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Abstract

We examine the economies of scope that derive from manure use as fertilizer for crops and their effects on marginal cost of milk production. We compare results for firms that use all manure on farm (non-exporters) and firms that send manure off farm (exporters). We find non-exporters to be smaller dairies compared to exporters, that non exporters face higher marginal cost, and that returns to scale drive marginal cost differences. If nutrient recovery technology adoption were to cause a shift towards the production characteristics of manure exporters, marginal cost could decrease as much as 16.4 percent and lead to an estimated increase in milk demand of 0.64 percent.

Keywords: dairy production, manure management, nutrient recovery technology

JEL Classification: D24, Q12, Q16

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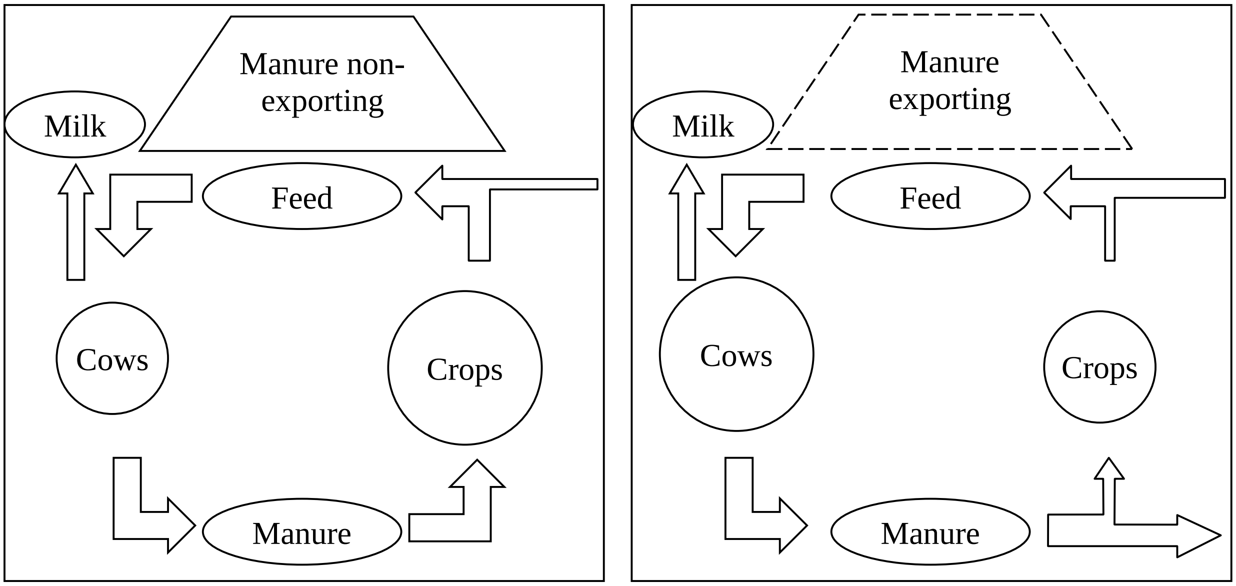
Introduction

Concentrated animal feeding operations (CAFOs) have become increasingly common due to production economies of scale, but they increasingly face environmental regulation due to the issues surrounding concentrated volumes of animal waste. The US Environmental Protection Agency (EPA 2014) reports that agricultural nutrients are the second and third largest causes of impairment of bodies of water and waterways, respectively. Much of the concern regarding water pollution comes from the manner and volume of manure application. Dairy waste has a high moisture content which makes transportation away from the CAFO very costly and leads to concerns about nutrient loading near the operation. Emerging nutrient recovery technologies have the potential to mitigate pollution from dairy waste, but they will also alter the production characteristics of firms who adopt them.

Milk output is accompanied by joint production of manure which firms can either export or use as an input for pasture or crop production. Of dairies surveyed in the 2010 Agricultural Resource Management Survey (ARMS), 88 percent apply all of the manure they produce ("non-exporters") to their own land as an input to crop production. These dairies grow four times as much of the feed they use compared to dairies that remove a portion of manure ("exporters"). Also, non-exporters have 1/6th as many milk cows on average compared to exporters. Gillespie *et al.* (2010) find that larger US dairies tend to purchase more feed than they grow, moving away from vertical integration of feed and milk production. Skolrud *et al.* (2009) conclude that, for Washington state dairies, economies of scale drive firm growth and that specialization in output increases as firm size increases. Other literature documents that increasing returns to scale have led to a trend in the dairy industry towards large firms (Melhim, O'Donoghue, and Shumway 2009; Mosheim and Lovell 2009; Skolrud *et al.* 2007). We present the contrasting characteristics of manure non-exporters and exporters in Figure 1.

Figure 1. Production characteristics of manure non-exporters vs. manure exporters.



Removing manure from dairies is costly due to high moisture content (or weight relative to nutrient content). Estimates of economically viable transport distances based on the nutrient content of manure range from 3 to 40 kilometers and depend on price and agronomic conditions (Paudel *et al.* 2009; Sanford, Posner, and Hadley 2009; Adhikari *et al.* 2005). Given the high cost of transporting manure, the trend towards larger dairies has increased water pollution concerns surrounding dairies from over-application of manure to nearby fields (Innes 2000). Following the Federal Clean Water Act in 1972, dairies have faced environmental regulation due to their potential for polluting water resources with excess nitrogen and phosphorus. Some states have imposed stronger environmental regulations. There is some evidence that dairies migrate from more strictly environmentally regulated states to less strictly regulated states (Isik 2004). While EPA regulations have established a minimum set of environmental requirements for

CAFOs, there is large variation in the stringency of additional policies that states impose (Hendrick and Farquhar 2008).

One approach to nutrient management issues on CAFOs has been to develop and adopt technologies that facilitate the separation of nutrients from water and manure. These technologies have been considered complementary to anaerobic digestion (Coppedge *et al.* 2012) which has been adopted by six percent of US dairies with at least 500 cows (U.S. Department of Agriculture, 2012; AgSTAR, 2015). Nutrient recovery technology encompasses a variety of mechanical and chemical mechanisms to remove fiber, nitrogen, phosphorous, and dissolved salts from animal waste (Chiumenti *et al.* 2013; Ma *et al.* 2013; Sindhöj and Rodhe 2013). These technologies have the potential to alter the joint production framework (milk, manure, and feed) on the dairy.

Dairies decide whether to export manure based on environmental regulations, the cost of exporting manure, and the cost of purchasing feed. In the context of new technologies that partition nutrients into more easily exportable forms, we consider the possibility that the production choices of firms that adopt nutrient recovery technology could resemble the production choices of firms that are currently exporting manure in its present form.

We examine the effects of manure usage on dairies by estimating the marginal cost and input demand equations controlling for manure exporters, organic producers, and methane capture. We estimate the impact of that change on the competitive price of milk and quantity demanded. We find that dairies which do not export manure face higher marginal costs than manure-exporting dairies. We predict that if more dairies adopt nutrient recovery technologies, it will lead to lower milk prices and increased quantity demanded by consumers.

Theory

We develop a multi-input, multi-output, joint production model using a normalized quadratic functional form for the restricted profit function:

$$\begin{aligned} \Pi = {} & A + P'B + Z'C + P'DZ + \frac{1}{2}P'EP + \frac{1}{2}Z'FZ \\ & + \left(G + P'H + Z'J + P'KZ + \tfrac{1}{2}P'LP + \tfrac{1}{2}Z'MZ\right) I_{Exp} \\ & + \left(N + P'O + ZQ + P'RZ + \frac{1}{2}P'SP + \frac{1}{2}Z'TZ\right) I_{O,M} \end{aligned} \tag{1}$$

where Π is variable profit normalized using the price of the numeraire good, P is the vector of n normalized netput prices, Z is the vector of m fixed netput quantities (which in our case includes a subset of both outputs and inputs), I_{Exp} is the manure exporter indicator variable which is one if the firm exports manure and zero otherwise, and $I_{O,M}$ is the vector of two indicator variables for dairies that produce organic milk and those that capture methane. Parameter vectors have dimensions 1x1 for A and G, 1x2 for N, nx1 for B and H, nx2 for O, mx1 for C and J, mx2 for Q, nxm for D and K, nx2m for R, nxn for E and L, nx2n for S, mxm for F and M, and mx2m for T. The normalized quadratic profit function maintains linear homogeneity of the restricted profit function in netput prices.

Using Hotelling's Lemma, we take the first derivative of the restricted profit function with respect to netput prices to derive netput supply equations:

$$\nabla_{\mathrm{P}}\Pi = X = B + DZ + EP + (H + KZ + LP)I_{Exp} + (O + RZ + SP)I_{O,M} \tag{2}$$

where X is the vector of netput quantities ($x_i > 0$ corresponds to an output and $x_i < 0$ corresponds to an input). From the estimated restricted profit function, we can derive the cost function from the definition of profit being the difference between revenue, $R = WZ$ (where W is the vector of shadow prices of fixed netputs), and cost, C:

(3) $$\Pi(P,Z) = R - C(P,Z)$$

(4) $$C(P,Z) = R - \Pi(P,Z).$$

Treating *R* as a constant, we derive the marginal cost of milk by taking the derivative of *C* with respect to milk output quantity:

(5) $$\frac{\partial C}{\partial z_1} = -\big(c_1 + P'D_1 + F_1Z + (j_1 + P'K_1 + M_1Z)I_{Exp} + (q_1 + P'R_1 + T_1Z)I_{O,M}\big)$$

where D_1, F_1, K_1, M_1, R_1, and T_1 are the coefficient vectors pertaining to milk output quantity. In competitive equilibrium, marginal cost of milk is equal to the price of milk, so milk price is used as the dependent variable in estimation.

We estimate equations (2) and (5) as a system of four equations using iterative seemingly unrelated regression in Stata 14. We normalize all prices by the cow and crop output price index. We estimate three input demand equations from equation (2) with quantity of land, labor, and an index of feed, fertilizer, and energy as dependent variables, respectively. The regressors, identical for each input demand equation, are price of land, price of labor, price index of feed, fertilizer, and energy inputs, quantity of milk output, and quantity index of machinery and building inputs. We assume a competitive market and estimate the marginal cost equation (5) by substituting milk price for marginal cost as the dependent variable. The regressors are the same as those in the input demand equations.

In the results section, we compare the marginal cost of milk production for manure non-exporters and exporters and discuss the implications of having more firms become manure exporters. We expect milk quantity terms in the *D* matrix to be negative because increased output requires increased input. We expect own price terms in the *E* matrix will be positive in accordance with the law of demand. We expect manure exporters to have higher marginal cost than manure non-exporters because manure is costly to transport.

Methods and Data

With few exceptions, all data comes from the 2010 ARMS, Phase III Dairy survey.[1]

We construct the numeraire (cow and crop) price index by dividing the sum of cow and crop revenues by the quantity index, described below. Quantity of animals sold and revenue is reported for cull cows, all milk cows including dry cows, heifers for herd replacement, cull bulls, breeding bulls, and other dairy calves, which we weight by revenue share and sum to get total quantity of "cows" sold and total revenue from animal sales. We sum crop acres harvested for all 24 reported categories to obtain crop quantity.[2] We calculate total crop revenue as the sum of all crops sold under production contracts, marketing contracts, and in cash or open market sales. We sum cow and crop revenues to get total cow and crop revenue and construct an arithmetic cow and crop quantity index weighted by revenue shares.[3]

The independent variables for each estimation equation are price of land, price of labor, price index of feed, fertilizer, and energy inputs, quantity of milk output, and quantity index of machinery and building inputs. The dependent variables are the quantity of land, quantity of labor, quantity index of feed, fertilizer, and energy inputs, and the price of milk.

For the price of land, we use land rental price calculated by dividing reported expenditure on rented land by reported acres of rented land. The quantity of land is reported by dairies as a single value.

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[1] Weber and Clay find dairies are the most likely to reply to ARMS requests, and that nonresponse bias does not undermine the conclusions of econometric models (2013).

[2] We are unable to weight crop category quantities in the index by revenue share because revenue is not reported for all 24 individual categories.

[3] We use arithmetic rather than geometric indices because some firms have zero netput quantities in some categories.

We use reported hourly paid wages and convert reported daily wages paid to obtain hourly wage using an 8-hour workday. We use this wage rate as the price of labor for both paid and unpaid labor. The quantity of labor is measured in hours per year and is calculated by summing reported quarterly average hours worked per week for paid and unpaid labor.

We calculate a feed-fertilizer-energy price index by dividing the sum of reported total expenditures on these inputs by the quantity index, described below. Quantity of feed is calculated as an arithmetic index of thirty feed items, converted to tons, purchased and grown.[4] Fertilizer quantity is calculated by dividing reported expenditure on fertilizer by 2008 state fertilizer prices (Ball 2014) adjusted to 2010 dollars using ratio of 2010 to 2008 national fertilizer prices (Ball *et al.* 2015). Similarly, energy quantity is calculated by dividing reported expenditure on energy by 2008 state energy prices (Ball 2014) adjusted to 2010 dollars using the ratio of 2010 to 2008 national energy prices (Ball *et al.* 2015). We combine feed, fertilizer, and energy quantities into a single arithmetic index using expenditure shares as weights.

Assuming fixity of the primary output in the short term, we treat milk quantity as an exogenous variable and use reported milk sold as the measure of milk quantity.[5] Milk price is constructed by dividing the sum of milk receipts reported from production contracts, marketing contracts, and cash or open market sales by reported milk sold.

Machinery and building inputs are also treated as fixed in the short term. Expenditures on machinery and buildings are used as proxies for missing quantity data and aggregated into an geometric index weighted by present value shares. We sum firms' reported estimated market value of owned trucks, cars, tractors, tools, equipment, and machinery. We convert the present

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[4] We are unable to weight feed categories by expenditure shares because we lack expenditure data on grown feed.

[5] The number of cows producing milk on the dairy are dependent on the buildings and machinery supporting them, which are regarded as fixed in the short run. Since milk output is directly related to the number of cows, there is some logic for treating milk as fixed in the short run as well.

value to an annual expenditure using a 10-year average lifetime (Wang *et al.* 2015) and four percent discount rate (Yang and Shumway 2015).[6] Similarly, we convert firms' reported estimated market value of buildings owned and rented to a yearly expenditure using a 35-year average lifetime (Wang *et al.* 2015) and four percent discount rate. We combine machinery and buildings into a single quantity index by multiplying annual expenditures exponentially weighted by present value shares.

Due to the nature of survey respondent reporting in ARMS, it is not uncommon for studies which use ARMS to remove up to a quarter of the sample due to missing or incoherent data (Skolrud 2015, Key and Sneeringer 2014). We remove 267 (nearly 14%) of the 1,915 observations due to unreasonable values likely due to data entry reporting error. We plot dependent and independent variables against number of milk cows and omit outliers that are distinctly beyond the 99th percentile and well beyond other closest observations. For most variables, it results in less than half of a percent of data points omitted. Across variables, problematic data points often belong to the same observation.

The one exception is for the feed price index and the feed quantity index per cow, for which we use the 94th and 96th percentiles, respectively. Both variables have values that are extremely skewed toward the right. For example, the 90th percentile of the feed price index is 180 times as large as the 5th percentile, and the 95th percentile is 270 times as large as the 90th percentile. Similarly, for the feed quantity index per cow the 90th percentile is 120 times as large as the 5th percentile, and the 95th percentile is 30 times as large as the 90th percentile. The

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[6] The discount rate is calculated by dividing Moody's Baa corporate bond yield by all maturities less the rate of inflation given by the CPI over the period 1919-2011.

standard deviation of each distribution is 30 and 6 times as large as the mean, respectively. Removing outliers reduces those ratios to 1.2 and 1.6, respectively.

We impute prices for crops, labor, and land for unreported firms which remain in the sample using state means for reported firms. Nearly 66 percent of dairies report zero revenues from crop sales, nearly 42 percent report a zero hourly wage rate, another 15 percent report wages per week or month which produce unreasonable hourly wage rates, and 31 percent report zero expenditure on land.

After normalizing the three independent price variables and milk price by the cow and crop price index, we scale independent price variables to have similar orders of magnitude at the mean. We multiply normalized land price by a factor of 186, normalized labor price by 136, and normalized feed, fertilizer, and energy index price by 55. We divide their quantities by the same factors.

Summary statistics are presented in Table 1 for the entire sample and distinguished by manure exporter status. The average farm in the sample has 267 milk cows, sells 52,000 cwt of milk per year, and harvests 322 acres of crops per year. Manure non-exporters are typically smaller with an average of 179 milk cows and selling on average 33,000 cwt of milk per year. Exporters are typically much larger with an average of 994 milk cows and selling on average just under 201,000 cwt of milk per year. However, manure non-exporters grow more acres of crops on average – 324 acres harvested compared to 297 acres harvested for exporters. Of the 1,684 dairies in our sample, 1,474 do not export any manure while the remaining 174 export at least one percent of their manure. Manure exporters tend to apply manure to more acres on their operations – 187 acres on average compared to 162 acres for non-exporters. In the sample, 513 firms produce organic milk, and 15 capture methane.

Table 1. Summary statistics.

Name	Variable	Sample (n=1,648)		Non-exporters (n=1,474)		Exporters (n=174)	
		Mean	S.D.	Mean	S.D.	Mean	S.D
Milk cows	-	267	778	179	544	994	1628
Crops acres	-	322	498	324	485	297	587
Own acres, manure applied	-	166	255	162	235	187	376
Cow and crop price index[a]	P_0	674	502	651	489	870	548
Land quantity[b]	Q_1	-2.54	3.41	-2.57	3.37	-2.21	3.68
Land price[c]	P_1	0.027	0.130	0.030	0.136	0.009	0.030
Labor quantity[b]	Q_2	-81	193	-64	150	-225	379
Labor price[c]	P_2	3.77	5.93	3.93	6.19	2.47	2.57
Feed, fertilizer, energy quantity index[b]	Q_3	-209	608	-176	577	-455	674
Feed, fertilizer, energy price index[c]	P_3	5.48	12.01	5.34	12.33	6.71	9.03
Milk quantity (millions of lbs.)	Z_1	5.20	16.79	3.30	12.05	20.97	33.79
Milk price[d]	$\partial C/\partial Z_1$	0.055	0.092	0.058	0.095	0.031	0.039
Machinery and buildings quantity index ($ thousands)	Z_2	-62	119	-53	92	-140	242

[a] Numeraire good.
[b] Scaled inversely to respective price. Negative because it is a netput (negative input) quantity.
[c] Normalized by numeraire good and scaled.
[d] Normalized by numeraire good. Used as an estimate of marginal cost in competitive equilibrium.

As shown in Table 2, of dairies who export their manure, on average 19.9 percent of manure is sold at an average price of $437 per cow, 11 percent of manure is taken for a fee at an average price of $447 per cow, and 69.2 percent of manure is given away. Thus, there is a wide range of prices for manure removal from negative to positive prices, with a majority of exporting firms facing a zero price.

Table 2. Manure exporter characteristics.

Variable	Mean	S.D.
Manure exported (percentage)	53.9	37.4
Sold (percentage)	19.9	38.8
Paid to take (percentage)	11.0	30.0
Exported manure provided free (percentage)	69.2	44.9
Income if sold (thousand $)	4.7	17.5
Income per cow ($)	437	1529
Expense if paid (thousands $)	2.9	14.4
Expense per cow ($)	447	1429

[a] Values are relative to "percent of manure exported". If 50 percent of manure is exported and 50 percent of exported manure is sold, then 25 percent of manure from the dairy is sold.

Dairies' reported monitoring of nutrients are reported in Table 3. Of the sample, 55 percent of firms have no nutrient management plan, while 7 percent have a nitrogen focused plan, 7 percent have a phosphorous focused plan, 26 percent have a nitrogen and phosphorus focused plan, and 5 percent have a plan focused on other issues. Only 39 percent of manure

Table 3. Manure exporting and nutrient plan descriptive statistics.

Nutrient Plan	Sample	Non-exporter	Exporter
Observations	1648	1474	174
No plan	55%	57%	39%
Nitrogen based plan	7%	6%	10%
Phosphorus based plan	7%	6%	10%
Nitrogen and phosphorus based plan	26%	25%	35%
Other plan	5%	5%	6%

exporters have no nutrient management plan compared to 57 percent of non-exporters. Thus, manure exporters are more likely to actively monitoring and managing the environmental impact of their waste management.

Results

We present parameter estimates for the entire sample and separated by non-exporters and exporters in Table 4. Estimates for each model maintain implications from linear homogeneity of the restricted profit function as well as cross-equation restrictions for shared parameters.

Table 4. ITSUR parameter estimates for dairy producers by exporter category.

Base[a] Parameters		Exporter Increment		Organic Increment		Methane Increment	
B1	-1.817** (0.121)	H1	0.885* (0.364)	O11	0.653** (0.195)	O12	3.552 (2.258)
B2	-61.51** (6.695)	H2	-17.71 (20.05)	O21	6.338 (10.77)	O22	57.26 (125.1)
B3	-105.2** (20.93)	H3	-133.8* (57.88)	O31	19.81 (34.69)	O32	444.6 (414.0)
C1	-0.0305**	J1	0.0128	Q11	-0.0216**	Q12	-0.0104

	(0.00271)		(0.00694)		(0.00440)		(0.0282)
D11	-6.03e-6**	K11	1.07e-6	R111	5.05e-6*	R112	1.54e-7
	(8.37e-8)		(1.21e-6)		(2.28e-6)		(4.31e-6)
D12	1.32e-5**	K12	-1.14e-5**	R121	9.29e-6**	R122	5.04e-6
	(1.24e-7)		(1.76e-6)		(2.34e-6)		(9.70e-6)
D21	-6.41e-4**	K21	-8.07e-5	R211	-0.00123**	R212	-4.57e-4
	(4.65e-5)		(6.71e-5)		(1.24e-4)		(2.39e-4)
D22	-1.28e-4	K22	1.50e-4	R221	-6.17e-4**	R222	4.22e-4
	(6.87e-5)		(9.73e-5)		(1.29e-4)		(5.37e-4)
D31	-0.00234**	K31	8.41e-4**	R311	-0.00189**	R312	0.00166*
	(1.19e-4)		(1.93e-4)		(2.30e-4)		(7.76e-4)
D32	6.94e-4**	K32	-7.30e-4*	R321	-0.00113**	R322	0.00134
	(2.04e-4)		(3.01e-4)		(3.43e-4)		(0.00178)
E11	-4.117**	L11	-16.87	S111	5.05e-6*	S112	1.54e-7
	(1.365)		(8.845)		(2.28e-6)		(4.31e-6)
E12	0.0152	L12	-0.0438	S121	-0.00574	S122	-0.978
	(0.0226)		(0.104)		(0.0340)		(0.506)
E13	0.00935	L13	0.0250	S131	-0.00367	S132	-0.0150
	(0.00989)		(0.0269)		(0.0154)		(0.221)
E21	0.0152	L21	-0.0438	S211	-0.00123**	S212	-4.57e-4
	(0.0226)		(0.104)		(1.24e-4)		(2.39e-4)
E22	3.355**	L22	3.265	S221	-1.104	S222	-10.28
	(1.134)		(4.919)		(1.807)		(28.00)
E23	-0.925	L23	1.555	S231	0.142	S232	6.138
	(0.543)		(1.470)		(0.848)		(12.27)
E31	0.00935	L31	0.0250	S311	-0.00189**	S312	0.00166*
	(0.00989)		(0.0269)		(2.30e-4)		(7.76e-4)
E32	-0.925	L32	1.555	S321	10.84*	S322	-136.9
	(0.543)		(1.470)		(4.722)		(92.46)
E33	5.030**	L33	6.360	S331	-6.492*	S332	-40.23
	(1.380)		(4.613)		(2.570)		(40.32)
F11	2.62e-8	M11	-9.45e-9	T111	-1.84e-8	T112	-9.47e-9
	(2.09e-8)		(3.00e-8)		(5.75e-8)		(9.54e-8)
F12	2.68e-8	M12	-1.76e-8	T121	-4.46e-8	T122	-1.14e-7
	(3.07e-8)		(4.34e-8)		(5.84e-8)		(2.26e-7)

[a] The base case is a non-exporting, non-organic, non-methane capturing dairy.
Note: Level of significance: ** $p<0.01$, * $p<0.05$
Codes: Parameters refer to the elements of the matrices in equation (1). For example, B_i is the *i*th entry of matrix *B*, *i*=1,2,3, where 1 is land price, 2 is labor price, and 3 is the feed- fertilizer-energy price index; *i* has the same meaning for all matrices except *F*, *M*, and *T*; in matrix *C*, *j*=1, where 1 is milk quantity, in matrix *D*, *j*=1,2, where 1 is milk quantity and 2 is the machinery-building quantity index; in matrix *E*, *j*=1,2,3 where 1 is land price, 2 is labor pirce, and 3 is the feed-fertilizer-energy price index; in matrix *F*, *i*,*j*= 1,2, where 1 is milk quantity and 2 is the machinery-building quantity index; in matrices *H*, *J*, *K*, *L*, and *M* which are interacted with the exporter indicator

variable, subscripts have the same meanings as in matrices *B*, *C*, *D*, *E*, and *F*, respectively; in matrices *O*, *Q*, *R*, *S*, and *T* which are interacted with the organic indicator variable and with the methane capture indicator variable, subscripts i,j have the same meanings as in matrices *B*, *C*, *D*, *E*, and *F*, respectively, and subscript k=1,2, where 1 is organic dairy and 2 is methane capture.

The parameter estimates of the model with the entire sample are qualitatively nearly identical to estimates from a model that does not maintain cross-equation shared parameter restrictions. Although 18 parameters change signs, only one of them is statistically significant at the 5 percent level.

However, the data do not support all cross-equation restrictions. For example, in tests of equivalency between parameters in the marginal cost equation and the input demand equations, we reject the null hypothesis that parameters are equal for the interaction terms between milk quantity and land price, milk quantity and labor price, and milk quantity and the feed-fertilizer-energy price index, with Wald test statistics of 84, 3,168, and 88, respectively. In tests for symmetry of shared parameters between input demand equations, we reject the null hypothesis for the labor price and feed-fertilizer-energy price index interaction term with a Wald test statistic value of 18. We fail to reject the null for the land price and labor price interaction term and for the and land price and feed-fertilizer-energy price index interaction term, with Wald test statistics values of 0.23 and 0.16, respectively. Because the cross-equation restrictions are implied by the twice differentiable second-order Taylor series approximation used in the formulation of the normalized quadratic profit function, they are maintained throughout our analysis for internal consistency.[7]

We perform Wald tests on the inclusion of indicator variables for exporters, organic, and methane capture, for each equation. For exporters and organic terms, we reject the null at the 1

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[7] Convexity of the profit function is also a theoretical implication, but our efforts to impose convexity conditions using non-linear SUR failed to converge.

percent level that indicator interaction terms are zero in all estimation equations, with Chi-square test statistics of 16 and 186, respectively. Thus, both sets of interaction terms are important to include in the model. For methane capture, we obtain a Chi-square test statistic of 6 and fail to reject the null at the 5 percent level. However, we only had 15 observations that reported using methane capture, so it could be the result of too small a sample size.

In the land netput supply (negative of input demand) equation, the own price parameter, E_{11}, is negative and statistically significant, which violates theoretical expectations for the own-price coefficient. However, if an increase in land rental price leads to an increase in land owned, we can interpret the effect as a form of investment, with dairies renting out land they own to other farmers at a higher price. In such a case, it would represent a substitution effect.

In the labor netput supply equation, the own price parameter, E_{22}, is positive and consistent with economic theory in all models. It is statistically significant for the manure exporter model at the 1 percent level. The cross price terms are not statistically significant at the 5 percent level. In the feed, fertilizer, and energy netput supply equation, the own price parameter for the index is positive and statistically significant at the 1 percent level as expected for all models.

From the marginal cost equation, all interaction parameters between milk quantity and input prices (D_{11}, D_{21}, and D_{31}) are statistically significant at the 1 percent level. They are all negative as expected and indicate that an increase in input price increases marginal cost.[8] The own quantity parameter on milk (F_{11}) is not statistically significant at the 5 percent level indicating that firms do not exhibit significantly increasing or decreasing returns to scale.

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[8] Recall that marginal cost increases in the variable if the estimated parameter is negative.

Comparing exporters to non-exporters, the land price and machinery-buildings quantity index interaction term, K_{12}, is significantly negative indicating that manure exporters face only 14 percent of the increase in marginal cost as non-exporters when land price increases.

The feed-fertilizer-energy price index and milk quantity interaction term, K_{31}, indicates that exporters face only two-thirds the increase in cost as non-exporters when the feed-fertilizer-energy price index increases. This result is particularly interesting because exporters typically purchase proportionally more feed than non-exporters. However, because feed price is measured as part of the index with fertilizer and energy, it appears that the impacts of fertilizer and energy price increases outweigh the impacts of increases in feed price. This could be related to the trend Gillespie *et al.* (2010) describe away from vertical integration of feed production among large dairies. If a dairy is growing most of its own feed, it makes sense to fertilize the crop with its own manure. However, if the dairy is purchasing most of its feed, it makes sense to sell the manure to the farm growing the crops.

Thirteen of the twenty-one organic interaction terms are statistically significant at least at the 5 percent level. Compared to non-organic milk producers, organic milk production leads to smaller increases in marginal cost when land price increases (R111 is positive and smaller in absolute value than D11), and larger increases in marginal cost when labor or feed-fertilizer-energy price index increase (R211 and R311 are negative). Thus, organic producers are relatively more susceptible to changes in the prices of labor and feed-fertilizer-energy than non-organic producers.

Only two methane interaction terms are statistically significant at the 5 percent level both of which include feed-fertilizer-energy price index, R312 and S312. Compared to producers who do not capture methane, the positive value of R312 indicates that methane capture leads to smaller increases in marginal cost when the feed-fertilizer-energy price index increases. This may be related to the use of captured methane as a substitute for purchased energy as a source of heat and electricity. The benefits of methane capture in reducing the sensitivity of marginal cost to energy input price increases help make combined methane capture and nutrient recovery systems appear more favorable.

Using the terms in the marginal cost equation, we calculate elasticities of marginal cost for both base and manure exporting producers at sample means and report them in Table 5. Note that the signs of the effects are flipped from the estimation results in Table 4 due to the negative sign in equation (5). The variable with the biggest statistically significant economic impact on marginal cost for base producers is the feed-fertilizer-energy price index, P_3, followed by labor price, P_2, and land price, $P_{1.}$ Milk quantity, Z_1, and machinery-building quantity index, Z_2, do not have a statistically significant impact on marginal cost. Only the feed-fertilizer-energy price index, P_3, has a significantly different elasticity on manure exporting producers. Although significant, its impact is only slightly lower for the manure exporters. Interpreting the elasticities, if the feed-fertilizer-energy price index were to increase by ten percent, marginal cost would increase by 2.3 percent compared to less than one ten-thousandth of a percent for a ten percent increase in land price. As expected, all increases in input prices lead to increases in marginal cost.

We now use the estimated difference in marginal cost between the two groups to simulate the impact of broader manure exportation, as might occur if integrated anaerobic digestion and nutrient recovery systems were widely adopted. At the data means, non-organic and non-

Table 5. Marginal cost elasticities.

Variable	Base Producer Elasticity	Change in Elasticity for Exporters
P_1	3.01e-6**	-1.9e-8
	(4.29e-7)	(2.14e-8)
P_2	0.044**	3.81e-4
	(0.003)	(3.17e-4)
P_3	0.234**	-0.011**
	(0.014)	(2.5e-3)
Z_1	-0.025	3.89e-3
	(0.020)	(0.012)
Z_2	0.031	-0.005
	(0.035)	(0.012)

Notes: Level of significance: ** $p<0.01$, * $p<0.05$.
All elasticities calculated at sample means.

methane capture firms face a normalized marginal cost of 0.043, while the subset of manure exporters face a 0.027 (with standard error of 0.002) marginal cost and the subset of manure non-exporters face a 0.047 (with standard error of 0.002) marginal cost. Performing a t-test, we reject the null that the means for the two groups are equal at the 1 percent level with a test statistic of 3.8.

Considering the price elasticity of milk, we predict likely outcomes on market price and quantity if dairies were to move from manure non-exporting operations to manure exporting operations. In a perfectly competitive market, market price for milk equals the marginal cost of production. Consumer demand at that price is determined by consumer preferences for milk, preferences for other goods, and budget constraints. Consistent with previous research, Cakir and Balagtas (2012) estimate regional retail elasticities of fluid milk to be highly inelastic. They also demonstrate that derived demand for milk from processors/retailers is even more inelastic than retail demand. We use Schmit and Kaiser's (2004) estimate of the derived milk demand elasticity, -0.039.

If dairies move towards becoming manure exporters such that the industry average marginal cost decreases by one quarter the estimated difference of the two groups, the percentage change in industry average marginal cost would be -16.4 percent. Assuming price follows closely due to competitive markets, a decrease of 16.4 percent in the price of milk leads to an increase in demand of 0.64 percent. Using reported national milk production for 2014 from Cessna (2015), annual quantity demanded would increase by 1,321 million pounds, from 206,046 million pounds per year to 207,367 million pounds per year.

Conclusions

We estimate a system of marginal cost and input demand equations for US dairies using ARMS Phase III survey data for 2010. We compare the results for manure non-exporters and manure exporters. We find that the marginal cost of milk production for manure non-exporters is significantly greater than that for exporters.

Nutrient recovery technologies facilitate export of environmentally sensitive nutrients from manure via the transformation of manure nutrients into lighter, solid, and more uniform substrates. Because these technologies lower the cost of transporting nutrients, they are likely to result in much greater export from the dairy. They could affect dairy production in ways that are qualitatively similar to those faced by current manure exporters. Thus, it is possible that widespread adoption would lead to a decrease in marginal cost across the dairy industry. Using a price elasticity estimate from the literature and considering that average marginal cost would decrease by half the difference between current non-exporters and exporters, milk price would be expected to decrease by 16.4 percent. This would lead to an estimated increase in milk product demand of 0.64 percent (or 1,321 million pounds of milk per year).

In light of the observed consolidation of firms in the dairy industry and increasing environmental oversight of large CAFOs, policy makers should consider both the environmental impacts of emerging nutrient recovery technologies for dairies and their wider market impacts. This study provides evidence that, in addition to providing environmental benefits, exporting manure off the farm via transformation into fertilizer products has the potential to shift the milk supply curve and stimulate additional consumption.

Further contributions in this area could explicitly model manure transportation decision considering the firm’s production function, local environmental constraints, transportation costs, and neighbors’ nutrient needs. Based on the range of manure export prices observed in the data, both positive and negative prices and heavily centered at zero, it is obvious that there are a range of factors that impact decisions to export manure. Delving into these factors and modeling them explicitly would give much greater insight into the potential effects of adopting emerging nutrient recovery technologies.

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