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Factors Affecting Cow-Calf Herd Performance and Greenhouse Gas Emissions

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A Cobb-Douglas stochastic frontier function is estimated for the cow-calf enterprises in the Texas Rolling Plains using Standardized Performance Analysis (SPA) data. We find that factors promoting higher herd productivity include machinery investment, pasture-quality improvement, and protein supplement. In contrast, herd productivity is compromised by a longer breeding season, percentage of hired labor, and deviation from mean annual rainfall. Interestingly, more technically efficient farms tend to emit fewer greenhouse gas units per unit of output. For example, net greenhouse gas emissions are 6.12 and -8.70 pounds of carbon equivalent, respectively, for farms with technical efficiency below 0.8 and above 0.96.

Key words: greenhouse gas emission, standardized performance analysis, stochastic frontier analysis, technical efficiency

Introduction

The beef cattle industry in the Rolling Plains region of Texas is inherently risky due to frequent drought conditions, volatile cattle prices, and rising input costs. Moreover, national beef consumption has declined steadily in the past three decades, dropping from 94.4 pounds per capita in 1976 to 59.7 pounds in 2010. In the face of these challenges, the Beef Cow-Calf Standardized Performance Analysis (SPA) provides an analytical tool to help farmers and ranchers identify their strengths and weaknesses in production and financial performance. In 1992, the National Cattlemen's Beef Association adopted the SPA program that had been developed through efforts of their member producers, the National Integrated Resource Management Coordinating Committee, and Cooperative Extension Specialists from multiple universities.

The goal of the Beef Cow-Calf SPA analysis is to integrate production and financial records into a single analytical tool for cow-calf operations. Typically, an SPA is completed by a rancher and an extension specialist working together. The results of each complete analysis are sent to a regional coordinator, who checks the results for accuracy and enters them into a regional database. Texas leads the country in the number of analyses completed since the SPA program began. Two decades after its inception, the SPA data provides a key tool for analyzing herd performance over multiple production regions and years.

Most previous literature analyzing SPA data has attempted to identify factors that affect the cost, production, and profit of cow-calf enterprises (Falconer, Parker, and McGrann, 1999; Dunn, 2000; Miller et al., 2001; Ramsey et al., 2005). Scant attention had been paid to determining efficiency measurements among beef cow-calf enterprises until Cho, Park, and Bevers (2011) evaluated technical efficiency and its determinants among cow herd operations.

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The study of efficiency measurements began with seminal work by Farrell (1957), who suggested constructing the production function either as a parametric function or as a nonparametric piecewise-linear convex isoquant. There are two approaches to estimate a parametric model. One is the deterministic estimation, which uses a linear programming method introduced by Aigner and Chu (1968). This method ensures nonviolation of the monotonicity conditions and parametric restrictions (Färe et al., 2005). The other approach is Stochastic Frontier Analysis (SFA), which was simultaneously introduced by Aigner, Lovell, and Schmidt (1977) and Meeusen and van den Broeck (1977). Their model specification added stochastic elements to the deterministic frontiers, thus overcoming a major shortcoming of the deterministic estimation method, in which all variation from the production frontier is interpreted as inefficiency. The most popular method for constructing a nonparametric model is the Data Envelopment Analysis (DEA) method, which became widely used after Charnes, Cooper, and Rhodes (1978) reformulated Farrel's (1957) approach. DEA employs a linear programming technique to construct a nonparametric piecewise-linear frontier. Unlike the parametric model, DEA can be implemented without knowing the relationship between input and output.

The analysis of efficiency measurement is now widely used, with a few applications to the beef cattle sector. For example, Trestini (2006) used the SFA approach to study the technical efficiency of Italian beef cattle production and concluded that the inefficiency term is negatively correlated with herd size and the proportion of concentrated feed in the whole diet. Otieno, Hubbard, and Ruto (2012) applied the same method and found that promoting controlled cattle-breeding methods improved efficiency. Nonparametric production analysis has also been applied to study the efficiency of Kansas beef-cow farms (Featherstone, Langemeier, and Ismet, 1997). Factors that have been identified as influencing inefficiency include herd size and the percentage of income from beef cows. Rakipova, Gillespie, and Franke (2003) studied technical efficiency determinants in Louisiana beef production with a DEA model and discovered that, besides a higher level of improved pasture and better breeding practices, technical efficiency also increases with farmers' experience and formal education.

This paper analyzes cow-calf enterprises in the Rolling Plains region of Texas, comprising approximately 24,000,000 acres of primarily grassland characterized by low rolling hills to rough canyon lands (Gould, 1975). The location of the Rolling Plains is depicted in figure 1. Using SPA data from 1996 to 2011, we attempt to determine the factors that affect the production output of cow-calf enterprises and to measure the technical efficiency of cow-calf herds in the region.

We also investigate whether firms that are more technically efficient are also more efficient in greenhouse gas emissions per unit of product. The climate impact of the beef industry has received increasing consideration in recent years, and an emerging literature investigates greenhouse gas (GHG) emissions among different beef production systems in various regions of the world. In line with current environmental impact concerns, this paper also attempts to establish the relationship between technical efficiency and GHG emission per pound weaned.

Data

The analysis uses SPA data for cow-calf producers from 1996 to 2011. Considering the geographic differences and disparities in farm practices among the vast regions covered by SPA data, we focus on the subset of cow-calf farms from the Texas Rolling Plains. A total of forty-two ranches participated in the study during this sixteen-year period. Among them, thirty ranches (71.4%) participated for only one year, eight (19.0%) participated for two to three years, and nine (9.5%) participated for more than five years. There are a total of seventy-six observations.

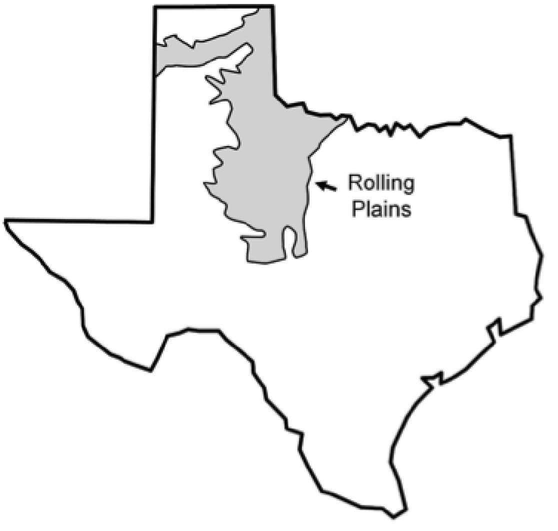

Figure 1. Location of Texas Rolling Plains

Variables in the Cobb-Douglas Stochastic Frontier Production

Following Ramsey et al. (2005) and Cho, Park, and Bevers (2011), we choose the variable pounds weaned per exposed female as the production output (i.e., the dependent variable). This variable is defined as the total pounds of calves weaned divided by the total number of females either exposed to bulls or in an artificial insemination program. Eight input factors are chosen as independent variables in the stochastic frontier production function.

The average age of weaning is included as a time input variable, as we expect that calves weaned at an older age will weigh more than calves weaned at a younger age. We also include three investment variables—real estate assets, machinery assets, and livestock assets on the cost basis—used in Ramsey et al. (2005) and Cho, Park, and Bevers (2011). These values are the total average assets value divided by the total number of breeding cows at the beginning of the fiscal year. As Ramsey et al. (2005) note, real estate assets may affect production negatively or positively depending on their management. The input of machinery assets is expected to play a positive role in production due to the increased capital intensity of the farm (Cho, Park, and Bevers, 2011). The sign of the coefficient of livestock assets is also equivocal, as we are not sure whether the investment in livestock is for better quality breeding stock with increased reproduction rates (Ramsey et al., 2005).

The variable purchased feed fed contains four components: roughage, complete feed, mineral and salt, and protein supplement. As each component has a different unit price and is likely to play a different role in production, we choose not to add them up as one aggregate variable. Instead, two major categories, pounds of roughage fed and pounds of protein supplement fed, are chosen as two independent variables in the study. The variables of complete feed and mineral and salt are not included, as they are not widely used. Our choice of feed variables is different from those used by Ramsey et al. (2005) and Cho, Park, and Bevers (2011), who use total pounds of feed as a single explanatory variable, but did not find it to be significant in the production function.

Koger et al. (1975) point out that improved pasture is more likely to increase cow production compared to native pasture because improved pasture typically provides forage of both higher quality and greater quantity. No direct data is available on the percentage of improved pasture, but we do have observations on costs of chemicals, fertilizer and lime, and seed and plants per breeding cow. Since these three inputs are essential for improved pasture, we add expenditures on these three variables as a proxy for percentage of improved pasture.

Similar to Battese and Coelli (1992), we include an adjusted input cost variable that includes gasoline, fuel and oil, hired labor and management, family living withdrawal (operator labor), and veterinary care and breeding. Expenses on these four categories are most likely to contribute to a higher productivity.[1] Costs on machine work, repairs and maintenance, supplies, utilities, professional fees, depreciation data, insurance, and property taxes are not included here, as they are unlikely to have any impact on pounds weaned per exposed female.

Variables in the Technical Inefficiency Effect Model

To investigate sources of productivity inefficiencies, we include five variables that capture farm and environmental characteristics. Calving season length is defined as the number of days from the beginning to the end of the breeding season. Shorter breeding seasons are typically an indicator of advanced management, as they result in better use of labor and productivity improvements (Ramsey et al., 2005). However, Deutscher, Stotts, and Nielsen (1991) found that a 70-day breeding season was better than 30- and 45-day seasons in terms of calf weaning weight per breeding female. They pointed out that optimal breeding season length should be determined with considerable care, as a shorter breeding season is not always better for productivity. In contrast, using SPA data from 1991 to 2001 for Texas, Oklahoma, and New Mexico, Ramsey et al. (2005) found that a shorter breeding season significantly improves pounds weaned per exposed females. Cho, Park, and Bevers (2011) showed that herd inefficiency level increases as the breeding season becomes longer, but this relationship was not significant using SPA Southern Plains data from 2004 to 2008.

The variable percentage of owned land is calculated as the acres of cattle land that are owned divided by the acres of cattle land that are owned and rented on the farm. A farmer who leases land is less likely to use sustainable practices and maintain long-term economic viability (Rakipova, Gillespie, and Franke, 2003); therefore, they are more likely to maximize their short-term profit. We also include the percentage of operator labor, which is the operator labor cost divided by the costs of operator and hired labor, to check whether farmers' who spend less time on their farms will have lower technical efficiency.

A favorable production condition for a cow-calf operation can be defined as favorable weather conditions. Therefore we include a rainfall variable to capture efficiency variances across years. Cho, Park, and Bevers (2011) directly used the variable of fiscal rainfall, which is the absolute value of rainfall during the fiscal year, and found it negatively affected herd productivity. Although above-average rainfall produces more grass growth if cattle numbers stay the same, forage quality decreases. Conversely, drier than average conditions can cause such low grass-growth rate that there is not enough to sustain animal numbers. In extreme cases plant mortality is increased. As both too little and too much rainfall can compromise herd productivity, we use a new variable, deviation from mean annual rainfall (MAR), as the absolute difference between percentage of MAR and 100. For example, if the percentage of MAR is 70, then deviation from MAR is $|70-100| = 30$. It is hypothesized that herd inefficiency levels will increase in proportion to deviation from MAR.

Finally, we include the variable total acres as an indicator of herd size. This variable captures the effects of two interconnected variables: the number of breeding females and acres per female, both of which may affect herd productivity. Featherstone, Langemeier, and Ismet (1997) found a positive relationship between herd size and technical efficiency, but Cho, Park, and Bevers (2011) demonstrated exactly the opposite result. We can infer that the relationship between herd size and efficiency may vary depending on whether the average herd size in the sample exceeds the optimal herd size.

[1] Personal communication with Professor S. Bevers, Extension Economist of Texas A&M AgriLife Center.

Table 1. SPA Variable Summary Statistics for Texas Rolling Plains (1996–2011)

Variable	N	Mean	Std Dev	Min	Max	Unit
Pounds Weaned Per Exposed Female	76	455	88	225	638	Pounds
Average Age at Weaning	76	8	1	3	12	Months
Livestock Assets (Cost Basis)	76	782	320	46	1,838	Dollars
Machinery Assets (Cost Basis)	76	258	490	0	3,842	Dollars
Real Estate Assets (Cost Basis)	76	2,295	3,673	0	25,551	Dollars
Roughage	76	1,131	1,254	0	5,217	Pounds
Protein Supplement	76	379	308	0	2,066	Pounds
Improved Pasture Proxy	76	40	40	0	177	Dollars
Adjusted Input Cost	76	119	49	24	251	Dollars
Breeding Season Length	76	125	86	45	365	Days
Percentage of Owned Land	76	53	41	0	100	Percent
Percentage of Operator Labor	76	29	36	0	100	Percent
Total Acre	76	8.10	14.92	0.381	102.63	Thousand
Deviation from Mean Annual Rainfall (MAR)	76	26	17	0	81	Percent

Summary Statistics

Table 1 provides a summary of statistics for the variables defined above. Other than the five variables included in the inefficiency model (that is, percentage of owned land, percentage of operator labor, breeding season length, deviation from MAR and total acre) all of the variables included in the stochastic frontier function are measured on the basis of number of exposed females on the farm.

Statistics in table 1 reflect diversity in farm characteristics and practices as well as environmental conditions across years. For example, the improved pasture proxy varies from $0 to $177 in the cost of chemical, fertilizer, and plant and seed categories of inputs. This means that the grazing land includes native rangeland, where the land is managed as a seminatural ecosystem, and improved pasture, where seed, establishment, and fertilizer are required to produce forage for grazing and hay production. Both machinery and real estate assets on a cost basis have a minimum of $0 and a maximum of $3,842 and $25,551 for range and cultivated pasture, respectively.[2] This demonstrates the dramatic differences in capital intensity. Similarly, both roughage and protein supplement range from a common minimum value of 0 pounds to a maximum of 5,217 and 2,066 pounds for range and cultivated pasture, respectively. This reflects a large difference in extensive and intensive grazing systems but also indicates the range of environmental conditions that inevitably affect farm grazing conditions and potential. Deviation from MAR provides a more specific measurement of abnormal environment conditions. A mean deviation of 26% with 17% standard error suggests considerable rainfall differences across years. Breeding season length varies from a minimum of 45 days to a maximum of an entire year, indicating a big difference in management intensity among farms. Finally, the huge range that exists in the total acre category reveals the coexistence of extremely small and large farms in the Texas Rolling Plains.

Methodology

To accommodate the analysis of unbalanced panel data, we use the SFA method, which is the most suitable approach for our purpose (Battese, Coelli, and Colby, 1989; Seale, 1990; Battese and Coelli, 1992, 1995). The SFA method has been used in a wide range of research dealing with unbalanced panels, as evidenced by recent works (see Jin et al., 2010; Mukherjee, Bravo-Ureta, and De Vries, 2013; Wang and Wong, 2012).

[2] Machinery assets value will be $0 if the machinery asset has been used past its depreciated life, while real estate assets value is assigned $0 if the ranch operates exclusively on leased land.

General Stochastic Frontier Production Function

We propose a stochastic frontier production function for unbalanced panel data (Battese and Coelli, 1992). On the observed dataset with N farms over T periods, the model can be defined as

$$Y_{it} = f(X_{it};\beta)\exp(V_{it} - U_{it}) \tag{1}$$

and

$$U_{it} = \eta_{it}U_i = \{\exp[-\eta(t - T_i)]\}U_i, t \in T(i);\ i = 1,2,\ldots,N; \tag{2}$$

where Y_{it} represents production output for the ith firm at the tth period of observation; $f(X_{it};\beta)$ is a function of a vector of input variables X_{it} and a vector of unknown parameters β; V_{it} denotes random errors that are independent and identically distributed as normal distribution $N(0,\sigma_v^2)$, accounting for the factors that are not under the control of the farm. A nonnegative term, U_{it}, is included to account for the technical inefficiency in production. It is assumed to be independent and identically distributed as nonnegative truncations of the normal distribution $N(\mu,\sigma^2)$, where $\mu = z_{it}\delta$. Additionally, z_{it} is a vector of explanatory variables associated with technical inefficiency in the cow-calf industry and δ is a vector of unknown parameters. The technical inefficiency effect U_{it} can be specified as

$$U_{it} = z_{it}\delta + W_{it}. \tag{3}$$

The random variable W_{it} follows truncated normal distribution of $N(0,\sigma^2)$, where the truncated point is $-z_{it}\delta$, so that $W_{it} \geq -z_{it}\delta$ and $U_{it} \geq 0$.

We can test whether the stochastic frontier production function is necessary by testing the significance of the parameter $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$. For example, if γ is close to 1, then σ_v^2 is zero, and a deterministic frontier function suffices. But if the null hypothesis, $\gamma = 0$, is accepted, then σ_u^2 is zero and term U_i can be removed from the model; the parameters can be consistently estimated using an ordinary least square method.

Parameter η is an unknown scalar to be estimated; a positive η means that farms tend to improve their technical efficiency over time, while a negative η stands for a decreasing level of technical efficiency and $\eta = 0$ indicates a constant technical efficiency over time. Here $T(i)$ is a subset of the integers, $1,2,\ldots,T$, representing the periods of observations involved. The mean technical efficiency of farm i over the observed periods can be defined as

$$TE_i = \frac{E(Y_{it}|U_i,X_{it},t \in T(i))}{E(Y_{it}|U_i = 0,X_{it},t \in T(i))} = E[exp(-U_{it})]. \tag{4}$$

This measure has values between 0 and 1. For example, if a farm has a technical efficiency of 0.90, then the farm realizes 90% of the output that is possible for a fully efficient farm employing comparable inputs.

Stochastic Frontier Production Function in Cobb-Douglas Form

The stochastic frontier function for the panel data on cow-calf enterprises in the Texas Rolling Plains can be tentatively specified in the following Cobb-Douglas form,[3] where subscripts i and t refer to the ith enterprise and the tth year, respectively:

[3] We also estimated the model using Translog form. Using the likelihood test, however, we find the Cobb-Douglas specification is preferred in our case.

$$\begin{aligned}(5)\quad \ln(PoundWeaned_{it}) = {} & \beta_0 + \beta_1 \ln(AgeWeaning_{it}) + \beta_2 \ln(Livestock_{it}) + \\ & \beta_3 \ln(Machinery_{it}) + \beta_4 \ln(RealEstate_{it}) + \\ & \beta_5 \ln(Roughage_{it}) + \beta_6 \ln(Protein_{it}) + \\ & \beta_7 \ln(ImprovedPasture_{it}) + \beta_8 \ln(InputCost_{it}) + \\ & V_{it} - U_{it};\end{aligned}$$

where the technical inefficiency effect U_{it} is defined as

$$\begin{aligned}(6)\quad U_{it} = {} & \delta_0 + \delta_1 BreedingLength_{it} + \delta_2 PercentOwnedLand_{it} + \\ & \delta_3 PercentOperatorLabor_{it} + \delta_4 TotalAcre_{it} + \\ & \delta_5 RainDev_{it} + W_{it}.\end{aligned}$$

As two-stage estimation may cause serious econometric problems (Kumbhakar, 2000, pp. 264), we estimate the parameters of equations (5) and (6) simultaneously using the Frontier 4.1 program written by Coelli (1996), which permits the unbalanced panel data to be estimated.

Technical Efficiency and GHG Emissions

To establish the relationship between technical efficiency and net GHG emissions per pound weaned,[4] we divide farms into several groups according to their technical efficiency levels. For each efficiency group, we choose an "average" farm, which takes the average variable values of all the farms in that group. We calculate GHG emissions from six sources: 1) enteric CH_4 emissions; 2) manure CH_4 emissions; 3) manure N_2O emissions and soil GHG emissions; 4) protein supplement; 5) energy use; and 6) fertilizer use. Using the most recent methods specified by the Intergovernmental Panel on Climate Change (2006), we obtain net GHG emissions for each technical efficiency group.

From SPA data, we can obtain the average conventional inputs related to GHG emissions for each group. For example, to calculate enteric CH_4 emission of a selected group, we first compute the average number of females and the percentage females that weaned a calf. Other input variables associated with GHG calculation include gasoline, fuel and oil expenses, and fertilizer and lime expenses. Besides the data available in SPA, other values or parameters required to calculate GHG emissions are assumed using the literature and local expert opinion.[5] The calculation for enteric and manure CH_4 requires the average number of bulls and heifers on the farm. As only number of cows is available in SPA data, we rely on expert opinion and assume the number of bulls and the number of stocker heifers make up 3.75% and 15% of the total number of cows.

Detailed methods using the example of a representative farm in the Texas Rolling Plains are described in the Appendix. We use the most recent method specified by the Intergovernmental Panel on Climate Change to calculate GHG emissions and sequestration for each technical efficiency category. Sources of parameter or input values that are needed for GHG emissions or sequestration are also provided. Methods for calculating the carbon emissions are provided on a production cycle basis, which were converted to a yearly basis after we obtained the results.

Results

Table 2 provides estimates of the stochastic frontier production function as specified in equation (5). Four explanatory variables (livestock assets, real estate assets, roughage, and adjusted input cost) in

[4] Net GHG emissions per pound weaned is defined as total net GHG emissions divided by the farm's total output in pounds, which is calculated as pounds weaned per exposed female multiplied by the number of cows.

[5] Professor S. Bevers, Extension Economist, Texas A&M AgriLife Center, Vernon Texas.

Table 2. Maximum-Likelihood Estimates for Parameters of Cobb-Douglas Stochastic Frontier Production Functions for Cow-Calf Enterprises on Texas Rolling Plains (1996–2011)

		MLE Estimates	
Variable	**Parameter**	**Model 1**	**Model 2**
Constant	β_0	2.2663***	2.3898***
		(0.1796)	(0.1152)
ln(Average Age at Weaning)	β_1	0.0980 **	0.0928*
		(0.0495)	(0.0508)
ln(Livestock Assets)	β_2	0.0358	–
		(0.0486)	
ln(Machinery Assets)	β_3	0.0213**	0.0207**
		(0.0103)	(0.0091)
ln(Real Estate Assets)	β_4	0.0026	–
		(0.0045)	
ln(Roughage)	β_5	−0.0039	–
		(0.0040)	
ln(Protein Supplement)	β_6	0.0295***	0.0301***
		(0.0116)	(0.0094)
ln(Improved Pasture Proxy)	β_7	0.0110**	0.0111***
		(0.0054)	(0.0041)
ln(Adjusted Input Cost)	β_8	0.0020	–
		(0.0458)	
	$\sigma^2 = \sigma_v^2 + \sigma_u^2$	0.0063***	0.0088***
		(0.0020)	(0.0034)
	$\gamma = \sigma_u^2/\boldsymbol{\sigma}^2$	0.5529***	0.7232***
		(0.1421)	(0.1161)
log(likelihood)		105.23	104.00

Notes: Estimated standard errors are given in parentheses. Single, doube, and triple asterisks (*, **, ***) indicate significance at the 10%, 5%, and 1% level.

Model 1 are not significant, thus we eliminate them and estimate the alternative model, referred to as Model 2, that includes the rest of the variables in equation (5). The coefficients for Model 2 are shown in table 2. Not surprisingly, average weaning age significantly increases the pounds weaned per exposed female, providing the greatest elasticity among all the explanatory variables. Without taking this factor into account, farmers who wean calves at an earlier age are likely to be assigned to the low-efficiency category. The only reason to wean at a younger age would be to ensure that rebreeding of the cows was not compromised, as the cows need to recover body condition after weaning to ensure a high conception rate.

The variable that generates the second greatest elasticity is protein supplement. Using pounds of feed fed as an explanatory variable directly, Ramsey et al. (2005) concluded that it did not lead to higher productivity. To understand the impact of this input, we divided pounds of feed fed into protein supplement and roughage. Protein supplement plays an important role in improving productivity, while the coefficient for roughage had a negative sign and is not significant. A plausible explanation is that roughage is most often fed as a substitute for forage grown on the farm when it is in short supply due to abnormal weather conditions. Therefore, roughage might be viewed as a proxy for unfavorable weather conditions. Plus, feeding of roughage to make up for a shortage of forage biomass is a practice that reduces profitability and causes damage to the rangeland or pasture (Díaz-Solís et al., 2009).

Similar to Cho, Park, and Bevers (2011), we also found that an increase in machinery and equipment assets significantly improves productivity, while livestock assets and real estate assets play no significant role. As an indicator of farm management and capital intensity, it is not surprising

Table 3. Tests of Hypothesis for Parameters of the Inefficiency Stochastic Frontier Production Function for Cow-Calf Farmers

Null Hypothesis	Log (Likelihood)	Test Statistic λ	Critical Value	Decision
$H_0 : \beta_2 = \beta_4 = \beta_5 = \beta_8 = 0$	104.00	2.46	9.49	Accept H_0
$H_0 : \gamma = \delta_i = 0$ for $i = 0, \ldots, 5$	83.25	41.50	14.07	Reject H_0
$H_0 : \delta_1 = \delta_2 = \delta_3 = \delta_4 = \delta_5 = 0$	88.75	30.50	11.07	Reject H_0
$H_0 : \eta = 0$	91.83	1.20	3.84	Accept H_0

to find that the variable of machinery and equipment assets has a positive effect on productivity. As Ramsey et al. (2005) point out, the ambiguous relationship found between livestock assets and productivity indicates that investment in livestock is not directly related to enhanced productivity. Also, investment in real estate assets may only reflect producers' personal goals, such as wealth accumulation, and will therefore have little to do with productivity.

The improved pasture proxy variable also had a positive impact on productivity, as improved pasture typically provides higher quality forage with greater quantity per acre. Koger et al. (1975) and Rakipova, Gillespie, and Franke (2003) observe the same positive relationship between improved pasture and cow productivity. Adjusted input cost, however, plays no significant role in productivity. Thus we can infer that labor and veterinary services actually contribute little to overall herd productivity in the Texas Rolling Plains area.

Hypothesis Testing

We carried out a series of tests on the joint significance of the four insignificant terms of Model 1 and some null hypotheses on technical efficiency. The results of those likelihood-ratio tests are provided in table 3. The likelihood-ratio test statistic is calculated as $\lambda = -2[\ln(L(H_0)) - \ln(L(H_1))]$, where $\ln(L(H_0))$ denotes the log(likelihood) of the restricted model and $\ln(L(H_1))$ represents the log(likelihood) of the unrestricted model. Table 3 also lists the log(likelihood) value of each restricted model.

The test statistic, λ, has approximately chi-square distribution with degrees of freedom equal to the number of parameters restricted to be zero. For example, for the first hypothesis, H_0: $\beta_2 = \beta_4 = \beta_5 = \beta_8 = 0$, λ follows chi-square distribution with degrees of freedom equal to 4. Since this hypothesis is accepted, Model 2 is preferred to Model 1.

The second hypothesis states that the inefficiency effect is completely absent from Model 2. Here $\gamma \equiv \sigma_u^2/(\sigma_v^2 + \sigma_u^2) = 0$ involves parameters associated with the variance of the technical inefficiency variable U_{it} and random variable V_{it}. If the null hypothesis $\gamma = 0$ is accepted, then σ_u^2 is zero and the inefficiency term U_i can be removed from the model. In other words, all farms are efficient and the model can be consistently estimated using the ordinary least square method. As this hypothesis is also rejected, it means technical inefficiencies exist in Model 2.

The third hypothesis states that the inefficiency effect for Model 2 exists, but it is not a linear function of the five explanatory variables specified in equation (6). This null hypothesis is rejected. Consequently, the joint effects of these five variables on the production inefficiencies are significant, although the individual effects of some variables may not be.

The last hypothesis states that the technical inefficiency effect for Model 2 does not vary over time. This hypothesis is accepted, which means there was no improvement in technical efficiency from 1996 to 2011 for cow-calf farmers in the Texas Rolling Plains.

Determinants of Technical Inefficiency

Technical efficiency provides a measure of the output of farm i over time t relative to the output that can be produced by the most efficient farm in the sample using the same inputs. The average technical efficiency level for the seventy-six cow-calf farms is 95.1%, which is comparable to the

Table 4. Estimation of Inefficiency Effect Model

Variable	Parameter	MLE Estimates
Constant	δ_0	−0.0955
		(0.0868)
Breeding Season Length	δ_1	0.0008***
		(0.0003)
Percentage of Owned Land	δ_2	−0.0009
		(0.0007)
Percentage of Operator Labor	δ_3	−0.0032***
		(0.0009)
Total acre	δ_4	−0.0065
		(0.0052)
Deviation from Mean Annual Rainfall (MAR)	δ_5	0.0029*
		(0.0016)
	σ^2	0.0088***
		(0.0034)
	γ	0.7232***
		(0.1250)

beef-cow production efficiency level obtained by Cho, Park, and Bevers (2011) using SPA data from three southern states from 2004 to 2008 and Rakipova, Gillespie, and Franke (2003), who studied the efficiency of Louisiana beef-cow producers. Meanwhile, our estimated efficiency level is far greater than the 78% found for beef-cow herds in Kansas (Featherstone, Langemeier, and Ismet, 1997) and the 69% found for beef-cow herds in Kenya (Otieno, Hubbard, and Ruto, 2012). This confirms that technical inefficiency, though it exists, is not a serious problem for most cow-calf farms in the Texas Rolling Plains.

Estimates for the technical inefficiency effect of Model 2 are provided in table 4. Breeding season length is positively related to the technical inefficiency. Thus farms with a longer breeding season have a significant lower productivity. This result is in accordance with that of Ramsey et al. (2005), suggesting that in the Texas Rolling Plains, an average farm can still improve its productivity by reducing breeding season length. Another variable that significantly affects technical efficiency is percentage of operator labor, which indicates that farm owners who devote more time on the beef-cow operation to decrease spending on hired labor will achieve higher efficiency.

A positive relationship exists between deviation from mean annual rainfall and technical inefficiency. A rainfall level close to mean annual rainfall will promote productivity, while too little or too much rain are both counterproductive. Severe drought is a serious threat to the beef industry in Texas (Independent Cattlemen's Association, 2011). We find that an 80% deviation from MAR increased technical inefficiency by 23.2%. Using absolute rainfall level as an explanatory variable (Cho, Park, and Bevers, 2011) was less instructive than the deviation from MAR used in this study.

Similar to Rakipova, Gillespie, and Franke (2003), we also found both percentage of owned land and total acres had negative values and were not significant in the inefficiency model.

Technical Efficiencies of Different Categories

Table 5 gives the technical efficiencies of cow-calf operations in the Texas Rolling Plains in three categories. The first is by farm, giving the average technical efficiency of each farm from 1996 to 2011. The second is by observation, where we treat the same farm sample in a different year as a different observation. The last is by year, where we average all farms' efficiency levels observed in the same year. The average technical efficiency level for each farm (first column) outperformed that for individual observations (second column). This suggests that although herd productivity may occasionally be negatively affected by some uncontrollable factors such as abnormal rainfall in

Table 5. Frequencies and Percentages of Technical Efficiencies for Cow-Calf Farms

Technical Efficiency	Frequencies and Percentages		
	By Farm	By Observation	By Year
0.70–0.79	0 (0%)	3 (3.95%)	0 (0%)
0.8–0.85	1 (2.5%)	3 (3.95%)	0 (0%)
0.86–0.9	3 (7.50%)	3 (3.95%)	2 (14.29%)
0.91–0.95	5 (12.50%)	13 (17.11%)	3 (21.43%)
0.96–1	31 (77.50%)	54 (71.05%)	9 (64.29%)
Total	40 (100%)	76 (100%)	14 (100%)

Table 6. Technical Efficiency by Size of Cow-Calf Farms

Size (Acres)	N	Technical Efficiency	Size (No. of Breeding Females)	N	Technical Efficiency
Below 1,000	22	0.913	Below 100	14	0.950
1,000–4,000	21	0.966	100–200	27	0.929
4,000–10,000	16	0.964	200–300	12	0.970
Above 10,000	17	0.970	Above 300	23	0.967
Total	76	0.951	Total	76	0.951

specific years, such unfavorable effects seem to level off over the years. From the perspective of the year (third column), we found a lower proportion of farms with efficiency values lying in the 0.96 to 1.00 range because all of the farms tend to be affected by the unfavorable environment in the same year, thus the average inefficiency level for those years can be relatively low.

To further understand how technical efficiency relates to herd scale, table 6 presents average technical efficiency for different categories of herd size, measured in total acreage and number of breeding females. No clear relationship exists between technical efficiency and number of breeding females. This can be seen from the ranking of technical efficiency, where herd size of 200–300 comes first, then herds with size over 300, then herds with size below 100, while the lowest technical efficiency occurs for herds of size 100–200. Although economy of scale is generally found when attempting to reducing costs, no study has shown that a larger herd is associated with increased productivity (Langemeier, McGrann, and Parker, 2004; Featherstone, Langemeier, and Ismet, 1997; Ramsey et al., 2005). However, when it comes to the total farm area, table 6 clearly shows that farms occupying a larger area generally have greater technical efficiency.

Technical Efficiency and GHG Emission

Based on the technical efficiency level, we divided observations into five groups according to their technical efficiency levels (70%–79%, 80%–85%, 86%–90%, 91%–95%, and 96%–100%) and refer them as efficiency groups 1 to 5. Then we applied the methods specified in the Appendix to obtain net GHG emissions for each group.

The final results are provided in table 7. We found that, in agreement with DeRamus et al. (2003), GHG emissions per pound weaned decline as technical efficiency increases. This is caused partly by the positive relationship between technical efficiency and pounds weaned. The average pounds weaned per exposed female for efficiency groups 1 to 5 are 300, 345, 354, 431, and 481, suggesting that the inputs generating GHG emissions are used more efficiently to produce each unit of output by groups with higher technical efficiency. Group 1 has the highest GHG emissions per pound weaned due to high fertilizer and protein supplement use and low pounds weaned. While GHG emissions tend to decline for groups with increased technical efficiency, GHG sequestration generally displays

Table 7. GHG Net Emissions among Five Technical Efficiency Categories for Cow-Calf Farms

Technical Efficiency	0.70–0.79	0.80–0.85	0.86–0.90	0.91–0.95	0.96–1
Enteric CH_4	3.97	3.49	3.46	2.86	2.58
Manure CH_4	0.15	0.13	0.13	0.11	0.10
Manure N_2O	1.75	1.52	1.48	1.22	1.09
Protein Supplement	0.09	0.04	0.04	0.06	0.04
Energy Use	2.68	3.18	2.66	1.82	1.45
Fertilizer Use	0.21	0.13	0.19	0.09	0.08
GHG Emission	8.85	8.48	7.95	6.15	5.32
GHG Sequestration	2.73	3.64	6.27	10.81	14.02
Net GHG Emission	6.12	4.84	1.69	−4.66	−8.70

Notes: Units are pounds of carbon equivalent per pound weaned.

the opposite pattern. This is because GHG sequestration is solely determined by total farm acres in our calculation, while a positive relationship exists between total acre and technical efficiency (table 6). The average total acres for efficiency groups 1 to 5 are 427, 458, 1,795, 4,982, and 10,054. In addition, the higher efficiency groups tend to have a higher number of acres per female, averaging 3.5, 7.3, 7.5, 17.1, and 23.5 for efficiency groups 1 to 5. This suggests that beef-cow operations with lower cow density (lower stocking rate) are more likely to be both technically more efficient and to have lower net carbon emission rates per pound weaned. For net GHG emissions, a negative sign indicates net sequestration rather than net emission.

Cow-calf farmers in efficiency groups 4 and 5 produce net carbon sequestration rather than carbon emission (table 7). More technically efficient farms also have more net carbon sequestration, suggesting that environment quality will not be compromised by pursuing higher technical efficiency. This will benefit more technically efficient cow-calf farmers who would likely be rewarded by any future carbon credit program. However, farms in lower efficiency categories, mostly those farms with dense (heavily stocked) beef-cow populations are not likely to benefit from a GHG reduction program.

Discussion

This paper investigates the relationship between various farm management practices and technical efficiencies. The stochastic frontier function used to investigate the factors that promote higher productivity for a typical cow-calf farmer indicated that there were significant but small increases in elasticity from different management factors. A 10% increase in each management action increased pounds weaned per breeding cow by 0.98% for average age at weaning, 0.30% for protein supplementation, 0.21% for investment in machinery, and 0.11% for pasture-quality improvement. In contrast, investment in real estate and livestock assets had no significant effect. The roles played by roughage feed and adjusted input cost—including labor and veterinary services—were also not significant.

The level of technical efficiency is assessed for cow-calf enterprises sampled by SPA data in the Texas Rolling Plains. At 95%, the average technical efficiency for cow-calf farms on Texas Rolling Plains is comparable to that of beef-cow herds in the U.S. Southern Plains (Cho, Park, and Bevers, 2011; Rakipova, Gillespie, and Franke, 2003), but greater than that of beef-cow herds in Kansas at 78% (Featherstone, Langemeier, and Ismet, 1997) and in Kenya at 69% (Otieno, Hubbard, and Ruto, 2012). Average technical efficiency is also found to increase as farm area increases. For example, average technical efficiency is 91.3% for farms below 1,000 acres and 97% for farms above 10,000 acres, suggesting increasing returns to scale as farm size increases. However, no significant improvement in technical efficiency was found over time during the 1996 to 2011 survey period.

Significant variables resulting in lower technical efficiency include a longer breeding season, lower operator labor percentage, and increasing deviation from MAR. We found that technical efficiency increased 8% if breeding season length decreased by 100 days. In addition, in the case of extreme drought (50% of MAR), estimated technical efficiency was reduced by 14.5%., which underscores the importance of favorable weather conditions for cow-calf operations. To help cow-calf operations mitigate losses due to severe drought, measures such as using management-intensive grazing with multiple paddocks and drought insurance should be promoted. In addition, we also find farm efficiency increases on average by 3.2% with a 10% increase in the percentage of operator labor.

This paper also aimed to determine the relationship between technical efficiency and environmental impact. Life-cycle analyses indicated that enteric CH_4, energy use, and manure N_2O generate about 95% of all GHG emissions for all efficiency groups, with 45%, 20%, and 20% attributable to enteric CH_4, energy use, and manure N_2O, respectively. In comparison, manure CH_4, protein supplement, and fertilizer use have little effect on GHG emissions per unit of output.

Direct linkages can be found between farm efficiency and carbon emission and sequestration. We found that carbon emissions per unit of output decrease as farm efficiency increases. This is partly due to the positive correlation between farm efficiency and output level. However, higher carbon sequestration occurs on farms that are more technically efficient as a result of more acres allocated to each breeding cow. The greatest net carbon sequestration was found for the two most technically efficient groups, indicating that pursuing technical efficiency will not compromise environmental quality.

Conclusion

This paper addresses two equally important issues. First, we use an SFA method and find that direct expenditures on protein supplement, machinery investment, and pasture-quality improvement enhance farm productivity. Factors that affect technical efficiency include breeding season length, percentage of operator labor, and deviation from MAR. Second, this paper provides the first study on the relationship between cow-calf farm technical efficiency and environmental consequences as indicated by greenhouse gas emission. Results suggest that for the cow-calf industry, pursuing farm efficiency aligns with environmental protection goals.

The focus of the SFA model in this paper is on output, or pounds weaned per breeding female, rather than profitability. In addition to our finding, future research could investigate whether the incentive to pursue financial profitability conflicts with environmental protection objectives. Future efforts could also extend the method to model the link between pursuing efficiency and environmental protection in different industries, such as cropping, or in different regions.

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Appendix A: Methods for Calculating Total GHG Emissions of a Representative Cow-Calf Farm

Data are provided by Stan J. Bevers, Professor and Extension Economist-Management for Texas A&M AgriLife Extension Service, who specializes in ranch management and analysis.

Farm Description

Calculatations are based on a herd size of 800 cattle, including 400 cows, 60 heifers, 325 calves, and 15 bulls. All of the calves except sixty heifers are sold immediately after weaning. We assume a breeding season from April to August and a birth season from January to May. For simplicity, we assume a 90% pregnancy and lactating rate (actual pregnancy rates range from 90–92% and lactating rates are about 88%). Weaning occurs from September to November. The life cycle we consider here is defined as the entire production period, which lasts from April to November of the following year. During the breeding season from April to August, the breeding cows also feed the previous batch of calves. For calculation purposes, the lactation period lasts 120 days. During the gestation period from August to the following May (based on a 283-day pregnancy) we assume 133 days of overlap between pregnancy and lactation and 150 days of pregnancy only. From May till the weaning season, we assume there are 90 days of lactation only and 120 days of overlap during which the lactating cows are pregnant with the next generation of calves. In a production cycle, we assume that a typical cow spend 210 days lactating, 150 days pregnant while not lactating, and 253 days both lactating and pregnant, for a total of 613 days.

We assume a 100% pasture manure management system, given that managing a dry-lot manure system is too costly. We also assume leaching and runoff does not occur on the pasture. Supplemental feed is either Coastal Bermuda hay or Sudan hay. However, supplemental hay is rarely used in the Southern Plains except in years of severe drought, so we ignore GHG emissions from this source. Typically, supplemental protein is used from December to March, when the grass protein is low. The 400 cows were fed two pounds of supplemental protein per head per day for 120 days, for a total of 96,000 pounds per production season. Supplemental proteins include grain-based protein made of corn and oil-based protein made of cottonseed and soybean meals. Here we calculate the GHG emissions from soybean meal as an example of protein supplement source.

Methodologies

We describe the methodologies used to calculate GHG emissions for five components of emissions on a typical cow-calf farm, including enteric methane emission, manure methane emission, manure N_2O emission, supplemental protein CO_2 emission, and GHG emission from farm energy use and fertilizer use. Carbon sequestration was also calculated.

Enteric CH_4

According to the Intergovernmental Panel on Climate Change (2006), we have $CH_{4enteric} = EF \times N/10^6$ Gg CH_4 per production cycle, where N is the number of head of livestock species and EF is the emission factor for the defined livestock population in kilograms of CH_4 per head per year. According to the Tier 2 approach,[6] EF should be developed by

$$EF = \frac{GE(\frac{Y_m}{100})365}{55.65}, \tag{A1}$$

[6] IPCC suggests the Tier 2 approach for beef cattle when estimating emissions from enteric fermentation. According to IPCC, "The Tier 2 method should be used if enteric fermentation is a key source category for the animal category that represents a large portion of the country's total emissions."

Table A1. Energy Use and Carbon Dioxide Emissions by Fuel Source on U.S. Farms, 2005

Fuels	Energy Consumed (BTUs)	CO_2 Emissions (g CO_2 eq)
Diesel	408.5	29.58
Gasoline	128.5	9.01
LP Gas	76	4.74
Natural Gas	53	2.80
Electricity	135	23.28

Source: Global Change Program Office, Office of the Chief Economist (2008, table 5-2)

where Y_m is the methane conversion factor, which is the percent to gross energy in feed converted to methane. According to the Intergovernmental Panel on Climate Change (2006, table 10.12), $Y_m = 6.5\% \pm 1.0\%$. The lower bound is more appropriate for feed with high digestibility and high energy value, and vice versa. For calves fed entirely on milk, $Y_m = 0$. As a result, we use $Y_m = 0$ for the preweaning calves. Factor 55.65 (MJ/kg CH_4) stands for the energy content of methane. If an animal subcategory is staying on the farm for less than 365 days, we replaced 365 with the number days that the animals actually stayed on the farm; GE is the gross energy intake in MJ per head per day, which is further defined as

$$\text{(A2)} \qquad GE = \frac{\frac{NE_m + NE_a + NE_l + NE_p}{REM} + \frac{NE_g}{REG}}{\frac{DE\%}{100}},$$

where NE_m is the net energy for maintenance, which is required by the animal so that the body energy is neither gained or lost. It can be calculated as: $NE_m = Cf_i \times (Weight)^{0.75}$. For nonlactating cows, $Cf_i = 0.322$; for lactating cows, $Cf_i = 0.386$; for bulls, $Cf_i = 0.370$; $Weight$ is the live-weight of animal in kilograms. According to the U.S. Environmental Protection Agency (2012, table A-173), Typical Animal Mass (TAM) in the year 2010 is 613 kilograms/head for cows and 919 for bulls. TAM for steers and heifers are 234 and 220, respectively, according to the expert's description. Therefore, for nonlactating and lactating cows, we have $NE_m = 0.322 \times (613)^{0.75} = 39.67$ and $NE_m = 0.386 \times (613)^{0.75} = 47.55$. For bulls, $NE_m = 0.370 \times (919)^{0.75} = 61.76$. The net energies for maintenance for steers and heifers are $NE_m = 0.322 \times (234)^{0.75} = 19.26$ and $NE_m = 0.322 \times (220)^{0.75} = 18.39$.

Next, $NE_a = C_a \times NE_m$ stands for the net energy for activity, which is energy needed by the animal to obtain food, water, and shelter. It is based on the feeding situation rather than the feed itself; for cattle confined in a small area such as a barn, $C_a = 0$; for cattle confined in areas with sufficient forage such as a pasture, $C_a = 0.17$; for cattle grazing in open range land, $C_a = 0.36$ In the Rolling Plains, most cattle feed on pasture, so we choose $C_a = 0.17$. Additionally, the NE_a for nonlactating cows, lactating cows, bulls, steers, and heifers are 6.74, 8.08, 10.50, 3.27, and 3.13.

Third, $NE_l = Milk \times (1.47 + 0.40 \times fat)$ is the net energy necessary for lactation, where $Milk$ is the amount of milk produced (kg/day) and fat is the fat content of milk (%). According to the U.S. Environmental Protection Agency (2012), the lactation estimates for beef cow from January to December are 3.3, 5.1, 8.7, 12.0, 13.6, 13.3, 11.7, 9.3, 6.9, 4.4, 3.0, and 2.8 lbs milk/beef cow/day. As we choose April to August as the breeding season, calves are born between January and May and weaned between September and November. If cows give birth in January, February, and March and wean the calves eight months later, the average daily milk production would be 9.32, 9.44, and 9.21 pounds. Thus we choose the average milk production as 9.32 lbs/day (4.24 kg/day). Also according to the U.S. Environmental Protection Agency (2012), the percentage of fat in milk is 4%. Therefore for lactating cows we have $NE_l = 4.24 \times (1.47 + 0.40 \times 4) = 13.02$.

Also, for pregnant cows, NE_p is the net energy required for pregnancy (MJ per day), where $NE_p = 0.1 \times NE_m = 0.1 \times 39.67 = 3.97$. For heifers and steers, NE_g is the net energy for growth (MJ per day), defined as $NE_g = 22.02 \times [BW/(C \times MW)]^{0.75} \times WG^{1.097}$, where BW is the average live body weight (BW) of the animals in the population (kg); C is a coefficient with a value of 0.8 for females, 1.0 for castrates, and 1.2 for bulls; *MW* is the mature live body weight of an adult female in moderate body condition (kg); and *WG* is the average daily weight gain of the animals in the population. *BW* and *WG* data for heifers and *MW* data are directly obtained from Professor Bevers. For heifers, we have $NE_g = 22.02 \times [220/(0.8 \times 613)]^{0.75} \times 2.5^{1.097} = 32.98$.

Cattle feed digestibility, denoted by *DE%*, ranges from 45% to 55% for crop byproducts and range lands; 55% to 75% for good pastures, good preserved forages, and grain-supplemented forage-based diets. Following the expert's opinion, for the Rolling Plains we chose the second category, thus the average *DE%* is 65%. Finally, based on *DE%*, we can calculate *REM*, the ratio of net energy available in diet for maintenance to digestible energy consumed:

$$\text{(A3)} \quad REM = 1.123 - 4.092 \times 10^{-3} \times DE\% + 1.126 \times 10^{-5} \times (DE\%)^2 - 25.4/DE\% = 0.51.$$

We can also calculate *REG*, is the ratio of net energy available in diet for growth to digestible energy consumed:

$$\text{(A4)} \quad REG = 1.164 - 5.160 \times 10^{-3} \times DE\% + 1.308 \times 10^{-5} \times (DE\%) - 37.4/DE\% = 0.31.$$

Now we are ready to calculate enteric methane emissions. For lactating only cows:

$$\text{(A5)} \quad GE = \frac{(NE_m + NE_a + NE_l)/REM}{DE\%/100} = \frac{(47.55 + 8.08 + 13.02)/0.51}{65/100} = 207.09;$$

$$\text{(A6)} \quad \begin{aligned} EF &= \frac{GE \times (Y_m/100) \times \textit{days on lactating only}}{55.65} \\ &= \frac{207.09 \times (6.5/100) \times 210}{55.65} = 50.80; \end{aligned}$$

$$\text{(A7)} \quad CH_{4enteric} = EF \times N/10^6 = 50.80 \times \frac{400 \times 90\%}{10^6} = 0.018.$$

For pregnant and not lactating cows:

$$\text{(A8)} \quad GE = \frac{(NE_m + NE_a + NE_p)/REM}{DE\%/100} = \frac{(39.67 + 6.74 + 3.97)/0.51}{65/100} = 151.98;$$

$$\text{(A9)} \quad \begin{aligned} EF &= \frac{GE \times (Y_m/100) \times \textit{days on gestation only}}{55.65} \\ &= \frac{151.98 \times (6.5/100) \times 150}{55.65} = 26.63; \end{aligned}$$

$$\text{(A10)} \quad CH_{4enteric} = EF \times N/10^6 = 26.63 \times 400 \times 90\%/10^6 = 0.010.$$

For pregnant and lactating cows:

$$\text{(A11)} \quad \begin{aligned} GE &= \frac{(NE_m + NE_a + NE_l + NE_p)/REM}{DE\%/100} \\ &= \frac{(47.55 + 8.08 + 13.02 + 3.97)/0.51}{65/100} = 219.06; \end{aligned}$$

$$\text{(A12)}\quad \begin{aligned} EF &= \frac{GE \times (Y_m/100) \times \textit{days both lactating and pregnant}}{55.65} \\ &= \frac{219.06 \times (6.5/100) \times 253}{55.65} = 64.73; \end{aligned}$$

$$\text{(A13)}\quad CH_{4enteric} = EF \times N/10^6 = 64.73 \times 400 \times 90\%/10^6 = 0.023.$$

For cows that are neither lactating nor pregnant (for simplicity we assume 10% of cows remain nonproductive in the 613-day period):

$$\text{(A14)}\quad GE = \frac{(NE_m + NE_a)/REM}{DE\%/100} = \frac{(39.67 + 6.74)/0.51}{65/100} = 140;$$

$$\text{(A15)}\quad EF = \frac{GE \times (Y_m/100) \times 613}{55.65} = \frac{140 \times (6.5/100) \times 613}{55.65} = 100.24;$$

$$\text{(A16)}\quad CH_{4enteric} = EF \times N/10^6 = 100.24 \times 400 \times 10\%/10^6 = 0.004.$$

For bulls:

$$\text{(A17)}\quad GE = \frac{(NE_m + NE_a)/REM}{DE\%/100} = \frac{(61.76 + 10.50)/0.51}{65/100} = 217.98;$$

$$\text{(A18)}\quad EF = \frac{GE \times (Y_m/100) \times 613}{55.65} = \frac{217.98 \times (6.5/100) \times 613}{55.65} = 156.07;$$

$$\text{(A19)}\quad CH_{4enteric} = EF \times N/10^6 = 156.07 \times 15/10^6 = 0.002.$$

For stocking heifers:

$$\text{(A20)}\quad \begin{aligned} GE &= \frac{(NE_m + NE_a)/REM + NE_g/REG}{DE\%/100} \\ &= \frac{(18.39 + 3.13)/0.51 + 32.98/0.31}{65/100} = 228.59; \end{aligned}$$

$$\text{(A21)}\quad EF = \frac{GE \times (Y_m/100) \times 613}{55.65} = \frac{228.59 \times (6.5/100) \times 613}{55.65} = 163.67;$$

$$\text{(A22)}\quad CH_{4enteric} = EF \times N/10^6 = 163.67 \times 60/10^6 = 0.010.$$

Together, on the representative farm we defined in the previous section, overall enteric emissions can be added up as

$$\text{(A23)}\quad \begin{aligned} CH_{4enteric} &= 0.018 + 0.010 + 0.023 + 0.004 + 0.002 + 0.010 \\ &= 0.067\ \textit{Gg}\ CH_4\ (67{,}000\ \textit{kg}\ CH_4)\ \textit{per production cycle.} \end{aligned}$$

Thus, the enteric methane emission is equivalent to 1,407,000 kg CO_2 per production cycle, or 1,551 tons CO_2 per production cycle (1 unit of CH_4 has a global warming potential of 21 units of CO_2).

Manure CH_4

The method we describe in this section is provided by ICF Consulting (1999b),which is similar to the Tier 2 method in IPCC, but is more informative in that it treats each U.S. state differently, rather than treating the North American region as a whole. Overall, the manure methane emissions can be calculated as: $CH_{4manure} = Total\ VS_i \times B_0 \times MCF_j \times WS\%_{ij}$; where $Total\ VS_i$ stands for the volatile solid produced by all the animals in each subcategory per year; it can be computed from

(A24) $\quad Total\ VS_i = Population\ of\ subcategory\ i\ (head) \times TAM_i\ (lbs/head) \times VS\ coefficient$

Typical Animal Mass (TAM) is 397 lbs/head for calves, 794 for steers and heifers, 1,102 for cows and 1,587 for bulls. From ICF Consulting (1999b, table 7.4–11), we know that the VS coefficient is 2.6 lbs VS/lb animal mass/year. Thus $TAM_i \times VS\ coefficient$ values for calves, heifers, cows, and bulls can be calculated as 469, 938, 1,302, and 1,875 kg/animal/year for all states. Estimates by ICF Consulting (1999b) will be used, as they include all four of the categories we need. Meanwhile, we adjust those values by a factor of $(1,600/1,302 = 1.23)$ to match the EPA's updated information.[7] The adjusted $TAM_i \times VS\ coefficient$ values for calves, heifers, cows, and bulls are 577, 1,154, 1,602, and 2,307 kg/animal/year (1,270, 2,539, 3,524, and 5,075 lbs/animal/year).

B_0 is the estimate of the maximum methane-producing capacity of U.S. livestock. For beef not in feedlots, $B_0 = 2.72$ ft^3 per lb VS;[8] MCF stands for the methane conversion factor for manure system j (%). In Texas, MCF is 1.4% for pasture/range/paddock manure system and 2.1% for dry lot manure system. In Oklahoma, those values are 1.4% and 1.9%. As we only consider a pasture/range/paddock manure system (since the dry lot system is too costly to maintain), we choose $MCF = 1.4\%$.

$WS\%_{ij}$ stands for the percentage of animal i's manure managed in manure system j. Here we assume a 100% pasture manure system based on the expert's opinion. We calculate manure methane emission as

$$\begin{aligned} CH_{4manure} &= Total\ VS_i \times B_0 \times MCF_j \times WS\%_{ij} \\ &= (325 \times 1,270 + 60 \times 2,539 + 400 \times 3,524 + 15 \times 5,075) \\ &\quad \times 2.72 \times 1.4\% \times 100\% \\ &= 78,094 \text{ ft}^3 \text{ CH}_4 \text{ per year.} \end{aligned} \tag{A25}$$

This is equivalent to 3,225 lbs of CH_4 per year given that 1 ft^3 = 0.0413 lbs; or 1466 kg CH_4 per year which equals 2,462 kg of CH_4 per production cycle. Thus the manure methane emission on this farm is 51,702 kg CO_2 per production cycle, or 57 tons CO_2 per production cycle.

Manure N_2O

N_2O emissions generated by manure in a "pasture, range, and paddock" system occur directly and indirectly from the soil (Intergovernmental Panel on Climate Change, 2006). Thus, we refer to the methods provided in (Intergovernmental Panel on Climate Change, 2006, Section 11.2), 'N_2O emissions from managed soils.'

[7] In EPA (2012), the calculation TAM_i (lbs/head)$\times$$VS\ coefficient$ (lbs VS/lb animal mass/year) is provided as a single value VS (kg/animal/year) for the year 2010. Three categories are provided in EPS Annex 3, Table A-193: Cow, Heifer, and Steer. Those values are 1,589, 1,013, and 923 for Oklahoma and 1664, 1,053, and 971 for Texas. Since the average value for a cow for those two states is roughly 1,600 in 2010 and 1,302 in 1999 (U.S. Environmental Protection Agency, 2012), we adjust the ICF Consulting (1999b) estimates by a factor of $1600/1302 = 1.23$ to obtain the updated estimates.

[8] Note that coefficients such as B_0 provided in ICF Consulting (1999b) require us to use inputs in English units, while inputs in metric units are required for calculations such as equation (1), where factor 55.65 has units of MJ/kg CH_4, according to Intergovernmental Panel on Climate Change (2006). To maintain the traceability of the original formulas and factors/coefficients, we choose different units correspondingly. In the main paper we convert all the final GHG net emissions uniformly into English units.

Direct N_2O emissions from urine and dung inputs to grazed soils can be calculated as $N_2O_{direct} = F \times EF_3 \times 44/28\ kg\ N_2O/year$, where F is the annual amount of urine and dung in kg N/year deposited by grazing animals on pasture, range, and paddock. The value of F can be estimated using the method from ICF Consulting (1999a):

$$\begin{aligned} F &= \textit{unvolatilized N excreted by subcategory i} \\ &= 0.8 \times \textit{Population of subcategory i (head)} \times [\textit{TAM}_i \textit{ (kg/head)/1,000}] \times \\ &\quad \textit{Kjeldahl N per day per 1,000 kg mass (kg/day)} \times \\ &\quad \textit{percentage of manure i on pasture/range/paddock} \times 365 \textit{ days per year}. \end{aligned} \tag{A26}$$

We take the Typical Animal Mass (*TAM*) in the year 2010 according to the U.S. Environmental Protection Agency (2012, table A-173) and convert it to kg/head. The *TAM* for calves is 40 kg at birth and 234 kg at weaning, averaging 137 kg; the *TAM* for steers stockers, heifers stockers, cows, and bulls are 330, 324, 613, and 919 respectively. Kjeldahl N per day per 1,000 kg mass (kg/day) takes the value of 0.34 for all subcategories listed above. Thus, F can be calculated as:

$$\begin{aligned} F &= 0.8 \times (325 \times 137 + 60 \times 324 + 400 \times 613 + 15 \times 919)/1,000 \times \\ &\quad 0.34 \times 100\% \times 365 \\ &= 32,062. \end{aligned} \tag{A27}$$

EF_3 is the emission factor for N_2O emissions from urine and dung deposited by grazing animals on pasture, range and paddock in kg N_2O/kg N. EF_3 takes a default value of 0.02 with uncertainty range between 0.007 and 0.06 (Intergovernmental Panel on Climate Change, 2006, table 1 1.1). Therefore:

$$\begin{aligned} N_2O_{direct} &= F \times EF_3 \times 44/28 = 32,062 \times 0.02 \times 44/28 \\ &= 1,008 \textit{ kg } N_2O\textit{/year; or } 1,692 \textit{ kg } N_2O\textit{/production period}. \end{aligned} \tag{A28}$$

In addition to direct N_2O emissions, emissions of N_2O also occur through the volatilization and deposition of N as NH_3 and nitrogen oxides and their products back into soils,[9] which can be calculated as $N_2O_{volatilization} = F \times Frac_1 \times EF_4 \times 44/28$, where F is the annual amount of urine and dung deposited by grazing animals on pasture, range, and paddock in kg N/year, which can be calculated as:

$$\begin{aligned} F &= \textit{Population of subcategory i (head)} \times [\textit{TAM}_i \textit{ (kg/head)/1,000}] \times \\ &\quad \textit{Kjeldahl N per day per 1,000 kg mass (kg/day)} \times \\ &\quad \textit{percentage of manure i on pasture/range/paddock} \times 365 \textit{ days per year} \\ &= (325 \times 137 + 60 \times 324 + 400 \times 613 + 15 \times 919)/1,000 \times 0.34 \times 365 \\ &= 40078. \end{aligned} \tag{A29}$$

The fraction of F that volatilizes as NH_3 and NO_x is denoted as $Frac_1$, which takes a default value of 0.2 with uncertainty range between 0.05 and 0.5 (Intergovernmental Panel on Climate Change, 2006, table 11.3). EF_4 is the emission factor for the atmospheric deposition of N on soils. EF_4 takes a default value of 0.01 with uncertainty range between 0.002 and 0.05 (Intergovernmental Panel on

[9] The other possible way is through nitrogen leaching and runoff in some regions. In the Rolling Plains we regard it as zero based on expert opinion.

Climate Change, 2006, table 11.3), thus:

$$\text{(A30)} \quad \begin{aligned} N_2O_{volatilization} &= F \times Frac_1 \times EF_4 \times 44/28 \\ &= 40078 \times 0.2 \times 0.01 \times 44/28 \\ &= 126 \textit{ kg } N_2O\textit{/year; or } 212 \textit{ kg } N_2O\textit{/production period.} \end{aligned}$$

Together these equations yield:

$$\text{(A31)} \quad N_2O_{direct} + N_2O_{volatilization} = 1,692 + 212 = 1,904 \textit{ kg } N_2O\textit{/production period.}$$

Give that one unit of N_2O has the same global warming potential as 310 units of CO_2, manure N_2O emissions are equivalent to 590,240 kg CO_2 per production cycle, or 651 tons CO_2 per production cycle.

Protein Supplement

We calculate GHG emissions in one pound of supplemental protein using soybean meal. According to the American Soybean Association (2012), one bushel (sixty pounds) of soybean yields about forty-eight pounds of soybean meal. Five-year average GHG emissions for soybeans between 1996 and 2000 are estimated as 15.1 pounds of CO_2 per bushel (Field to Market, 2012). To produce the 96,000 pounds of soybean meal required by the typical farm in the 120-day period, GHG emissions are estimated to be $96,000/48 \times 15.1 = 30,200$ pounds CO_2, or 15.1 tons CO_2 equivalent.

CO_2 from Energy Use

Ryan and Tiffany (1998) report fuel-related energy expenses of $10.24 per head for cow-calf operators in 1995. We use the energy-use data breakdown from Ryan and Tiffany (1998): 6.07 gallons for diesel, 0.74 for gasoline, and 1.62 for LP gas, and 59.24 kWh for electric. After converting all the units to BTU based on 124,884 BTU/gallon and 3,413 BTU/kWh, we have 758,048 BTU for diesel, 92,414 for gasoline, 202,312 for LP gas, and 202,186 for electric.

According to the conversion unit provided in table S1, GHG emissions from diesel, gasoline, LP gas, and electric are 54.89, 64.80, 126.18, and 348.66 kg CO_2 equivalent. Overall, CO_2 emissions per head for cow-calf operators are 1,088.55 kg CO_2 equivalent. Given 400 head of cattle on our example farm, farm energy use generates 435,420 kg, or 480 tons CO_2 equivalent.

Use of Fertilizers (Nitrogen, Phosphorus, Potassium, Lime)

The price of N and P is 0.6 dollars per pound, obtained from district 2 (Southern Plains) data accessible from http://agecoext.tamu.edu/resources/crop-livestock-budgets/by-district.html. The ratio of N and P applied to the grass per acre in one production season on a representative farm is 2.5:1.

Equivalent carbon emission for the production, packaging, storage, and distribution of N and P takes the mean value of 1.3 kg CE/kg and 0.2 kg CE/kg (Lal, 2004, table 5).

Carbon Sequestration

Total GHG sequestration per year for Texas rangeland is 447 kg C per hectare (Potter et al., 1999), or 180.90 kg C per acre.