and operator education positively influence adoption. Further, results indicate that averaged *across herds* bST adoption was not profitable. The model developed above allows us to re-examine the bST valuation distribution *across cows* and determine that the average values from the previous studies are consistent with economic theory. This framework highlights a short-coming of previous research which focused on profitability at the herd level only. By regressing the bST use by herd on average profit per cow in each herd, the parameters find the average relationship across herds (or producers). If we recognize that bST is injected into individual cows rather than the whole herd (or the producer) we show that averaging across herds, without recognizing the large variation in herd size and production technology, masks the profits made by large farm adopters. Further, we find that Monsanto is likely sharing profits with adopters.

Data

To illustrate the model in the case of bST, we use data from the Michigan Dairy Farm Industry Survey of 1999 (Wolf, et al.). Lacking detailed information that would allow a structural equation estimation of bST adoption as in the literature described above, we instead use the distribution of herd size and profit on Michigan dairy farms. Michigan is in many ways representative of the US dairy industry. The average herd size in Michigan is 100 cows, which is in line with the national average. Michigan also possesses a mixture of many smaller, older farms and some very large, new dairy farms. The adoption of bST is not explicitly identified in the data so both adopters and non-adopters are present and cannot be separated.

Detailed dairy herd enterprise data from two sources places the cost of bST use on Michigan dairy farms at $59 per cow in 1999 (Harsh, Wolf and Wittenberg; Nott). Farm information was derived from the 1999 Michigan State University Dairy Farm Survey (Wolf et al.). Profit was represented by net farm income. Herd size, technology utilized and other characteristics were available from random, stratified sample of 458 (of approximately 3,200 total) Michigan farms.

To calibrate the model we relied on two empirical statistics and an assumption. The statistics are that bST is used on about 1/3 of Michigan cows, and that the average farmer using bST spends $59 per year per cow on bST. Used according to label, at any given time bST is injected into selected cows for the latter part of the lactation. The assumption we made is that bST has an equi-proportionate effect on the annual profit per cow (gross of bST costs) for all farmers. The idea that bST raises profits per cow gross of bST costs is non-controversial. It is consistent with findings by Tauer, Foltz and Chang, and Barham et al. that bST increases production per cow. The assumption that bST has an equi-proportionate effect is made for simplicity, and is fairly innocuous in this instance. For example, our results would be even stronger were we to assume that larger farmers increase their profits by a higher percentage than do smaller farmers. Barham et al., among others suggests, that bST is scale increasing. This seems consistent with anecdotal evidence that suggests that the production technology which best complements bST use is more common on large farms.

It order for bST to be profitable on 1/3 of Michigan cows at a price of $59 per cow, the proportional increase in profits per cow gross of bST costs must be 17%. We also want the endogenous pricing in the model to be consistent with farmer payments of $59 per cow for bST; this requires that the cost to Monsanto of producing Posilac be on the order of $10 for a comparable amount (due to some lumpiness in the data, the price to farmers is not particularly sensitive to numbers in the $10-$20 range).

The first result is the density function for incremental profits from adoption and use of bST. Two density functions are represented in graphical form in Figure 2; one is the density by herd and the other is the density by number of cows. The density by herd is unimodal and very skew right, with a mode of 20. This means that the modal farmer would make $20 per cow gross of bST costs by using bST; in other words, the modal farmer would lose about $39 per cow by purchasing bST at a price of $59. The mean and median farmers would lose $36 and $47, respectively. Only 14% of farmers will find it profitable to adopt bST. These findings are consistent with the literature finding little evidence of bST profitability.

The density by cow is also unimodal and skew right, but not as much as the herd density, and with a noticeably fatter upper tail. In other words, the proportion of cows on which bST use is profitable is greater than the proportion of herds for which bST is profitable; this results from the positive correlation between herd size and profits.

Is it then irrational for farmers to adopt bST? Our second result shows that this is not the case. The incremental bST profits per cow (net of bST costs) averaged across cows in adopting herds is $88. This figure differs from those presented in the first result in two ways: first, it relates only to adopting herds, and second it averages across cows rather than across herds. To the extent that larger herds generally tend to be more profitable, the distinction between averaging across cows compared to across herds is important.

The average incremental profit per herd for those herds adopting bST is $31,500, on an average herd size of 355 cows. This clearly indicates that farmers adopting bST are behaving in a manner consistent with rational optimization.

The ratio of incremental farmer profits to incremental surplus is 65%; that is, farmers retain nearly 2/3 of the rents generated from bST. While this slightly lower than the 72% that Falck-Zepeda et al find for bt cotton, for example, it is in the same ballpark and certainly more realistic than the 0% that the earlier literature seems to imply. Monsanto retains 35% of the available rents.

Conclusions

We have successfully constructed a model of farmer heterogeneity and monopoly pricing that is applicable to agricultural biotechnology. Calibrating the model to different markets allows explanation of a range of pricing behavior, from transgenic crops to livestock innovations.

Applying the model to the Michigan bST market provides a number of important results:

- The average (mean, median or mode) farmer would make no money from adopting bST, as is consistent with existing literature.
- The average (mean) cow in herds adopting bST provides incremental net profits of $88 per year from the bST.
- The average incremental net herd profits among adopting herds is $31,500.
- 64% of the available rents from bST accrue to farmers (eventually to consumers as price falls); 36% to Monsanto.

- The deadweight loss due to monopoly pricing is about 14% of total potential bST surplus.

Several conclusions follow. First, dairy farmers are not homogeneous in their valuations of bST. Second, dairy farmer decisions about the adoption of bST are consistent with rational profit-maximizing behavior, even though the average dairy farmer may see no incremental increase in net profits from adopting bST. Third, the hypothesis of a positive relationship between farmer heterogeneity and rents retained by farmers is supported by the farmers' retention of nearly 2/3 of the rents from bST. We note that some deadweight loss is necessary if we are to provide profit incentives for research investment. Although our gut reaction is that 14% is relatively small, a thorough investigation of this issue is beyond the scope of the current paper.

More generally, we conclude that Monsanto is leaving money on the table (or in farmers' pockets) from its biotechnology innovations, but that this isn't necessarily by choice. Pricing of biotechnology innovations is close to optimal, given farmer heterogeneity and the inability to price discriminate.

This paper examined heterogeneous farmer valuations of new biotechnologies, but has not allowed these valuations to change over time. An interesting opening for further research would be to model endogenous shifts in valuation distributions over time, where the shifts might take into account changes in farm structure and farmer demographics, thus allowing for bi-directional causality between industry structure and innovation.

References

Barham, B.L., D. Jackson-Smith, and S. Moon. “The adoption of rbST on Wisconsin Dairy Farms.” *Agbioforum* 3(2000):181-187.

Foltz, J. and H. Chang. “The adoption and profitability of rbST on Connecticut Dairy Farms” *Amer. J. Agr. Econ.*

Harsh, S. C. Wolf, and E. Wittenberg. “Profitability and Production Efficiency on Michigan Dairy Farms.” MSU Staff Paper.

Hyde, J., M.A. Martin, P.V. Preckel, and C. R. Edwards. “The Economics of Bt Corn: Valuing Protection from the European Corn Borer.” *Rev. Agr. Econ.* 21(1999):442-454.

Nott, S.B. Michigan Business Analysis Summary 1999.

Qaim, Matin. “Potential Benefits of Agricultural Biotechnology: An Example from the Mexican Potato Sector.” *Rev. Agr. Econ.* 21(1999):390-408.

Saha, A. H. Love, and R. Schwart. “Adoption of emerging technologies under output uncertainty.” Amer. J. Agr. Econ. 76(November 1994):836-46.

Stefanides, Z. and L. Tauer. “The empirical impact of bovine somatotropin on a group of New York dairy farms.” *Amer. J. Agr. Econ.* 81(Feb. 1999):95-102.

Tauer, L. 2001. “The estimated impact of recombinant bovine somatotropin on New York dairy farms for the years 1994 through 1997.” *Agbioforum* 2(2001):115-123.

Wolf, C., S. Bucholtz, S. Harsh, A. Damon, and J. Lloyd. Michigan Dairy Farm Industry Survey: Results and Analysis. Michigan Agricultural Experiment Station Research Report No. 573. December 2000.

Zepeda, L. “Predicting bovine somatotropin use by California dairy farmers.” *Western J. Agr. Econ.* 15(1990):55-62.

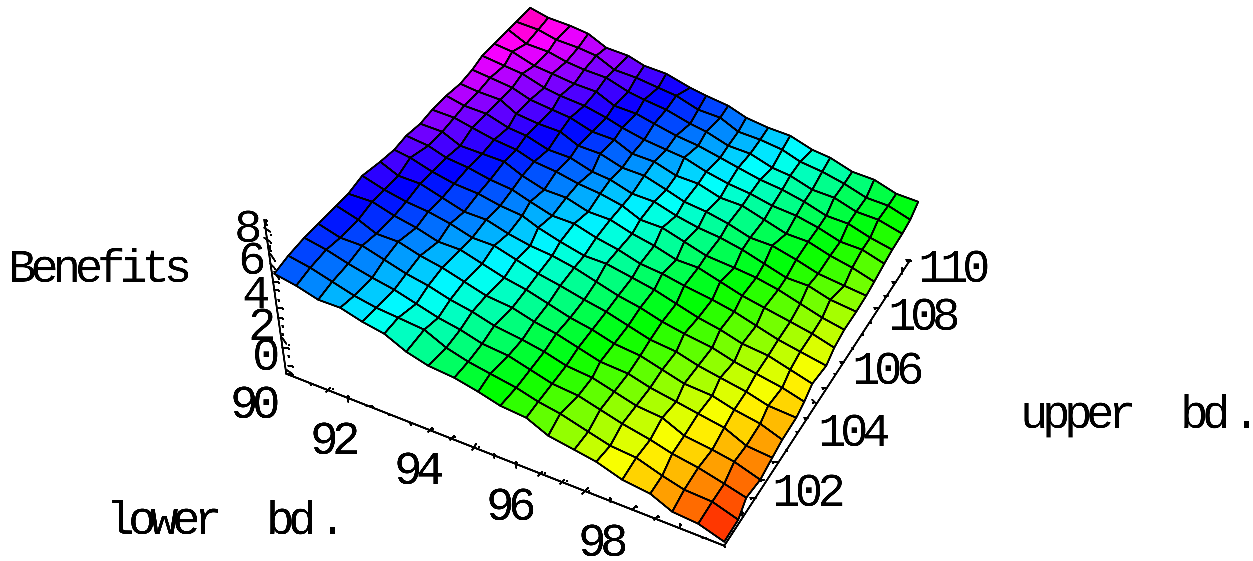

Figure 1. Farmer Benefits from Innovation, By Distribution Parameters.

Source: Mathematica™ graphics.

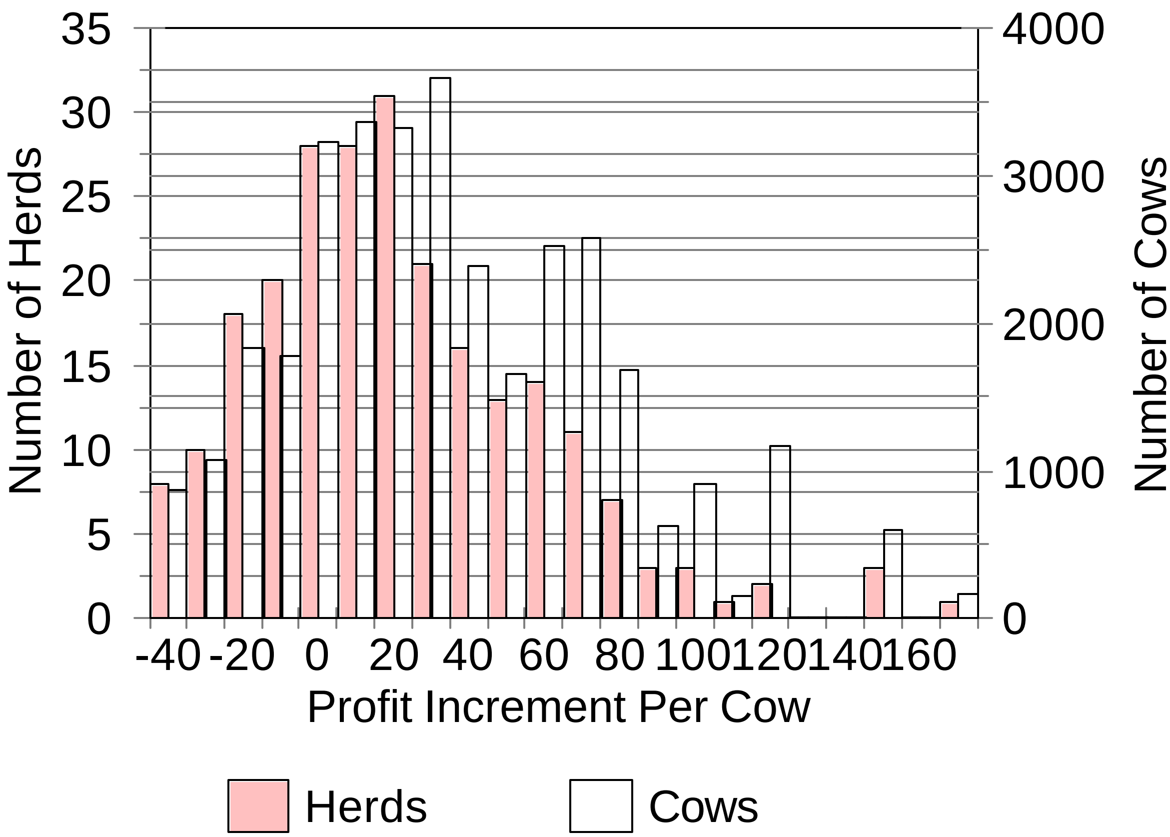

Figure 2. Densities of annual, incremental profit per cow from bST use, gross of bST cost, net of other fixed and variable costs, by number of herds and number of cows.