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

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October 16, 2019

Abstract

Milk production is allegedly inelastic to changes in milk price and feed cost in the short-run. In the literature on dairy farm supply response, studies almost always find short-run response to be small or insignificant. Such studies, however, are usually done at the herd and quarterly level where the mechanisms of supply response cannot be distinguished. Using a monthly, animal level data set, we analyze supply response at the animal level which isolates the intensive margin response, that is use of more inputs, subject to the production process. In our empirical analysis of over ten million animal records, we reject the null hypothesis of no response, finding that dairy cow milk production is impacted by changes in milk price and slaughter price. Specifically, milk production increases in response to milk price at the point in the lactation curve where the marginal returns to feeding are highest. We also find that current month milk price does not explain milk production but the milk price lagged two months does. Further, movements in the slaughter price have a much larger effect on production than milk or ration prices, suggesting a future area of research for dairy farm supply response.

Keywords: supply response, dairy, supply elasticity, production functions

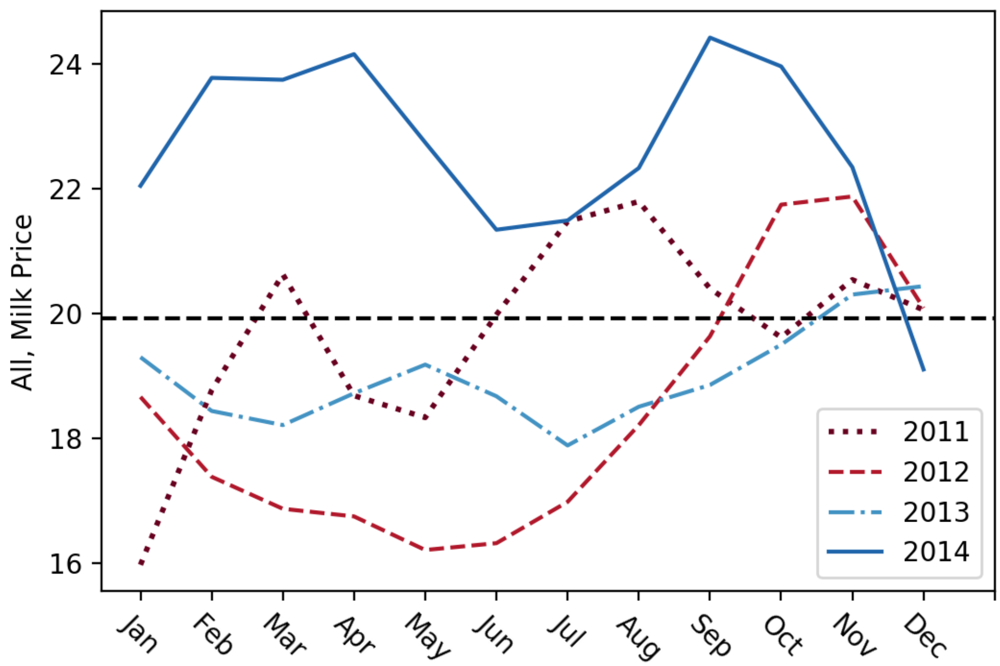
1 Introduction

Since the 1980's, dairy farmers in the United States have found themselves to be in an increasingly volatile price environment. The ratio between the highest and lowest All Milk Price divided by the average has gone from 16.5% in 1980-95 to 67.3% by 2005-2010 (Bozic et al., 2012). When making production decisions, dairy farmers can no longer expect the same price stability that they did decades ago, even at the monthly level. Figure 1 illustrates the extent to which prices have swung month to month in the period 2011 to 2014, with some changes exceeding two dollars per hundred-weight; milk prices in this period fail to even show a seasonal trend that would help dairy farmers know what to expect month-to-month. How are dairy farmers handling these inter-month changes, and how do they change supply decisions, if at all?

In our empirical analysis of over ten million animal records, we reject the null hypothesis of no supply response, finding that cow-level milk production within a given production cycle responds to changes in price. We calculate own-price elasticities as high as 0.2 depending on the stage of the production cycle; as predicted, we find the response to milk price is highest when feed is most efficiently converted into milk, and thus where the marginal product would be the highest. Interestingly enough, we find that current price changes occurring two months in the past explain deviations in production better than the current period milk price, and that slaughter price has a large effect on inter-month supply response.

In the agriculture economics literature, short term supply response to milk price, in this case inter-month, are often considered to be zero or at the very least small due to the biological nature of production; when dairy cows begin to lactate, most dairy scientists would consider their fluctuations in milk production due entirely to biological or environmental factors and not to changes in inputs such as feed. This appears to be supported empirically by most economics studies of milk supply response, which find that "short-run" supply response is quite small, with an elasticity of around .08-.1 (Bozic et al., 2012; Chavas and Klemme, 1986). This has led economists to conclude that the extensive response, changes in herd size, is much larger than the intensive response, changing an individual cow's production. The assumption of little to no price response within a lactation is reflected in how profit margins are calculated in the dairy industry. The measure Income over Feed Cost (IOFC), is essentially the milk price minus a weighted average of several feed costs; implicit in this calculation is the idea that there is a fixed, nutritional requirement for lactating dairy cows that must be borne by the producer. While this measure is good at capturing the general picture of profitability, it reflects the assumption that the the level of production determines

Figure 1: All, Milk Price over the data sample period;
black dotted line is sample average

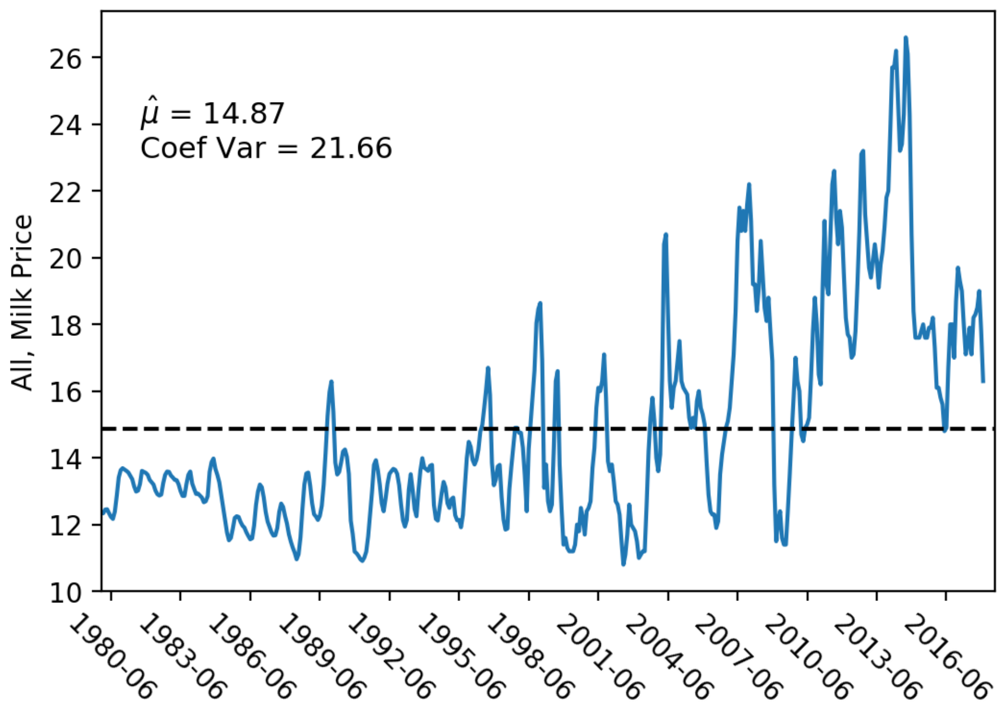


the amount of feed inputs and cost and not, as economists would naturally think, vice versa.[1] With such an assumption, dairy cow production at the monthly level (intensive responses) is indeed fixed in the short term and the milk supply will only respond to changes in herd size (extensive responses).

These conclusions may not be valid for two reasons. First, most studies of dairy farm supply response have been in done using data from periods where price volatility has been very small. Note, for example, Figure 2 which shows the All, Milk Price since 1980. While on average the price is about \$15 for this period, the coefficient of variation is 21.66% of the mean, and volatility has increased since 1992. Studies that report small price elasticities such as Chavas and Klemme (1986) and Tauer (1998) would were done in this period, which does not reflect the reality of the industry today. In the current price environment, there are many more incentives to change production in reaction to inter-month price changes. Still this does not explain why more recent studies such as Bozic et al. (2012) and Miller (2015) do not find larger short-run price elasticities. However, a second reason that the current understanding of short-run supply response may be incomplete is that all previous studies of

[1] In a simple profit function, production y is a function $f(x)$ of inputs x which cost $c(x)$ so that profit $pf(x) - c(x)$. In this case, changes in prices affect x and thus y. If we view production as fixed and cost as a function of the production level, we would instead write profit as $py - c(y)$ and could, in the simple case of linear cost, just factor out y and get $py - c(y) = my$, where m is the IOFC.

Figure 2: All, Milk Price since 1980;
black dotted line is sample average



dairy farm supply response have used data at such a scale that short-run supply responses may not be detected. Specifically, most studies use data at the national or herd level over an entire year that sum together cow level production. As Bozic et al. (2012) points out, at that scale there are extensive and intensive decisions that can cancel each other out at the herd level; with a higher milk price, farmers are incentivized to both increase feed, increasing milk production, and retain older cows that produce less, which may decrease it. Even with data available at the monthly time scale, these two effects are impossible to disentangle at the herd level.

In this paper, we disentangle the two mechanisms at play by use of a new theoretical framework and new data. Using the Wood model of dairy cow lactation, we incorporate response to prices within the biological process and estimate the model on an animal level data set of dairy cow production in Wisconsin. Focusing on the short-run supply response, we test the following hypothesis:

> **RQ**: Does the supply-price elasticity of milk production vary over the production stages of dairy cows, specifically lactation number and days in milk?

We test the hypothesis that there is an increase in milk production in reaction to increases in milk price early in the lactation but not in the rest of the lactation due to the fact that the gains from feeding are highest early in the lactation. By looking at the effects of price at the animal-month level we have the advantage of holding all extensive decisions about herd size fixed, only looking at whether fluctuations in one cow's output at different stages can be explained by the economic environment.

In our empirical analysis of over ten million animal records, we reject the null hypothesis of no response, finding that milk price and slaughter price do indeed explain deviations from the Wood lactation curve in a manner consistent with facts we know about the biological process; the response to milk price is highest when feed is most efficiently converted into milk, and thus where the marginal product would be the highest. Interestingly enough, we find that current price changes occurring two months in the past explain deviations in production better than the current period milk price. Further, movements in the slaughter price have a much larger effect on production than milk or ration price. These results offer a number of interesting directions for future research on how farmers form price expectations and change monthly input decisions.

2 Literature Review

Agriculture supply response has most often been studied as an application of the Nerlove supply response model (Nerlove and Bessler, 2001). In this model, agricultural output is regressed on the lag of production, the price, and other economic variables; according to the structural model, the short-run supply response is the coefficient on price from that regression, and the long run supply response is the short-run response divided by one minus the coefficient on the supply lag. This relatively simple formulation is the default method of estimating price response of agricultural commodities, despite its relatively strict assumptions about how price expectations are formulated. Later work tried out several different behavioral models of expectation formation of price in agricultural supply, though Rational Expectations (RE) appears to be the most popular (see Nerlove and Bessler (2001) for a review). Recent work has shifted towards using the basic Nerlovian regression model assuming RE but giving special attention to endogeneity; specifically, models use fixed effects or first differencing to control for time-invariant factors either with aggregate time series data or farm level panel data (Subervie, 2008; Haile et al., 2016; Brockhaus et al., 2016).

The earliest estimates of milk supply response date back to some of the early applications of the Nerlovian supply response model. Several studies done in the period 1947 - 1970 of Australia and Europe show short-run supply elasticities were highly variable, ranging from .06 to around .4 (Askari and Cummings, 1977). Data was almost always aggregated to the country level and at the annual or quarterly time scale. Different specifications using lags of prices showed that milk supply did in fact react to changes in lagged prices, suggesting that price expectation formation has an influence on milk supply (Chen et al., 1972; Levins, 1982). More sophisticated analyses of milk supply response now incorporate not just the effect of milk prices, but also feed and slaughter prices. Studies have shown that all three of these prices have significant effects but are very small in the short-run, usually .1 or less (Chavas and Klemme, 1986; Chavas et al., 1990; Bozic et al., 2012; Subervie, 2008). (Chavas and Klemme, 1986) found that virtually all supply adjustments in the long run (97%) are through adjustments in herd size rather than cow level production. This points to the importance of extensive supply decisions over intensive supply decisions when trying to understand fluctuations in milk supply.

However, there are, as Pope (1981) notes, significant problems with analysis done an aggregated data. Aggregate milk production data often hides heterogeneity in supply response, as some studies using farm level data have found. Tauer (1998) showed just how much variability there can be in price response across farms by estimating farm specific supply elasticities, which varied from above one to below zero. Adelaja (1991) used farm level financial data in the Northeastern US on dairy farms with less than one-hundred cow and found significant differences in supply response across farm size; smaller farms had a larger short-run supply response than larger farms, for example.

What is even more problematic about aggregated milk production data is that is sums together different production functions. Far from being uniform month to month, for an individual cow milk yield will rise immediately after giving birth to a calf and then gradually begins to decline. In dairy science, the relationship between milking days since calving, called “days in milk,” and milk yield is called the “lactation curve.” In addition to changes in milk production, the lactation curve also determines how much feed is converted into milk production, or the marginal product of milk production with respect to feed. An early study, Broster et al. (1969) found the most significant increases in milk production to be at the peak of the lactation curve, that is usually around 4-6 weeks into the lactation, and then a gradual decline in responsiveness. It also found that the general descent of milk production as a function of days in milk can be decreased with higher feeding; this means a peak can be sustained with more feeding. Kirkland and Gordon (2001) confirm these results. Other studies of feed response such as Jensen (2014) also show that marginal change in milk production is decreasing in energy intake, suggesting that feed response is concave, and feed response is higher for later lactation cows (multiparous) than first lactation cows (primiparous).

Since different cows are at different points of their lactation curves in any given month, herd level milk production can be lower because of economic behavior or just simply biology.

Simply looking at changes in prices and changes in herd level production only accurately estimates price response in the case that managers treat all of their cows the same when there is a price change. Since any given herd has cohorts that have different marginal product with respect to feed, basic firm theory would suggest price response would instead be highest for the cow with the highest marginal product, that is the one with the largest response to feed.

Our work is a novel contribution to the literature on milk supply response because it tests whether this incentive affects supply response on dairy farms. It works at a level of disaggregation hardly ever seen in economics and specifically suited to understanding price response on dairy farms: the animal level. Without such data, supply response to monthly price changes cannot be truly determined without data on inputs. Rather than exploring the underlying behavioral model of price expectation, we focus on specifically estimating short-term supply response at the animal level and test whether different cohorts of cows are treated differently when prices change.

3 Hypotheses

Similar to previous studies, we focus on four prices: the price of milk, the price of feed, the slaughter price, and the price of a heifer replacement. All four of these prices have been shown to have significant effects on milk supply (Chavas et al., 1990; Chavas and Klemme, 1986). The last of these is only looked at divided by slaughter price, since the true cost of replacement is net of the revenue received from slaughtering the current dairy cow.

Own price elasticities, that is the elasticity with respect to the milk price or the ratio of milk to feed, are predicted to be weakly positive; from dairy science, we know that the milk output is increasing and concave in feed (Jensen, 2014). This implies the elasticity with respect to milk production should be weakly positive. To see this, imagine that dairy cow production y is a function of both "production stage" s and feed input x. If the output price is p and the input price is w, then profit at a given production stage would be:

$$\pi(s,x) = py(s,x) - wx$$

. The first order condition gives the typical condition: that feed input is determined by equating marginal product, $\partial y(s,x)/\partial x$, to the price ratio w/p. The marginal product of feed $\partial y(x,s)/\partial x$ also determines the own-price supply elasticity η:

$$\eta(x,s) = \frac{\partial y(x,s)}{\partial p} = \frac{\partial y}{\partial x}\frac{\partial x}{\partial p}$$

This elasticity is positive under the condition that 1) the marginal product of feed is positive (y is increasing in x) and 2) y is concave in x, meaning $\partial x/\partial p \geq 0$.[2] The input price, that is feed price, should have a weakly negative elasticity under the same conditions.

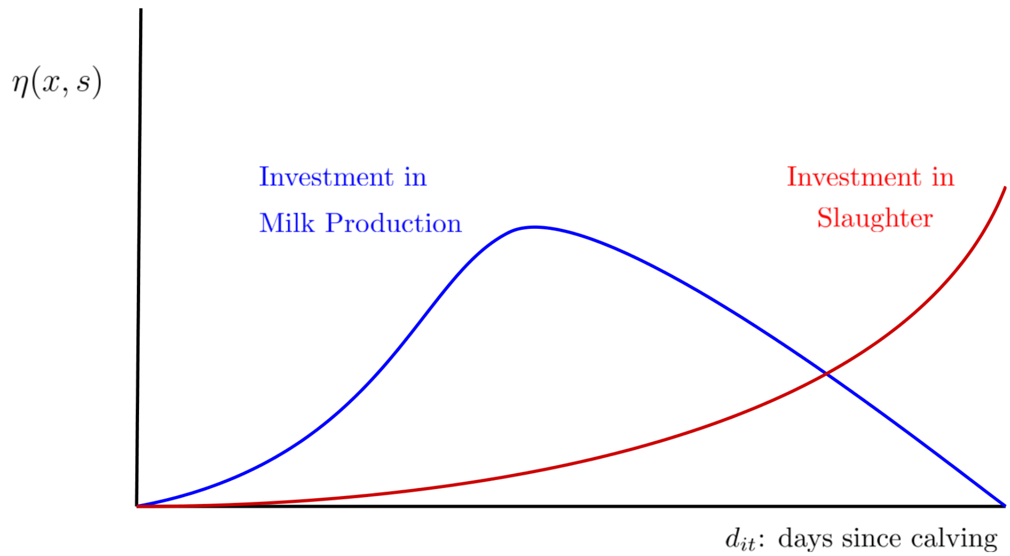
The magnitude of the elasticity depends on the marginal product of feed inputs, where the production stage s has its chief effect. From what we know about the production function of dairy cows, we expect larger elasticities at the peak response time, which is middle to late lactation at older ages (especially if managers are sustaining a peak in milk production). A similar condition holds for the price ratio p/w, which we also study.

The cross-price elasticity of meat production, that is the elasticity of the slaughter price, at this timescale is ambiguous; in most studies, herd level production reacts to slaughter price and replacement price because of culling or retention (Bozic et al., 2012; Chavas and Klemme, 1986). Here we identify within cow variations in yield, which takes out this confounding factor. Taking out 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 the extensive margin (cow replacement). This leaves the sign of elasticities for slaughter price and replacement price ambiguous; specifically, the sign depends on whether there is an incentive to increase salvage value. If in preparation for slaughter the manager increases feed rations because of a higher slaughter price, this would increase milk production and make the supply elasticity positive. Conversely, the manager, knowing the cow is going to be slaughtered, may neglect other actions to increase milk production that would make the elasticity negative. The direction of the elasticity would depend on which of these incentives is stronger. Put differently, the sign of the elasticity depends on whether milk production and meat production are substitutes or complements. One way to determine whether the motive is specifically to increase salvage value is to look at what point the elasticity is positive. If salvage value is an incentive, slaughter price should have its strongest effects when feed goes more into body maintenance instead of milk production, which is the end of the lactation. As this mechanism of supply response has been unexplored, our work distinguishes this mechanism by both looking at the sign of the elasticity and where it is largest. If it is positive and highest at the end of the lactation, this evidence of a motive to increase salvage value.

Finally, we also test whether the ratio between replacement price and slaughter price has an effect on milk supply. The conditions for the sign of this elasticity are similar to that of the slaughter price. If an increase in the cost of a replacement incentivizes farmers to

[2] This follows from applying the implicit function theorem to the first order condition. It can also be seen intuitively by noting that if p is to increase, then the FOC can only hold with equality if $\partial y(s,x)/\partial x$ decreases, which is accomplished by increasing x only if $\partial y(s,x)/\partial x$ is decreasing in x (or y is concave in x).

Figure 3: Hypothesized Pattern of Elasticity



invest more in the production of their current cows, then this elasticity will be positive. If it incentivizes them to care less, it will be negative. If they are incentivized to invest more resources into their current cow, then the pattern across production stage should be similar to that of the own-price elasticity; it should be highest where the marginal product of feed inputs are highest.

Table 1: Hypotheses Direction and Conditions

		Expected Sign	Condition
Prices (Separated)	**Milk Price**	+	Increasing and concave production
	Ration Cost	-	Increasing and concave production
	Slaughter Price	+/-	Positive if aim to slaughter, negative if aim to neglect
Prices (Ratios)	**Milk Price/ Ration Cost**	+	Increasing and concave production
	Replacement Price/ Slaughter Price	+/-	Positive if invest, negative if disinvest

4 Data and Estimation

4.1 Herd Testing Data

Dairy Herd Improvement Associations (DHIA) collect monthly, cow level observations on milk yield, somatic cell count, fat, protein, and other breeding and replacement decisions. The only management decisions recorded in the data are number of times milked on the test day, the calving date, and dates of breeding attempts. The data do not record feed inputs or health management decisions such as antibiotic treatments or hoof trimming.

Our sample covers all herds serviced by on Dairy Records Process Center in Wisconsin during the period June 2011 through January 2015, representing 2,747 farms and approximately 1 million cows. From these herds and cows, we observe 14.1 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.

State level prices for milk, feed, slaughter weight, and replacement price are from the U.S. Department of Agriculture, National Agricultural Statistics Service (USDA NASS). For 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). We use the price of 16% crude protein dairy ration to proxy for the feed price and the cow slaughter price for a cow weighing 14 cwt, roughly the weight of a mature dairy cow. The replacement price is dollars per head for milk cows.

Finally, 95% of the data consists of cows within the first six lactations; dairy cows surviving to more than lactation number five is quite rare, as cows on average exit at the second or third lactation. Cows that live past their sixth lactation are usually extraordinarily productive, and so production will appear to slope downward over the lifetime and then spike up again at later lactations. This is simply reflecting the survival bias of cows that live to be this old, and does not indicate anything about the pattern of supply response for cows on average. Since they are not comparable to the average dairy cow, for simplicity and saving parameters they are omitted from the analysis.

4.2 Empirical Model

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

$$lnf(d_{it}|\theta) = lna + blnd_{it} - cd_{it}$$

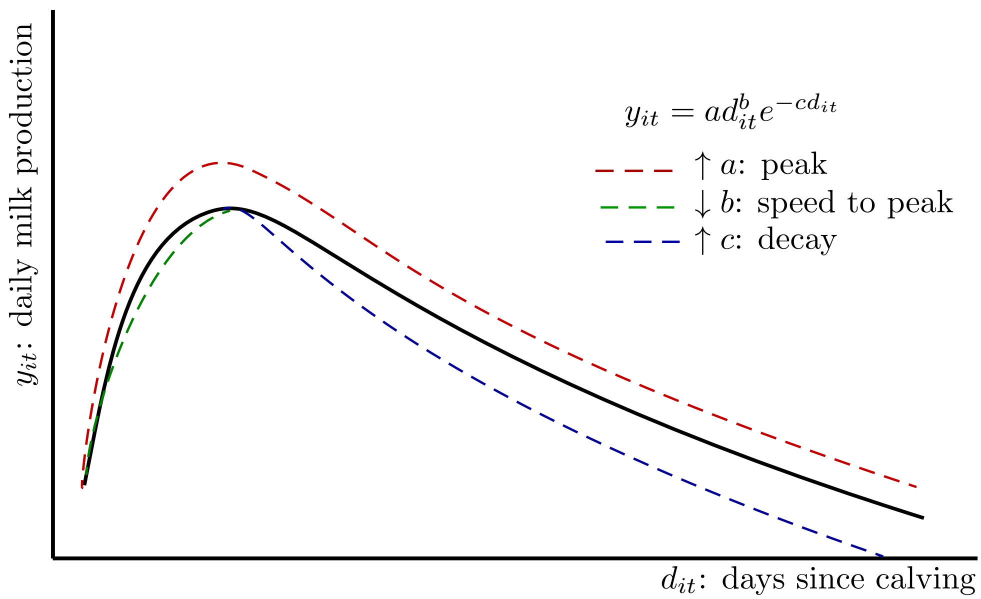


Figure 4: Lactation Curve and Wood Model

where d_{it} is days in milk for animal i and time t. ℓ We capture how the curve changes with each lactation 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:

$$lnf(s_{it}|\theta) = ln(a) + bln(d_{it}) + cd_{it} + \ell_{it} + bln(d_{it}) \times \ell_{it} + cd_{it} \times \ell_{it}$$

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

How do we model prices in this production function? Since prices change month to month, it would be inaccurate to model the price as shifting the entire curve over the course of a year; the presumption of intensive supply response implies that shifts at price would affect different production stages differently, taking into account both the price's effect on management decisions (e.g. changing feed rations) and the responsiveness of milk production at that particular stage. In fact, if a cow's 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 into milk into intervals of roughly sixty 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 the price to matter to the decision, and consequently the lag of production. Omitting lagged production introduces endogeneity because lags of prices were considered in the previous period's production decision but lagged production also affects current period production. Since genetics undoubtedly play a role in milk production, for this question we want to interpret price response independent of genetics, and could do this by including a cow level intercept μ_i for the model. Unfortunately, both the lag of production and a cow specific intercept cannot be included 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 effect 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 et al. (2012) and Haile et al. (2016). Since milk production lags must be within lactations, by using two lags of production we omit the first two months of milk production in the data, reducing the data to around 11 million observations.

Thus our empirical model is a two stage model:

$$\Delta ln(y_{it}) = \rho \Delta ln(y_{i,t-1}) + \Delta ln f(s_{it}) + \sum_{j=1}^{S} \sum_{m=1}^{L} \eta_{jm} \Delta ln(P_{t-m}) \times I\{s_{it} = s_j\} + \gamma_2 \Delta X_{it} + \Delta \epsilon_{it}$$

$$\Delta ln(y_{i,t-1}) = \beta ln(y_{i,t-2}) + \Delta ln f(s_{it}) + \sum_{j=1}^{S} \sum_{m=1}^{L} \eta^1_{jm} \Delta ln(P_{t-m}) \times I\{s_{it} = s_j\} + \gamma_1 \Delta X_{it} + \Delta \upsilon_{it}$$

- y_{it}: Energy corrected milk (ECM) production of cow i at time t .
- $s_{it} = (d_{it}, \ell_{it})$: Production stage, (days in milk, lactation number).
- $f(s_{it})$: Modified Wood lactation curve
- P_t: Vector of prices.
- X_{it}: Time variant cow covariates (calving month, number of times milked, ect.).

The price vector is either ratios of prices, specifically milk price to feed price and replacement price to slaughter price, or milk price, feed price, and slaughter price separately. We choose $L = 2$, two lags, as sufficient to capture the autocorrelation in the first difference of log prices.

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 autocorrelated; 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 also estimate the AR(m) regression of first difference, log prices:

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

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

$$\frac{\partial \Delta lny_{it}}{\partial \Delta lnP_t} = \eta_{j0}$$
$$\frac{\partial \Delta lny_{it}}{\partial \Delta lnP_{t-1}} = \eta_{j0}\alpha_1 + \eta_{j1}$$
$$\frac{\partial \Delta lny_{it}}{\partial \Delta lnP_{t-2}} = \eta_{j0}\alpha_2 + \eta_{j1}\alpha_1 + \eta_{j2}$$
$$\frac{\partial \Delta lny_{it}}{\partial \Delta lnP_{t-m}} = \eta_{j0}\alpha_m + \eta_{j1}\alpha_{m-1} + ... + \eta_{j,m-1}\alpha_1 + \eta_{jm}$$

Point estimates for the above derivatives are estimated in addition to the coefficients from the empirical model. In general, η estimates for lagged prices by themselves are not inherently meaningful other than describing the data; they map to a variety of behavioral models which fit the data. We would like to see, however, if the effects of lagged prices from the main empirical specification change radically when the effects of the system are taken into account.

5 Results

5.1 Elasticities

In the results from the regression model, the interpretation of the elasticities over different production stages is most easily thought of as how the production of each cohort changes in

Table 2: Price Elasticities over All Stages

	No Lags		Lags	
	OLS	IV	OLS	IV
$ln(y_{i,t-1})$	-0.326^{***}	-0.082^{***}	-0.326^{***}	-0.082^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
$ln(d_{it})$	-0.002^{***}	-0.002^{***}	-0.002^{***}	-0.002^{***}
	(0.00002)	(0.00002)	(0.00002)	(0.00002)
d_{it}	0.329^{***}	0.270^{***}	0.330^{***}	0.270^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
$ln(d_{it}) \times \ell_{it}$	0.014^{***}	0.012^{***}	0.014^{***}	0.012^{***}
	(0.001)	(0.001)	(0.001)	(0.001)
$d_{it} \times \ell_{it}$	-0.001^{***}	-0.001^{***}	-0.001^{***}	-0.001^{***}
	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Milk Price	-0.025^{***}	-0.022^{***}	0.033^{***}	0.042^{***}
	(0.001)	(0.001)	(0.002)	(0.002)
Milk Price Lag 1			-0.068^{***}	-0.085^{***}
			(0.003)	(0.004)
Milk Price Lag 2			0.050^{***}	0.062^{***}
			(0.003)	(0.003)
Ration Cost	-0.023^{***}	-0.021^{***}	-0.019^{***}	-0.015^{***}
	(0.002)	(0.002)	(0.003)	(0.003)
Ration Cost Lag 1			0.061^{***}	0.061^{***}
			(0.002)	(0.002)
Ration Cost Lag 2			0.027^{***}	0.006^{***}
			(0.002)	(0.002)
Slaughter Price	0.089^{***}	0.066^{***}	0.209^{***}	0.203^{***}
	(0.003)	(0.003)	(0.004)	(0.004)
Slaughter Price Lag 1			-0.133^{***}	-0.172^{***}
			(0.005)	(0.005)
Slaughter Price Lag 2			0.116^{***}	0.130^{***}
			(0.004)	(0.005)
Observations	10,449,004	10,447,786	10,449,004	10,447,786
Adjusted R^2	0.126	0.078	0.127	0.078
F-stat for Instrument		9155.829		7117.666

*p<0.1; **p<0.05; ***p<0.01

Controls: Month of test, calving month, milked three times, time trend response to a change in prices. Calculating price elasticities for each cow production stage is similar, in theory, to estimating separate equations for each cohort.

As a baseline, Table 2 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 -0.02. Using lags, the contemporary price has the hypothesized positive direction but is still less than 0.05. The feed cost has the expected direction and is also very small, less than 0.02. Slaughter price has the largest effect and is positive, about 0.2, suggesting that increases in slaughter price increase cow level production. Surprisingly, the lag one coefficient is consistently the opposite direction of the contemporary effect. For this reason, not including them tends to bias the contemporary effect downward.

By breaking out elasticities by production stage, we see another source of downward bias on the elasticities. The top row of Figure 5 shows elasticities averaged across all lactations for each category of days in milk. It is clear that elasticities are not uniform across the lactation, and so every price elasticity is biases downward when averaging across production stage. For current period prices, there is almost no response to milk price, a small response to ration cost, and a relatively strong response to the slaughter price; this response tends to be highest in the middle of the lactation and gradually decreases. For the first lag, the magnitudes for milk and ration are small but the signs are opposite of what is expected; milk price is negative, ration cost is positive and slaughter price is strong and negative. The second order lag coefficients, in contrast, are in the hypothesized direction; milk price is positive in the middle of the lactation and then begins to decline and slaughter price shows the same pattern. The elasticities for milk price are in line with what was previously found: around 0.1. Overall, we reject the null hypothesis that milk supply response is zero within a lactation. However, the pattern of the slaughter price elasticity appears to suggest that both milk price and slaughter price cause investments in milk production.

The bottom two graphs in Figure 5 show the lag two elasticity broken out by cow age. Cows of $\ell = 1$ are on their first lactation, usually at around 2-3 years old, and since calving intervals are usually roughly one year cows at lactation number two are usually around 3-4 years, ect. Our hypothesis was that older cows should have a higher price response due to their higher production and higher marginal response. This is in general supported by the data; cows at later lactations, say four, five and six, have own-price elasticities of about 0.2 as opposed to less than 0.1 for first lactation cows. This pattern appears to be true for cows at $\ell > 2$, but production response is higher for first lactation cows than for cows on their second lactation. This may reflect survival bias, in that many cows do not survive past lactation three; "fresh" cows are heavily invested in, but cows at their second lactation may be likely to exit the herd and are subsequently not invested in. For cows that survive past the second lactation, there may be an even greater incentive to invest in these "survivors" when prices change.

The effect of the slaughter price was theorized to be positive if there was incentive to make cows put on weight by feeding them more and negative if cows are given less feed since they are likely to be sold once the lactation is over. We also theorized that price response would be highest at the end of the lactation because of an incentive to put on weight before slaughter. Neither of these theories appears to describe what is shown in this model, however. Slaughter price instead tends to show the exact pattern that would be expected with the milk price; the response is large in the middle of the lactation and then gradually goes back to zero. This appears to suggest that farmers on average react to increases in the slaughter price, holding all other prices constant, by increasing feed at times when feed response is highest. One ex-post explanation could be that there is loss aversion; when the value of the cow's slaughter goes up, farmers must keep a cow that is mid lactation, since selling in the middle of its lactation is not profitable if it is still making money. Having given opportunity to sell, they may feed more to recoup the lost revenue from having kept the cow. Holding the extensive decision fixed, a model would need to explicitly include a reaction to slaughter price within the lactation in order to test this explanation.

Figure 6 shows elasticities with respect to ratios of prices as opposed to the prices by themselves. It is natural to think that, for example, movements in milk price alone are not as important as movements in milk price relative to ration cost. By the same argument, movements in the slaughter price are alone are not as important as movements relative to the price of a replacement cow. Specifically, we might expect that increases in replacement cost relative to the salvage value of a dairy cow (the slaughter price of a 14 cwt cow) might increase the incentive to invest in milk production as opposed to slaughtering the cow.

On average, these elasticities have a similar pattern but are smaller than the elasticities found in Figure 5: around 0.05-0.10 here as opposed to 0.10-0.30 found previously. We find smaller elasticities for milk over feed cost than for milk price, albeit in this specification there is a current period reaction in addition to a reaction to lag two. Similar to before, fresh cows have a high elasticity which dips at lactation two before increasing again. Reactions to increases in replacement costs show the same significance at lag two, but also show an interesting relationship in the current period; the largest increase in milk production from an increase in replacement cost occurs at the end of a lactation. Inversely, decreases in replacement costs decreases milk production for late lactation cows. This is intuitive, as it suggests that cows that are near the end of their lactation, a typical time to sell a cow, are not as heavily invested in when they are cheaper to replace.

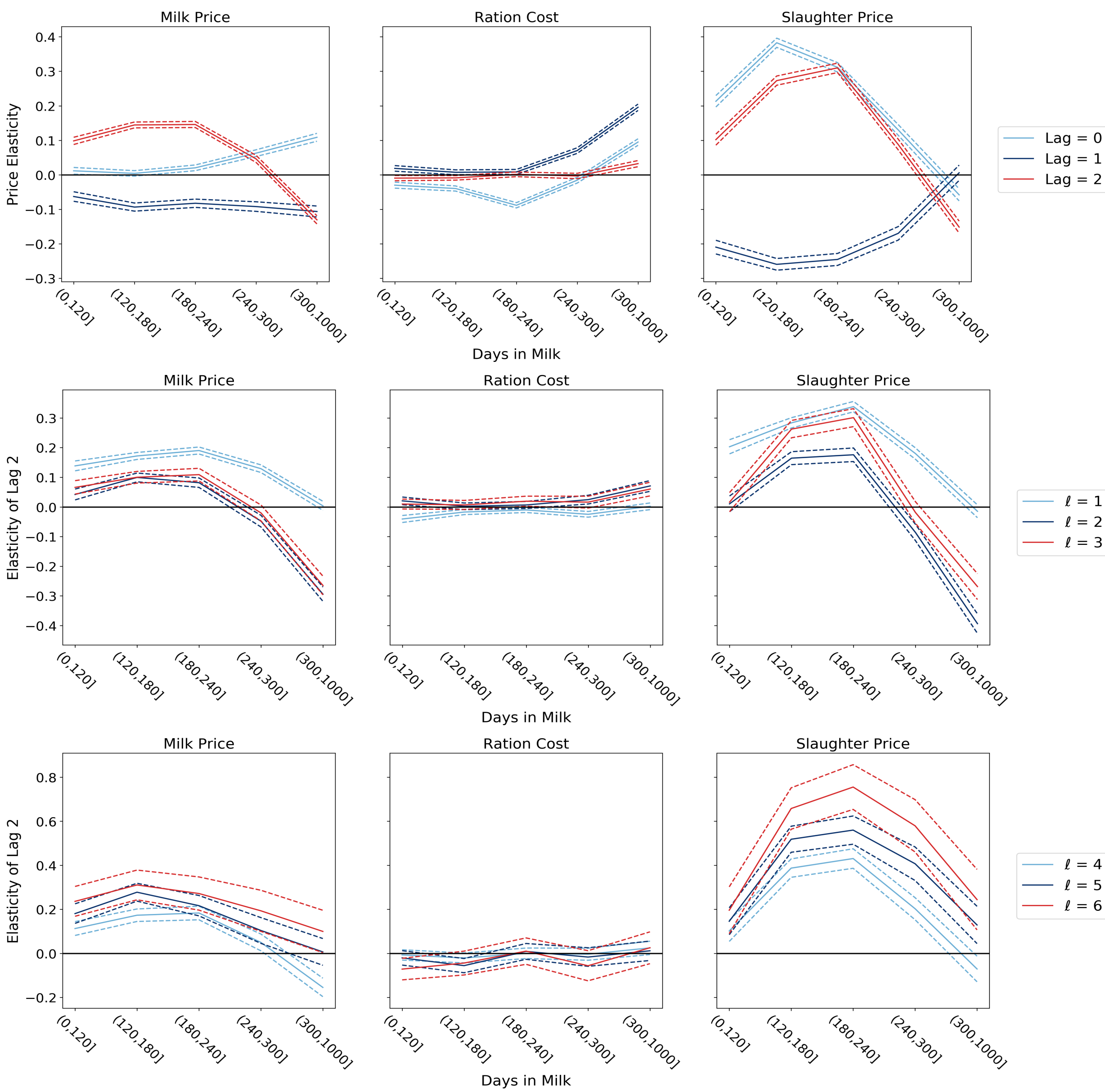


Figure 5: Price Elasticities over DIM and Lactation

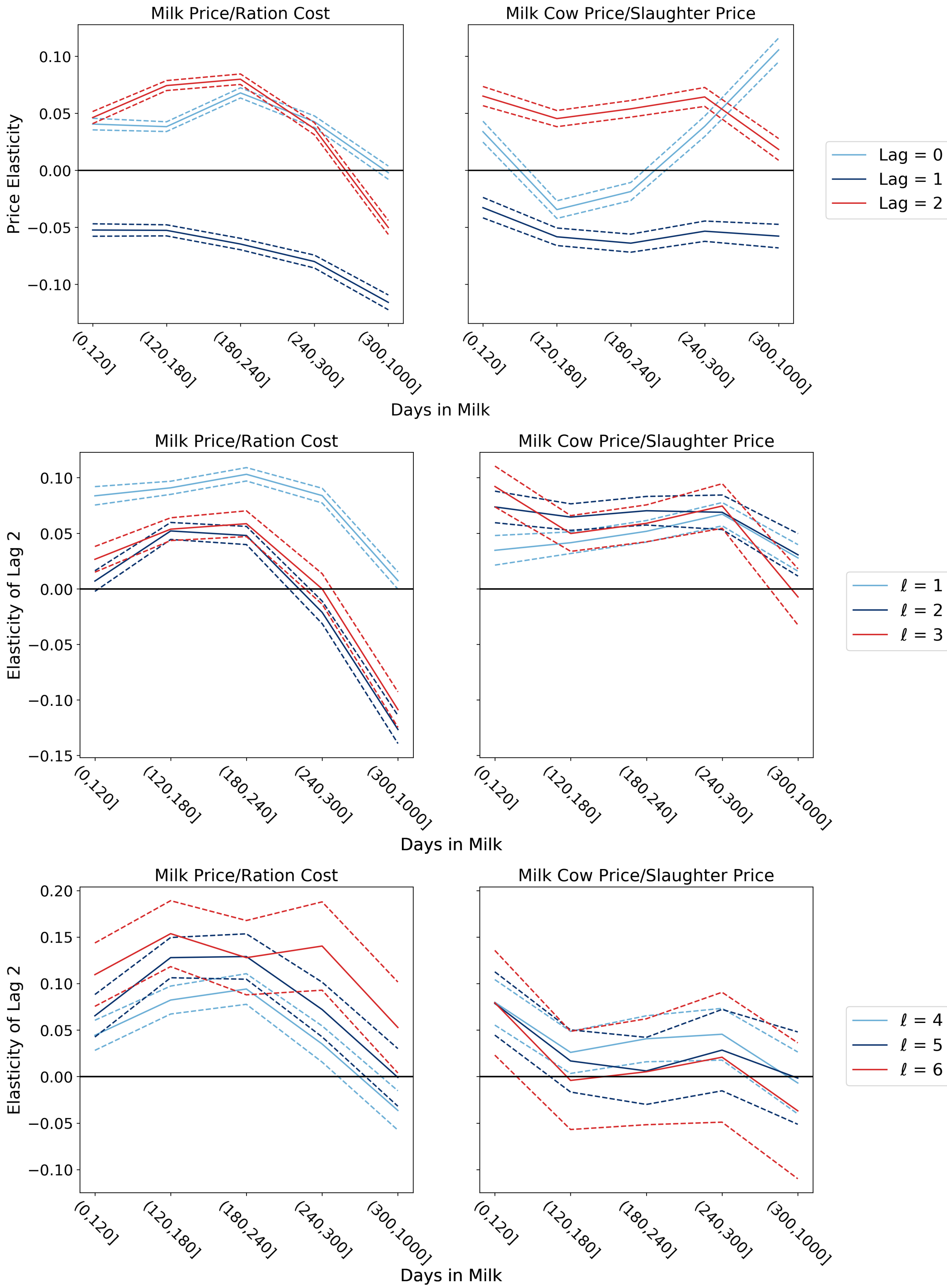


Figure 6: Price Ratio Elasticities

Table 3: AR(2) Regression

	Milk Price	Ration Cost	Slaughter Price	Milk/Ration	Replacement/Slaughter
α_1	0.7722***	0.1143	0.8613***	0.3775***	0.4560***
	(0.1069)	(0.1150)	(0.1115)	(0.1137)	(0.1151)
α_2	-0.3801***	-0.0765	-0.3120***	-0.1848	-0.1113
	(0.1068)	(0.1166)	(0.1112)	(0.1159)	(0.1149)
R^2	0.412	0.014	0.478	0.128	0.178
Sample Size	77	77	77	77	77

Data used June 2010 to September 2016

5.2 Supply Response

Using the AR(2) regression results for each of the prices, we implement a type of impulse response by multiplying the coefficients in a way that gives the supply response taking into account the effect of lagged prices on supply and also the effects of each price on each other. The results of the AR(2) regression are shown in Table 3.

Figure 7 shows the revised supply elasticities. The relationships are more or less the same except for the lag one coefficient for slaughter price 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 4 confirms that for the rations between prices results are similarly unchanged. This confirms that in most of these cases the negative elasticity with respect the lag one price is not because of the effect of the system. Instead, there is actual negative supply response for prices one month out as opposed to the current month or two months out.

6 Discussion and Conclusion

The goal of this analysis was to shed light on intensive supply response on dairy farms, that is animal level changes in milk production in response to prices. Previous analyses of "short-run" supply response have shown herd level milk supply to be sluggish to prices in the short-run, recent estimates being about 0.05-0.10. None of these studies, however, disentangle the mechanism of increased feeding from retention of older cows. Consequently, a commonly held belief is that farmers do not adjust feed rations to increase production in response to prices but rather view the lactation curve as fixed, adjusting herd size instead. Our goal was to test this hypothesis using an expansive dataset of dairy cow milk production where we can hold the extensive decision fixed. To study the importance of this intensive supply response, we integrated prices into an empirical lactation curve based on Wood (1980)

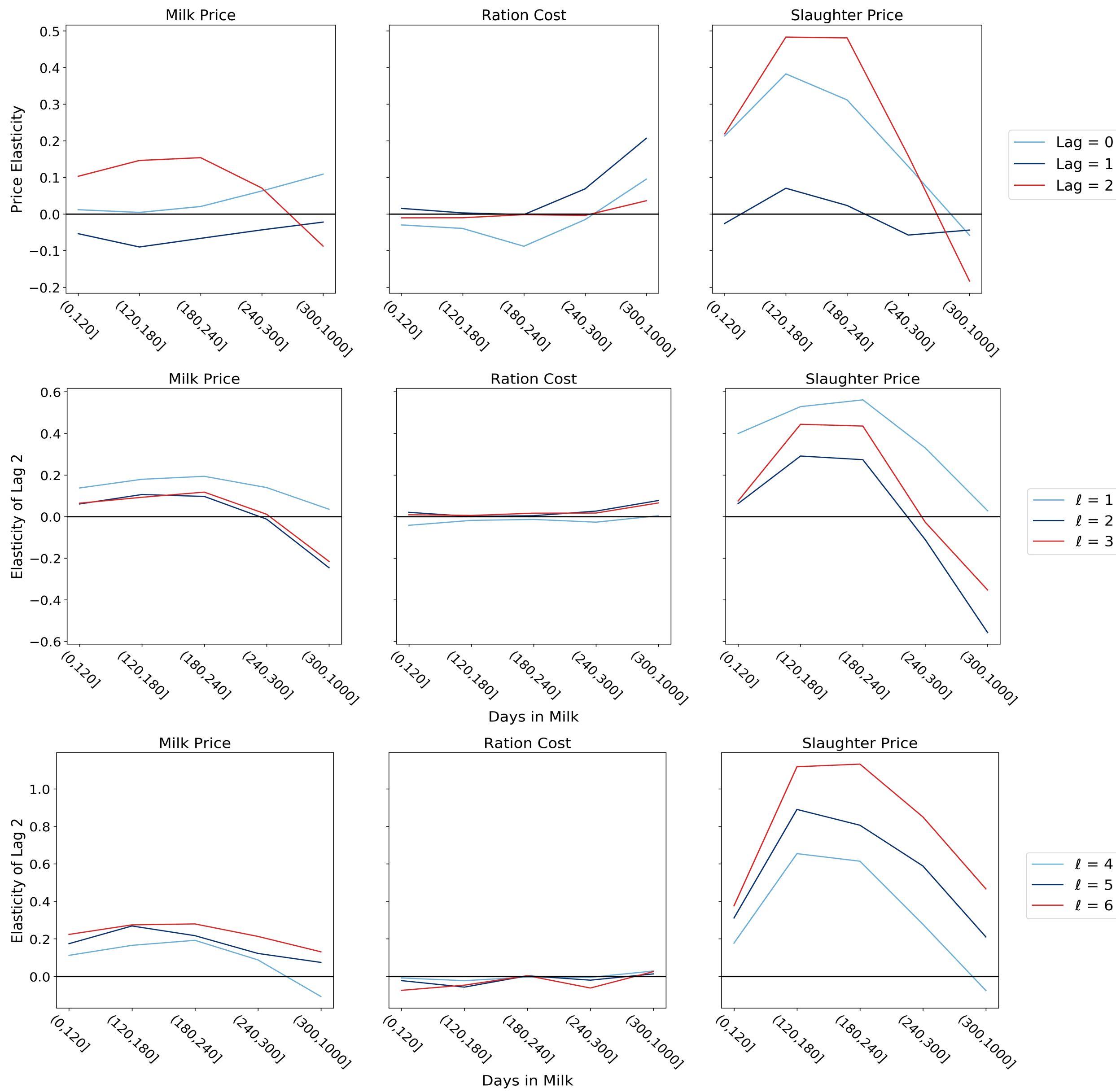


Figure 7: Supply Response over DIM and Lactation

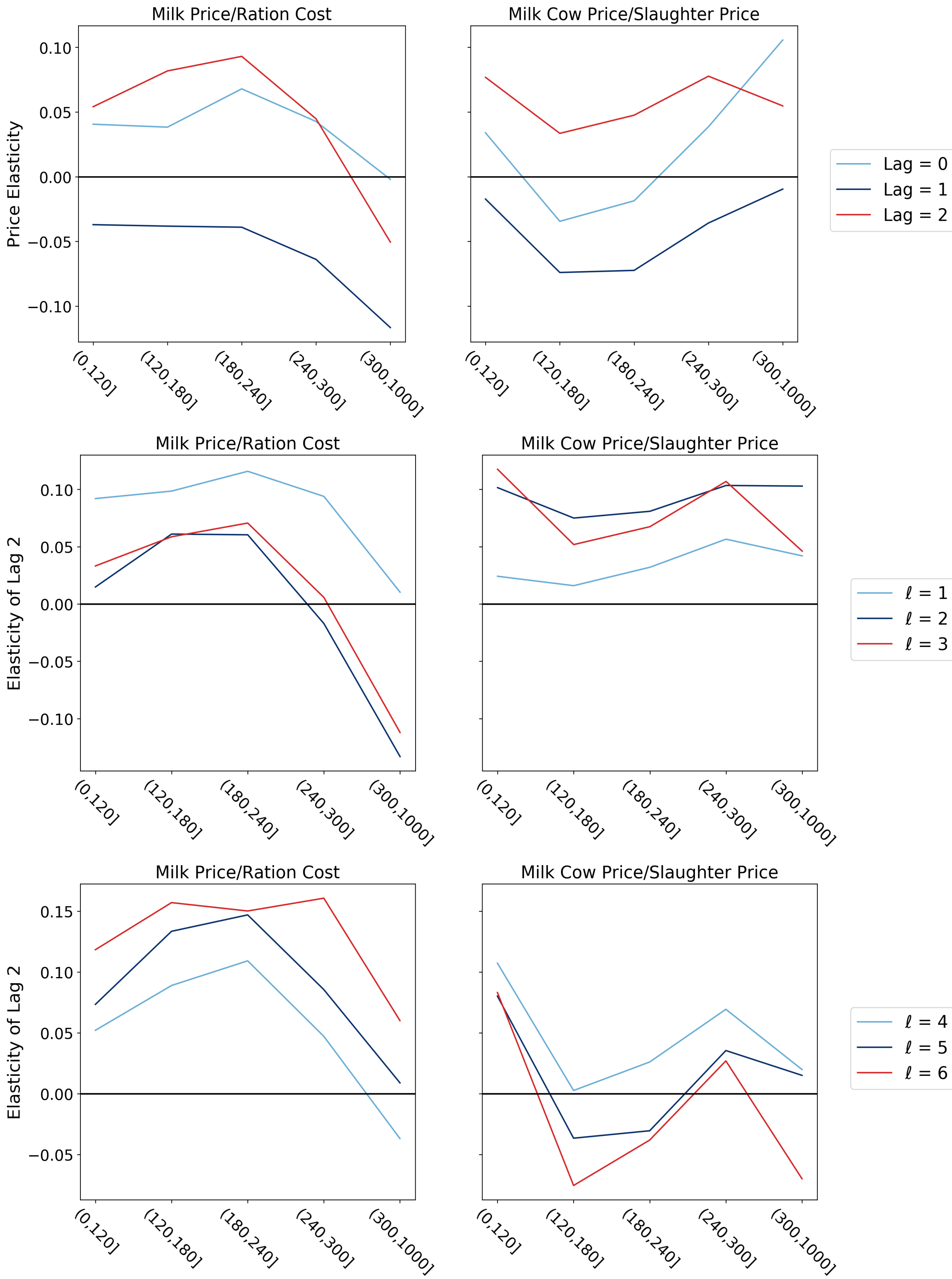


Figure 8: Supply Response of Ratios over DIM and Lactation

and analyzed whether deviations in price explain deviations in the the response.

Using an animal level data set and an empirical model integrating the Wood lactation curve, we reject the hypothesis that farmers do not respond to prices within the lactation; animals that are the most responsive to feed, late lactation and multiparous cows, have the highest supply response to the milk price, albeit milk prices two months previously. Compared to what was found in previous studies, an elasticity of less than 0.1, the response to milk supply can be from 0.1 to 0.3 in the middle of the lactation. This is evidence that previous studies using aggregated data may have underestimated short-run supply response due to confounding factors such as culling patterns. The analysis has also uncovered some interesting aspects of supply response that are beyond the scope of our analysis but are directions for future research.

Changes in milk price or milk over feed price two months prior are significant predictors of cow level output, as are slaughter prices. This is even true when the effect of the lagged price on the whole system is taken into account. In understanding month to month changes in milk production, current period prices are not the only prices that matter. Prices at the two month horizon appear to important to production decisions, either as a signal by themselves or a critical variable in formation of the "expected price." Further research, either qualitative and quantitative, could focus on how the time horizon works in price expectation month to month.

A second aspect of supply response uncovered in this analysis is that slaughter price has a larger effect on cow level supply than milk price, with elasticities in the range of 0.2-0.8 compared to 0.1-0.2 for milk price. This result was robust, surviving in every single specification tried. It appears that the mechanism of this response is in fact increasing feed, as the largest elasticities are in periods of high feed response. This is contrary to our hypothesis, which was that slaughter price response would be in highest at times when cows put on weight, not in times when they convert feed to milk production. In general, our expectations of the slaughter price were ambiguous, since typically the slaughter price in theory has a stronger effect on the culling decision than production decisions. Why and if increases in the slaughter price should encourage farmers to feed their cattle more should be a future subject of research.

Overall, we show that behavioral response to changes in prices do indeed occur at the animal level; farmers do not treat all animals equally in production decisions, appearing to take into account which animals have higher marginal response to inputs. This is typically not assumed in studies of agriculture supply response, however, as most plot or animal level supply response is disregarded either because lack of data or because of a belief that heterogeneity at that level is not an important determinant of supply response. Finally, we have illustrated some of the benefits of animal or asset level data, which is being able to observe asset level decision making of firms. Not only does this open up new avenues of research concerning asset management behavior, but also new ways to advise farm managers on supply management.

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