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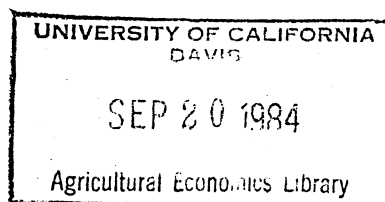
Aggregate Milk Supply Response and Investment Behavior
on U.S. Dairy Farms

By

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I. Introduction

Government involvement in marketing and pricing of milk has stimulated a considerable amount of research on the supply/demand characteristics of the markets for milk. On the supply side, Halvorson, Wipf and Houck, Hammond, Wilson and Thompson, Prato, Novakovic and Thompson, Hutton and Helmberger, Chen et al., Levins and others have investigated milk supply response in the U.S. However, the empirical results obtained from econometric estimation of aggregate supply functions have varied widely among studies. For example, Wilson and Thompson as well as Prato found, surprisingly, that the estimated coefficient of milk price in the milk production equation was not significant. In general, the short run elasticity of milk supply was found to be very small: between .07 and .16 (Hammond; Wipf and Houck; Chen et al.; Hutton and Helmberger). The estimates of the long run elasticity of supply have varied from .14 (Hammond) to .15 (Wipf and Houck), .36 (Hutton and Helmberger), .4 (Halvorson) and 2.53 (Chen et al.). This suggests that the long run elasticity of milk supply may be very different from the corresponding short run elasticity. These wide variations in long run supply estimates further indicate that additional research on the dynamics of milk production response is needed. In particular, a better understanding of the speed and magnitude of economic adjustments in dairy production would aid in anticipating long run production impacts of alternative dairy policy options.

The objective of this paper is to investigate the dynamics of milk supply response in the U.S. dairy sector. This is done by considering the dairy herd as a capital good. Changes in the capital stock thus represent

investment (or disinvestment) decisions which are influenced by market prices. Furthermore, as a dairy cow grows, its capital value is expected to change, implying that investment decisions in the dairy herd are different for each age cohort. On this basis, a dynamic model of the aggregate dairy herd's size and age structure is developed which, together with an analysis of milk cow productivity, constitutes a model of U.S. milk production. By considering explicitly the influence of market prices on culling and replacement decisions for each age cohort in the dairy herd, the proposed model departs significantly from previous dairy supply models. In particular, the dynamics of the dairy cow population are shown to play a crucial role in the economic adjustments of milk production to changes in relative prices. Short and long run supply elasticities, obtained by simulating the estimated model, give considerable insight on milk supply adjustments over time. For example, it is found that while short run supply elasticity is small, the long run milk supply elasticity is considerably larger than the ones reported in most previous studies. Implications of the results for dairy policy are then explored.

II. A Model of Population Growth:

Following Jarvis, and Novakovic and Thompson, the cattle herd is considered as a capital stock, implying that a dairy cow is treated as a biological asset producing milk and calves as joint products. Milk is directly marketable while calves are valuable either after fattening for slaughter or after being raised for replacement in the dairy herd. In addition, the dairy cow has a salvage value: its meat value at slaughter. The production of milk and meat by a cow depends on the genetics and physiology of the animal, its biological growth and the environment (daily

feed ration, resistance to disease, etc.) A dairy farmer typically has two major types of management decisions to make: a/ how large a dairy herd should he manage, and b/ how to choose the factors of production in order to order to obtain desired output levels. The former set of decisions includes selecting both cows to cull and calves to keep for replacement in the dairy herd.^{1/} These decisions correspond to those found in the economics of replacement and investment (Perrin; Jarvis). Milk and slaughter price taken at various points of the cow's life cycle should be important in these decisions. The second set of decisions includes the choice of feed ration throughout the life of each cow. Since feed intake is usually considered the most important variable input in dairy production, feed cost is expected to heavily influence the cost of milk production.

Assuming that dairy farmers maximize the present discounted value of net returns associated with milk and meat production from the dairy herd, the influence of market prices on management decisions can be further investigated. In particular, under competition, the capital value of a dairy cow is then the sum of the discounted values of a/ the profit from its milk production, b/ its salvage value, and c/ the profit from its future calves (Jarvis). Since a ceteris paribus increase in the price of milk increases profits, it is expected to raise the dairy animal's capital value. This would provide the incentive for dairy farmers to increase their herd size in response to a ceteris paribus increase in milk price. However, the change in the capital value of the animal would depend on its age. Those animals further from slaughter will be involved in productive activities for a longer time; their capital value is therefore expected to be more sensitive to a change in milk price or feed cost. Thus, different retention behavior for each age cohort should be expected in response to a

change in milk price. Moreover, with genetic progress, there are economic incentives to replace old cows with younger, more productive dairy cows (Perrin). An increase in milk price as well as the existence of short run constraints on feed availability or milk parlor capacity would augment these incentives. Therefore, a milk price increase should have a large negative impact on the culling rate of female calves and heifers, which would increase herd size in the future. The impact of increased milk price on the culling rate of older cows is expected to be smaller in general and could be positive under short run constraints or under genetic progress.

Similarly, a *ceteris paribus* rise in slaughter price would also increase the animal's capital value. As noted by Jarvis, female calves tend to have a bimodal optimal slaughter age because more female calves are born than are usually needed for replacement in the dairy herd. As a result, some female animals are slaughtered as fattened heifers before they begin to bear calves while others are slaughtered only after their value as a breeding and milk producing animal has declined. If the value of a female as a slaughter animal rises relative to its other values, some females formerly destined to be retained in the herd will be slaughtered. These females culled will typically have relatively low milk productivity or reproduction problems which would lower their breeding or milk producing values compared to their slaughter value. An increase in slaughter price would increase both the slaughter value of a female animal and its calf stream value. Since the calf stream value of an older cow is rather small, an increase in slaughter price is expected to increase the culling rate of older cows. However, the culling rate of young female animals could either increase or decrease in response to a rise in slaughter price depending upon the relative importance of their slaughter value versus their calf stream value.

The above discussion indicates that it is crucial to differentiate the economic behavior of dairy producers according to the age and sex of their dairy animals. Since male animals have values in dairy production only through their breeding value and since, with artificial insemination, one bull can service many cows, then, with male and female calves being born in roughly equal numbers, the proportion of male calves retained for breeding in the dairy herd is quite small. Although this proportion is crucial in genetic selection and productivity improvement, it suggests that the number of male animals plays only a minor role in the dynamics of the dairy herd population. Thus, we will focus here on the influence of economic conditions on the number and productive use of heifers and cows.

Denoting by COW_t the number of dairy cows in the U.S. herd in year t and by H_t the number of two-year old dairy heifers held for replacement in year t , then the following identities characterize the dynamics of the dairy herd population

$$H_t = (.5 \times COW_{t-2}) \cdot \rho_t^H \quad (1)$$

and

$$COW_t = \sum_{i=1}^N \left\{ H_{t-i} \prod_{j=1}^i \left[\rho_{jt}^c \right] \right\} \quad (2)$$

where the ρ_t 's denote proportions of various categories of female animals retained in the dairy herd.

Equation (1) describes the replacement decisions in the dairy herd, where $\{.5 \times COW_{t-2}\}$ denotes the potential number of female calves for replacement in the dairy herd at time t (assuming a 12 month calving period and no death loss). The term ρ_t^H is the proportion of these calves actually retained at time t . Similarly, equation (2) describes the culling decisions in the dairy herd, where $i = (\text{cow age}-2)$, $N = [(\text{age of the oldest$

cow)-2], H_{t-i} is the potential number of cows of age (i+2) at time t (assuming no death loss) and ρ_{jt}^c is the proportion of cows of age (j+2) that are actually retained in the herd at time t. Using this notation, then

$(\prod_{j=1}^i \rho_{jt}^c)$ is the cumulative proportion of cows of age (i+2) actually retained, or alternatively, the probability that a two-year old heifer would still be in the dairy herd at age (i+2).

As argued above, changes in the economic situation would affect the replacement and culling decisions by shifting the proportions ρ_t^H and ρ_{jt}^c in (1) and (2). In other words, these proportions are expected to be functions of feed cost, milk price and slaughter price, as well as of the animal age. Thus, changes in relative prices would influence the dairy population through the proportions ρ in (1) and (2).

In order to further analyze population dynamics in the dairy herd, note that substituting (1) into (2) yields the relationship

$$COW_t = \sum_{k=3}^{N+2} a_k(\text{prices}) \cdot COW_{t-k} \quad (3)$$

with $a_k = (.5) \rho^H \left\{ \prod_{j=1}^{k-2} [\rho_j^c] \right\} \geq 0$. Expression (3) is a homogeneous difference equation of degree (N+2) which is characteristic of a growth model (e.g. Hicks). In the stationary case where prices are constant over time, its solution is determined by the characteristic roots associated with (3). The location of these roots determine the dynamic properties of the dairy cow population. It can be shown that the dominant root lies between 1 and $(\sum_{k=3}^{N+2} a_k)$, while the non-dominant roots are in the unit circle (Sydsaeter). Consequently, given stationary prices, the dairy herd would be expanding, at a steady state, or contracting depending upon whether $(\sum_{k=3}^{N+2} a_k)$ is greater, equal, or less than one, respectively.

Since the a_k 's coefficients are function of relative prices, it follows that the levels of relative prices will determine the dynamic properties of the dairy cow population.

III. Empirical Evidence:

Equations (1) and (2) provide the basis for specifying and estimating a model of the U.S. dairy herd. Since the proportions ρ in (1) and (2) are bounded by 0 and 1, they are specified here as logit functions of the form $\rho_t = 1/(1 + \exp(X_t \beta))$ where X_t is a set of explanatory variables and β is a parameter vector. In our model, the X's include slaughter price (SP), milk price (MP) and feed cost (FC); specified as price ratios (SP/FC and MP/FC). In the heifer equation (1), H_t is measured by the number of heifers over 500 lbs which are on dairy farms on January 1 of each year, as reported by USDA. The proportion ρ_t^H is assumed to be function of market prices at time $t-3$ and $t-1$, the former reflecting the economic situation just before the female calves are born, the latter reflecting the market conditions just before the heifers reach two years of age. This specification corresponds to a framework where the decision to slaughter young female animals is made either at their birth or when they are two years old, with basically no market opportunity to slaughter heifers between 6 and 18 months of age.

In the cow equation (2), COW_t is measured by the number of cows on dairy farms on January 1 of each year, as reported by USDA, and N is chosen equal to 9.^{2/} The proportions ρ_{jt}^c are specified as a function of the proportion of two-year old heifers ready to enter the dairy herd (H_{t-j}/COW_{t-j}), of market prices at time $(t-j)$ and of the age of the cow. The proportion of heifers (H_{t-j}/COW_{t-j}) measures the influence of replacement availability on culling decisions. In general, the culling rate of 3 year old cows is not expected to be significantly affected by a

ceteris paribus change in heifer numbers. However, under genetic progress, one would expect a high proportion of heifers in the dairy herd to give added incentives to cull older, less productive, cows. On this basis, the proportion of heifers is specified in the cow equation as an interaction variable with age: $(H_{t-j}/COW_{t-j}) \cdot (age-3)$. The prices at time $(t-j)$ reflect the economic situation just before the decision to retain (or slaughter) the cows of age $(j+2)$ is made. As discussed in section II, one expects age to affect the influence of market prices on the culling decision. Thus, the proportions ρ_{jt}^c are specified here as a function of prices, age along with their interactions (prices x age).

Finally, to complete the production model, dairy cow productivity is measured by average cow production per year (YLD). A productivity equation is specified in linear form as a function of milk price, feed cost and a time trend which reflects technological progress in the dairy herd. Dairy production at time t is then simply given by the number of cows times their average productivity.

The model is estimated using U.S. yearly data from 1960 to 1982. Each equation is estimated by the least squares method. The empirical results are reported in table I.^{3/} The R^2 of the COW and YLD equations (2) and (3) are high, indicating that these equations give a reasonable representation of the real world. The R^2 of the heifer equation (1) is lower, suggesting perhaps that there is considerable "noise" in the dairy herd replacement decision. However, except for the variable MP_{t-1}/FC_{t-1} , the price variables are all significantly different from zero (at the 10 percent level) in the replacement equation (1). Also, all the price variables have the expected signs: a higher milk price increases the retention of replacement heifers while a higher slaughter price increases the slaughter of young females.

Table I - U.S. Dairy Production Model^{a/ b/}

$$(1) H_t = (.5 COW_{t-2}) / \left\{ 1 + \exp \left[\frac{2.722}{(.691)} + \frac{.2521}{(.1215)} \left(\frac{SP_{t-3}}{FC_{t-3}} \right) - \frac{3.458}{(.997)} \left(\frac{MP_{t-3}}{FC_{t-3}} \right) + \frac{.2924}{(.0897)} \left(\frac{SP_{t-1}}{FC_{t-1}} \right) - \frac{.6118}{(.5601)} \left(\frac{MP_{t-1}}{FC_{t-1}} \right) \right] \right\}$$

$$R^2 = .4073$$

$$(2) COW_t = \sum_{i=1}^9 H_{t-i} / \left\{ \pi \left[1 + \exp \left(\frac{11.565}{(1.1916)} + \frac{.3814}{(.1647)} \left(\frac{SP_{t-j}}{FC_{t-j}} \right) - \frac{8.140}{(1.098)} \left(\frac{MP_{t-j}}{FC_{t-j}} \right) - \frac{2.739}{(.270)} \cdot AGE \right. \right. \right. \right. \\ \left. \left. \left. - \frac{.0795}{(.0335)} \left(\frac{SP_{t-j}}{FC_{t-j}} \right) \cdot AGE + \frac{1.668}{(.228)} \left(\frac{MP_{t-j}}{FC_{t-j}} \right) \cdot AGE + \frac{.937}{(.156)} \left(\frac{H_{t-j}}{COW_{t-j}} \right) \cdot (AGE-3) \right) \right] \right\} R^2 = .9874$$

$$(3) YLD_t = \frac{.003827}{(.000495)} + \frac{.0002202 T}{(.0000108)} + \frac{.0007956}{(.0002895)} \left(\frac{MP_t}{FC_t} \right) R^2 = .9774$$

$$(4) PROD_t = YLD_t \times COW_t$$

^{a/} Asymptotic standard errors are in parentheses below the parameter estimates.

^{b/} The variables are defined as follows: H_t = number of replacement heifers over 500 lbs on dairy farms on January 1 (1000 head); COW_t = number of dairy cows on dairy farms on January 1 (1000 head); SP_t = Omaha slaughter cow utility price (\$/100 lbs); MP_t = milk price received by farmers (\$/100 lbs); FC_t = value of dairy ration (\$/100 lbs); T = time trend (1 = 1950; 2 = 1951; etc.); AGE = (i-j+3) in equation (2); YLD_t = production per cow in year t; $PROD_t$ = U.S. dairy production (billion lbs). The data are from USDA sources: Livestock and Meat Statistics and the Dairy Situation.

This result is consistent with recent high milk price to feed cost ratios and the increase in the number of heifers per 100 cows in the U.S. dairy herd. Also, equation (1) indicates that, while the retention decision of a female animal is strongly influenced by milk price at its birth, the slaughter price plays an equally important role in that decision whether it occurs when the animal is born or when it is two years old.

All variables in the cow equation (2) are significantly different from zero at the 5 percent level. The results support the hypotheses discussed in section II. As expected, higher slaughter price or lower milk price tends to stimulate the culling of young cows. However, the opposite result is obtained for older cows. Presumably because of genetic progress, lower slaughter price or higher milk price stimulates culling as younger, more productive dairy cows are substituted for older cows. Such substitution is also significantly stimulated by the proportion of young heifers ready to enter the dairy herd (H_{t-j}/COW_{t-j}). This underlies the importance of differentiating among age cohorts in the analysis of dairy supply response.

Finally, the productivity equation (3) in table 1 indicates that the milk price to feed cost ratio has, as expected, a significant positive influence on production per cow. Also, the time trend variable T shows that considerable technological progress has taken place in the dairy herd during the last 20 years; milk cow productivity has been increasing at a rate of 1.8 percent per year.

IV. Some Implications:

The above model can be used to further analyze economic adjustments of dairy production over time. This can be done in two ways: a/ by investigating the dynamics of the dairy herd population given a set of market prices, and b/ by evaluating the dynamic supply elasticities of milk production in response to changes in relative prices.

First, the estimated model was dynamically simulated over time for given values of the relative prices.^{4/} Both within-sample and out-of sample predictions for milk production are presented in Figure 1. The within sample predictions, based on actual prices, indicate that the model does reasonably well tracking history. The out-of sample predictions are based on stationary prices set at particular levels. The results indicate that the economic situation facing U.S. dairy farmers in 1982 gave them the incentive to increase dairy production by about 4 percent per year, 1.8 percent being due to productivity increase and about 2.2 percent being due to increased herd size (see figure 1). This high rate of increase should not be surprising since, during the last three decades, the milk price to feed cost ratio (MP/FC) reached its highest value in 1982. There is considerable doubt that the demand for dairy products could match such a high expansion rate. Our results (see figure 1) also indicate that market prices appear to have given incentives for dairy farmers to increase milk production since the mid 1970's; all milk price to feed cost ratios from 1978, 1980, and 1982 lead to increased production. The current surplus in dairy products is just another indication that the market prices of the late 1970's and early 1980's were not equilibrium market prices and that the dairy price support program of the recent years has helped create an excess supply disequilibrium in the dairy market.

Second, the response of milk production to changing market prices was analyzed from the estimated model. Using the 1980 prices in a base simulation, the model was simulated again by changing each market price by 10 percent. A comparison of the simulation results provided the estimates of short run and intermediate run supply elasticities presented in table 2.^{5/} The short run ($j=0$) elasticity of milk production with respect to milk price (.115) is comparable to the ones reported in previous studies

FIGURE 1: ACTUAL AND PREDICTED U.S. DAIRY PRODUCTION

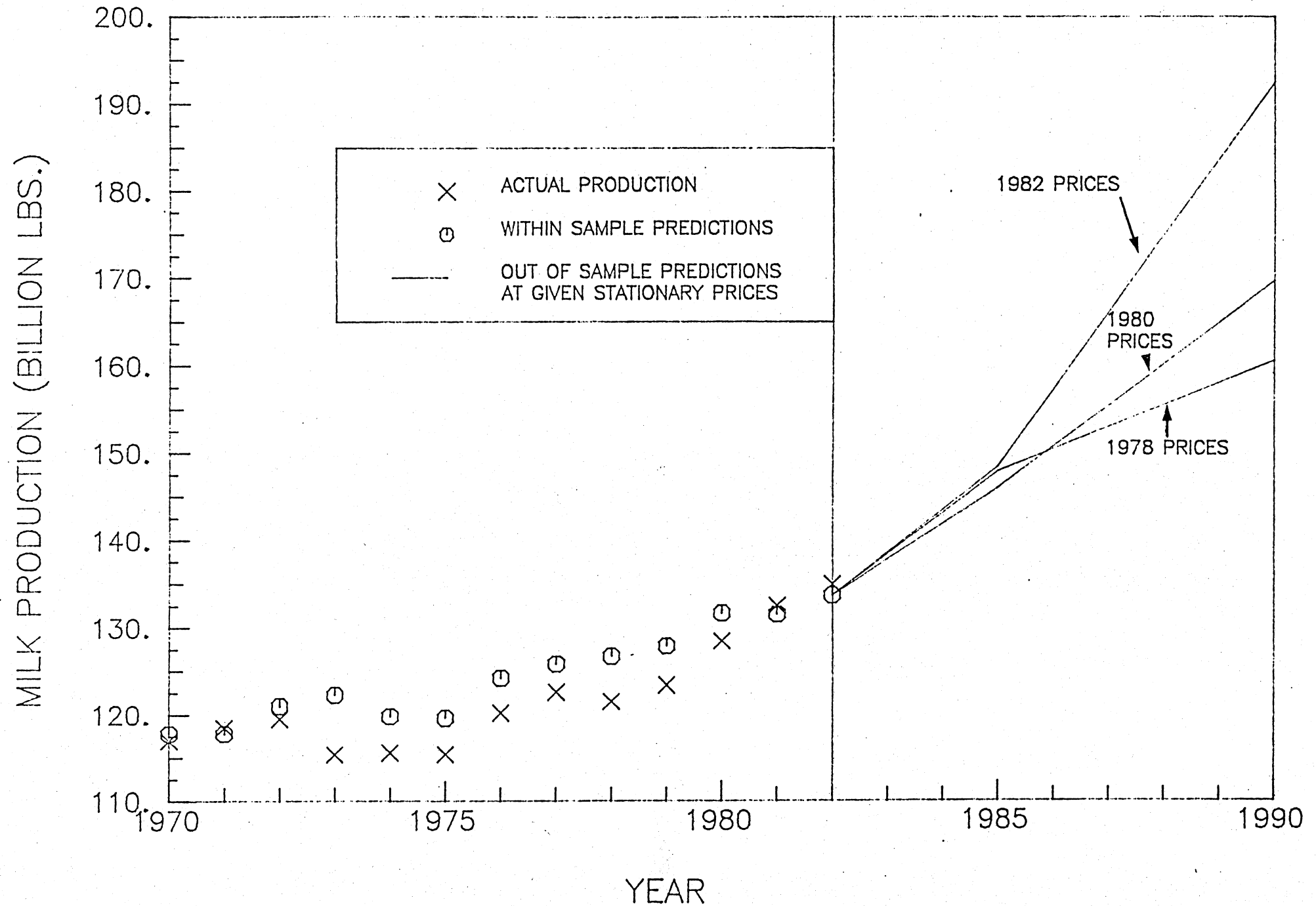


Table 2 - Short-Run and Intermediate Run Elasticities of

$$\text{U.S. Dairy Supply} \left[\frac{d \text{ Prod}_t}{d \text{ Price}_{t-j}} \cdot \frac{\text{Price}_{t-j}}{\text{Prod}_t} \right]$$

Supply Elasticity	w.r.t. milk price (MP _{t-j})	w.r.t. slaughter price (SP _{t-j})	w.r.t. feed cost (FC _{t-j})
Lag(j years)			
0	.115	0	- .115
1	.118	.056	- .097
2	.198	.016	- .102
3	.225	-.026	- .086
4	.485	-.102	- .217
5	.888	-.244	- .475
6	1.166	-.352	- .637
7	1.415	-.454	- .766
8	1.853	-.556	-1.067
9	2.272	-.681	-1.318
10	2.463	-.794	-1.419

15	3.903	-1.366	-2.375
20	5.031	-1.974	-3.194
25	5.947	-2.616	-3.916
30	6.696	-3.290	-4.569

(e.g. Hammond; Wipf and Houck, Hutton and Helmberger; Chen et al.). It reflects the increased productivity associated with higher milk price (see equation (3) in table 1). As expected, the intermediate run supply elasticities with respect to milk price are found to increase with the length of the run (j). In the long run ($j=20$ to 30 years), the supply elasticity is found to be very large, as dairy farmers expand the size of the dairy herd (see table 2). In particular, the long run supply elasticity is found to be substantially larger than the ones reported in previous studies (Hammond; Wipf and Houck; Hutton and Helmberger; Halvorson; Chen et al.).

The elasticity of milk supply with respect to slaughter price is found to be zero in the short run ($j=0$) (Table 2). In the intermediate run, the elasticity is close to zero for $j=1,2,3$ but becomes negative for $j>3$. This indicates that, although slaughter price does not influence much dairy supply for the first few years, its long run impact on milk production is negative, suggesting that meat and milk production are long run substitutes on dairy farms.

Finally, the elasticities of milk supply with respect to feed cost presented in table 2 indicate that, as expected, a feed cost increase has a detrimental influence on dairy production. Again, although the short run elasticity is rather small ($-.115$ for $j=0$), the long run elasticity is found to be very large. This suggests that government programs supporting feed grain prices can have a large negative influence on dairy production in the long run.

V. Concluding Remarks

The analysis presented in this paper suggests that the modeling of cow population dynamics provides considerable insights in the economic adjustments taking place on dairy farms. The results show that farmers respond strongly (particularly in the long run) to changing relative prices in the management decisions concerning the size and productive use of the dairy herd. They also indicate the importance of a constant monitoring of the dairy support price in the design of dairy policy. Indeed, given a rather small short run supply elasticity, setting the support price higher than the market equilibrium price may not create noticeable excess supply of dairy products in the short run. However, the long run effects of such a policy may be very costly since, once the dairy farmers have expanded their herd, the elimination of excess supply can become a rather difficult task.

Future research directions fall into different areas. Regional supply response may be interesting given the diverse nature of production in different parts of the country. The dynamics of dairy production along with the ability to move production units and output across regions should be important in determining the regional distribution of production.

Genetic progress is another area of research that merits considerable attention. Sire selection through artificial insemination has had a large influence of milk cow productivity over the last few decades. However, advances in genetics on the female side now seem possible in the future. For example, advances in genetic engineering, sex determination and embryo transfer could have significant impacts on the industry. While these events will likely not occur in the immediate future, they could affect significantly the dynamics of the dairy cow population as well as milk production in the coming decades.

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Footnotes

- 1/ The purchase or sale of cows and heifers from a dairy farmer to another does not affect the size and composition of the aggregate dairy herd. Since this paper focuses on aggregated supply response, such actions are neglected in the analysis.
- 2/ The model specification assumes implicitly that no dairy cow is kept in the herd beyond the age of eleven. The number of cows of more than eleven years of age actually present in the U.S. dairy herd is relatively small. Thus, the model is expected to provide a reasonable approximation to the dairy herd population.
- 3/ While equation (3) is estimated by OLS, equations (1) and (2) are estimated by non-linear least squares, using the Gauss-Newton method.
- 4/ The model was simulated using the Newton method.
- 5/ The intermediate run elasticity over j years measures the percentage change in production due to a one percent price change sustained over j years. Note that, in general, the elasticities presented in table 2 may not satisfy the price homogeneity condition of the milk supply function. The reasons are that the model is highly non-linear and that the elasticities have been calculated from 10 percent changes (rather than "small" changes) in the respective prices.