ABSTRACT: The econometric analysis contained in this study adopts the modeling principle currently used by USDA for policy analysis whereby milk production is modeled as a product of dairy herd size and yield per cow, stochastic elements that are modeled separately (USDA 2007). We account for herd size dynamics along the lines of models proposed by Chavas and Klemme (1986) and Schmitz (1997). We contribute to the literature by introducing a mixed frequency approach that allows us to model yield using quarterly data, while dairy herd and replacement heifer pool is modeled using annual frequency. That allows us to model the yield as a trend-stationary process with the economic environment inducing both short-term shocks and impacting the speed of reversion to trend yields. In addition, we design and implement dynamic residual-based bootstrap technique that can be used in testing for changes in non-marginal simulated long-run supply responsiveness. We obtain strong in-sample predictive power and very high significance of key economic and herd structure variables. Despite dramatic yield improving technological change, improved genetics and the increasing importance of large farms, all of which we would expect to increase the milk supply price responsiveness, we find a declining trend in long-run supply responsiveness from 1975 through 2005. If such decline were to persist or continue that would be a major cause for worry, as ever larger price swings would be needed to quickly equilibrate the market in face of demand shocks. However, we find that milk supply is getting more responsive in recent several years both to milk and feed prices. We recommend extending this analysis using micro-level data to examine farm-level behavior in face of price-swings. Increasing responsiveness to feed prices further justifies focusing the next generation of dairy policy toolbox on managing dairy profit margins rather than just revenue streams. Further research needs to be done to develop a partial equilibrium model of the U.S. dairy sector based on insights on structural characteristics of the production presented in this article. We believe that when combined with a model of the demand for dairy products our work has a potential to improve reliability of long-run projections of the U.S. milk production.

Keywords: milk supply, herd dynamics

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1. Introduction

The U.S. dairy industry has experienced significantly increased price volatility both at the farm level and for manufactured dairy products over the last 15 years. Reacting to this volatility a number of farm groups have proposed significant changes in U.S. dairy policy in advance of the 2012 Farm Bill debates. Some of these proposed changes include the implementation of supply management, modifying (or eliminating) the current milk price deficiency payment program (i.e., the Milk Income Loss Contract, MILC, program), elimination of the Dairy Product Price Support program, and placing greater emphasis on dairy farm operator price/revenue risk management (Holstein Association USA, 2009; Nicholson and Stephenson, 2010; National Milk Producers Federation, 2011). It is unclear as to how producers will respond should any of these proposals be enacted and what would be the resulting milk supply impacts. As such it is important for analysts and policy makers to obtain an estimate as to how responsive dairy producers are to changing economic and technological conditions.

Examples of previous research on supply response in the U.S. dairy sector include LaFrance and de Gorter (1985), Chavas and Klemme (1986), Thraen and Hammond (1987), Chavas, Krauss and Jesse (1990), Chavas and Krauss (1990), Yavuz, et al, (1996), Pagel (2005), and USDA (2007). These analyses are limited in that they are either dated or they do not fully account for dairy herd dynamics. Historical studies of the U.S dairy industry may provide inaccurate responses to changing economic conditions given that (i) there has been a significant structural change in dairy farm size and number implying a different type of adjustment process, (ii) there has been a structural change in U.S. dairy policy and milk pricing resulting in a much more volatile pricing environment, and (iii) the development of new value-added dairy products over the last twenty years implying a greater flexibility in the use of the components of the U.S.
milk supply. As much of the adjustments have occurred since these previous analyses were undertaken, conclusions of those studies may no longer be reflecting today’s dairy industry’s supply characteristics.

The present study incorporates both annual and quarterly data encompassing the 1975-2010 period and builds a mixed-frequency milk supply model that extends the specification originally developed by Chavas and Klemme (1986). The three main objectives of this study are to develop an econometric model that allows analysts to: (i) quantify the current structure of the U.S. milk supply, (ii) gain insight into impacts of technological and economic changes that have occurred over the last 25 years and (iii) generate forecasts of long-run milk supply response to price changes and possible future technological advancements.

The structure of this paper is as follows. We first provide an overview of the U.S. dairy sector and policy. We describe the econometric model used in this analysis. We then provide a description of the data used in estimation followed by an outline the estimation procedure and design of post-estimation tests. After presenting our econometric model results, long-run simulations of milk production and supply elasticities are estimated. In the concluding section we summarize our findings and implications for U.S. dairy policy.

2. Overview of the U.S. Dairy Sector

In 2010, there were approximately 62,500 U.S. dairy farms with an aggregate herd size of 9.2 million cows that produced 192.8 billion lbs of milk. With this milk valued at more than $34.7 billion, the dairy sector accounted for approximately 10% of the gross value of US agricultural production (USDA, 2009). The U.S. dairy industry is continuing to undergo structural changes that started in the early 1970’s as evidenced by: (i) increases in average farm size, (ii) adoption of supply impacting technological innovations such as yield-increasing genetic selection,
adoption of rBST, increased adoption of sexed semen and changes in feeding systems to rotational grazing, and (iii) a shifting of farm milk production away from traditional supply areas as evidenced by increased production in the West and Southwestern regions of the U.S.

Concurrent with the above changes, price volatility at all marketing levels has become commonplace. Figure 1 shows the relationship between the USDA support price and the minimum price paid for manufacturing milk (i.e. milk used in production of hard cheeses) under the Federal Milk Marketing Order (FMMO) system. Prior to the mid-1980’s there was very little milk price variability as the dairy support price was an effective and binding milk price floor. Since the late 1980’s not only has the manufacturing milk price diverged from the support price but its variability has dramatically increased.

In terms of its domestic market, total annual dairy product demand is growing in the 2-3% range reflecting a relatively mature market compared to China, Southeast Asia and Latin America where demand is growing at annual rates greater than 10% (Balyney et al., 2006). This increased demand has been met with a continuously increasing productivity and decline in the size of the U.S. dairy herd, as illustrated in Figure 2. In 1950 the U.S. dairy herd was composed of 21.9 million cows with average annual productivity of 5,313 pounds. By 1975, the dairy herd had decreased by 48.9% to 11.2 million head with an annual productivity of 10,358 lbs., a 94.9% yield increase. The 2010 herd size was 41.5% of the 1950 level with a total milk production 65% greater.

Concurrent with the reduction in the U.S. dairy herd, between 1980 and 2010 the average herd size increased from 32 to 146 head per farm. Since 1993 the contribution to the total U.S. milk production from farms with less than 100 cows decreased from 45% to 15%. In contrast, in
2010, the largest 760 of the 62,500 U.S. dairy farms (i.e., 1.2%) accounted for 32.5% of total U.S. milk production.

One can characterize current U.S. dairy policy as having two primary objectives: (i) to provide a price support level to generate a minimum level of farm income and (ii) to ensure an orderly supply and marketing of farm milk. The Dairy Product Price Support Program, the Milk Income Loss Contract (MILC) program and the use of classified pricing of milk within the FMMO system are key elements of U.S. dairy policy designed to achieve these two goals.

As shown in Figure 1, the market price of manufacturing milk since the mid 1990’s has usually been much higher than the $9.90 support price but subject to considerable variability. In addition, with the milk support not being increased since January 1990, the level of support is felt by many in the industry to be too low to provide sufficient income. In response to both the high volatility and low price support levels, a new Federal dairy policy was enacted in December 2000 referred to as the Milk Income Loss Contract (MILC) program. This program provides payments to dairy farm operators to partially reimburse their forgone income when the price of (Class I) milk falls below a predefined target level.\(^1\)

3. Description of an Econometric Model of U.S. Milk Supply

To provide a representation of the supply structure of the U.S. dairy industry, we adopt an econometric model similar to that used for policy analysis by USDA’s Agricultural Marketing Service (USDA, 2007). Under their modeling framework, total U.S. milk production in the year \(t\) \((MILK_t)\) is the product of the number of milk cows in the U.S. dairy herd \((COW_t)\) and average yield per cow \((YLD_t)\). Under their model specification equations used to define herd size and

\(^1\) A more detailed description of the U.S. dairy industry and recent historical dairy policy can be found in Blayney et al (2006) and Blayney (2002). Classified pricing of milk under the FMMO system are explained in Jesse and Cropp (2008). An overview of the dairy sub-title of the 2008 Farm Bill can be found in Jesse, Cropp and Gould (2008).
average yield are stochastic. We introduce a mixed frequency model of the milk supply by modeling herd dynamics using annual frequency, and yield using quarterly data. We used quarterly data to account for the seasonality that has historically been observed in milk yield. Annual milk production is represented as:

$$MILK_t = COW_t \times \sum_{i=0}^{3} YLD_{t-i}$$

(1)

where $\tilde{t}$ is the 4th quarter of year $t$.

Modifying the supply specifications of Chavas and Klemme (1986) and Chavas and Krauss (1990) we extend the USDA model by accounting for herd size dynamics via specific modeling of producer culling/replacement decisions and the characteristics of dairy cow biology. The understanding of biological and economic decisions governing the dairy herd dynamics can best be exploited by separately examining herd size and yield determinants via the use of two separate models.

The herd size specification used here is based on the 14 month dairy cow reproductive cycle assuming a 9 month pregnancy and 5 months between freshening (giving birth to a calf) and next pregnancy. Cows produce milk from the initial birth to approximately two months prior to next birth at which time they are removed from the milking herd to rest before the next delivery. A newborn calve takes approximately 9 months to reach the weight of 500 pounds, the threshold used by USDA to be classified as a replacement heifer. Heifers are first impregnated at approximately 15 months of age and give birth when approximately 2 years old. For our current model, a replacement heifer ($\text{HEF}_t$) is a female calf at least one year of age at the beginning of the year and expected to enter the herd before the end of the year. Upon first calving, a replacement heifer is then considered to be a dairy cow and part of the dairy herd.
While the maximum biological dairy cow age exceeds 20 years, intensive milking and frequent calving make cows susceptible to various diseases. Although such health problems are mostly treatable, they tend to make the economic life of the cow much shorter than the maximum physical age especially given reduced milk yields observed during later lactation cycles. When culled from the herd, a dairy cow is typically sold for slaughter. The age at which a cow is removed from the herd depends on a number of factors including expected future productivity, current and expected prices (i.e. milk, feed and slaughter price), higher yield potential of cow replacements and current/expected replacement heifer costs.

The U.S. dairy herd can be described not only by its size but also with respect to the cow age distribution within the herd. Both these characteristics are determined primarily by the timing of culling and subsequent cow replacement. For the present study we assume that heifers enter the herd when they are 2 years old, and the maximum productive lifetime of a dairy cow is 9 years. The term we use to refer to the nine age-related cohorts is *productive age class*. For each productive age class we create the variable CLASS that takes a value from one to nine. For example, for dairy cows between 2 and 3 years old CLASS = 1, those between 3 and 4 years of age CLASS = 2, etc.

We assume that a dairy farm operator makes replacement and culling decisions at the end of each year. All cows that are in the 9th productive age class are removed from the herd and a decision is made as to how many cows within each of the remaining 8 productive age classes will be kept in the herd for another year. The manager also adds to the dairy herd replacement heifers that have successfully calved. We represent the outcome of the above culling decisions by survival rates, $S_{t,i}$, defined as the probability that a cow in the $i^{th}$ productive age class in year $t$
will be selected to stay in the herd through the forthcoming year. Using the logistic functional form, we specify the survival rate as:

$$S_{t,i} = \frac{1}{1 + e^{Z_{t,i} \beta}}$$  \hspace{1cm} (2)$$

where $Z_{t,i}$ is a vector of explanatory variables reflecting the state of technology, economic conditions, and class at the time of selection decision and $\beta$ is a vector of coefficients to be estimated. $S_{t,5}$ is assumed zero, i.e. all cows that have completed 9 years in the dairy herd are assumed to be culled. $S_{t,0}$ represents the survival rate of replacement heifers, interpreted as the probability that an impregnated heifer will complete the pregnancy without major health complications necessitating culling. We assume that $S_{t,0}$ is not primarily an economic decision, hence the vector of explanatory variables $Z_{t,0}$ does not include prices or herd structure related variables. The only variables that we include in $Z_{t,0}$ are binary variables identifying government policies in the 1980’s that may have made dairy managers consider culling even freshened replacement heifers.

The number of cows in the $i^{th}$ productive age class is determined by the product of the number of replacement heifers $i$ years ago and their retention rate, $R_{t,i}$, defined as the product of survival rates in the past $i$ selection decisions:

$$R_{t,i} = \prod_{j=1}^{i} S_{t,j,i-j}$$  \hspace{1cm} (3)$$

where $j$ indexes previous years. As an example, to calculate the retention rate for cows entering the $3^{rd}$ age class in 1990 we have: $R_{1990,3} = S_{1987,0} \times S_{1988,1} \times S_{1989,2}$. 


Total herd size \( (COW_t) \) can be represented as the sum of the number of cows in each of the 9 productive age classes, \( COW_{i,t} \). We specify a stochastic herd size equation that accounts for the relationship between the number of heifers in previous years and current dairy herd size and structure:

\[
COW_t = \sum_{i=1}^{9} COW_{t,i} + \epsilon_t = \left( \sum_{i=1}^{9} HEF_{t,i} \times R_{t,i} \right) + \epsilon_t
\]  

(4)

where \( HEF_{t,i} \) are the number of heifers \( i \) years prior to year \( t \) and \( \epsilon_t \) is a stochastic error term.

We can substitute the age-specific retention rate definitions from (3) into (4):

\[
COW_t = \left( \sum_{i=1}^{9} HEF_{t,i} \left[ \prod_{j=1}^{i} \left( \frac{1}{1 + e^{z_{i,j}^j}} \right) \right] \right) + \epsilon_t
\]

(5)

Thus, given (5) we can predict not only the number of cows in the dairy herd but the distribution of cows across productive age class. The \( CLASS \) variable is related to summation index \( i \) and multiplication index \( j \) via the identity \( CLASS = i - j \).

The complement to the survival rate is the age-specific culling rate \( k_{t,i} \) defined as the proportion of the \( i^{th} \) productive age class removed from the herd at the end of \( t \).

\[
k_{t,i} = 1 - S_{t,i}
\]

(6)

Replacement decisions describe the selection of female calves to become replacement heifers. Underpinning the replacement decision is a representation of the probability \( \Gamma_t \) of a cow being selected for reproduction, becoming pregnant and calving and the calf surviving until 1 year of age:

\[
\Gamma_t = \frac{1}{1 + e^{W_{t-1} \Gamma_t}}
\]

(7)
where \( W_t \) represents a vector of exogenous variables hypothesized to impact the calving/survival probability and \( \gamma \) are parameters to be estimated. Although subscript \( t \) is used in the equation above, it is important to notice that included economic variables of interest are lagged 1 and 3 years, to account for both the factors affecting intended replacement decision and the successful completion of the heifer growth process.

The number of replacement heifers ready to be impregnated in the period \( t \) can be represented as:

\[
HEF_t = 0.5 \left\{ (COW_{t-2} + HEF_{t-2}) \times \frac{1}{1 + e^{W_t \gamma}} \right\} + \zeta_t
\]

(8)

where \( \zeta_t \) is a stochastic error term. The value 0.5 represents the fact that half of newborn calves are assumed to be male animals and cannot be used as a cow replacement. The male-to-female calve ratio can be altered with the use of sexed semen, but that technology was not widely used prior to 2008 (de Vries and Nebel, 2009, Overton, 2007). In the above we depart from Chavas and Klemme (1986) and adopt the specification of Schmitz (1997) where we model the pool of fertile animals that can produce offspring to include not just dairy cows in period \( t-2 \), but also replacement heifers at that time. Thus we include \( HEF_{t-2} \) in (8).

In contrast to the COW and HEF specifications, the yield equation is modeled using quarterly data due to seasonality in milk yields. In forecasting annual milk production, annual yield is then found as a simple sum of quarterly yields. We assume that potential yield grows linearly in time, adjusting for seasonality. We define potential yield in quarter \( t \) as

\[
YLD_{t}^P = \beta_0 + \beta_1 \bar{T} + \beta_2 \text{DumQ}_2 + \beta_3 \text{DumQ}_3 + \beta_4 \text{DumQ}_4 + \beta_5 \left( \text{DumQ}_2 \times \bar{T} \right) + \beta_6 \left( \text{DumQ}_3 \times \bar{T} \right) + \beta_7 \left( \text{DumQ}_4 \times \bar{T} \right) + \beta_8 \text{Dum85} + \beta_9 \left( \text{Dum85} \times \bar{T} \right)
\]

(9)
where \( \tilde{t} = t - 1974:Q4 \). We allow changes in seasonality with time, as regional shifts in milk production from Midwest to more western states and improvements in herd management that have occurred over the study period may have dampened the significance of the “spring flush”, i.e. increased yield in spring, as well as potentially higher drop in yield during summer months due to increased heat problems. Finally, to account of beneficial impact of government policies in 1980s on yield, we allow for continuity-preserving change in slope in 1985.

Potential yield can be thought of as long-run average trend yield whose dynamics are governed solely by technological and genetic improvements. Changes to yield from one quarter to next are assumed to arise from economic shocks, random weather conditions as well as reversion to potential yield. We allow the speed of correction back to trend yield to vary depending on the economic environment. Our stochastic yield equation can be represented via the following:

\[
\Delta \text{YLD}_t = \left( \alpha_1 + \alpha_2 \overline{\text{MP}}_{t-1} \right) \left( \text{YLD}_{t-1}^p - \text{YLD}^p_t \right) + \delta_1 \Delta \text{MP}_{t-1} + \delta_2 \Delta \text{FP}_{t-1} + \nu_t \tag{10}
\]

where \( \overline{\text{MP}}_{t-1} \) is the average milk price over previous four quarters, \( \Delta \text{MP}_{t-1} = \text{MP}_{t-1} - \text{MP}_{t-2} \) is the change in the milk price, \( \Delta \text{FP}_{t-1} = \text{FP}_{t-1} - \text{FP}_{t-2} \) is the change in feed prices from the previous quarter, \( \nu_t \) is a stochastic error term and \( \text{YLD}^p_t \) is defined by (9).

### 4. Description of Data Used in the Analysis

The parameters associated with the econometric model components outlined above are estimated using data over 1975-2010. Given the use of lagged explanatory variables in the herd size equation, the data actually used in estimation started in 1966. Table 1 provides a representation of the three categories of exogenous variables used in the stochastic equations: (i) those that capture the state of technology and herd structure; (ii) variables that describe the
economic environment; and (iii) a set of dummy variables that identify time periods during which unique government policies had an impact on the U.S. dairy industry.

**Technological Progress and Herd Structure Variables**

The level of technology is accounted for in heifer equation (8) by a simple trend variable. Given the non-linear functional form allows for the marginal impact of technology to change over time. For example due to improved technology, attempts to fertilize cows may be more successful, calf death rates reduced, and more calves grown into replacement heifers may actually be completing the process without severe health problems causing involuntary culling.

Herd structure is incorporated in herd size equation (5) by two variables. First, as noted above, inclusion of the productive age class variables ($CLASS$) allows survival rates to differ across the 9 productive age classes. Secondly, we include lagged values of the ratio of replacement heifers to dairy cows. A higher replacement ratio implies that more heifers are ready to enter the herd, and consequently, more of the older, less productive cows, can be removed from the herd without reducing herd size. We hypothesize that the impacts of higher replacement ratios will differ across productive age classes. As such we interact the $CLASS = i - j$ and associated replacement ratio, $\frac{HEF_{t-L}}{COW_{t-j}}(i - j)$. In the yield equation (10) technological progress is modeled as a linear time trend in potential yield given in (9). Structural changes in the dairy sector are captured by the interaction variables between time trend and seasonal dummies.

**Variables Representing the Economic Environment**

Three set of prices are hypothesized to impact production-related decisions: The U.S. average All-Milk price ($MP_t$), feed price ($FP_t$) and slaughter cow price ($SP_t$). To account for inflation, all prices are expressed in 2010 U.S. dollars via the use of the consumer price index.
published by the Bureau of Labor Statistics. In contrast to Chavas and Klemme (1986) who use milk/feed and slaughter/feed ratios as principal economic variables we allow the data to determine the relative milk-feed and slaughter-feed price impacts (Bailey and Ishler, 2007).

The U.S. All-Milk price (MP, $/cwt) is simply the average price of milk calculated as total milk-revenue divided by the pounds of milk marketed and reported by USDA’s NASS. Starting in December 2000 the MILC program was adopted as a Federal dairy policy. We account for the MILC program by calculating average per cwt payment and add this value to the U.S. All-Milk price. We define feed price (FP, $/cwt) in a manner similar to that of USDA (2007) and by Chavas, Klemme and Krauss (1990) who use the cost of a 16% protein dairy ration. This ration is assumed to be composed (by weight) of 41% corn, 8% soybeans and 51% dry alfalfa hay. This is the same feed price used as the current MILC deficiency payment adjuster. We use the Omaha and Sioux Falls boning-utility grade cow slaughter price as the slaughter cow price (SP, $/cwt).

In our model, cows are akin to capital goods, hence culling and replacement decision are best analyzed if understood as investments in dairy herd undertaken to maximize present value of future stream of revenue from milk and salvage value (i.e., sold to slaughter). Therefore, it is not past, but expected future prices that are relevant to culling and replacement decisions.

Schmitz (1997) uses linear forecast of next period prices as a way to model expectations. Implicit in his approach is the assumption that it is only expected next period prices that matter for the decision-making process. If that was so, using last observed prices would be equivalent to assuming naïve adaptive expectations. However, when a dairy producer makes a decision, he needs to take into account expected prices in the next period as well as over a cow’s potential remaining lifetime. We do not impose a particular structure on expectations or length of
planning horizon. Our approach should be interpreted as an attempt to capture the complex impact of last observable price on culling and replacement decisions in a tractable manner.

In his analysis of U.S. poultry producers, Chavas (1999) finds that only a small majority of agricultural producers use rational expectations in making investment decisions, while the majority employ a backward-looking expectations. It would not be surprising to find that in the dairy sector, the share of producers who base their investment decisions on historical prices is even larger. The Dairy Industry Advisory Committee concludes that tax-treatment of dairy farm income induces farmers to invest a large share of profits in those years when profit margins are good (USDA, 2011). Such behavior is consistent with modeling last observed price as an important driver of herd investment decisions.

Changes in the economic environment will influence each productive age class differently. When production is more profitable, the herd manager might decide to replace more of the older, less productive cows. Alternatively, when prices make for less lucrative production, it may not be profitable to invest in more productive, but expensive, replacement heifers, and that might be reflected in higher retention rates of older cows. To capture the differentiated price change impacts upon each productive age class, we use price-class interaction variables (e.g. $MP_{t-j} \times CLASS$) in the herd size equation (5).

To understand how prices influence replacement heifer numbers, recall that it takes 1 year for a female calf to grow into a replacement heifer ready to freshen and that a cow is pregnant for 9 months before giving birth to a replacement heifer calf. The relevant pool of dairy animals that could give birth to calves that will have grown to replacement heifers by period $t$ consists of cows and replacement heifers in period $t−2$. The number of replacement heifers available today

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2 Following Chavas and Klemme (1986) we model the U.S. dairy herd as one representative herd in a competitive market. For this specification we cannot account for the importation of dairy replacement heifers from Canada or Mexico into the U.S.
is first determined by how many of these cows and replacement heifers were chosen to be impregnated in period $t - 2$ and how many animals were culled. Culling decisions are influenced by prices observed in period $t - 3$. A second factor impacting the number of replacement heifers available today is the share of female calves that are selected to be grown into replacement heifers. To capture the effect the economic environment has on this decision we include prices in period $t - 1$.

The simpler structure of the yield equation may make it appear that effects of economic explanatory variables are straightforward to interpret. In fact, the price impacts on yield are theoretically the most challenging to capture as there are possibly two opposing effects. One of the most important day-to-day decisions a dairy farm operator must make pertains to the feed ration. With higher milk prices lower feed costs, the producer would like to increase the feed ration to capture the opportunity for additional income by increasing the yield from cows currently in the herd. In addition, these relative price changes impact the desired herd size of many producers. That is, dairy farm operators with relatively high milk prices would like to enlarge their herds and those farm operators who intended to exit the industry may decide to postpone retirement. If there is a scarcity of replacement heifers and those that are available being relatively expensive, producers will tend to increase the retention rate of older cows, not just to increase their milk output, but to increase the future pool of heifers. Retaining more of older cows and thus increasing overall herd size, however, will increase in the short run the share of less productive animals in the herd, and will work to decrease yield, even while increasing milk production. While we expect the overall effect of increase in milk or decrease in feed price to be positive, should the impact be small it is important to remember that it may be the net effect of two opposing strong influences.
In equation (10), prices play a dual role. Average milk price over the previous four quarters is used to model speed of adjustment to potential yield, and changes in the previous quarter milk and feed prices have a direct short-term impact on yield. Variables Representing the Dairy Policy Environment

The third category of explanatory variables used in the model consists of a set of binary variables used to capture the impact of specific government policies on the U.S. dairy industry. In the early 1980s there was a large surplus of milk production due to relatively high support prices introduced several years earlier. The first government program designed to restore market equilibrium was the Milk Diversion Program (MDP), in effect from January 1984 to March 1985. Under this program participating producers were eligible for payments of $10 per hundredweight on the difference between their "base period" sales and actual sales, provided their actual sales were between 5% and 30% below base (Lee and Boisvert, 1985; Boynton and Novakovic, 1984). The binary variable Dum84 is used to capture the effect of this program.

The MDP was complemented by the Dairy Herd Termination Program (DHTP) in effect from September 1986 to the end of 1987, and accounted for by variable Dum86. Under the DHTP participating farmers were paid to slaughter or export their entire dairy herds and not to resume production for at least 5 years.

Under our model structure we assume that all selection decisions are undertaken at the end of a calendar year. Thus herd size and structure at the beginning of the year as determined by past selection decisions. The MDP and DHTP policies were modeled as influencing selection decisions done at the end of 1984 and 1985 for the MDP, and at the end of 1986 and 1987 for the DHTP (Table 1). As an example, in cow equation, Dum84 will take a value based on the following rule
where \( t \) is the year for which herd size and structure is predicted, and \( i \) and \( j \) are indexes of summation and multiplication in Eq. (5). For example, to predict dairy herd size and structure in 1987, \((t = 1987)\) we need to predict number of cows that are entering the 5\(^{th}\) productive age class in 1987 \((i + 1 = 5)\). Those cows were in the 2\(^{nd}\) productive age class in 1984, the time Milk Diversion Policy was active \((j = 2)\), and therefore, selection decision for those cows in 1984 was affected by the policy, i.e. \( t - (i + 1 - j) = 1984 \). Although this policy was in effect for just over one year, it directly impacted the herd size and structure for almost the entire next decade.

Rules for assigning values to these binary variables will be different in the heifer equation. The policies represented by the above dummy variables could have affected the number of heifers in year \( t \) by changing the probability that a female calf \((t - 1)\) will be grown into a replacement heifers and/or by impacting the number of cows and heifers \((t - 2)\) selected to stay in the herd thus changing the base of animals that are used to produce dairy calves later grown to replacement heifers. For example, the Milk Diversion Program in effect in 1984 influenced the number of heifers in 1985 through impact on calves and number of heifers in 1986 through impact on cow culling rates in 1984. Therefore, the appropriate rule for assigning values to \( Dum84 \) in the heifer equation is

\[
Dum84_H = \begin{cases} 
1 & \text{if } t - 1 \text{ or } t - 2 = 1984 \\
0 & \text{otherwise} 
\end{cases}
\]  

(12)

Due to its design the DHTP had more complex impact on data generating process for replacement heifers. To maintain simplicity, and since heifers are counted at the beginning of the
year, we assume that the DHTP impacted the number of heifers measured at the beginning of 1987 and 1988:

\[
\text{Dum86H} = \begin{cases} 
1 & \text{if } t - 1 = 1986 \text{ or } 1987 \\
0 & \text{otherwise}
\end{cases}
\] (13)

To keep yield equation tractable, we include only one continuity-preserving dummy variable that accounts for the change in time trend as a result of less productive herds exiting the sector in face of the incentives provided by the above two policies.

There were several significant Federal dairy policy changes such as enactment of the Milk Income Loss Contract program, Federal Order Reform, changes in relative commodity support prices. We attempted to account for these changes in various components of the model but were unable to find any statistically significant impacts except for the impacts of Federal Order Reform. That dummy variable FMMO was defined by the following for all the equations comprising our model

\[
\text{FMMO} = \begin{cases} 
1 & \text{if } t \geq 2000 \\
0 & \text{otherwise}
\end{cases}
\]

The dairy herd termination auctions organized under the Cooperatives Working Together (CWT) program from 2003 to 2010 had an objective of increasing the speed of herd contraction in periods when milk prices are below the level needed for profitable production. In earlier versions of our model we included a dummy variable to capture CWT effects on herd size changes.\(^3\) We found conflicting evidence on significance of CWT impact, which can likely be attributed to aggregate nature of our econometric models.

**Description of the Dependent Variables**

\(^3\) For more detail concerning this program access the following URL: [http://www.cwt.coop](http://www.cwt.coop).
There are three dependent variables in our econometric model: \( COW_t \), \( YLD_t \), and \( HEF_t \).

Data representing the U.S. dairy herd size, \( COW_t \), was obtained from the January 1st USDA inventory estimate of the number of U.S. milking cows. Data pertaining to quarterly per cow milk yield (\( YLD_t \)), was obtained from the National Agricultural Statistical Service’s (NASS) online database. The number of replacement heifers (\( HEF_t \)) was obtained by multiplying USDA’s January 1st Cattle inventory data for “500lbs+ dairy heifers” by 0.75. Heifer calves that are between 8 and 12 months of age on January 1 when the survey is undertaken, weigh between 500 and 800 lbs, and are included in the USDA estimate as replacement heifers. Those animals are too young to give birth in the current period. With pregnancy duration of 9 months, a heifer must be impregnated no later than the end of March to freshen before the end of the period. Since heifers are inseminated at 15 months of age, only those animals that are at least 1 year old should be treated as replacement heifers according to definition we employ for model estimation. Our 0.75 adjuster originates from our assumption that there are 3 times more heifers 12-24 months old then heifers 8-12 months.

5. Estimation of an Empirical Model of U.S. Milk Supply

We estimate each of the stochastic equations separately using nonlinear least squares methods via the Gauss-Newton (GN) algorithm. Given the degree of nonlinearity of Eq. (5) and Eq. (8) the sum of squared errors (SSE) functions are likely not globally convex over the parameter space implying the potential for numerous local SSE minima. To insure that the algorithm converges to a global minimum, we first performed a ‘wide-range’ search where we estimated Eqs. (5) and (8) 2,000 times, and with each estimation we used a different randomly drawn vector of starting values centered around zero. The best fitting coefficient estimates were then
used in ‘narrow’ search where models were estimated another 2,000 times, with randomly drawn vector of starting values centered around the best fitting values from the ‘wide-range’ search phase, and with spread equal to three standard deviations from the point estimation. The result presents the solution with the lowest SSE obtained from this two-step process.

**Estimation of Parameter Standard Errors**

The use of small samples, such as the one used here, to estimate the parameters of a highly non-linear model implies that the applicability of large sample theory may be inappropriate as any estimate of coefficient asymptotic standard errors and results of tests for significance based on asymptotic normality must be interpreted cautiously. One clear indicator that large sample theory performs poorly for a particular model would be that bootstrap estimates of coefficient confidence intervals being much different than the same confidence intervals based on asymptotic theory.

To determine if our model exhibits such discrepancy, we use a dynamic residuals-based bootstrapping procedure to obtain alternative estimates of parameter confidence intervals (Hansen, 2008). The bootstrapping procedure is used to dynamically simulate alternative samples assuming the estimated coefficients are the true unknown parameter values, and the model structure is the true data generating process. Alternative dependent variable vectors are generated by using random draws from joint empirical distribution of estimation residuals.\(^4\) We use the percentile-t method to obtain bootstrap confidence intervals of parameter estimates and compare them with asymptotic confidence intervals based on the original parameter information matrix (Hansen, 2008).

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\(^4\) A detailed description of this procedure can be found in _______ and ________, 2009. [Author’s names removed for review purposes] The GAUSS software system was is used in estimation. Due to the computationally intensive estimation, bootstrap and simulation, time needed for calculations is 24 hours on a standard dual-core PC notebook.
6. Overview of Estimation Results

Results obtained from grid searches indicated non-convexity of the SSE function in herd size (5) and heifer (8) equations, but also give us confidence that in each nonlinear regression the global minimum is indeed found. For example, in the estimation of the herd size equation, under the ‘wide-range’ search phase (i.e., step 1), 371 out of 2000 rounds converged. Since our parameters appear in an exponential term, it is reasonable to assume that for values far away from the minimum, the SSE function will not behave properly. In the ‘narrow-range’ search phase (i.e., step 2) all 2,000 rounds converged and 83 unique minima were found. Second ranked minima in the ‘narrow-range’ search had SSE 39.8% higher than the result identified as the global minimum. In contrast, for the Heifer equation only one unique minimum was found in the ‘narrow range’ search.

The estimated coefficients for the three stochastic equations are presented in Table 2 along with their bootstrapped estimated standard errors. LJung-Box tests results indicate the presence of residual autocorrelations in all three equations (Greene, 2008, p.729). Therefore we calculate asymptotic standard errors via the Newey-West heteroskedasticity and autocorrelation robust covariance matrix (Greene, 2008, p. 643). These standard errors are shown in parentheses in Table 2.

Bootstrapped and Information Matrix based confidence intervals were found to be consistent. There is no other evidence based on bootstrap results that inference based on asymptotic theory would be inappropriate. In the heifer equation (8) the explanatory variables are used within a survival rate function which represents the probability a female calf will be successfully delivered and selected to be grown into a replacement heifer. With the exponential function in the denominator, this implies that the marginal effect of a change in an exogenous variable on
survival probability will have the opposite sign as the estimated coefficient. Alternatively, the marginal effects on heifer culling rates will have the same sign as the estimated coefficients in the heifer equation. In terms of interpreting the herd size equation, one needs to recognize that the number of cows of a particular age in the herd is the product of the number of heifers in previous years times the combined probability of surviving to the current time period. Similar to the heifer equation, these survival probabilities are specified as being logistic. Thus as shown by Eq. (6) the marginal impacts of a change in an exogenous variable on cow culling rates will have the same sign as the estimated coefficient in the herd size equation.

Given the above, we would expect the All-Milk milk price coefficient in equations (14.1) and (14.2) and shown in Table 2 to be negative as we anticipate the heifer and cow culling rates to be negatively related to milk price. Other things equal, the higher the milk price, the greater the expected profitability associated with milk production and a reduced incentive for culling female calves or dairy cows. In the herd size equation, increases in the All-Milk price will stimulate higher substitution of more productive freshened heifers for old cows. Therefore, we expect the coefficient of All-Milk price – age class interaction variable to be positive. Thus we expect higher culling rates of older cows as milk price increases. Conversely, our initial hypotheses are that higher feed and slaughter prices have a positive impact on heifer and milk cow cull rates and reduces the substitution of heifers for aging cows.

As reviewed above, the Milk Diversion Program and DHTP dairy policies had as their primary objective the reduction in the U.S. herd size. We expect a positive effect of these policies on both cow and heifer culling rates the culling rate and therefore expect positive coefficients on the associated policy-related binary variables in the herd size equation. Even though it decreased the number of dairy cows, the Milk Diversion Program did not have a
requirement that producers permanently leave the dairy industry. As such, we expect the producers to react by a short-term reduction in the milking herd while the policy is active, but at the same time increasing the number of female calves grown for replacement, in anticipation of a subsequent increase in the demand for heifers, after policy terminates. Thus we anticipate the sign of the estimated coefficient associated with the variable Dum84 to be negative in the heifer equation (8).

Estimating the above three equations by nonlinear least squares, we obtain a high degree of in-sample prediction accuracy. Examining in-sample prediction accuracy, we find maximum absolute prediction error of 0.5% for the cow equation, 1.2% for the heifer equation and 0.7% in the yield equation. In Figure 3 we provide a representation of the actual, static prediction and dynamic simulations of the number of heifers and size of the U.S. dairy herd. By static prediction we refer to in-sample, one step ahead forecast. In contrast, dynamically simulated predictions are obtained by using past predicted cow and heifer values in forecasting. In addition we provide a bootstrapped 95% confidence interval for dynamically simulated values.

In the heifer equation, all estimated coefficients were found to be statistical significant at the 95% confidence level except for $SP_{t-1}, FP_{t-1}, MP_{t-3},$ and $Dum2000$. In the herd size equation, we find all key variables significant at 99% confidence level except for real interest rates, $Dum2000$, CLASS, cow slaughter price and class-slaughter interaction variable. All statistically significant coefficients in the heifer equation were found to have the expected sign, except for the first lag of the interest rate $r_{t-1}$. We find evidence of asymmetry in effect of milk prices on the number of replacement heifers. A decline in milk prices has a stronger effect on heifer numbers. This makes sense, at least in the short-run, as it is easier to shrink than to expand a dairy herd. In the yield
equation, we find evidence of shifts in seasonal yield patterns, consistent with migration of diary production to Western states.

We fail to find evidence that feed prices influence yield. This result may be driven by the fact that high and volatile feed prices have been a major drive of profit margins only in the last several years, while our model is estimated over the past 35 years. We find weak evidence that, higher milk prices increase the speed of adjustment to potential (trend) yield.

In Table 3 we show estimates of the 2010 distribution of the U.S. dairy herd across cow age, the associated class-specific cull rates and predicted marginal impact of price changes on culling rates of each cow productive age class. As an example, the culling rate for cows in the first productive age class, which corresponds to cows between 2 and 3 years of age, is 18.4%. This implies that of the cows that survived the first year in the herd, 18.4% will be culled in 2010. Increase in milk price by 10% over average real All-Milk price for 2010 ($18.29 /cwt) would decrease the culling rate by 1.8% to 16.6%.

7. Evaluation of Long-Run Price Effects on the U.S. Milk Supply

To evaluate the long-run (10 year) impacts of price changes on the U.S. dairy herd we address the following question: *If real prices remain constant over the next ten years, what will be the impacts on U.S. milk production?* To address this question, we evaluate 10 year production profiles under the following three price scenarios (2010 $):


(ii) *Scenario 2*: Prices remain at 2007 levels. It should be noted that 2007 was a relatively good year for the dairy industry with the average All-Milk Price
being $19.87. The average corn grain price was $3.52/bu, hay was at 
$135.60/ton and average soybean price was $8.04/bu.

(iii) Scenario 3: To investigate the long-run impact of extremely high feed costs, 
under this scenario we assume that real corn and soybeans prices over the next 
ten years are constant at the high levels observed during June 2011, but the 
milk price is lower: Corn $7.00/bu, Soybeans $14.50, Hay $116.00, All-milk: 
$17.00/cwt.

For all scenarios, cow productivity improvements are assumed to follow the structure 
represented by the estimated yield equation (14.3) regardless of scenario. Figure 4 is used to 
portray milk production under the above three scenarios over the 2011-2020 period. In addition 
we have plotted the bootstrapped confidence interval for Scenario 1.

It is not surprising that the milk price environment represented by Scenario 2 generates a large 
increase in milk production relative to the Scenario 1 base case. Scenario 2 production is above 
the upper 95% Scenario 1 production confidence interval starting in 2013. Similarly, the high 
feed cost scenario, Scenario 3, generates significantly lower milk production levels starting with 
production in 2012. In 2012, milk production under Scenario 3 is 2.5% less than the milk 
production under Scenario 1. This relative decline increases to 18.8% by 2018.

Long-run adjustment dynamics can be best understood by analysis of long-run elasticities of 
the number of replacement heifers, herd size and milk production to changes in milk, feed and 
slaughter prices. Our long run elasticities measure the impact of a one-time permanent 10% 
increase of a particular price in base period on forecasted number of heifers, U.S. herd size and 
total U.S. milk production $j$ years ahead, as compared to base scenario where prices over the 
forecasting period are assume equal to prices in base year. In Table 4 we provide point estimates
of the milk and feed price elasticities along with the limits that define the 2.5 (Low) and 97.5 (High) percentiles of the empirical distribution of bootstrapped long-run elasticities average over the 1978-1982 and 2003-2010 periods. Regardless of the starting year, the elasticities increase with the length of forecasting period given that it takes time for herd size to fully adjust to changes in economic environment.

To investigate the issue of long-run supply responsiveness, in Figure 5 we plot the 10-year milk supply elasticities with respect to milk and feed prices, calculated for each year in the sample. When we compare the elasticities across different starting periods we find that All-Milk price responsiveness of the milk supply exhibits downward trend from the beginning of our estimation period in 1975 through 2005. We found this result startling, as one might reasonably expect just the opposite. With better genetics, improved heifer management and larger farms we had expected to find evidence that the industry likely adjust to favorable price changes more quickly than compared to twenty years ago when the percentage of milk originating from small to medium-sized operations was much greater than today.

Given the size of the confidence intervals around those point estimates, we need a formal test to conclude if the decline in estimated price responsiveness is statistically significant. We simulate the distribution of differences of average 10-year elasticities in the period 2001-2005 vs. 1978-1982. If the null hypothesis of no change is correct, than the distribution of differences should be centered around zero. We reject the null hypothesis if number of simulations in which average 10-year elasticity in the period 2001-2005 is less price-responsive than in 1978-1982 is less than 5% of total number of bootstrap simulations. Results of these tests are presented in Table 5. Results confirm the decline in the supply elasticities with respect to milk prices through
2005, however comparing the same benchmark period with 2006-2010 we no longer find a decrease in supply responsiveness.

To explore the potential causes for the decrease in All Milk price elasticities through 2005, we exploit the fact that while we only observe annual inventory data for cows, the structure of our model allows us to predict the herd structure by age at any year in the sample. In Figure 6 we plot the distribution of herd by cow age and retention rates for each age class for two time periods, 1978-1982 and 2005-2010. The implication from this figure is that while cow retention rates for cows age 3-5 (first three lactations) have changed little over these two time periods older cows are substantially less likely to be kept in herd. For dairy operations, the major adjustment to changes in the economic environment is accomplished via herd culling and replacement activities. When dairy farm operators experience positive changes in the economic environment and they desire to expand their herd, they can (i) keep current milking cows longer in the herd while maintaining previous number of replacement heifers entering the herd or (ii) increase the share of female calves that are grown into replacement heifers and ultimately added to the herd. It is important to note that the younger the herd, the higher is the replacement ratio needed to keep the herd size unchanged.

The downward trend in long-run price responsiveness may be the result of increases in involuntary cull rates that makes it harder for dairy farm operators to increase the retention rate of cows in the process of adjustment to favorable changes in economic environment. Hadley (2006) reports that in herds participating in Dairy Herd Improvement program (DHI), health culls, i.e. culls induced by health problems of a cow, constitute 79.5% of all culls. If the share of health culls in all culls has increased over time that would imply that culls are starting to be less of an economic decision, and are increasingly a consequence of biological constraints.
However, a more convincing explanation could be that long-run price responsiveness simply varies along the supply curve. Small increase in milk prices may not bring about substantial additional investments if the returns are meager to start with. However, if returns are originally already sufficient to cover opportunity costs of money, permanent increase in the milk price that allows for extra returns may bring about substantial new investments to the dairy sector. Increase in responsiveness in the recent years might be due to very lucrative milk production over the 2007-08. However, long-run elasticity remained higher in 2009, a year that will be remembered as a period when dairy sector experienced particularly difficult economic environment. That may reflect a number of important influences in the recent years. For example, De Vries and Nebel (2009) assert that a technology that will have a significant impact on dairy supply is the increased adoption of sexed semen in replacement heifer breeding as it would increase the pool of available replacement heifers. The uptick in estimated supply elasticities in the second half of 2000s could reflect that. Alternatively, it could be the case that herd adjustment programs operated by Cooperatives Working Together (CWT) induce faster adjustment of the herd size to economic conditions. Although we could not establish the link directly in our model, Brown (2011) suggests that CWT herd retirement program had substantial net impact on U.S. dairy herd size.

It is interesting to examine if supply elasticity with respect to feed prices examine similar trends. As we can see from Figure 5, there was no clear trend in long-run supply responsiveness to feed prices, and these elasticities were much smaller than the milk price elasticities until very recently. Dramatic increases in feed prices in the last several years have altered this pattern, and using formal tests (results in Table 5) we find that milk supply responsiveness to feed prices has been significantly higher in the period 2006-2010 than in the period 1978-1982.
8. Conclusions

The econometric analysis contained in this study adopts the modeling principle currently used by USDA for policy analysis whereby milk production is modeled as a product of dairy herd size and yield per cow, stochastic elements that are modeled separately (USDA 2007). We account for herd size dynamics along the lines of models proposed by Chavas and Klemme (1986) and Schmitz (1997). We contribute to the literature by introducing a mixed frequency approach that allows us to model yield using quarterly data, while dairy herd and replacement heifer pool is modeled using annual frequency. That allows us to model the yield as a trend-stationary process with the economic environment inducing both short-term shocks and impacting the speed of reversion to trend yields. While yield is the channel through which short-term adjustments to milk prices can be done, dairy herd size responsiveness governs the medium- and short-run supply. In addition, we design and implement dynamic residual-based bootstrap technique that can be used in testing for changes in non-marginal simulated long-run supply responsiveness.

We obtain strong in-sample predictive power and very high significance of key economic and herd structure variables. For years for which our estimation period overlaps with the one used in previous research, our results on 10-year price elasticities are more conservative than those in Chavas and Klemme (1986), but are comparable to results reported by Chavas and Krauss (1990).

In response to calls for changes in U.S. dairy policy, it is crucial to provide policymakers with a comprehensive framework that can be used to forecast both short-term and long-run impacts of changes in dairy policy. Several conclusions emerge from our study. First, given the large difference between short-run and long-run responses of production to price changes, policy makers should consider more than short run responses to future policy changes. What may in the
short-run seem like a minor impact that does not disturb market equilibrium can indeed lead to large production surpluses after more time has passed and dairy herd size has had adequate time to adjust to the new policy environment. As the experience from late 1970s and early 1980s has hopefully taught us, unintended medium-run consequences may dwarf the impact of well-intended policy measures that seem to work in the short run.

Second, despite dramatic yield improving technological change, improved genetics and the increasing importance of large farms, all of which we would expect to increase the milk supply price responsiveness, we find a declining trend in long-run supply responsiveness from 1975 through 2005. If such decline were to persist or continue that would be a major cause for worry, as ever larger price swings would be needed to quickly equilibrate the market in face of demand shocks. However, we find that milk supply is getting more responsive in recent several years both to milk and feed prices. We recommend extending this analysis using micro-level data to examine farm-level behavior in face of price-swings. Increasing responsiveness to feed prices further justifies focusing the next generation of dairy policy toolbox on managing dairy profit margins rather than just revenue streams.

Finally, further research needs to be done to develop a partial equilibrium model of the U.S. dairy sector based on insights on structural characteristics of the production presented in this article. We believe that when combined with a model of the demand for dairy products our work has a potential to improve reliability of long-run projections of the U.S. milk production.
### Table 1. Explanatory Variables by Category

<table>
<thead>
<tr>
<th>Equation</th>
<th>Exp. symbol</th>
<th>Technology, Herd Dynamics</th>
<th>Prices</th>
<th>Government Policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$COW_i$</td>
<td>$Z_{t-j,i-j}$</td>
<td>CLASS $= i - j$</td>
<td>$MP_{t-j}$</td>
<td>$Dum84 = \begin{cases} 1, &amp; \text{if } t - (i + 1 - j) = 1984 \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
<tr>
<td></td>
<td>$i=1,...,9$</td>
<td>$FP_{t-j}$</td>
<td>$MP_{t-j} \times CLASS$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\forall i, j = 1,...,i$</td>
<td>$SP_{t-j}$</td>
<td>$FP_{t-j} \times CLASS$</td>
<td></td>
</tr>
<tr>
<td>$HEF_i$</td>
<td>$W_t$</td>
<td>$T = t - 1974$</td>
<td>$MP_{t-1}$</td>
<td>$Dum84_H = \begin{cases} 1, &amp; \text{if } t - 1 \text{ or } t - 2 = 1984 \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$FP_{t-1}$</td>
<td>$Dum86_H = \begin{cases} 1, &amp; \text{if } t - 1 = 1986 \text{ or } 1987 \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$SP_{t-1}$</td>
<td>$Dum2000_H = \begin{cases} 1, &amp; \text{if } t \geq 2000 \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$r_{t-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$r_{t-3}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1 { MP_{t-1} &gt; MP_{t-2} }$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$YLD_i$</td>
<td>$X_t$</td>
<td>$\tilde{T} = \tilde{t} - 1974Q_4$</td>
<td>$\tilde{MP}_{t-1}$</td>
<td>$Dum85 = \begin{cases} 1, &amp; \text{if } t &gt; 1985 \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta FP_{t-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta MP_{t-1}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Estimated Model of U.S. Dairy Supply (1975-2010)

\[ H_{EF_t} = \frac{1}{2} (COW_{t-2} + HEF_{t-2}) \left[ 1 + \exp \left( 0.945 - 0.023 T - 0.140 Dum84 + 0.079 Dum86 + 0.015 Dum2000 + 0.0008 MP_{t-1} I \{ MP_{t-1} > MP_{t-2} \} - 0.012 r_{t-1} - 0.009 MP_{t-1} + 0.0009 FP_{t-1} - 0.001 SP_{t-1} + 0.007 r_{t-3} - 0.006 MP_{t-3} + 0.014 FP_{t-3} - 0.002 SP_{t-3} \right] \right] \]

\[ R^2 = 0.921 \]

\[ COW_t = \sum_{i=1}^{9} H_{t-i} \left[ \prod_{j=1}^{i} \left( 1 + \exp \left( -1.547 + 0.199 Dum84 + 0.245 Dum86 - 0.032 Dum2000 - 0.102 MP_{t-j} + 0.185 FP_{t-j} - 0.001 SP_{t-j} + 0.001 r_{t-j} - 0.044 CLASS + 0.024 MP_{t-j} \cdot CLASS - 0.054 FP_{t-j} \cdot CLASS + 0.0002 SP_{t-j} \cdot CLASS + 1.130 \frac{HEF_{t-j}}{COW_{t-j}} \cdot CLASS \right) \right] \]

\[ \Delta YLD_t = \left( -0.243 - 0.055 \frac{MP_{t-1}}{0.03} \right) \left[ YLD_{t-1} - \left( 2673.14 + 17.47 \tilde{T} + 517.44 DumQ2 \right) \right] \]

\[ R^2 = 0.994 \]

\[ -286.74 DumQ3 - 404.34 DumQ4 - 3.138 DumQ2 \cdot \tilde{T} - 4.515 DumQ3 \cdot \tilde{T} - 0.329 DumQ4 \cdot \tilde{T} \]

\[ -143.691 Dum85 + 4.351 Dum85 \cdot \tilde{T} \]

\[ \Delta YLD_t = \left( 3.489 \Delta MP_{t-1} + 3.214 \Delta FP_{t-1} \right) \]

\[ MILK_t = COW_t \times \sum_{i=0}^{3} YLD_{t-i} \tilde{t} = t : Q4 \]

Note: Newey-West heteroskedasticity and autocorrelation robust standard errors are in parenthesis. The variables are defined as follows:

- \( T \) – annual time trend (1=1975; 2=1976; etc.)
- \( \tilde{T} \) – quarterly time trend (1=1975:Q1, 2=1975:Q2, etc.)
- \( H_{EF_t} \) – replacement heifers, calculated as 75% of heifers over 500lbs. on dairy farms on 1 Jan. (1,000 head)
- \( COW_t \) – the annual average number of dairy cows on dairy farms (1,000 head)
- \( YLD_t \) – Yield per cow (lbs/quarter)
- \( r_t \) – real interest rate for operating loans
- \( MP_t \) – U.S. All-Milk price plus MILC payments ($/cwt)
- \( FC_t \) – the value of a 16% protein dairy ration (51% corn, 41% hay, 8% soybeans) ($/cwt)
- \( SP_t \) – Omaha/Sioux Falls slaughter cow bonning/utility price ($/cwt)
- \( CLASS = (i - j) \) where \( i = 1, \ldots, 9 \) and \( j = 1, \ldots, i \) – represents productive age class.
- \( Dum_{CLASS} \) – binary variable that is equal to zero only when \( CLASS \) is equal to zero, and one otherwise.
- \( Dum_{84} \) – binary variable identifying the Milk Diversion Program active in 1984.
- \( Dum_{86} \) – binary variable identifying the Whole-herd Buy-out Program active in 1986-87
Dum2000 – binary variable identifying Federal Milk Marketing Order reform (1 if \( t \geq 2000 \))
DumQ2, DumQ3, DumQ4 – binary variables for quarters.

**Table 3.** Predicted Marginal Impact of Prices on Cow Culling in 2010

<table>
<thead>
<tr>
<th>Cow Age</th>
<th>% of Herd</th>
<th>Cull rate % (( k_{it} ))</th>
<th>Marginal Price Impact (%)</th>
<th>( \Delta k_{it} / \Delta MP_{2009} )</th>
<th>( \Delta k_{it} / \Delta FP_{2009} )</th>
<th>( \Delta k_{it} / \Delta SP_{2009} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Value</td>
<td>S.E.</td>
<td>Value</td>
</tr>
<tr>
<td>3</td>
<td>28.89</td>
<td>17.10</td>
<td>-1.72</td>
<td>0.34</td>
<td>1.38</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>24.91</td>
<td>22.99</td>
<td>-1.52</td>
<td>0.30</td>
<td>1.00</td>
<td>0.13</td>
</tr>
<tr>
<td>5</td>
<td>18.56</td>
<td>30.19</td>
<td>-1.02</td>
<td>0.16</td>
<td>0.35</td>
<td>0.08</td>
</tr>
<tr>
<td>6</td>
<td>13.05</td>
<td>38.50</td>
<td>-0.23</td>
<td>0.13</td>
<td>-0.52</td>
<td>0.10</td>
</tr>
<tr>
<td>7</td>
<td>8.33</td>
<td>47.54</td>
<td>0.73</td>
<td>0.43</td>
<td>-1.51</td>
<td>0.21</td>
</tr>
<tr>
<td>8</td>
<td>4.09</td>
<td>56.75</td>
<td>1.67</td>
<td>0.71</td>
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<td>0.33</td>
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<td>9</td>
<td>1.59</td>
<td>65.52</td>
<td>2.39</td>
<td>0.90</td>
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<td>10</td>
<td>0.47</td>
<td>73.34</td>
<td>2.77</td>
<td>1.01</td>
<td>-3.60</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Note: These are the effects of a 10% increase over 2010 price levels
Table 4. Short Run and Intermediate Run Elasticities of U.S. Dairy Supply to Milk and Feed Price Changes

<table>
<thead>
<tr>
<th>Years Since Price Change (j)</th>
<th>1</th>
<th>3</th>
<th>6</th>
<th>10</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity of</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{HEF}<em>t \text{ w.r.t. } \text{MP}</em>{t-j} )</td>
<td>0.078 &amp; -0.106 &amp; 0.260 &amp; 0.316 &amp; 0.092 &amp; 0.540 &amp; 0.625 &amp; 0.332 &amp; 0.926 &amp; 1.064 &amp; 0.605 &amp; 1.533 &amp; 2.920 &amp; 1.788 &amp; 4.105</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{COW}<em>t \text{ w.r.t. } \text{MP}</em>{t-j} )</td>
<td>0.041 &amp; -0.006 &amp; 0.076 &amp; 0.236 &amp; 0.165 &amp; 0.301 &amp; 0.561 &amp; 0.394 &amp; 0.726 &amp; 1.020 &amp; 0.692 &amp; 1.351 &amp; 2.943 &amp; 1.915 &amp; 4.017</td>
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<td></td>
</tr>
<tr>
<td>( \text{PROD}<em>t \text{ w.r.t. } \text{MP}</em>{t-j} )</td>
<td>0.055 &amp; 0.000 &amp; 0.097 &amp; 0.241 &amp; 0.169 &amp; 0.306 &amp; 0.565 &amp; 0.397 &amp; 0.729 &amp; 1.024 &amp; 0.697 &amp; 1.356 &amp; 2.947 &amp; 1.917 &amp; 4.022</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elasticity of</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{HEF}<em>t \text{ w.r.t. } \text{FP}</em>{t-j} )</td>
<td>-0.006 &amp; -0.065 &amp; 0.056 &amp; -0.068 &amp; -0.165 &amp; 0.036 &amp; -0.134 &amp; -0.259 &amp; 0.003 &amp; -0.257 &amp; -0.440 &amp; -0.055 &amp; -0.754 &amp; -1.132 &amp; -0.331</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{COW}<em>t \text{ w.r.t. } \text{FP}</em>{t-j} )</td>
<td>0.039 &amp; 0.019 &amp; 0.070 &amp; 0.004 &amp; -0.033 &amp; 0.055 &amp; -0.099 &amp; -0.171 &amp; -0.013 &amp; -0.225 &amp; -0.360 &amp; -0.071 &amp; -0.760 &amp; -1.108 &amp; -0.365</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{PROD}<em>t \text{ w.r.t. } \text{FP}</em>{t-j} )</td>
<td>0.045 &amp; 0.019 &amp; 0.080 &amp; 0.004 &amp; -0.033 &amp; 0.055 &amp; -0.099 &amp; -0.171 &amp; -0.013 &amp; -0.225 &amp; -0.360 &amp; -0.071 &amp; -0.760 &amp; -1.108 &amp; -0.365</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

2006-2010

<table>
<thead>
<tr>
<th>Years Since Price Change (j)</th>
<th>1</th>
<th>3</th>
<th>6</th>
<th>10</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity of</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{HEF}<em>t \text{ w.r.t. } \text{MP}</em>{t-j} )</td>
<td>0.054 &amp; -0.014 &amp; 0.120 &amp; 0.194 &amp; 0.098 &amp; 0.294 &amp; 0.451 &amp; 0.310 &amp; 0.602 &amp; 0.791 &amp; 0.562 &amp; 1.047 &amp; 2.186 &amp; 1.577 &amp; 2.902</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{COW}<em>t \text{ w.r.t. } \text{MP}</em>{t-j} )</td>
<td>0.090 &amp; 0.070 &amp; 0.113 &amp; 0.280 &amp; 0.219 &amp; 0.349 &amp; 0.531 &amp; 0.410 &amp; 0.671 &amp; 0.887 &amp; 0.675 &amp; 1.137 &amp; 2.329 &amp; 1.713 &amp; 3.073</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{PROD}<em>t \text{ w.r.t. } \text{MP}</em>{t-j} )</td>
<td>0.094 &amp; 0.072 &amp; 0.119 &amp; 0.283 &amp; 0.222 &amp; 0.352 &amp; 0.534 &amp; 0.412 &amp; 0.674 &amp; 0.890 &amp; 0.678 &amp; 1.140 &amp; 2.331 &amp; 1.715 &amp; 3.075</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elasticity of</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{HEF}<em>t \text{ w.r.t. } \text{FP}</em>{t-j} )</td>
<td>-0.003 &amp; -0.034 &amp; 0.028 &amp; -0.076 &amp; -0.132 &amp; -0.023 &amp; -0.203 &amp; -0.287 &amp; -0.123 &amp; -0.373 &amp; -0.518 &amp; -0.245 &amp; -1.017 &amp; -1.368 &amp; -0.708</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{COW}<em>t \text{ w.r.t. } \text{FP}</em>{t-j} )</td>
<td>-0.034 &amp; -0.050 &amp; -0.019 &amp; -0.127 &amp; -0.082 &amp; -0.257 &amp; -0.350 &amp; -0.174 &amp; -0.433 &amp; -0.588 &amp; -0.299 &amp; -1.092 &amp; -1.465 &amp; -0.772</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{PROD}<em>t \text{ w.r.t. } \text{FP}</em>{t-j} )</td>
<td>-0.031 &amp; -0.049 &amp; -0.015 &amp; -0.127 &amp; -0.082 &amp; -0.257 &amp; -0.350 &amp; -0.174 &amp; -0.433 &amp; -0.588 &amp; -0.299 &amp; -1.092 &amp; -1.465 &amp; -0.772</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Tests for changes in long-run price responsiveness

<table>
<thead>
<tr>
<th></th>
<th>1978-1982 vs.</th>
<th>2001-2005</th>
<th>Milk price</th>
<th>Feed price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2001-2005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heifers</td>
<td>1978-1982 vs.</td>
<td></td>
<td>39</td>
<td>1693</td>
</tr>
<tr>
<td></td>
<td>2001-2005</td>
<td></td>
<td>(0.010)*</td>
<td>(0.423)</td>
</tr>
<tr>
<td></td>
<td>1978-1982 vs.</td>
<td></td>
<td>113</td>
<td>3654</td>
</tr>
<tr>
<td></td>
<td>2001-2005</td>
<td></td>
<td>(0.028)*</td>
<td>(0.086)</td>
</tr>
<tr>
<td>Cows</td>
<td>1978-1982 vs.</td>
<td></td>
<td>1038</td>
<td>861</td>
</tr>
<tr>
<td></td>
<td>2001-2005</td>
<td></td>
<td>(0.260)</td>
<td>(0.215)</td>
</tr>
<tr>
<td>Yield</td>
<td>1978-1982 vs.</td>
<td></td>
<td>108</td>
<td>3654</td>
</tr>
<tr>
<td>Milk Production</td>
<td>1978-1982 vs.</td>
<td></td>
<td>(0.027)*</td>
<td>(0.086)</td>
</tr>
</tbody>
</table>

Note: Tests were performed using simulated long-run forecasts of the series tested. 3999 simulation rounds were used. Reported figures indicate the number of rounds in which the average long-run elasticity in the later period was higher (in absolute value) than the long-run elasticity in the earlier period, denoted $N_{\eta_j \eta_j}$. Reported p-values in the brackets are calculated simply as $\min(N_{\eta_j \eta_j}, 3999 - N_{\eta_j \eta_j})/3999$. Intuitively, very small p-values relate to events highly unlikely under the null hypothesis of no change in supply responsiveness.

For example, comparing the supply responsiveness to change in milk prices, we find that in only 108 out of 3999, or 2.7% of rounds was the milk production 10-year elasticity with respect to milk price higher in the period 2001-2005 than in 1978-1982.
Figure 1. Relationship Between Class III/M-W and Manufacturing Support Price
Note: Composition of the U.S. dairy herd is given in percentages. In 1998, the first year such data is available, farms with 1000+ cows constituted 16.8 percent of the total U.S. dairy herd. By 2010, that share increased to 44.1%.

**Figure 2.** Yield per Cow, Size of the U.S. Dairy Herd and Composition by Farm Size.
Figure 3. Comparison of Actual and Predicted Number of Dairy Cows and Replacement Heifers
Note: All three scenarios take a set of feed and milk prices and keep them constant at a given level for 2011-2020 period. Scenario 1 is consistent with average 2012 futures prices observed in late June 2011. (Corn: $6.50/bu, Soybeans: $14.00/bu, All-milk: $19.00/cwt, Hay: $116/ton). Scenario 2 takes average 2007 prices (Corn $3.52/bu, Soybeans: $8.04/bu, All-milk: $19.87 and, Hay: $135.60/ton). Scenario 3 examines the impact of extreme feed prices, as we have briefly seen in futures markets in June 2011, but with lower milk prices (Corn $7.00/bu, Soybeans $14.50, Hay $116.00, All-milk: $17.00/cwt).

**Figure 4.** Impact of Alternative Price Scenarios on Future U.S. Milk Production
Figure 5. Estimated 10-year Supply Elasticities and Associated Confidence Intervals.
Figure 6. Predicted Herd Size and Retention Rates by Cow Age
Bibliography


