# Selective Breeding, Heritable Characteristics and Genetic-Based Technological Change in the Canadian Beef Cattle Industry

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The paper presents an examination of genetic-based technological change in the Canadian beef cattle industry. A model of technological change is explicitly developed in characteristics space. Production functions with genetic characteristics as arguments are estimated and two forms of technological change identified. Shadow values for characteristics are then calculated and actual genetic improvements are compared to the improvements suggested by the shadow prices. It is concluded that market forces are sufficient to regulate the process of genetic-based technological change in the Canadian beef cattle industry.

In agriculture a major component of technological change is genetic improvement. Economic analysis of technological change has traditionally been carried out in goods space. Economists have treated new varieties of rice or wheat as new goods which act as arguments in aggregate production functions. Genetic research, however, is carried out in terms of characteristics which are quantifiable and heritable. The process of selecting the characteristics to improve has been left to geneticists.

In the North American beef cattle industry, however, the responsibility for genetic improvement lies primarily with the individual stock breeder. As the potential for genetic improvement in beef cattle is large, some assurance that the market provides the incentives to initiate improvements and that stockmen (most of whom have no formal training in genetics) recognize the incentives is desirable. Using the goods approach to production does not provide the means of examining the problem of selecting the appropriate genetic characteristics for improvement. A "characteristics" approach to production is suggested.

Although the "characteristics" approach to consumption has received considerable attention since Lancaster's "New Approach," a parallel development has not taken place in production theory. Archibald and Rosenbluth present a tentative first step toward the examination of production theory in terms of characteristics. They suggest that if production Y can be defined over a vector of characteristics x where $x = (X_1 \ldots, X_i \ldots, X_n)$ and $Y = F(x)$ three types of technological change can be identified: (1) the development of a new process which is a true shift in the production function—e.g., F(x) to C(x); (2) quantifiable additions to the vector of existing characteristics—e.g., $X_i' > X_i$ for some $X_i \in x$; and (3) an addition to the set of characteristics contained in x, e.g., $x' = (X_1 \ldots, X_i \ldots, X_n, X_{n+1})$. This paper sets out a model of genetic-based technological change in the beef cattle industry defined in characteristics space and presents evidence that technological change of type 1 and type 2 outlined above are occurring simultaneously. The development of the

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model and the empirical investigations suggest some of the advantages of using the characteristics approach to examine technological change.

Section II provides a brief review of economic studies of genetic-based technological change within the more general context of production theory. Section III presents a formal statement of the model and Section IV the empirical analysis and results. Section V presents the conclusions of the study.

## Economics and Genetic-Based Technological Change

Selective breeding is a major means of improving the productivity of plant and animal species. In the beef cattle industry, using the traditional straightbred technology, considerable progress was made in developing an animal ideally suited to existing production methods and consumer preferences. After the second world war, however, improvements in genetic knowledge led to the extension of the successful crossbreeding technology, which had revolutionized the plant industry, to poultry, swine and beef cattle. At the same time the tastes of consumers were changing so that less fat was desired in beef cuts (Warwick). Canadian grading systems were altered to reflect these changes in preferences. In Europe the development of some breeds had been concentrated on producing cattle with heavy muscling for draught purposes. These animals were larger and produced leaner carcasses than North American breeds. Therefore, there appeared to be in Europe a set of germ plasm with the genetic diversity necessary for effective crossbreeding and with developed characteristics which would complement the breeds evolving in North America.

Due to quarantine regulations, however, no cattle could be imported from continental Europe. Lobbying by cattlemen led to the opening of quarantine stations by the Canadian government in 1966. Within ten years a large number of breeds had been imported and the number of animals registered annually for these new, so-called, "exotic" breeds approached those of the traditional breeds.

The possibility of genetic change exists in the Canadian cattle industry. However, the realization of genetic change depends on the ability of the Canadian beef cattle industry to improve the divergent genetic strains and cross the purebred strains to take advantage of hybrid vigor.

Econometric studies of genetic-based technical change have generally followed a production function approach. They define a production function (implicitly or explicitly) and then add new varieties over time as shift parameters in the form of investment expenditures or dummy variables (Evenson and Kislev; Hertford *et al.*; Nagy and Furtan). Such studies do not, however, provide insights into the process of genetic improvement itself. Although the characteristics improved (drought resistance, fertilizer response, etc.) are discussed, the actual process of determining which characteristics researchers improve upon is ignored.

Induced innovation theorists (Fellner; Hayami and Ruttan) suggest that the key may lie with changes in relative factor prices which provide incentive to develop new products which require less of the now relatively expensive input. Such models, however, may be too restrictive in application. The theory assumes that there must be *ex ante* equilibrium and that a change in relative prices must be observed. In our case of genetic change in the beef cattle industry, the potential exists for continuing change (until all the genetic variability is exhausted), whether or not there are changes in the relative factor prices. Further the theory of induced innovation suggests only that new goods will appear, but provides no information on the composition of such goods except that they will be less intensive relative to the new higher cost input. In our case this would tell us that a new input will appear and that it will be the input with the highest additional value over the feasible interval of improvement, but it cannot provide any descriptive information regarding the inherent qualities of the new good. Clearly, this is the Lancastian problem in production space. The problem is one of heterogeneous inputs to production. As genetic improvement is specified in characteristics, traditional production theory, based on the assumption of homogeneous inputs to production, does not provide the tools to analyze the problems of genetic improvement. If the process of technological change in the beef cattle industry is to be evaluated, then further incursions into the use of the characteristics approach seems necessary.

Genetic progress in the animal industry is, in reality, the provision of additional quantities of existing inputs to production. Livestock can, for example, be bred for "disease resistance," "feed conversion," "egg laying ability," "backfat," etc. The expected quantities of these characteristics vary from breed to breed. In the cattle industry (as well as other branches of the livestock sector), there is no market for specific genetic characteristics. The characteristics are subsumed under one purchasable commodity, a bull (or semen in the case of artificial insemination). The value of a bull in commercial production is related to the genetic characteristics which the animal carries. Improvements to the genetic mix should be reflected in the value of such breeding animals. Economists have paid scant attention to the market for genetic factors of production. Yet, it provides the key to an efficient process of genetic progress.

In consumption theory there has been considerable effort (Lancaster; Lipsey and Rosenbluth; Griliches; Terleckjy) directed to the so-called "characteristic approach." These developments have not been paralleled in production economics. The paper by Archibald and Rosenbluth represents a tentative step towards formal theoretical analysis of production theory in a characteristics framework. Two elements of their paper are relevant to this study. First, "The characteristic approach is well adapted to deal with the observed heterogeneity of inputs." Second, they suggest that the characteristic approach could be helpful in analyzing the source of technological change. In addition, Archibald and Rosenbluth suggest that:

> "We do not suppose that producers compute them formally, but it is natural to assume that 'good management' has an appropriate rule of thumb or intuitive understanding of the shadow prices of important characteristics required to select the cost minimizing mix."

In the case of exotic cattle, we seem to have both heterogeneity of inputs based on production characteristics and a process of technological change which should be responsive to the shadow prices of those characteristics.

Only recently have economists turned their attention to disaggregating the genetic components of production. The paper by Ladd provides the first attempt to systematically incorporate animal genetics into production theory using characteristics. His approach defines the production process of commercial operations partially in terms of genetic characteristics. Standard production theory optimization procedures are then used to determine the theoretical value of additional units of characteristics. Such values could help the commercial operator determine what he should pay for breeding stock. Thus prices for breeding stock should reflect the value of the genetic characteristics internalized in the individual breeding animal, which is the subject of this inquiry.

Only a few empirical investigations have, as yet, been conducted. They have used the method of linear programming to estimate the value of genetic inputs.

Ladd and Gibson, for example, attempt to derive the value of the genetic-based economic traits in swine production—backfat, feed efficiency and average daily gain. They use their model to discern "the amount by which maximum profit may be expected to increase for each unit of improvement in that animal." Burkholder provides similar information for ten breeding characteristics for integrated broiler operations.

In the beef industry similar studies have, as yet, not been conducted. Further, there has been no examination of the interaction between those who use purebred cattle and those who improve them.

## *The Model*

The basic premise of this study is that the mix of production characteristics produced by the suppliers of genetic materials (the purebred breeders) will be determined by the production process used by commercial cattlemen. The specific hypothesis is that the prices paid for bulls are a function of identifiable characteristics, internalized by bulls, which are phenotypic (observable) proxies for the genetic components of the production function. Implicit values for these characteristics may then be determined. A further hypothesis is that the process of genetic selection followed by purebred breeders conforms to the market forces indicated in the commercial cattle operations' selection of bulls.

Given their biological nature, processes in primary agriculture can be portrayed with a stylized production function of the form

$$Y = F(X_1, X_2, \ldots, X_m, G_1, G_2, \ldots, G_n) \qquad (1)$$

where Y stands for units of output, the $X_j$'s are non-genetic components of the production function, and the $G_i$'s are the underlying genetic components.

For the purpose of our study of the cattle industry, we shall assume that all genetic components of the production function are subsumed under the bull. The production enterprise will be defined in terms of individual bulls. In other words, the commercial cow-calf producer is assumed to treat each set of cows which a bull can serve as a separate enterprise in terms of the decision to purchase a bull. Therefore the production function can be reduced to:

$$Y_B = F^B(g, x) \qquad (2)$$

where

$Y_B$ = the output/bull, pounds of calf/bull/year.

g = the bull component of the production function which is a vector of genetic-based characteristics, i.e., $g = (G_1, G_2, \ldots, G_n)$ internalized in one bull.

x = the vector of non-genetic inputs associated with the production expected from the number of cows one bull is expected to service.

The profit maximizing firm will be expected to utilize each non-genetic input of production to the point where, assuming perfect competition,

$$W_j = P_Y(\partial Y_B/\partial X_j) \qquad (3)$$

in equilibrium
where

$W_j$ = the price of input j.

$X_j$ = the quantity of input j.

$P_Y$ = the price of output (the price of calves).

Under the assumption of perfect competition, the value of a bull will be determined by what it is expected to add to the value of production:

$$W_g = P_Y Y_B - \sum_{j=1}^{m} W_j X_j^* \qquad (4)$$

where the $X_j^*$'s are the solution values for (3) and $\sum_{j=1}^{m} W_j X_j^*$ includes "normal" returns to the rancher's labor and capital.

Of course, a bull is used as the herd sire for a number of years. Hence, the bull's contribution to production would be expected to continue over its useful breeding life, so that there would be a $W_{gt}$ for each year (t) the bull is used in production. What one would be willing to pay for a bull would therefore be

$$P_B = W_{g1} + \frac{W_{g2}}{(1 + r)} + \frac{W_{g3}}{(1 + r)^2} + \ldots + \frac{W_{gT}}{(1 + r)^{T-1}} \tag{5}$$

where the $W_{gt}$ are the quasi-rents expected from the bull from (4), T is its expected productive life and r is the purchaser's perceived discount rate.

As bulls are heterogeneous, each bull's price is determined individually. The market for breeding stock is of the traditional auction form, with the price determined by competitive bidding. If the commercial cattleman has an intuitive understanding of the production relationship, then the price of a bull, $P_B$, should reflect its expected value in production (Wilson; Vickrey).

The importance of the heterogeneity of genetic inputs becomes more obvious when the actual process of genetic improvement is examined. The breeder of purebred cattle is the supplier of genetic improvement to the commercial cow-calf enterprise. Once established, the purebred breeder is relatively constrained in the amount of genetic improvement which he can expect to produce. The expected phenotypic change in any characteristic for one generation is described by Lasley as

$$\Delta G_{iI} = (G_{iS} - \bar{G}_{iS})\frac{H_{Gi}}{2} \tag{6}$$

where

$\Delta G_{iI}$ = the expected increment in the characteristic $G_i$ over a generation interval.

$G_{iS}$ = the measurable quantity of characteristic $G_i$ of the sire selected for breeding.

$\bar{G}_{iS}$ = the mean quantity of characteristic $G_i$ of the selected sire's male contemporaries within a herd.

$H_{Gi}$ = the heritability of characteristic $G_i$ (%).

I = the generation interval which is defined as the average age of the parents when their first offspring are born. Thus, $\Delta G_{iI}$ is the rate of improvement in the next generation of sires which the breeder can expect to realize, on average, for any one characteristic.

The problem of the purebred breeder, thus becomes, in any time period, to choose the $G_i$ which will maximize the value of the bulls he will sell in the next generation. As the costs of raising and maintaining bulls with various mixes of characteristics are not significantly different, the decision should depend on the absolute level of the $\bar{G}_i$'s, the $\Delta G_{iI}$'s and the implicit values of the characteristics. The $\bar{G}_i$'s and the expected $\Delta G_i$'s should be known by the purebred breeder. Although diminishing returns may eventually be reached for some characteristic, as the physiological limits to genetic improvement are approached, no such limit has yet been reached for the characteristics in beef cattle. The $\Delta G_{iI}$'s can therefore be assumed constant in succeeding I's. The value to the purebred breeder of additional units of characteristics should be reflected in the prices received for bulls sold to commercial cow-calf enterprises. If the commercial cattleman is to make the breeding decision which will maximize his profits, he must have an appropriate rule-of-thumb, or an intuitive understanding of the shadow prices of important characteristics, and thus, through the market, establish their value to the purebred breeder. Then it should be possible to determine whether purebred breeders are following the market forces indicated, given that information on $\bar{G}_i$'s and $\Delta G_{iI}$'s is generally available.

Of course, the actual genetic components of the production function are not readily observable. Instead, the purebred breeder and the cow-calf operator must rely on phenotypic (observable) traits, or characteristics which are known to correlate with genetic improvement. Data for individual animals are usually collected on two phenotypic characteristics:

1) the weaning weight, $G_1$, and
2) the average daily gain on feed post weaning, $G_2$.

In addition, statistics are collected by herd on the incidence of calving difficulty (dystocia) and breed-by-breed indexes of calving difficulty, $G_3$, are published and well-known. These characteristics represent surrogates for the major contribution of a bull to the process of herd production—the rate of growth while suckling, the rate of growth and conversion of feed post weaning, and the number of calves expected per bull. It is well-known (Lasley; Woodland) that,

$$\partial Y_B/\partial G_1 > 0$$
$$\partial Y_B/\partial G_2 > 0$$
$$\partial Y_B/\partial G_3 < 0$$

Profit ($\Pi$) for the production enterprise is defined as[1]

$$\Pi = P_y Y_B - \sum_{j=1}^{m} W_j X_j. \qquad (7)$$

If we assume that equation (2) is homogeneous of degree one[2] and that $g = (G_1, G_2, G_3)$ are the genetic-based inputs suggested above, it follows that:

$$Y_B = \sum_{j=1}^{m} X_j \frac{\partial Y_B}{\partial X_j} + \sum_{i=1}^{3} G_i \frac{\partial Y_B}{\partial G_i}. \qquad (8)$$

Using this and equation (3) it follows that

$$P_y Y_B = \sum_{j=1}^{m} W_j X_j + \sum_{i=1}^{3} G_i \frac{\partial Y_B}{\partial G_i} P_y. \qquad (9)$$

If we define $X_j^*$'s as the solution values this becomes

$$P_y Y_B^* = \sum_{j=1}^{m} W_j X^* + \sum_{i=1}^{3} G_i \frac{\partial Y_B}{\partial G_i} P_y \qquad (10)$$

substituting into equation (7) we have

$$\Pi^* = P_y Y_B^* - \sum_{i=1}^{m} W_j X_j^* \qquad (11)$$

where $Y_B^* = F^B(g,x^*)$ and $\Pi^*$ is maximized profit. Thus $\Pi^*$ is equivalent at the maximum to $W_g$ in equation (4). Hence, from (10) and (11) we have

$$W_G = \sum_{i=1}^{3} G_i \frac{\partial Y_B}{\partial G_i} P_y. \qquad (12)$$

It follows from equation (5) that

$$P_B = \sum_{i=1}^{3} G_i \frac{\partial Y_B}{\partial G_i} \sum_{i=1}^{t} P_{yt}^* \qquad (13)$$

where $P_{yt}^*$ is the discounted expected value of $P_y$ in time t.

If (13) can be estimated, then the $\partial P_B/\partial G_i$'s can be derived for each genetic-based characteristic. $\partial P_B/G_i$ represents the marginal product in money terms of improving each $G_i$. Then given information on the expected rate of improving each $G_i$, i.e., $\Delta G_{iI}$, the appropriate $G_i$ to be improved can be discerned.

As measures of the mean values for the $G_i$'s and their standard deviations, along with estimates of $H_{Gi}$, are available for each characteristic, estimates of $\Delta G_{iI}$ can be made. Combining this information with the estimates of marginal product in value

[1] I am indebted to an anonymous reviewer for this shortened derivation. For an alternative and more cumbersome derivation see (Kerr, 1981).

[2] This is a simplifying assumption to make the analysis manageable. It suggests that as each genetic argument in the production function increases by $\lambda$ percent, output increases by $\lambda$ percent. This may not in fact always be true but for the range of values utilized it is not unrealistic. Future works may wish to address this issue.

terms for each $G_i$, one can determine the characteristic upon which improvement should be made for a given vector $\bar{g}$. These estimates can then be compared to actual observed trends in breed improvement over time. This provides an indication of whether registered breeders respond to the demands of the commercial sector when making breeding decisions and, therefore, do have an appropriate rule-of-thumb or intuitive understanding of the shadow prices of important characteristics.

## Empirical Analysis and Results

Much of the transfer of genetic material between purebred breeders and commercial cow-calf operators is carried out at bull auctions. To collect a set of observations on the genetic characteristics and prices of individual bulls, a large number of bull auctions in Canada's four western provinces were attended during March, April and May of 1979. A subset of twenty-one sales which provided consistent information was selected for statistical analysis. These sales provided observations on 616 individual bulls from 15 breeds. A detailed breakdown is provided in Table 1.

All bulls auctioned at these sales were officially classed as one year olds (born between December 1977 and June 1978), and no information would therefore be available on their progeny, but all animals carry a guarantee of fertility. In addition to the performance characteristics (weaning weight and average daily gain on feed), all catalogues or sale sheets provided information on the birth date of bulls, the name of the consignor and, in most cases, some information on the animal's pedigree.

The information for average daily gain on feed is directly comparable for all the bulls in the sample. Weaning weights were converted to the standard 200 day measure utilized by the Federal-Provincial Record of Performance for Beef Program (R.O.P.). Incidents of dystocia, of course, are an *ex-post* measure for any individual bull. In other words, such information must come from the births of the progeny of the individual bull. No such information exists for bulls which have not been bred. There are, however, significant differences between breeds, and such information should still enter into the price a potential purchaser is willing to pay for a bull. An index of calving difficulty is calculated for each breed by province by the Federal-Provincial Record of Performance for Beef Program, based on the records collected on approximately 100,000 animals each year. These are published annually and the summaries reprinted in the various trade journals as a matter of course.

**TABLE 1. Number of Bulls By Breed.**

| Breed | No. of Bulls |
|---|---|
| 1. Hereford | 207 |
| 2. Aberdeen Angus | 88 |
| 3. Charolais | 86 |
| 4. Simmental | 67 |
| 5. Limousin | 47 |
| 6. Maine Anjou | 33 |
| 7. Blonde d'Aquitaine | 22 |
| 8. Shorthorn | 21 |
| 9. Murray Grey | 19 |
| 10. Brown Swiss | 9 |
| 11. Salers | 9 |
| 12. Chianina | 3 |
| 13. Pinzgauer | 3 |
| 14. Welsh Black | 1 |
| 15. Red Angus | 1 |
| Total | 616 |

Assuming constant returns to scale, Diewert has shown that a generalized transformation function of the form

$$y_1 = t(y:)$$
$$= t(z)$$
$$= a_{00} + \sum_{i=1}^{k} \sum_{j=1}^{k} a_{ij} Z_i^{½} Z_j^{½},$$
$$a_{ij} = a_{ji}$$

where z is a k dimensional vector of non-negative outputs $(y_2, \ldots, y_m)$ and an "n" dimensional vector of non-negative inputs

$(x_1, \ldots, x_n)$ $k = m - 1 + n$, provides a second order approximation to a twice differentiable transformation function which satisfies desired non-negativity, monotonicity and convexity and/or concavity properties. This is subject to the coefficients, $a_{ij}$, being consistent with the restrictions necessary to satisfy the suggested regularity conditions. In the production function case (one output), it is sufficient that "all the coefficients $a_{ij}, \ldots$, be nonnegative" (Diewert, p. 297).

In our case from (13) the function to be estimated would be

$$P_B = a_{00} + \sum_{i=1}^{3} \sum_{j=1}^{3} a_{ij} G_i^{1/2} G_j^{1/2},$$
$$a_{ij} = a_{ji}. \qquad (14)$$

Estimates were conducted by ordinary least squares (OLS).

A priori, however, it seemed reasonable that the index of calving difficulty could be considered weakly separable from weaning weights and average daily gain. The index of calving difficulty is an indication of the number of live calves one can expect from the number of cows one bull is expected to service. Increases or decreases in the number of live calves should not affect the marginal rate of substitution between weaning weights and average daily gains for those calves which are successfully dropped. Initially, however, estimation was done without the assumption of weak separability and no meaningful results could be obtained. Subsequently, the cross product terms $G_1^{1/2}$ $G_3^{1/2}$ and $G_3^{1/2} G_4^{1/2}$ were omitted.[3]

Prices for bulls ranged from $700 to $24,000 with a mean of $2,250. The prices realized for certain bulls were much greater than their indicators of genetic merit suggested, and were beyond the price a commercial producer would be willing to pay. An arbitrary price of $3,000 was selected as the suspected maximum commercial price. Names of buyers who paid over $3,000 were checked against a list of names of registered breeders.[4] It was found that a disproportionate number of purebred breeders purchased such animals. Very few animals purchased for less than $3,000 were bought by members of purebred organizations. This suggested that there were two markets at the auctions, one for transfers from purebred breeders to commercial cow-calf operators, and one for transfers between purebred breeders, each with its own pricing criteria.

All bulls transferred between purebred breeders were removed from the sample. Of the 616 sample bulls, 99 were purchased by purebred breeders. Hence the final data set used for estimation is 517 bulls with prices ranging from $700 to $4000.

For the realization of genetic-based technological change, i.e., a change in the form of production function from $Y = F^B(x)$ to $Y = C^B(x)$, cross-breeding must be undertaken. The biological phenomenon upon which genetic-based technological change is founded is heterosis, commonly observed as the physical expression of hybrid vigor. Heterosis is defined as the greater vigor or capacity for growth frequently displayed by crossbred animals or plants, as compared with those resulting from inbreeding. Although the majority of breeds imported in the last decade are larger than those developed from stocks in Britain and North America before the opening of the quarantine stations, inbreeding of such animals would yield the progress which can be obtained only from heritability and additive gene action.

Bulls of exotic breeds purchased by

[3] As this suggested that $\partial P_B/\partial G_3$ was constant, a quadratic term was added. This proved insignificant and was omitted. Given the range of observations on $G_3$, a constant value for $\partial P_B/\partial G_3$ does not seem unreasonable.

[4] Available from a separate study. See (Kerr, 1982).

commercial cattlemen are, therefore, used for crossbreeding. Bulls of "British" origin are still used extensively in commercial straightbred operations. One would expect, therefore, that the production functions from the two mating schemes would differ. Hence a separate regression was specified for "exotic" breeds from which hybrid vigor would be expected using 209 bulls, and another for the 308 bulls of mainly "British" origin.

The index of calving difficulty was removed from the estimating equation for straightbred technology. As a result of their generally smaller frames, the index of calving difficulty ranged from 1.03 to 1.10, which did not provide sufficient variability. These figures represent no appreciable calving difficulty and reflect individual rather than breed-related problems. At one sale in Alberta bulls brought considerably higher prices than their merit suggested. This was not the case for animals of the same breed purchased at other sales. A dummy variable (SALE) is included in the estimation. The results of the regressions are presented below, with t statistics in parentheses.

CROSSBREEDING EXPECTED
(New Production Technology, C(x))
– 209 OBSERVATIONS

$$\begin{aligned} P_B = {} & -7550.1 + 5.02G_1 + 1159.4G_2 \\ & (-10.60^{**})\ (2.76^{**})\quad (3.43^{**}) \\ & + 65.42G_1^{1/2}G_2^{1/2} - 246.04G_3 \\ & (1.21)\qquad (-4.68^{**}) \end{aligned} \tag{15a}$$

$\bar{R}^2 = .5156$ ** Significant at .05
Mean Values: $\bar{G}_1 = 569$; $\bar{G}_2 = 3.39$; $\bar{G}_3 = 1.45$

CROSSBREEDING NOT EXPECTED
(Old Production Technology, F(x))
– 308 OBSERVATIONS

$$\begin{aligned} P_B = {} & -4372.0 + 4.99G_1 + 547.4G_2 \\ & (-10.91^{**})\ (3.88^{**})\quad (2.26^{**}) \\ & + 52.36G_1^{1/2}G_2^{1/2} + 754.15(\text{SALE}) \\ & (1.48)\qquad (7.47^{**}) \end{aligned} \tag{15b}$$

$\bar{R} = .4738$ ** Significant at .05
Mean Values: $\bar{G}_1 = 492$; $\bar{G}_2 = 3.12$

$P_B$ = price of bull
$G_1$ = weaning weight (lbs.)
$G_2$ = average daily gain (lbs./day)
$G_3$ = index of calving difficulty
SALE = Dummy

These estimates appear consistent with theoretical analysis. The larger values for the coefficients of weaning weight and average daily gain in the equation for bulls which would be expected to be used in crossbreeding suggest an awareness of hybrid vigor among purchasers of such cattle and the shift in the production function expected from technological change. Although the estimates presented would not allow a breeder to predict, with any accuracy, the price of an individual bull, given the low $\bar{R}^2$, the results do indicate that the identificable genetic factors of production significantly affect the price of bulls.[5] Further, the estimates should indicate to the breeder (with a given characteristics mix for his herd) which characteristics will be most valuable for him to improve. It is to this problem that we now turn.

To estimate whether breeders, in their selection process, emphasize the characteristic which would maximize the expected value of bulls in the next generation (as indicated by the bull price equations estimated above), it is first necessary to establish an expected increase for the phenotypic characteristics in physical terms using equation (6), or

$$\bar{G}^*_{iI+1} = G_{iI} + \frac{H_{Gi}(G_{iI} - \bar{G}_{iI})}{2} \tag{16}$$

[5] Physiological traits which are not heritable still determine, to some extent, the animal's ability as a breeder. For example, the "set of legs" and the "size and depth of the scrotum" may indicate physical rather than genetic breeding ability, while general conformation and apparent temperament may affect the price of any individual animal. The low $\bar{R}^2$ tends to corroborate this. At any individual sale of 20 to 30 animals, the relation of prices to the genetic characteristics may therefore be obscured by such random fluctuating. There may also be some biases in the estimated shadow prices due to the omission of these variables.

**TABLE 2. Expected Value of Improving Weaning Weight and Average Daily Gain of Saskatchewan Bull Test Station Bulls.**

| | | Weaning Weight | | | Average Daily Gain | | | Predicted Change in Value ($) | | Change in Value from Observed Phenotypic Change | | Predicted Equals Observed Emphasis[a] | Predicted Difference in Value of Improved Characteristics[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Herd | Breed | Mean (1975) | Best (1975) | Mean (1977) | Mean (1975) | Best (1975) | Mean (1977) | WW | ADG | WW | ADG | | |
| Blacklock | Angus | 569 | 617 | 595 | 2.49 | 2.79 | 2.72 | $ 54 | $ 70 | $ 175 | $ 215 | ** | |
| Cook | Anugs | 473 | 553 | 542 | 2.72 | 2.92 | 2.68 | $ 97 | $ 62 | $ 476 | $−177 | ** | |
| McCall | Angus | 522 | 557 | 499 | 2.92 | 3.39 | 2.71 | $ 42 | $115 | $−189 | $−160 | ** | |
| McNinch, C. | Angus | 522 | 608 | 545 | 3.03 | 3.09 | 3.15 | $104 | $ 13 | $ 160 | $ 106 | ** | |
| McNinch, J. | Angus | 517 | 543 | 624 | 2.94 | 3.24 | 3.09 | $ 31 | $ 66 | $ 48 | $ 133 | ** | |
| Perryvills | Angus | 621 | 657 | 602 | 3.08 | 3.19 | 2.74 | $ 40 | $ 28 | $−130 | $−316 | ** | |
| Stables | Angus | 514 | 581 | 557 | 2.93 | 3.22 | 2.74 | $ 79 | $ 67 | $ 297 | $−173 | ** | |
| Toner | Angus | 454 | 505 | 520 | 2.80 | 2.90 | 2.91 | $ 49 | $ 22 | $ 390 | $ 96 | ** | |
| Willmot | Angus | 495 | 529 | 591 | 2.63 | 2.75 | 2.99 | $ 37 | $ 27 | $ 654 | $ 322 | ** | |
| Sparrow | Charolais | 588 | 644 | 657 | 3.40 | 3.70 | 3.22 | $ 71 | $118 | $ 513 | $−287 | | $ 47 |
| Bardick | Hereford | 540 | 607 | 549 | 2.77 | 3.03 | 2.79 | $ 78 | $ 59 | $ 61 | $ 18 | ** | |
| Decorby | Hereford | 494 | 521 | 558 | 2.84 | 3.01 | 3.02 | $ 42 | $ 39 | $ 521 | $ 159 | ** | |
| Ferguson | Hereford | 527 | 557 | 587 | 2.72 | 2.97 | 3.01 | $ 34 | $ 58 | $ 409 | $ 261 | | $ 24 |
| Horkoff | Hereford | 494 | 522 | 564 | 2.85 | 3.12 | 2.78 | $ 31 | $ 62 | $ 483 | $− 62 | | $ 31 |
| Hougham | Hereford | 428 | 479 | 466 | 2.48 | 2.67 | 2.83 | $ 59 | $ 44 | $ 290 | $ 279 | ** | |
| Jenson | Hereford | 431 | 469 | 457 | 2.76 | 3.05 | 2.70 | $ 46 | $ 65 | $ 183 | $ 52 | | $ 19 |
| Johnson | Hereford | 586 | 619 | 592 | 3.13 | 3.61 | 3.19 | $ 38 | $107 | $ 41 | $ 54 | ** | |
| Kaeding | Hereford | 499 | 535 | 574 | 3.10 | 3.20 | 3.14 | $ 42 | $ 37 | $ 521 | $ 114 | ** | |
| Konschuh | Hereford | 484 | 565 | 506 | 2.64 | 2.93 | 2.87 | $ 73 | $ 76 | $ 134 | $ 205 | ** | |
| McKenzie | Hereford | 452 | 497 | 522 | 2.72 | 2.96 | 2.73 | $ 52 | $ 47 | $ 485 | $ 35 | ** | |
| McTaggart | Hereford | 516 | 580 | 533 | 2.70 | 3.06 | 2.92 | $ 75 | $ 81 | $ 116 | $ 198 | ** | |
| Millham | Hereford | 523 | 539 | 569 | 2.77 | 3.12 | 3.21 | $ 17 | $ 63 | $ 315 | $ 393 | ** | |
| Nobs | Hereford | 479 | 509 | 511 | 2.71 | 3.03 | 3.10 | $ 34 | $ 71 | $ 221 | $ 344 | ** | |
| Palaschuk | Hereford | 509 | 525 | 565 | 2.87 | 3.01 | 3.06 | $ 21 | $ 31 | $ 385 | $ 186 | ** | |
| Spencer | Hereford | 431 | 457 | 462 | 2.59 | 2.78 | 2.57 | $ 31 | $ 44 | $ 216 | $− 17 | | $ 13 |
| Wainman | Hereford | 549 | 581 | 509 | 2.47 | 2.95 | 2.87 | $ 37 | $111 | $−271 | $ 369 | ** | |
| Brown | Shorthorn | 458 | 485 | 465 | 2.67 | 2.94 | 2.81 | $ 17 | $ 62 | $− 20 | $ 124 | ** | |
| Campbell | Shorthorn | 465 | 498 | 557 | 2.91 | 3.13 | 3.11 | $ 39 | $ 48 | $ 640 | $ 174 | | $ 9 |
| Cooper | Shorthorn | 494 | 540 | 515 | 3.20 | 3.24 | 2.94 | $ 56 | $ 9 | $ 148 | $−228 | ** | |
| Morton | Shorthorn | 540 | 580 | 671 | 2.76 | 3.11 | 2.88 | $ 48 | $ 81 | $ 885 | $ 109 | | $ 33 |
| McLeod | Simmental | 637 | 753 | 747 | 3.09 | 3.35 | 3.10 | $145 | $105 | $ 792 | $ 16 | ** | |

**TABLE 2. Continued.**

| Herd | Breed | Weaning Weight Mean (1975) | Weaning Weight Best (1975) | Weaning Weight Mean (1977) | Average Daily Gain Mean (1975) | Average Daily Gain Best (1975) | Average Daily Gain Mean (1977) | Predicted Change in Value ($) WW | Predicted Change in Value ($) ADG | Change in Value from Observed Phenotypic Change WW | Change in Value from Observed Phenotypic Change ADG | Predicted Equals Observed Emphasis[a] | Predicted Difference in Value of Improved Characteristics[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (1976) | (1976) | (1978) | (1976) | (1976) | (1978) | | | | | | |
| Anaka | Angus | 522 | 643 | 592 | 2.78 | 3.17 | 2.66 | $105 | $ 90 | $ 272 | $−110 | ** | |
| Dryland | Angus | 498 | 513 | 597 | 2.85 | 3.12 | 2.81 | $ 17 | $ 62 | $ 681 | $− 36 | | $ 45 |
| McCall | Angus | 508 | 545 | 578 | 3.28 | 3.51 | 2.84 | $ 64 | $ 52 | $ 490 | $−388 | ** | |
| McNinch | Angus | 574 | 629 | 601 | 3.11 | 3.17 | 3.18 | $ 65 | $ 13 | $ 186 | $ 63 | ** | |
| Sauder | Angus | 594 | 649 | 605 | 3.00 | 3.53 | 2.87 | $105 | $102 | $ 74 | $−119 | ** | |
| Stables | Angus | 510 | 541 | 547 | 2.85 | 2.94 | 2.78 | $ 34 | $ 22 | $ 255 | $− 62 | ** | |
| Willms | Angus | 533 | 547 | 592 | 2.85 | 2.97 | 2.84 | $ 24 | $ 22 | $ 370 | $− 18 | ** | |
| Begrand | Charolais | 683 | 750 | 653 | 3.29 | 3.72 | 3.54 | $ 84 | $178 | $−219 | $ 405 | ** | |
| Howe | Charolais | 650 | 712 | 649 | 3.18 | 3.63 | 3.11 | $ 65 | $186 | $− 80 | $−114 | | $121 |
| McKenzie | Charolais | 540 | 623 | 697 | 3.66 | 4.02 | 3.70 | $126 | $119 | $ 1183 | $ 62 | ** | |
| Plewis | Charolais | 743 | 792 | 629 | 3.51 | 4.02 | 3.68 | $ 61 | $211 | $−939 | $ 277 | ** | |
| Simpson | Charolais | 672 | 713 | 618 | 3.62 | 3.92 | 3.49 | $ 51 | $121 | $−403 | $−209 | | $ 70 |
| Wiens | Charolais | 575 | 594 | 551 | 3.51 | 3.97 | 3.84 | $ 22 | $180 | $−182 | $ 517 | ** | |
| Bardick | Hereford | 493 | 517 | 570 | 2.62 | 2.77 | 3.03 | $ 27 | $ 36 | $ 525 | $ 366 | | $ 9 |
| Decorby | Hereford | 484 | 537 | 554 | 2.78 | 3.19 | 3.04 | $ 63 | $ 93 | $ 483 | $ 230 | | $ 30 |
| Gamble | Hereford | 533 | 543 | 555 | 2.76 | 3.06 | 3.02 | $ 10 | $ 67 | $ 150 | $ 234 | ** | |
| Gress | Hereford | 472 | 527 | 496 | 2.92 | 3.15 | 2.92 | $ 60 | $ 65 | $−113 | $ 00 | ** | |
| Jenson | Hereford | 429 | 461 | 484 | 2.72 | 2.95 | 2.80 | $ 39 | $ 52 | $ 385 | $ 69 | | $ 13 |
| Jones | Hereford | 509 | 565 | 481 | 2.62 | 2.85 | 2.94 | $ 58 | $ 59 | $−193 | $ 288 | ** | |
| Millham | Hereford | 532 | 573 | 563 | 2.88 | 2.96 | 2.76 | $ 48 | $ 18 | $ 213 | $−108 | ** | |
| Misty, M. D. S. | Hereford | 509 | 537 | 506 | 3.16 | 3.38 | 3.12 | $ 31 | $ 48 | $− 21 | $− 35 | | $ 17 |
| Wainman | Hereford | 542 | 585 | 535 | 2.61 | 2.89 | 2.84 | $ 50 | $ 64 | $− 47 | $ 210 | ** | |
| Cooper | Shorthorn | 500 | 542 | 522 | 2.94 | 3.39 | 3.27 | $ 49 | $101 | $ 153 | $ 290 | ** | |
| Mann | Simmental | 609 | 652 | 661 | 3.47 | 4.02 | 3.38 | $ 56 | $221 | $ 396 | $−143 | | $165 |
| McLeod | Simmental | 590 | 670 | 637 | 3.41 | 3.55 | 3.00 | $104 | $ 55 | $ 350 | $−657 | ** | |

[a] ** Denote those cases where the characteristic, which the estimating equation (15a or 15b) indicated should be emphasized for improvement, coincided with the charactersitic actually emphasized for improvement.

[b] Values in this column denote, for those cases where the characteristic predicted for emphasis did not coincide with the characteristic actually emphasized, the difference in the predicted value of improvement between the former and the latter.

where

$\bar{G}^*_{iI+1}$ = the expected mean value of characteristic $G_i$ for bulls in generation I+1.

$G_{iI}$ = the value of $G_i$ for the sire to be bred in generation I.

$\bar{G}_{iI}$ = the mean value of characteristic $G_i$ of the selected sire's male contemporaries within a herd.

$H_{Gi}$ = the heritability of characteristic $G_i$.

Once estimates for each $G^*_{iI+1}$ are obtained from (16), these values can be utilized in the estimating equations (15a, 15b) for the relevant breed and the expected increase in value for improvement on each characteristic obtained. The characteristic, which the breeder would be expected to emphasize in his selection program, can be identified. The estimates can then be compared to the actual characteristics emphasized by breeders over a generation.

Ideally, one would like to have data on individual herds over time. Such data are, however, not generally available. Fortunately, some data on groups of individual bulls are available. The Saskatchewan Bull Test program publishes the results of its trials for individual animals identified by herd. Data were available for the 1975–76, 1976–77, 1977–78 and 1978–79 tests. Assuming that bulls on test are representative of the sample herd's genetic material, an estimate of the mean values, $\bar{G}_i$'s, and the range for each characteristic can be obtained. Then, assuming the animal which ranked the highest for each $G_i$ would be used for rebreeding, an estimate of $G^*_{iI+1}$ can be made for each characteristic. These can be substituted into (15a) or (15b) and the expected increase in dollar value calculated. The characteristics which the breeder would be expected to emphasize can then be identified. These results can be compared to the actual improvements observed in bulls of the same herd in the next generation—in this case, bulls on test two years later.

For the 1975–76 & 1977–78 and the 1976–77 & 1978–79 tests, fifty-seven herds with representative bulls have been identified. The results of the comparisons are presented in Table 2. For the calculation of heritability, $H_{Gi}$, a value of .35 was used for $G_1$ and .50 for $G_2$ (Lasley).

The characteristic actually selected for emphasis in improvement coincided with the characteristic predicted from equations (15a) and (15b) in seventy-two percent of the cases. Further, in only three cases when the characteristic actually emphasized for improvement did not agree with the predicted characteristic to be emphasized, did the differences in the predicted additional dollar value of alternative improvements to characteristics exceed \$50. The average differences in predicted value of improvement to alternative characteristics for inconsistent predictions is \$43. This would indicate either that the estimated coefficients or the markets are not precise. If the markets are not precise this would suggest either that breeders are indifferent about the characteristics they select for improvement, or that random elements are sufficient to distort the perception of breeders as to the correct choice of emphasis in improvement. On the other hand in only three cases of fifteen where the difference exceeded \$50, did the predicted and actual emphasized characteristic differ.

## Discussion and Conclusions

These results suggest three conclusions: (1) commercial cattlemen recognize the important genetic inputs to their production process and this is reflected in the prices they are willing to pay for bulls; (2) the prices of bulls reflect the change in the production process expected from the hybrid vigor associated with crossbreeding; (3) the selection of characteristics emphasized in the breeding programs of purebred breeders corresponds, in general, to the choices indicated by the estimated implicit values of characteristics. Taken together, they indicate that both producers and breeders have sufficient intuitive understanding of the shadow values of important characteristics for the market to regulate the process of genetic improvement.

There are, however, a number of factors which may make it appear as if the market is chaotic and that the process of genetic improvement is poorly regulated. The most obvious distorter of perception is the market institution itself. As purebred breeders and commercial cowmen both participate at the same auctions, one has two markets simultaneously. As purebred breeders likely have different criteria upon which they select bulls or may attempt to distort the market through collusive bidding, the combination of two markets at the same time and place may give the impression that the pricing of bulls is largely a random exercise.

Further, it seems clear that any evaluation of genetic characteristics must be made within the context of the breeding technology employed. The value of a vector of genetic characteristics to be used in a straightbred system will differ from those employed in a crossbreeding system. In sales at which a selection of breeds is auctioned, correlations between the price of the animals and their characteristics will be low unless the type of breeding technology is taken into account.

The conclusions also lend support to the induced innovation hypothesis. At least improvements to existing technologies, both new and old, appear to follow the prices indicated by the market. If the marginal changes in prices predicted for bulls can initiate changes in breeding programs, then the more dramatic changes in prices, usually observed by those conducting empirical research on induced innovation, would also be expected to elicit a response from the input sector. The characteristic approach to change in technology utilized in this study may also suggest that more meaningful results could be obtained by those who study technological change, if their analyses were conducted in characteristics space rather than goods space.

The use of the characteristics approach can also help identify various types of technological change: e.g., (1) the introduction of a new production function; or (2) the introduction of an altered input which combines additional quantities of existing input characteristics. In our case, it would appear that we have been discussing technological change of both kinds. A change in the production function implies that there is a new way of producing an existing good. The new production function in beef cattle results from the discoveries of applied geneticists who identified the increased production expected from crossbreeding. The change in the production process is indicated by the different production functions implied from the estimation of (15a) and (15b).

On the other hand, genetic improvements in existing purebred herds, whether they are used in a straightbred system or a crossbreeding system, represent new inputs combining additional quantities of existing characteristics. The full realization of the genetic potential, internalized in the collective germ plasm, will depend upon the selective breeding of purebred strains. Improvements to the characteristics mix of bulls appear to be determined by the prices imputed to characteristics.

The importance of this result should not be ignored. If the price of bulls did not reflect their genetic characteristics, three possible situations would be suggested: (1) that the characteristics selected for measurement by animal scientists and subsequently ranchers are unimportant; (2) that the purchasers of bulls are ignorant of genetic processes; or (3) that the production process is heterogeneous. Each of these situations would have particular ramifications for the process of genetic-based technological change. If the current characteristics are unimportant then relevant alternative characteristics which are important should be identified by animal scientists. Otherwise, there is no method whereby genetic progress can be monitored and the ranchers engaged in the collection of the existing set of characteristics would be expending a great deal of effort to no avail.

If ranchers are ignorant of the genetic process, then one would expect that little genetic progress could be made. A case might then be made for increased expenditure on education and/or the institution of a sire monitoring and regulated breeding program where the decision process was removed from the operator.

If production at the farm level proved to be heterogeneous, then the problem would be more severe. Heterogeneous production is taken here to mean that each farm would derive different relative shadow values for genetic characteristics. In this case, even if each farm could maximize its potential in the short run, the prices received for bulls would not provide consistent information on the shadow values for genetic characteristics and purebred breeders would not be able to effectively regulate the process of genetic improvement and some alternate mechanism would have to be found. The results of the study, however, indicate that none of the above cases exist. Bull sales provide sufficient information to influence the direction of genetic progress.

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