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Supply Response in Dairy Farming: Evidence from Monthly, Animal-Level Data

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We estimate short-run price response in dairy farming using nearly 10 million monthly animal-level observations across 2,311 Wisconsin farms in the years 2011–2014. We control for herd size and account for the age distribution of dairy cattle to identify changes in variable inputs in response to price movements. We find heterogeneous supply response across the animal life cycle to lagged movements in monthly milk and beef prices. Specifically, we find the greatest supply response in age cohorts with relatively high marginal returns from feeding, with supply elasticities as high as 0.286 for milk price and 0.713 for beef price. The results are primarily driven by significant producer response to prices in 2014, a period of volatile milk and beef prices.

Key words: biological production function, dynamic panel, livestock, volatility, cattle cycle

Introduction

A number of economics studies find that the short-run supply response elasticities of dairy farms are small, if not 0 (e.g., Bozic, Kanter, and Gould, 2012; Chavas and Klemme, 1986; Miller, 2015). These studies argue that supply response occurs primarily through adjustments to herd size, which is largely fixed in the short run (Chavas and Klemme, 1986). In theory, dairy farms can also increase yield for relatively high-productivity cows with feed and other managerial inputs when milk prices increase. One reason these changes can go undetected in aggregate data is that higher milk prices also incentivize farmers to retain less-productive cows in their herds, which brings average milk yield down (Bozic, Kanter, and Gould, 2012). Combined, these responses can generate small or no aggregate supply response, even when significant responses are in fact occurring. Understanding the extent to which these responses occur is important for farm policy design and for precision decision support aimed at increasing farm profitability (Bellingeri et al., 2020; Kalantari et al., 2016; Wu et al., 2019). Existing research on dairy supply response using national-level aggregate data has not been able to characterize this important component of dairy farm supply response.

In this article, we help fill this gap by estimating short-run supply elasticities using animal-level production data on over 2,000 farms in Wisconsin from 2011 to 2014. Using within-animal variation in milk production, we examine the extent to which dairy farmers adjust animal-level supply independent of decisions about herd size and culling. Much like the cattle cycle literature, we explicitly incorporate the age distribution of the cattle into supply response by estimating supply elasticities for each age cohort of dairy cattle (Jarvis, 1974; Aadland, 2004; Rosen, Murphy, and Scheinkman, 1994). Utilizing a rich dataset of monthly, cow-level production, we test for changes in

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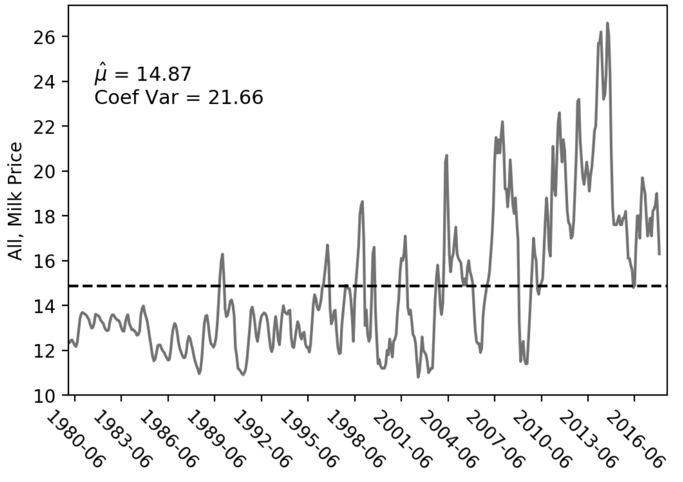

Figure 1. All Milk Price since 1980

Notes: Dotted line is sample average.

inputs by testing whether supply elasticities are highest for cows with the highest marginal product for feed, which are older cows in the middle of their yearly production cycle. We find that milk production increases in response to lagged movements of milk and beef prices at points of the production cycle when the returns from feed are relatively high, with supply elasticities as high as 0.286 for milk price and 0.713 for beef price. In a robustness check, we find that in the year 2014, a year of record-high milk and relatively high beef prices, dairy farmers made even more short-run adjustments than in previous years. Our study is the first to specifically analyze supply response at the level of individual animals and therefore accurately examine the extent to which supply changes independent of herd size adjustments.

Dairy farmers have the choice of adjusting output by changing the size of the herd (an “extensive” response) or changing how individual cows are managed or fed (an “intensive” response). In some cases, adjusting output via feed and management may be preferable if the farm faces a short-term capacity constraint and cannot acquire new animals. It does not appear, however, that dairy farms make significant changes in supply month to month. Most economics studies of milk supply response find that short-run supply response is quite small, with an elasticity of around 0.08–0.10, or else not statistically different from 0 (Bozic, Kanter, and Gould, 2012; Chavas and Klemme, 1986). This has led economists to conclude that dairy farmers react to changes in milk price by changing the size of their herd rather than managing their individual cows differently.

These conclusions may not be valid for today’s dairy farms for two reasons. First, most studies of dairy farm supply response have used data from periods in which price volatility was relatively low. Figure 1 shows the All Milk price since 1980, which has increased in volatility since the 1990s. Studies done in this period report small price elasticities (e.g., Chavas and Klemme, 1986; Tauer, 1998), but they do not reflect the reality of the industry today. In the current price environment, there are stronger incentives to change production in reaction to intermonth price changes. Further, dairy farmers may be less willing to make investments in capacity to increase herd size when milk prices are volatile and may instead choose to adjust production at the intensive margin.

The second reason that short-run supply response merits attention today is that existing studies have only been able to examine yield changes at the herd level. When testing for intensive margin changes, studies often examine milk production per cow, which is calculated as the total milk output divided by the number of cows (Bryant, Outlaw, and Anderson, 2007; Bozic et al., 2012). But as Bozic et al. (2012) points out, milk yield per cow measured this way may appear to be inelastic to price changes because movements in average yield involve both intensive and extensive decisions. Increases in milk price make it profitable to both increase milk production of existing cows (increasing milk production per cow) while also delaying the replacement of older, less productive cows (decreasing milk production per cow). At such a level, the intensive margin decision (whether to feed more) is confounded by the extensive margin decision (decisions about culling and replacement).

Our main findings in this article are threefold. First, we find that milk price and beef price explain deviations from the Wood lactation curve in a manner consistent with changes in feed. The response to milk price is highest when feed is most efficiently converted into milk, and thus where the marginal product is highest. Second, we find that current month price changes and those occurring 2 months in the past both explain milk supply at this level. Price changes a month prior have the opposite sign, which is similar to some of the findings in the cattle cycle literature where capacity constraints can cause negative supply response. Finally, we find that movements in beef price have a a large effect on milk production at the monthly level. When beef price goes up, dairy farmers appear to respond by increasing feed. The magnitude of all of these elasticities is even greater in the year 2014, a year of abnormally high prices. This suggests that short-run adjustments may be greatest when prices are above a certain threshold.

These results offer a number of interesting directions for future research on dairy farm supply response and formation of price expectations. They also have implications for dairy farm management focused on animal-level decision making. With the adoption of new precision technologies, dairy producers are gaining the ability to adjust feed to individual animals in real-time (Cabrera et al., 2020). The results we report here suggest that dairy producers make economically significant month-to-month managerial adjustments that impact herd-level milk yields. This adjustment behavior should be accounted for within the context of emerging precision dairy-farm management technologies.

Literature Review

The earliest estimates of milk supply response date back to some of the early applications of the Nerlovian supply response model. Several studies using data from Australia and Europe between 1947 and 1970 report highly variable short-run supply elasticities, ranging from 0.06 to around 0.40 (Askari and Cummings, 1977). Data in these studies are almost always aggregated to the country level and at the annual or quarterly time scale. Specifications using lags of prices show that milk supply did in fact react to changes in lagged prices, suggesting that price expectation formation has an influence on milk supply (Chen, Courtney, and Schmitz, 1972; Levins, 1982). More sophisticated analyses of milk supply response now incorporate not only milk prices but also feed and beef prices. Studies have shown that all three of these prices have significant effects, but the elasticities are very small in the short run, usually 0.10 or less (Chavas and Klemme, 1986; Chavas, Kraus, and Jesse, 1990; Bozic, Kanter, and Gould, 2012; Subervie, 2008).[1] Chavas and Klemme (1986) find that virtually all supply adjustments in the long run (97%) are through adjustments in herd size rather than cow-level production. This strand of literature stresses the importance of extensive supply decisions over intensive supply decisions when trying to understand fluctuations in milk supply.

However, biological components of production can hamper a farm's ability to change production in the short run. In the case of beef cattle, Jarvis (1974) estimates negative short-run supply elasticities because of the length of time required to mature beef cattle for slaughter. Rosen, Murphy, and Scheinkman (1994) explores how this component of production also explains the 10-year price cycles in beef cow prices. To model these cycles, Aadland (2004) specifically incorporates the age distribution of capital into the supply response model. This has not been done when studying dairy despite the fact that there is significant heterogeneity in supply response across farms. Tauer (1998) found farm specific supply elasticities which varied from above 1 to below 0. Adelaja (1991) uses

[1] "Short run" in this case is usually defined as within 1 year, as opposed to over multiple years.

farm-level financial data on dairy farms with fewer than 100 cows in the Northeastern United States and finds significant differences in supply response across farm size. These studies suggest that there is significant heterogeneity in supply response, which may be explained by the age distribution of animals within a farm.

Our work goes one step further than previous studies by exploiting *within*-farm heterogeneity on dairy farms to explore the effect of biological constraints on short-run dairy farm supply response. The primary biological constraint we study is the marginal product of feed, which changes throughout the dairy cow's life. For example, Broster, Broster, and Smith (1969) and Kirkland and Gordon (2001) find that the most significant increases in milk production from increased feed are at the peak of the lactation curve—around 4–6 weeks into lactation—and that the peak can be sustained with more feeding. Another study shows that feed response is higher later in a cow's life than in its first year (Jensen, 2014). Together, these findings suggest that dairy farmers only have an incentive to increase milk production in response to price for cows at these stages. Using these insights, we can use animal-level data to isolate within-animal variation in milk output to discern whether monthly output responds to price and whether the pattern of response is consistent with feeding cows with the highest marginal product.

Conceptual Framework

Similar to previous studies, we focus on four prices—the price of milk, the price of feed, the beef price, and the price of new dairy cow replacement—all of which have been shown to have significant effects on milk supply (Chavas, Kraus, and Jesse, 1990; Chavas and Klemme, 1986). The price of new dairy cow replacement is only looked at divided by beef price, since the true cost of replacement is net of the revenue received from slaughtering the current dairy cow.

Own-price elasticities—the elasticity with respect to the milk price or the ratio of milk price to feed price—are predicted to be weakly positive. From dairy science, we know that milk output is increasing and concave in feed (Jensen, 2014). This implies that the elasticity with respect to milk production should be weakly positive and fluctuate over the animal's life. From what we know about the production function of dairy cows, we expect larger elasticities at the peak response time, which is middle to late lactation at older ages (especially if managers are sustaining a peak in milk production). A similar condition holds for the ratio of milk price to feed cost, which we also study.

Supply response need only be positive in the static context, however. Incorporating dynamics creates the possibility that supply response can be negative for some periods if lessening production today can increase production in the next period. For example, Jarvis (1974) finds that cattle ranchers decreased the number of cows being slaughtered in the short run to allow them to put on more weight in the long run. For dairy, supply elasticities may be negative in the short run if, in reaction to a price change, dairy farmers feed their cows less in the current month to expand output in later months. This would especially be the case if the amount of feed was fixed within a given time period, so that a manager would have to give up feed now to be able to feed more in the future. Because of these dynamic incentives, we may see negative elasticities for current-period prices and positive elasticities for prices farther out.

The cross-price elasticity of meat production—the elasticity of the beef price with respect to milk output—could be positive or negative. In most studies, herd-level production reacts to beef price and replacement price because of culling or retention (Bozic, Kanter, and Gould, 2012; Chavas and Klemme, 1986). Here we identify within-cow variations in yield, which can only be affected by changes in variable inputs. Removing this confounding factor allows us to investigate the effect of slaughter and replacement price through the intensive margin only, in contrast to previous work, which studies only the effect on changes in herd size. This leaves the sign of the elasticities for beef price and replacement price ambiguous. The elasticity would be positive under the condition that dairy farmers feed these cows more as beef price goes up, presumably to put weight on the animal to increase its salvage value. This feeding could marginally increase milk production. This is unlikely

Table 1. Hypothesized Direction of Elasticities

		Expected Sign
Prices (separated)	Milk price	+
	Feed cost	−
	Beef price	+/−
Prices (ratios)	Milk price/feed cost	+
	Replacement price/beef price	+

since feeding an animal that would eventually go to slaughter would be costly, but in theory the incentive exists. Fortunately, using data on the production stage we can test whether this is the case. We should expect the elasticity to be positive at the end of the lactation rather than in the middle if the manager were aiming to increase salvage value by increasing feed.

The beef price elasticity can be negative, however, if a decrease in beef price prompts a reinvestment in the current animal. If the beef price is low, then a replacement is more costly and the manager may want to invest resources in the current animal rather than neglect it for its replacement. A similar argument suggests that an increase in the cost of replacement, in this case the price of replacement over the beef price, would be positively related to supply. If the cost of replacement is high, then resources may be reinvested into the current animal instead of into a future animal. Replacement price and beef price elasticities are both determined by the propensity to "invest" in the current occupant, or to "divest" from the current animal in favor of the future replacement animal.

To summarize, Table 1 lists the predicted directions of coefficients. Figure 2 displays what pattern of elasticities in the lactation curve are consistent with each mechanism of supply adjustment. Days into the production cycle is on the *x*-axis and daily milk production is on the *y*-axis. The relationship between these two variables is referred to as the "lactation curve." According to the dairy science literature, feed is converted into milk the most efficiently in the middle of the curve, right after the peak; near the end of the lactation, feed is converted into body weight. For this reason, the pattern of elasticities on the *y*-axis tells us something about the possible motives of input use. For feed and milk price, we expect the largest elasticity for supply in middle of the lactation and for older cows. For the beef price, we expect the largest elasticity at the end of the lactation if there is a motive to increase salvage value via body weight.

While these incentives exist on the biological level, it is easy to think of reasons why dairy farmers would not take advantage of them. For example, there may be significant costs to adjusting supply in the short run that explain low response. If additional feed is difficult to procure, then these elasticities will not be significant across any stage of production. Similarly, if farmers behaviorally choose to treat milk output within 1 year as fixed and deterministic, we will see low or no supply response, irrespective of production stage. Our analysis serves as a test of the hypothesis that such adjustments are made and also whether the pattern across production stages is consistent with dairy farmers feeding cows when marginal product is high. In order to test these predictions, we use a combination of animal-level data and an empirical model that embeds the biological process controlling milk production.

Empirical Strategy and Data

Our empirical model identifies the effects of prices on deviations from the deterministic component of production (i.e., the lactation curve). To do this, we include an estimate of the lactation curve based on the Wood (1980) model of the lactation curve, $f(d_{it}|\theta) = ad_{it}^{b}e^{-cd_{it}}$. In logarithm form, this

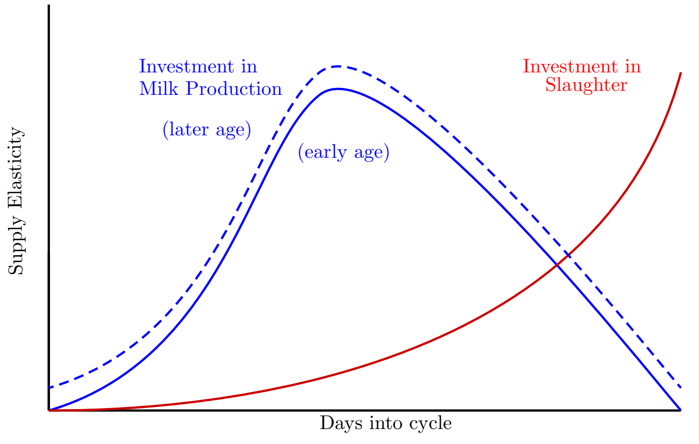

Figure 2. Hypothesized Pattern of Elasticity

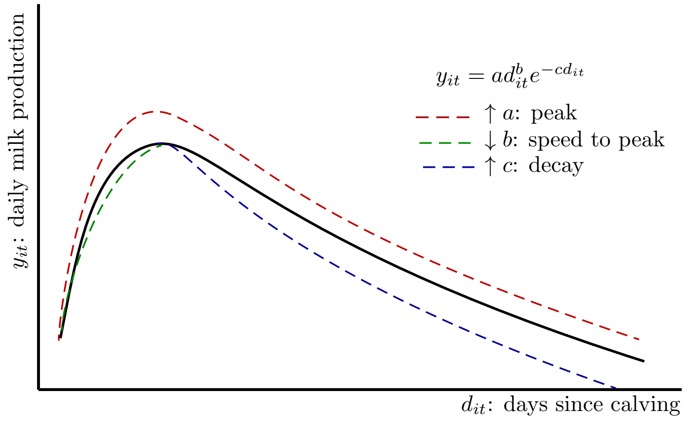

Figure 3. Lactation Curve and Wood Model

is $\ln f(d_{it}|\theta) = \ln a + b\ln d_{it} - cd_{it}$, where d_{it} is "days in milk" (number of days since starting the production cycle) for animal i and time t. The shape of the lactation curve and the effects of each of the parameters on the shape of the curve are displayed in Figure 3.

We capture changes across production cycles by interacting d_{it} and $\ln(d_{it})$ with ℓ_{it}, the number of year-long lactations of cow i at time t. Our final lactation curve specification is:

(1) $$\ln f(s_{it}|\theta) = \ln(a) + b\ln(d_{it}) + cd_{it} + b_\ell \ln(d_{it}) \times \ell_{it} + c_\ell d_{it} \times \ell_{it},$$

where $s_{it} = (d_{it}, \ell_{it})$ is the production stage. From the perspective of dairy science, observed milk output is entirely a function of these variables and other "environment" variables such as temperature, calving month, herd group, and feeding system. Physical and management environment are taken into account either by estimating separate lactation curves for each group or by having the variables entering linearly into the equation relating observed output to the lactation curve. This means that management variables play the same role as the intercept a by shifting the lactation curve at every production stage.

If a cowâĂŹs milk response to feed depends on production stage, then price response should also depend on production stage. To capture this dynamic response, we discretize days in milk into intervals of 60 days and interact price with both the lactation number and the days in milk category, allowing price response to be different at each production stage.

According to a Nerlovian supply response model and rational expectations, we should also expect lags of price and production to be correlated with output. In this case, production levels can be correlated across months independent of the lactation curve if there is a bad shock in one month that carries over to the next month (e.g., a shock to health). Since genetics undoubtedly play a role in milk production, we also want to control for permanent cow characteristics such as genetics. Unfortunately, we cannot include both the lag of production and a cow fixed effect in the same regression without introducing dynamic panel bias (Nickell, 1981).

To avoid this bias, we first difference the equation to remove the cow-specific intercept and instrument for the first difference lag $\Delta y_{i,t-1}$ using the level $y_{i,t-2}$, as suggested by Arellano and Bond (1991). This approach to agricultural supply response, instrumenting the difference with the level, is also implemented in Yu, Liu, and You (2012) and Haile, Kalkuhl, and von Braun (2016). Since milk production lags must be within lactations, by using two lags of production we omit the first 2 months of milk production in the data, reducing the data to around 9.9 million observations.

Thus, our empirical model is a two-stage model:

$$\begin{aligned}\Delta \ln(y_{it}) = \rho \Delta \ln(y_{i,t-1}) + \Delta \ln f(s_{it}) + \sum_{j=1}^{S} \sum_{m=0}^{L} \eta_{jm} \Delta \ln(\boldsymbol{P}_{t-m}) \times \mathbb{1}\{s_{it} = s_j\} \\ + \gamma_2 \Delta \boldsymbol{X}_{it} + \Delta \varepsilon_{it};\end{aligned} \tag{2}$$

$$\begin{aligned}\Delta \ln(y_{i,t-1}) = \beta \ln(y_{i,t-2}) + \Delta \ln f(s_{it}) + \sum_{j=1}^{S} \sum_{m=0}^{L} \eta^{1}_{jm} \Delta \ln(\boldsymbol{P}_{t-m}) \times \mathbb{1}\{s_{it} = s_j\}; \\ + \gamma_1 \Delta \boldsymbol{X}_{it} + \Delta \upsilon_{it}\end{aligned} \tag{3}$$

where y_{it} is the energy-corrected milk production of cow i at time t, $f(s_{it})$ is our modified Wood lactation curve, $\boldsymbol{P}_t$ is a vector of prices, and $\boldsymbol{X}_{it}$ is a vector of time-variant covariates (calving month, number of times milked, time trend, and month dummy).

The price vector is either ratios of prices (specifically, milk price to feed price and replacement price to beef price) or milk price, feed price, and beef price separately. As controls, we include other variables that are typically included as controls in explaining cow-level milk production. For example, the month of calving can have significant effects on production, as can the month in which the test happens (effectively controlling for seasonal trends that affect production). Time dummies cannot be included since prices do not vary across farms, so instead a time trend is included to capture any linear processes evolving over time. We also include somatic cell count, a measure of cow health, and whether the cow is pregnant as additional control variables.

Another significant control variable is number of times milked. In a typical milking schedule, cows are milked twice a day, though dairy farms with large capacity and labor have the option to milk three times. The dummy variable here captures whether the cow was milked three times that day. This, by itself, is a mechanism by which farmers may increase production in reaction to prices. Incorporating this into the model is beyond the scope of this article, and so for now is only used as a control. Future work should explore whether prices explain this as the outcome, possibly using a different framework altogether.

To estimate the above equations, we use herd testing data collected by one Dairy Records Processing Center from Wisconsin through various Dairy Herd Improvement Associations (DHIAs) throughout the state. In Wisconsin, DHIAs serve roughly half of all dairy farms in the state. The DHIAs collect monthly, cow-level observations on milk yield, somatic cell count, fat yield, protein yield, and other breeding and replacement decisions. The data do not record feed inputs or health management decisions, meaning we only observe supply response but must look at the pattern of response to discern whether it is consistent with increased feed use.

Table 2 summarizes the data. Our sample covers all herds serviced by a Dairy Records Processing Center in Wisconsin from June 2011 through January 2015, representing 2,311

Table 2. Data Description

	Number
Herds	2,311
Average herd size	182.99
Cows	796,939
Number of lactations	1,442,185
Lactation records	9,939,892
Time of sample	June 2011–January 2015

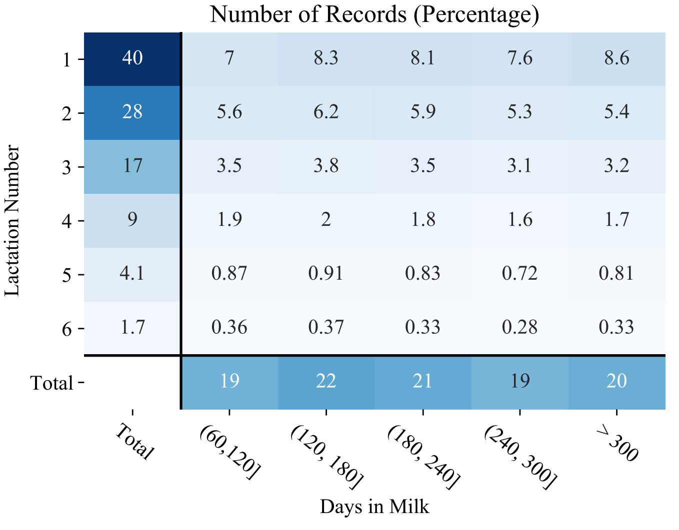

Figure 4. Percentage of Records in Each Stage

Wisconsin dairy farms and approximately 800,000 cows. The average herd size in this sample is around 180 cows per herd, a little higher than the Wisconsin average herd size in 2014 of around 120 cows.[2] From these herds and cows, we observe 9.9 million cow–month observations of milk yield. We standardize milk yield in our empirical model to energy-corrected milk that is 3.5% fat and 3.2% protein. About 95% of the data consists of cows within their first six lactations, and we follow the dairy science literature standard and omit cows that are past their sixth lactation.[3]

Figure 4 shows the proportion of records that are in each lactation year and stage of the lactation curve. Since the first 2 months of data for each cycle are not used, the first category begins at the 2 month mark, or 60 days in milk.[4] A lactation is considered "complete" at about 300 days in milk, and all records at more than 300 days are condensed into one bin. When using 2 month bins, each bin is around 20% of the data, meaning there is about the same sample size for each category within a lactation to estimate the model. Over lactations, cows in their first year of production account for 40% of the records with a gradual decline in records after that. The gradual decline reflects the fact that older cows are eventually culled and replaced with new cows producing in their first year.

[2] Author calculation done by dividing number of total cows by number of farms using Wisconsin Department of Agriculture data via USDA NASS for the year 2014. It should be noted that the high average in this sample is driven by fewer than 100 farms with more than 500 cows; more than 1,200 of the farms in the sample have fewer than 100 cows.

[3] Because of selective culling behavior, cows past the sixth lactation are not typically considered in analyses of herd testing data since they are not comparable to the average dairy cow.

[4] From a dairy science perspective, the first 4 months are generally when cows are getting to the peak, and are prone to health issues in the first 2 months. This makes production variable in this period, and possibly untrustworthy from a measurement perspective. In our conversations with dairy scientists, it was generally suggested that we not use the first 2 months of data for this reason.

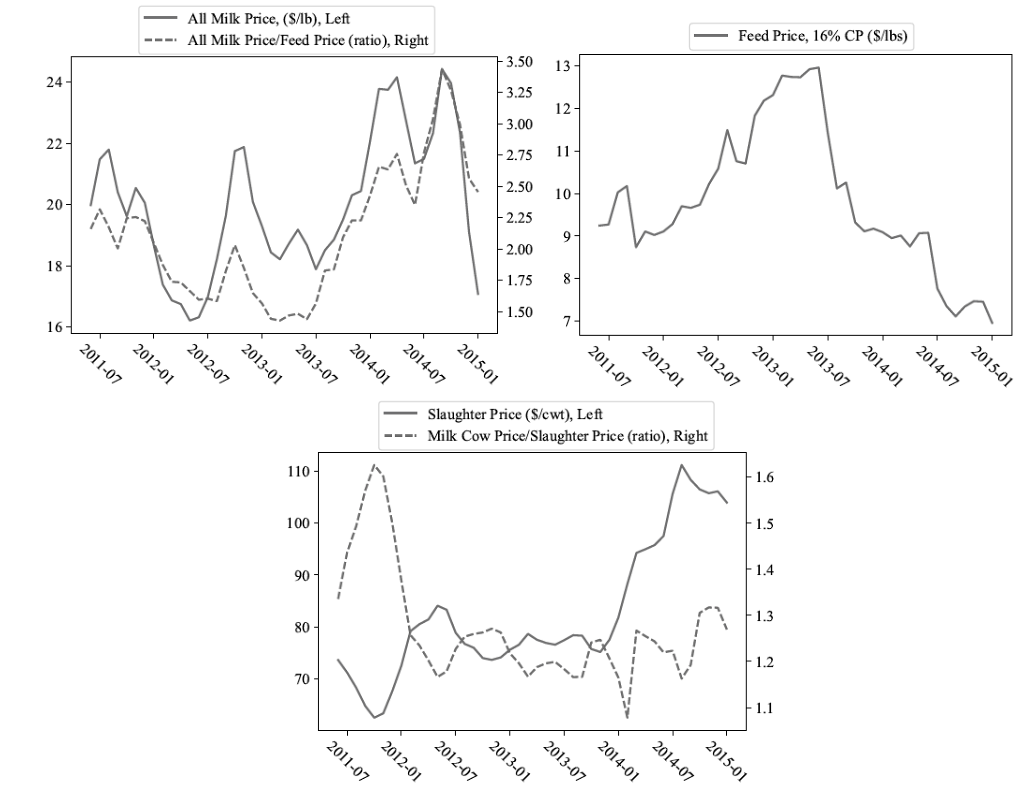

Figure 5. Prices during Sample Period, June 2011–January 2015

State-level, monthly prices for feed, beef price, and heifer replacement price are from the USDA National Agricultural Statistics Service (USDA NASS). We use the price of 16% crude protein dairy ration to proxy for the feed price, a price series found to be significant in explaining milk supply in previous studies (Bozic, Kanter, and Gould, 2012; Chavas and Klemme, 1986). While many farmers grow their own feed, the market price of dairy ration is significant to production in the short run when farmers want to increase feed rations quickly and have to supplement their existing feed stocks. The cow beef price is the price of a cow weighing 14 cwt, roughly the weight of a mature dairy cow. The replacement price is dollars per head for replacement milk cow heifers. For the own-price elasticity we use the All Milk price, which is dollars per hundredweight of the average test day milk for that market order (in this case the Upper Midwest market order). The monthly prices are linked to the monthly production data by applying the price to the month in which the milk measurement was taken; for example, a milk measurement taken in January 2013 will be matched to the prevailing prices for the month of January 2013.

Figure 5 shows the time series for all the prices and their relevant ratios during the study period. We note that the year 2014 is distinctly different from the previous years, especially in terms of milk and beef prices. The year 2014 contains record highs for milk prices and relatively high prices for beef. Because of these extraordinary price movements, there is reason to believe producers may have had greater sensitivity in these years than in previous years. After we estimate the model on the entire sample, we estimate the model on two subsamples: June 2011 to December 2013 and the year 2014. This extra step helps us to evaluate the specific influence of the year 2014 on our results.

Table 3. AR(3) Regression (*N* = 40)

	Milk Price	Feed Price	Beef Price	Milk/Feed	Cow/Beef
Constant	−0.0013	−0.0082	0.0063	0.0046	−0.0050
	(0.0072)	(0.0095)	(0.0041)	(0.0122)	(0.0067)
Lag 1	0.7134***	0.1415	0.8213***	0.3821***	0.1567
	(0.1427)	(0.1562)	(0.1493)	(0.1245)	(0.2145)
Lag 2	−0.2711	−0.1172	−0.4001*	−0.1142	−0.0142
	(0.2004)	(0.1610)	(0.2132)	(0.1983)	(0.1226)
Lag 3	−0.1191	0.1616	0.0412	−0.0343	−0.1628
	(0.2018)	(0.1584)	(0.1514)	(0.1665)	(0.1032)
Adjusted R^2	0.410	0.048	0.442	0.135	0.053

Notes: Single, double, and triple asterisks (*,**,***) indicate statistical significance at the 10%, 5%, and 1% level. Numbers in parentheses are standard errors clustered at the cow level.

Results

Table 3 reports the results of an AR(3) regression of the first difference of prices. Based on the Akaike information criterion and Bayesian information criterion, two lags were sufficient to capture the autocorrelation in the price first differences. The results of the AR(3) regression suggest that many variables do not exhibit strong auto-correlation in first difference. Part of this may be able to be explained by the inherent volatility of many of these prices month to month.[5]

Table 4 shows the ordinary least squares (OLS) model and instrumental variables (IV) models, as well as the first stage of the IV model. The estimation method uses only $\ln(y_{i,t-2})$ as an instrument for $\Delta\ln(y_{i,t-1})$ and not multiple lags (as in Blundell and Bond, 2000) because the level had significant power as an instrument on its own. Instrumenting the production lag brings the effect closer to 0 and has only small effects on the other coefficients. The lactation curve coefficients estimated off of the variables $\ln(d_{it})$ and d_{it} are more or less in line with previous models that estimate these coefficients (e.g., Wood, 1980; Macciotta, Vicario, and Cappio-Borlino, 2005).

As a baseline, Table 5 shows the elasticities of the model with and without instruments and with and without lags. Without lags, the own-price elasticity is negative and very small, about −0.03. Using lags, the current price has the hypothesized positive direction but is still less than 0.05. Since milk price lagged 1 period has a negative elasticity, omitting it biases the contemporary coefficient downwards. The feed cost has the expected direction but is also very small, and even smaller when lags are included due to the positive effect of the first lag. Beef price has the largest effect and is positive, about 0.2, suggesting that increases in beef price increase cow-level production. In all of these specifications, the lag 1 coefficient is consistently the opposite direction of the contemporaneous effect, which pulls the contemporaneous effect downward when the lags are omitted.

After breaking out elasticities by production stage, we see how different cohorts of dairy cows are affected when prices increase. Figure 6 shows elasticities averaged across all lactations for each category of days in milk. For current-period prices, there is almost no response to milk price, a small response to feed price, and a relatively strong response to the beef price. The beef price response tends to be highest in the middle of the lactation and gradually decreases, which is the period of the lactation with the highest marginal return to feed. For the first lag, the signs are opposite of the current-period effect: Milk and beef prices have negative elasticities, and feed prices have positive

[5] Note that the sample size here is only 40 months, hence the larger standard errors; a longer time frame might be needed to capture their relationship with more accuracy.

Table 4. OLS versus IV (N = 9,939,892)

	OLS	Second Stage	First Stage
$\ln(y_{i,t-1})$ (difference)	−0.330***	−0.091***	
	(0.001)	(0.001)	
$\ln(y_{i,t-2})$ (level)			−0.280***
			(0.001)
$\ln(d_{it})$	0.343***	0.274***	0.198***
	(0.001)	(0.001)	(0.001)
d_{it}	−0.002***	−0.002***	−0.001***
	(0.00001)	(0.00001)	(0.00001)
$\ln(d_{it}) \times \ell_{it}$	0.010***	0.010***	0.064***
	(0.0005)	(0.0004)	(0.001)
$d_{it} \times \ell_{it}$	−0.001***	−0.001***	−0.0005***
	(0.00000)	(0.00000)	(0.00000)
Milk price	−0.029***	−0.025***	−0.013***
	(0.002)	(0.002)	(0.001)
Feed price	−0.020***	−0.018***	−0.011***
	(0.002)	(0.002)	(0.002)
Beef price	0.072***	0.051***	0.038***
	(0.005)	(0.004)	(0.004)
Somatic cell count	−0.016***	−0.016***	0.004***
	(0.0001)	(0.0001)	(0.0001)
Pregnant	0.012***	0.011***	0.011***
	(0.0003)	(0.0003)	(0.0003)
Time trend	−0.0002***	−0.0002***	0.0003***
	(0.00001)	(0.00001)	(0.00001)
Milked 3× (1 = yes)	0.094***	0.096***	−0.010***
	(0.002)	(0.002)	(0.001)
Adjusted R^2	0.141	0.092	0.164

Notes: Single, double, and triple asterisks (*,**,***) indicate statistical significance at the 10%, 5%, and 1% level. Additional controls: month of test, calving month, time trend. All variables are in first difference unless otherwise specified. Standard errors (in parentheses) are clustered at the cow level.

Table 5. Price Elasticities over All Stages (*N* = 9,939,892)

	No Lags		Lags	
	OLS	**IV**	**OLS**	**IV**
Milk price	−0.029***	−0.025***	0.026***	0.036***
	(0.002)	(0.002)	(0.002)	(0.002)
Milk price lag 1			−0.070***	−0.086***
			(0.003)	(0.004)
Milk price lag 2			0.040***	0.052***
			(0.003)	(0.003)
Feed price	−0.020***	−0.018***	−0.006*	−0.003
	(0.002)	(0.002)	(0.003)	(0.003)
Feed price lag 1			0.062***	0.063***
			(0.003)	(0.003)
Feed price lag 2			0.020***	−0.0002
			(0.003)	(0.002)
Beef price	0.072***	0.051***	0.197***	0.193***
	(0.005)	(0.004)	(0.005)	(0.005)
Beef price lag 1			−0.127***	−0.167***
			(0.005)	(0.005)
Beef price lag 2			0.075***	0.094***
			(0.006)	(0.006)
Adjusted R^2	0.141	0.092	0.141	0.093
F-stat for instrument		6,114.428		5,195.051

Notes: Single, double, and triple asterisks (*,**,***) indicate statistical significance at the 10%, 5%, and 1% level. Additional controls: month of test, calving month, time trend, times milked, lactation curve. All variables are in first difference unless otherwise specified. Standard errors (in parentheses) are clustered at the cow level.

elasticities. The second-order lag coefficients, in contrast, are positive at the parts of the curve where marginal product is highest; milk and beef prices are positive in the middle of the lactation and then begin to decline. This is consistent with our hypothesis that farmers increase milk supply in reaction to increases in milk price when the marginal product for feed is highest. We can reject the null hypothesis that milk supply response is 0 within a lactation, so dairy farmers do not view animal-level production as fixed within a given year. Instead, in this level of disaggregation there is evidence that farmers change variable inputs in response to changes in lagged movements of prices. The pattern of elasticities is consistent with increases in feed being the input that is being changed, since the highest elasticities correspond to periods with the highest marginal products for feed.

Figure 7 shows the lag 2 elasticity broken out by cow age to get a sense for how the interyear response changes with each new cycle.[6] The lightest colors correspond to coefficients close to 0 while darker colors correspond to coefficients farther from 0, with their sign and magnitude indicated in each cell. Coefficients that are *not* statistically different from 0 at the 95% level are indicated with a superscript.

[6] Lag 2 is displayed since most coefficients for lags 0 and 1 were not different across lactations, with the exception of feed cost (which exhibited the same pattern as lag 2). These results can be inspected via this online graph: https://results-lact-app1.herokuapp.com/.

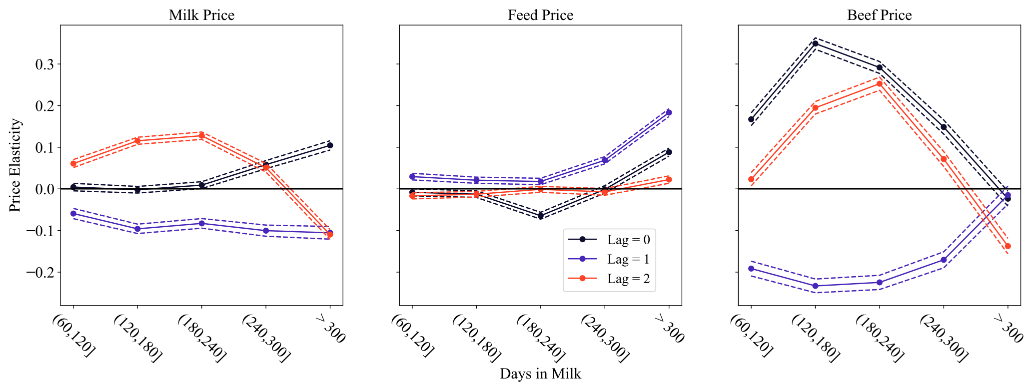

Figure 6. Price Elasticities over Days in Milk

Note: The results for all lags and lactations can be examined here: https://results-lact-app1.herokuapp.com/.

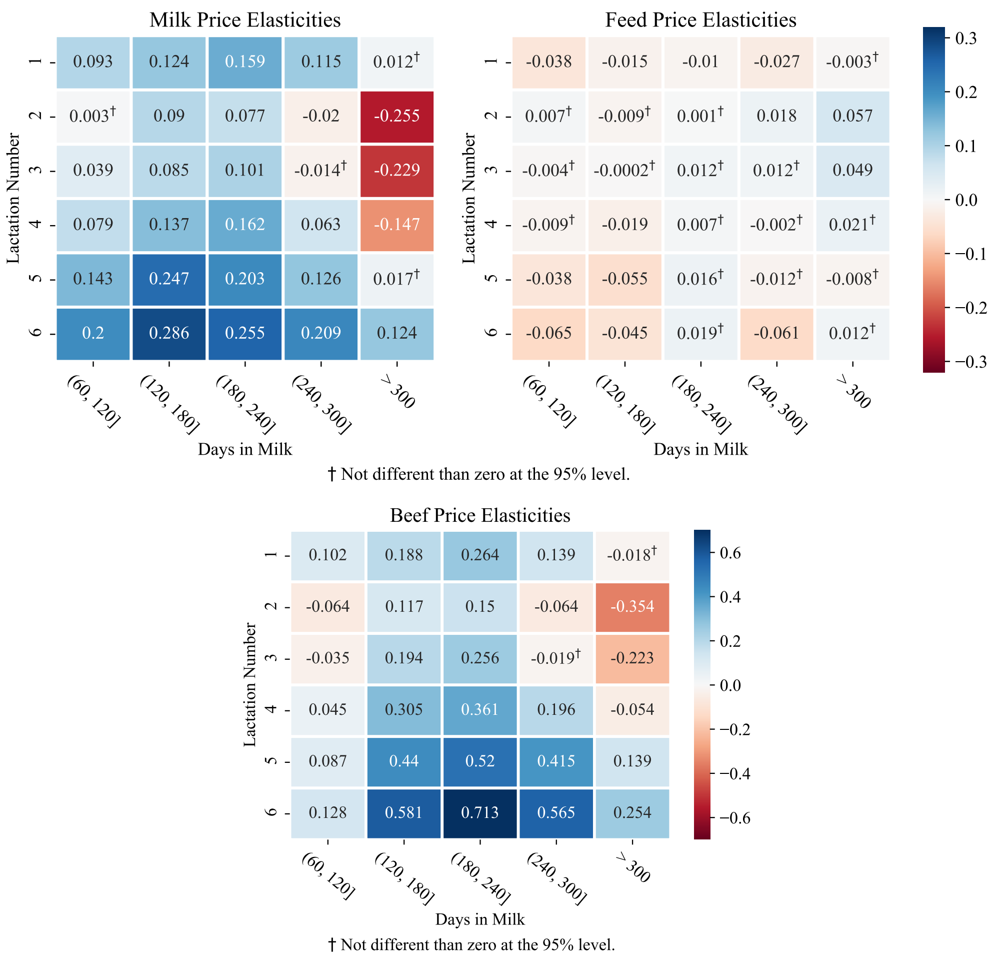

Figure 7. Lag 2 Price Elasticities over Days in Milk and Lactation

Note: The results for all lags and lactations can be examined here: https://results-lact-app1.herokuapp.com/.

Our hypothesis is that older cows should have a higher price response due to their higher marginal product. This is supported by the data; the oldest cows in the data have own-price elasticities as high as 0.286, whereas first-lactation cows have own-price elasticities of, at most, about 0.16. Beef price elasticities are as high as 0.713 for the oldest cows in the middle of their lactation. Similar to Figure 6, the largest effects for milk and beef price are in the middle of the lactation, where we expect the highest marginal returns to feeding.

Because we do not observe feed inputs, it is possible that producers feed cows across all age cohorts uniformly when prices rise. Our results are not consistent with this explanation, however. While second- and third-year cows have higher marginal returns to feed, their supply response is lower than that of their first-year counterparts. Animals at their fourth year or higher, however, have a higher elasticity than first-year animals. If animals were fed uniformly when prices rise, then supply elasticities for second- and third-year cows would be higher, not lower, than elasticities for first-year cows. One alternative explanation for these results is that farmers focus resources into both fresh cows, which need the most nutrients, and older cows, which are the most productive. Cows are usually culled after their third year, meaning that cows at their fourth year or higher were likely selected to survive because of their high productivity. When prices rise, it appears that farmers focus feed and inputs into these two groups of animals and not uniformly.

Not only does the beef price have the same pattern of elasticities as the milk price, but the elasticities are even larger. The highest elasticities for beef price are 0.713 as opposed to only 0.286 for milk price. They are highest in about the middle of the lactation, though their highest point for older cows appears to be at the 180-day mark as opposed to the 120-day mark. This is not as consistent with our original hypothesis that the largest elasticities for beef price would be found at the end of the lactation. Instead, the pattern is the most similar to the milk price. Why increases in beef prices translate into increased production for the cows with the highest marginal returns to feed is an interesting direction for future research.

Finally, we examine these same prices as ratios. Figures 8 and 9 shows elasticities with respect to milk price over feed price and cow replacement price over beef price. On average, the elasticities for milk price over feed cost have a similar pattern to the milk price alone but are smaller than the elasticities found in Figure 6, around 0.05–0.10 here as opposed to 0.15–0.28 for the milk price. We find smaller elasticities for milk over feed cost than for milk price; however, in this specification there is a current-period reaction in addition to a reaction to lag 2. Both of these elasticities have a pattern consistent with feeding for high production. The elasticities with respect to replacement over beef price do not consistently match up with any story, however. They are positive for lag 0, negative for lag 1, and alternating positive and negative for lag 2. In contrast to the beef price, there is no discernible pattern of elasticities consistent with any of our hypotheses.

Robustness Check

The last year of our study sample, 2014, was a year of very high prices for both milk and beef. At the end of 2014, the milk price fell drastically to its pre-2014 levels. Since this year had unusually high volatility in these prices, we examine the influence of 2014 on the elasticities by estimating the model on 2014 alone and also without 2014. Since ratios of prices were somewhat more stable in 2014, we specifically examine the milk, feed, and beef prices in this robustness check. The results of this analysis for the price ratios can be found in the online supplement (see www.jareonline.com).

Figure 10 shows the elasticities for milk, feed, and beef prices on both of the subsamples. For the 2014 sample, the elasticities have a much larger magnitude than their counterparts in years prior. For milk price, the pattern remains consistent with feed response but is only statistically significant for cows with four or more lactations. The elasticities are as high as 0.52 for cows in the middle of their sixth lactation. Though the elasticities for feed price did not exhibit a clear pattern on the whole sample, in 2014 they are even larger in magnitude than milk price and exhibit a pattern consistent with our hypothesis. Feed price elasticities reach −0.739 in the middle of the lactation for the oldest

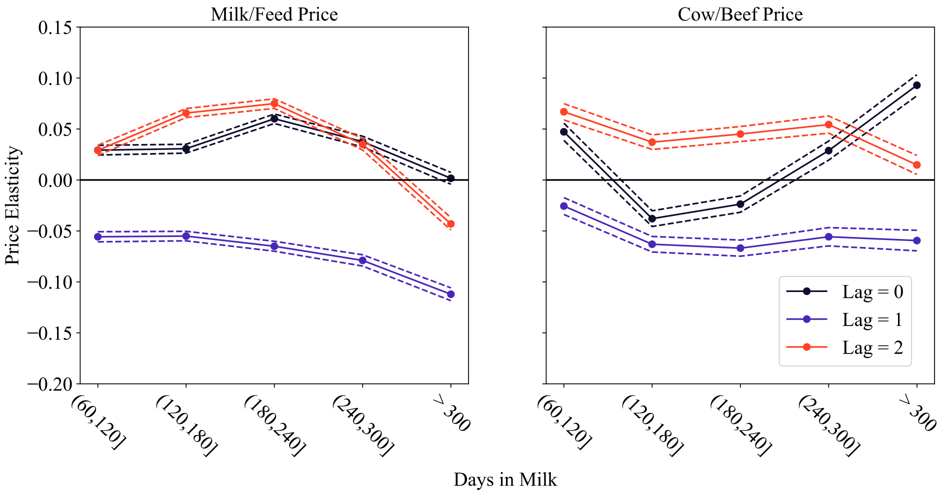

Figure 8. Price Ratio Elasticities over All Lags

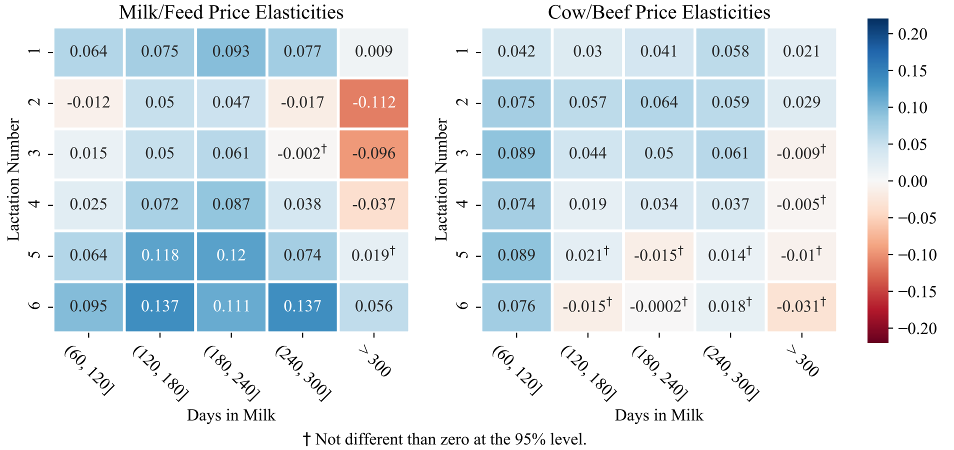

Figure 9. Price Ratio Elasticities for Lag 2

cows, which is consistent with our expectations; when the feed price decreases, supply for the cows with highest marginal product increases the most. In the case of beef prices, not only does the pattern remain in 2014, but it is even stronger: Supply is unit elastic for some of the oldest cows in the middle of their lactation. Notably, this pattern for beef persists before 2014 for the oldest cows.

Overall, these results suggest that the elasticities calculated on the whole sample are mostly driven by behavior in 2014. Before 2014, there is no clear relationship between the magnitude of the supply elasticity and the age of the cow. In 2014, a pattern emerges that is consistent with supply increasing the most for cows that have the highest marginal returns to feed. Part of this is explained by the fact that in 2014 farms experienced the most variation in prices, but it is also plausible that producers paid more attention to adjusting their monthly supply in 2014 than in other years. Milk prices rose and fell drastically during this year and beef prices rose consistently, which may have incentivized farmers to make dynamic supply adjustments more than they had in previous years. Our results suggest therefore that short-run adjustments to supply are being made in reaction to prices, but producers may not make these changes unless prices cross a certain threshold. It may be that adjusting production in the short run is costly, leading to low response at low milk prices, but can be

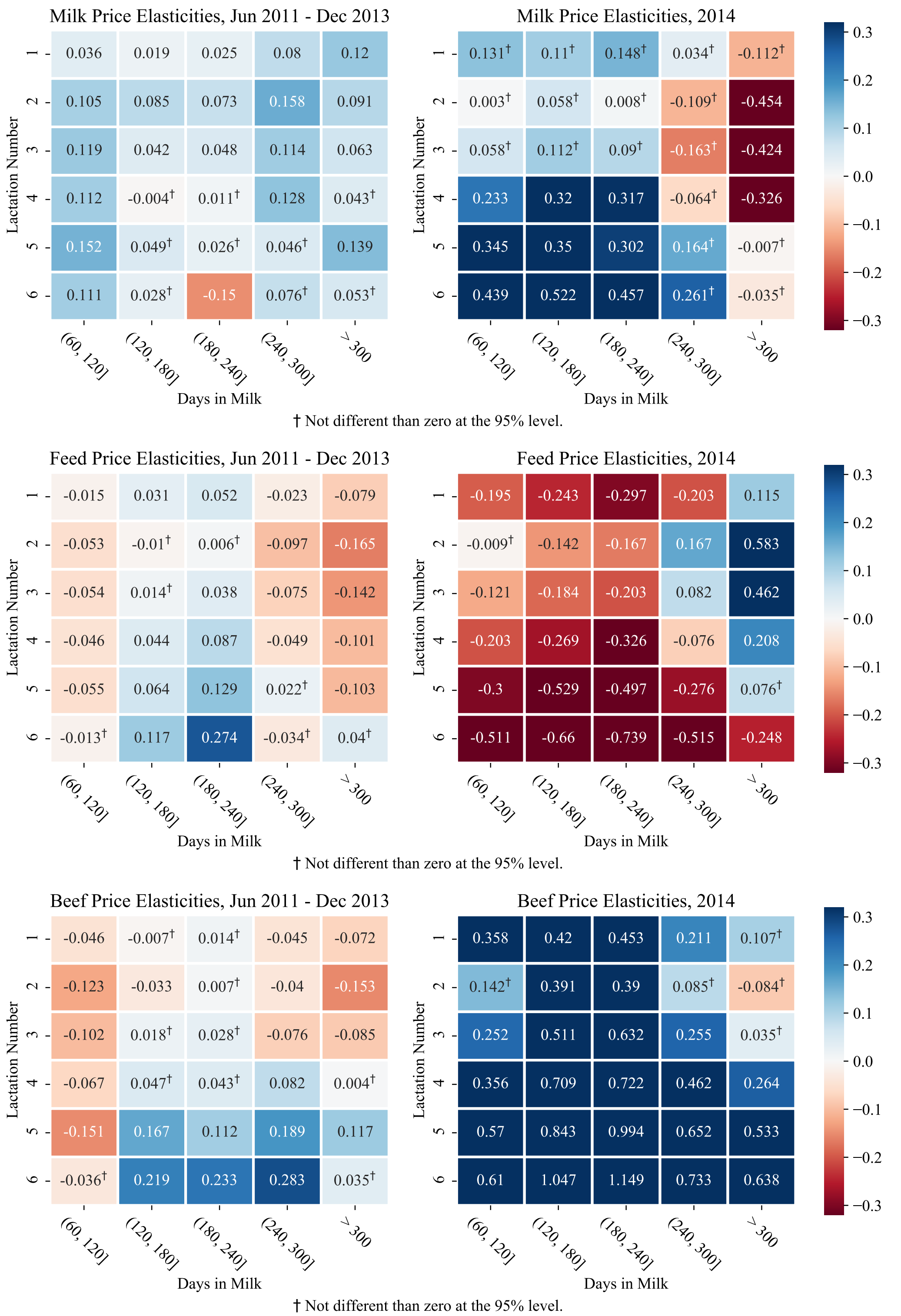

Figure 10. Lag 2 Elasticities by Subsample

justified at a certain level of milk price. Investigating this behavior is a fruitful direction for future research.

In the online supplement, we examine the elasticities with respect to the price ratios in these subsamples and present an additional robustness check on these results by accounting for the correlations between the prices in calculating a supply response. Since the prices have autocorrelation, an increase in the price lagged by 2 months also affects the price lagged by 1 month and the price in the current period. We calculate simple point estimates of the supply elasticity taking into account the correlations to see whether this adjustment changes the patterns we see across the animal life cycle. With the exception of the beef price lagged 1 month, the pattern of elasticities remains across all lags, including the negative elasticities for milk production in the price lagged 1 month. This confirms that the above results are not simply a result of correlation between prices and that the negative elasticities we find here are quite robust.

Discussion and Conclusion

The goal of this analysis was to shed light on intensive supply responses on dairy farms, specifically animal-level changes in milk production in response to prices. Previous analyses of short-run supply response have shown milk supply to be inelastic in the short run, leading many to argue that supply adjustments predominantly manifest through changes in herd size. None of these studies, however, have incorporated the age of the dairy cattle into the analysis to test the extent to which biological processes determine short-run supply response. Our goal was to test this hypothesis using an expansive dataset of dairy cow milk production where we can control for cattle age and retention of older cows in the herd. To study the importance of this intensive supply response, we integrated prices into an empirical lactation curve based on Wood (1980) and analyzed whether deviations in price explain deviations in the lactation curve.

We reject the hypothesis that farmers do not respond to prices within the lactation; animals that are the most responsive to feed—cows that are older or in the middle of their lactation—have the highest supply response to the milk price, albeit milk prices 2 months previously. In particular, the year 2014 was a period in which short-run supply reacted strongly to changes in prices for the cows with the highest marginal returns to inputs. Supply was practically inelastic to changes in these prices prior to 2014, either because 2014 prompted a specific change in management or else because short-run adjustments are costly and 2014 was the only year in which milk prices were high enough to incentivize producers to make adjustments. In this analysis, we uncover dynamic supply adjustments not previously uncovered by the economics or farm management literature. The analysis has also uncovered some interesting aspects of supply response that are beyond the scope of our analysis but suggest directions for future research.

First, in most of the specifications, the second lag of the price was the most significant to supply. Prices at the 2-month horizon appear to be important to production decisions, either as a signal by themselves or a critical variable in formation of the expected price. Further research, either qualitative or quantitative, could focus on how the time horizon works in forming month-to-month price expectations. The analysis also uncovered negative supply elasticities that suggest dynamic incentives in month-to-month supply response. Beef production can show negative supply response when ranches decide to delay slaughter and put more weight on their animals to increase future revenue (Jarvis, 1974; Reutlinger, 1966; Gordon, 1990), though this motive applies less to dairy; lessening milk production in one month does not lead to more milk production in the next month. However, if feed supply is constrained in the short run, than dairy farmers may decrease feed in one period to feed more in subsequent periods. To test this explanation, a more sophisticated integration of herd- and animal-level decision making would be needed to link the herd-level constraints to the animal-level decision making. A third aspect of supply response uncovered in this analysis is that beef price has a larger effect than milk price on cow-level supply, exhibiting as high as unit elasticity with cow production. This result was robust, surviving in every single specification tried, including a robustness check in which the correlations between the prices were taken into account (see the online supplement). Why and whether increases in the beef price should encourage farmers to feed their cattle more should be a future subject of research.

Overall, we show that behavioral responses to changes in prices do indeed occur at the monthly level. In the sample we study, and especially in 2014, dairy farms made significant adjustments to animal-level supply when prices changed. With the increasing adoption of precision agriculture technology, it will be easier for dairy farmers to make these kinds of adjustments to specific groups of animals for whom the marginal return to feed is the highest. A fruitful direction for farm management consulting would be to pay special attention to the role of these short-run adjustments to inputs in a new market paradigm of price volatility for the dairy industry.

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doi: 10.22004/ag.econ.310524

Online Supplement: Supply Response in Dairy Farming: Evidence from Monthly, Animal-Level Data

Jared Hutchins and Brent Hueth

Robustness Check on Ratios

In Figure S1, we estimate the elasticities with respect to the price ratios on our two sub-samples. In the top row of the figure, we calculate the elasticity with respect to milk price over feed price. The results here are similar to the results for milk and feed price separately. Prior to 2014, there is no discernible pattern to the elasticities over age or within age. In 2014, there is a significant supply response for animals in their first year, in the fourth year or higher, and in the middle of their lactation. It once again appears that the results in Figure 9 for this ratio were mostly driven by behavior in 2014.

In Figure 9, there is no discernible pattern for the effect of the replacement ratio, that is the price of a heifer divided by the price of beef. When breaking these results out on the sub-samples, two patterns appear that are opposite to one another. Before 2014, younger cows had a positive response to this price and older cows had a negative response. In 2014, the opposite is true; cows at young ages have negative response to this price while older cows have positive responses. In both periods, interestingly, the strongest responses are at the ends of the lactations and not in the middle where response is highest. Without a full theoretical framework that integrates decisions about culling and replacement into short-run input use, there is no way to contextualize these results and say anything definite about their interpretation. We emphasize here that it does appear that a significant shift took place in 2014 with how dairy farmers incorporate these prices into their decisions. A subject of future work would be to integrate culling and short-run input use into one theoretical framework to help explain and contextualize the patterns we see here.

Revised Estimates Using AR Regression

Given the fact that prices are correlated with their lags, it is difficult to interpret the effect of lag elasticities independent of one another. While η_{j0}, the elasticity of the current period price, is the true supply response to a change in the current period price, the supply response to lagged prices must also take into account the fact that prices are auto-correlated. A unit increase in the price last month not only directly affects supply (through a behavioral response) but also affects the current period price. To adjust the supply response for the relationship between the prices, we use the AR(m) regression of first difference, log prices:

$$\Delta lnP_t = \alpha_0 + \sum_{m=1}^{L} \alpha_m \Delta lnP_{t-m} \tag{S1}$$

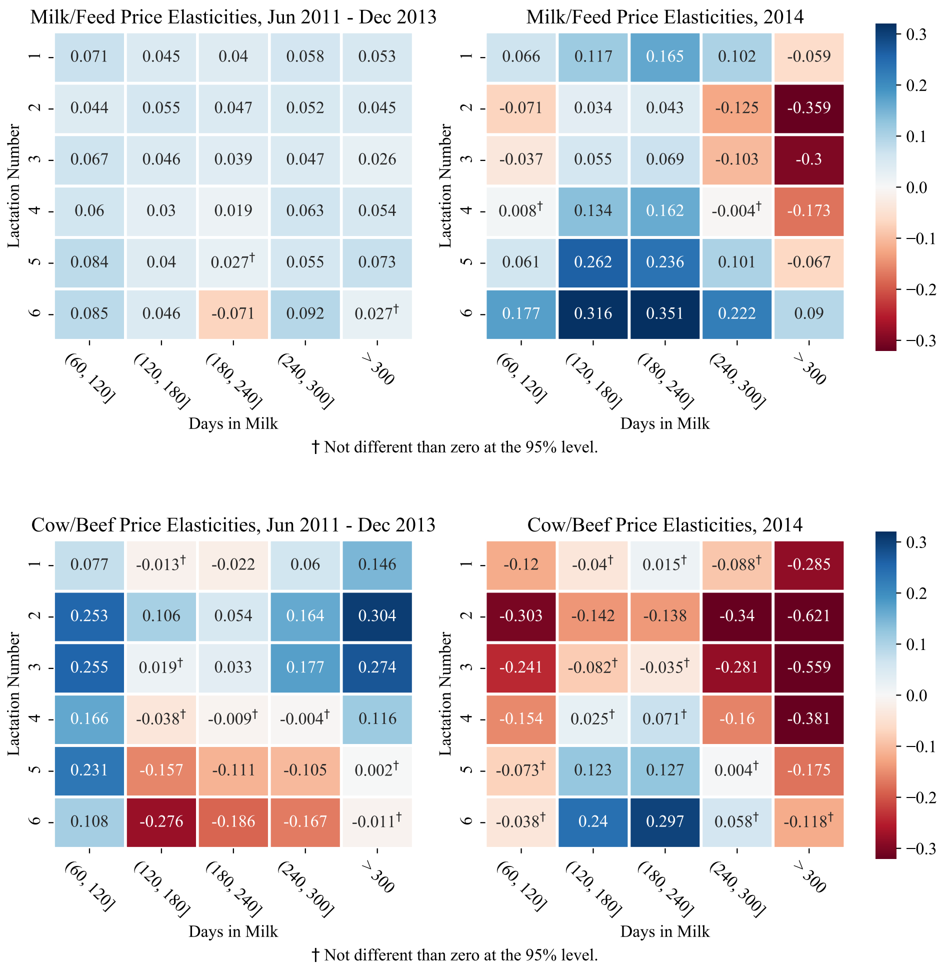

Figure S1. Lag 2 Ratio Elasticities by Sub-sample

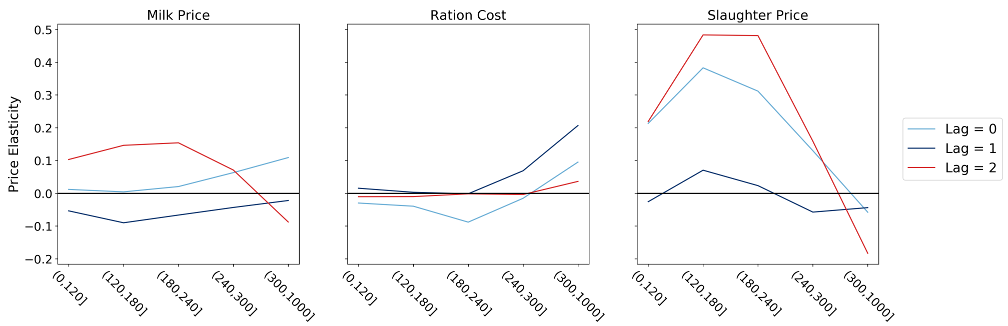

Figure S2. Adjusted Elasticities for Prices

Figure S3. Adjusted Elasticities for Ratios

Assuming Rational Expectations, the change in $\Delta ln(y_{it})$ associated with a change in a lagged price is:

(S2) $$\frac{\partial \Delta ln y_{it}}{\partial \Delta ln P_t} = \eta_{j0}$$

(S3) $$\frac{\partial \Delta ln y_{it}}{\partial \Delta ln P_{t-1}} = \eta_{j0}\alpha_1 + \eta_{j1}$$

(S4) $$\frac{\partial \Delta ln y_{it}}{\partial \Delta ln P_{t-2}} = \eta_{j0}\alpha_2 + \eta_{j1}\alpha_1 + \eta_{j2}$$

(S5) $$\frac{\partial \Delta ln y_{it}}{\partial \Delta ln P_{t-m}} = \eta_{j0}\alpha_m + \eta_{j1}\alpha_{m-1} + ... + \eta_{j,m-1}\alpha_1 + \eta_{jm}$$

To discern whether these relationships explain some of the elasticities we see in the main results, we present point estimates (without standard errors) of the above derivatives. Figure S2 shows the revised supply elasticities. The relationships are more or less the same except for the lag one coefficient for slaughter price which is no longer negative, instead hovering around the zero line. The other effects of slaughter price are even larger here than calculated in the model. Milk price and ration cost are almost completely unchanged. Figure S3 confirms that for the ratios between prices results are similarly unchanged. This confirms that in most of these cases the negative elasticity with respect to the lag one price is not because of the effect of correlations between prices. Instead, there is actual negative supply response for prices one month out as opposed to the current month or two months out.

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