Energy and Carbon Costs of Selected Cow-Calf Systems

Cody J. Zilverberg,[1] *Phillip Johnson,*[2] *Justin Weinheimer,*[3] *and Vivien G. Allen*[4]

Authors are [1]*Graduate Research Assistant, Department of Plant and Soil Science,* [2]*Professor and* [3]*Post-doc Research Associate, Department of Agricultural and Applied Economics, and* [4]*Horn Professor, Department of Plant and Soil Science, Texas Tech University, Lubbock, TX 79409, USA.*

Abstract

Fossil fuel-derived inputs can increase cow-calf production per unit of land or labor but can raise financial and environmental concerns. Eleven US cow-calf systems from nine ecological regions in Iowa, South Dakota, Tennessee, and Texas were analyzed to determine quantities of energy used and carbon (C) emitted due to fossil fuel use (excluding emissions from soils and biota) and to determine how management and environment influenced those quantities. Total energy and C cost, calculated cow^{-1} or ha^{-1}, were highly correlated (0.99). Energy use cow^{-1} and ha^{-1} varied greatly across systems, ranging from 3 000 to 12 600 megajoules (MJ) $\cdot cow^{-1} \cdot yr^{-1}$ and from 260 to 20 800 $MJ \cdot ha^{-1} \cdot yr^{-1}$. As stocking rate increased, $MJ \cdot cow^{-1}$ increased at an increasing rate. Differences in quantity of fertilizer accounted for most variation in energy use. Fertilizer allowed higher stocking rates but reduced energy efficiency of liveweight marketed. Compared to intensive, higher stocking rate systems, rangeland systems based on native or naturalized forages used little or no fertilizer, but used more energy cow^{-1} for crude protein (CP) supplementation, fencing, and pickup trucks. Across all systems, energy used to produce winter feed ranged from 0% to 46% of total energy. Northern systems used higher percentages of total energy for winter feed and fed for more days $year^{-1}$, but southern systems that included large amounts of bermudagrass (*Cynodon dactylon* L.) hay used the most $MJ \cdot cow^{-1}$ for winter feed. Systems with high $MJ \cdot cow^{-1}$ were vulnerable to shocks in energy prices. Reducing energy use and C emissions from cow-calf operations is possible, especially by reducing fertilizer and hay use, but would likely reduce productivity ha^{-1}. Forages with high nitrogen use efficiency, locally adapted plants and animals, and replacement of hay with unfertilized dormant forage and CP supplementation could reduce energy use.

Resumen

Insumos derivados de los combustibles fósiles pueden incrementar el costo por unidad de tierra o trabajo dentro del sistema vaca-becerro pero a la vez pueden incrementar las preocupaciones financieras y medioambientales. Once sistemas de producción vaca-becerro de 9 regiones ecológicas de Estados Unidos ubicadas en Iowa, Dakota del Sur, Tennessee, y Texas se analizaron para determinar las cantidades de energía consumidas y el carbono (C) emitido debido al uso de combustibles fósiles (exceptuando las emisiones inherentes al suelo y al medioambiente), y a la vez determinar como el manejo y el medioambiente afecta estas cantidades. El total de energía y costo de carbón C, calculado por vaca o hectárea fue altamente relacionado (0.99). El uso de energía por vaca y hectárea tuvo una gran variación en los sistemas, fluctuando de 3 000 o 12 600 $MJ \cdot vaca^{-1} \cdot año^{-1}$ y de 260 a 20 800 $MJ \cdot ha^{-1} \cdot año^{-1}$. Mientas, la densidad animal incrementaba $MJ \cdot vaca^{-1}$ también se incrementó a una tasa a la alza. Las diferencias en cantidad de fertilizante fueron las que provocaron una mayor variación en uso de energía. El uso de fertilizante permite una alta densidad de animales pero reduce la eficiencia energética del peso vivo comercializado. En comparación con el uso intensivo, sistemas de alta carga animal, sistemas de pastoreo basados en forrajes nativos o naturalizados usan una pequeña cantidad o no fertilizante en absoluto, pero a su vez usan más energía $vaca^{-1}$ debido a la suplementación de proteína cruda, alambrado, y uso de vehículos. En todos los sistemas, la energía usada para producir alimentos durante el invierno fluctúo de un 0% a 46% del total de la energía consumida. Los sistemas del norte del país usan mayores porcentajes del total de la energía consumida para proveer alimentación durante el invierno por mas días al $año^{-1}$, mientras que los sistemas del sur que incluyen grandes cantidades de heno de pasto bermuda (*Cynodon dactylon* L.) usan la mayor cantidad de $MJ \cdot vaca^{-1}$ para alimentación durante el invierno. Los sistemas con alto MJ $vaca^{-1}$ fueron los más vulnerables a cambios bruscos en los precios de energía. La reducción del uso de energía y las emisiones de C en los sistemas de producción vaca-becerro es posible, especialmente mediante la reducción de fertilización y uso de heno, aunque podría ocasionar reducción en la productividad ha^{-1}. Los forrajes con alta eficiencia en el uso de nitrógeno, así como plantas y animales adaptados a las condiciones locales, y el reemplazo de heno por forrajes no fertilizados y el uso de suplementación proteica podría reducir el uso de energía.

Key Words: beef cattle, carbon emission, climate change, feed costs, fossil fuel

INTRODUCTION

Many agricultural inputs, including fertilizers, pesticides, and diesel fuel, rely on fossil fuels for their production or feedstock. These hallmarks of intensive agriculture increase productivity per unit of land and/or labor and reduce the need to expand cultivation into fragile ecosystems (Burney et al. 2010).

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Correspondence: Cody J. Zilverberg, Dept of Plant and Soil Science, Texas Tech University, Box 42122, Lubbock, TX 79409, USA. Email: cody.zilverberg@ttu.edu

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However, reliance on fossil fuel-based inputs exposes producers to price fluctuations, contributes to food insecurity for energy importing countries, releases greenhouse gasses, and constitutes unsustainable use of finite resources. Recent fluctuations in fertilizer prices, food prices, and climate change concerns highlight the need to better understand society's fossil fuel use.

Previous estimates of energy use in production of beef and livestock feeds have shown that fossil fuel use varies greatly across regions, crop types, and management styles (see Heichel [1973] and Ward et al. [1977]). Research on fossil fuel energy in livestock production has provided estimates of energy use by beef feedlots (Cook 1976; Cook et al. 1976, 1980; Heitschmidt et al. 1996), several western US range types (Cook 1976; Cook et al. 1976, 1980; Heitschmidt et al. 1996), a pair of central Great Plains cow-calf operations (Cook et al. 1980), and several improved pasture types for beef cows and steers in Alabama, Indiana, and North Dakota (Hoveland 1980). However, there is little recent work examining specific cow-calf management practices in relation to their energy use intensity and carbon (C) emissions under different environmental conditions.

Our objective was to determine how much fossil fuel energy was used to operate selected US cow-calf production systems across a range of stocking rates, management strategies, and environmental conditions. A further objective was to determine C emission values from agricultural activities associated with these cow-calf systems. Such information is needed to enable producers, researchers, and policy makers to develop strategies to improve agricultural energy-use efficiency, conserve energy, and reduce negative environmental impacts.

METHODS

Eleven cow-calf production systems from nine ecological regions in four states (Iowa, South Dakota, Tennessee, and Texas) were investigated and evaluated for fossil fuel energy consumption and C emissions (Fig. S1; available online at http://dx.doi.org/10.2111/REM-D-10-00190.s5). Budgets for each system resembled financial budgets, except that each line item had an associated "cost" in megajoules (MJ) of energy in addition to its expense in dollars. Budgets for the South Dakota and Tennessee systems were based on actual cow-calf operations and extension budgets for those states (University of Tennessee, Department of Agricultural and Resource Economics [UT] 2007; South Dakota State University, Department of Economics [SDSU] 2008). For all other systems, a revenue and expense budget published by the agricultural extension service in that region (Ag Decision Maker 2008; Extension Agricultural Economics 2009) was used and budget parameters were validated and adjusted through communication with a livestock extension specialist, range extension specialist, and/or producer in each region. All budgets were from years 2007 to 2009 and used a standard set of prices for common inputs except land rent, which was site-specific. Livestock prices kg^{-1} were as follows: \$2.36 for steers, \$2.14 for heifers, \$1.43 for cull bulls, and \$1.17 for cull cows.

Fossil fuel energy cost of each system included onsite and offsite inputs required to maintain the cow herd for one calendar year. We included all inputs that made significant contributions to energy and/or financial costs of cow-calf production. The most important inputs were fertilizer, pesticides, machinery, fuel, transportation, feed, fencing, buildings, herd bulls, veterinary expenses, labor, and land rent. No systems used irrigation. Input use and stocking rates were such that they would not compromise the biological ability of the system to continue indefinitely. A portion (12–26% of heifers) of each year's calf crop was retained as replacement heifers with the remainder marketed as stocker calves at weaning. On an annual basis, cows were retained in the herd, culled and sold at market (10–25%), or died (0–8%). Stocking rates were calculated as number of $cows \cdot ha^{-1}$ of permanent pasture $\cdot yr^{-1}$. Energy values presented on a cow^{-1} basis were calculated by summing energy inputs for the entire system and dividing by the number of cows in the system.

$$MJ \cdot cow^{-1} = \left(\sum \text{system energy inputs}\right) / \#\text{of cows in system} \quad [1]$$

Energy per kg of liveweight marketed was calculated by dividing total system energy by the sum of the weight of cull cows, cull bulls, and marketed weaned calves.

$$MJ \cdot kg^{-1} \text{ liveweight marketed} = \left(\sum \text{system energy inputs}\right) / (\text{kg cull cows} + \text{kg cull bulls} + \text{kg marketed weaned calves}) \quad [2]$$

Energy ha^{-1} was calculated by dividing total system energy, which included energy required for production of supplemental forages (hay, silage, and corn stalks [*Zea mays* L.]), by system area, which included permanent pasture areas only.

$$MJ \cdot ha^{-1} = \left(\sum \text{system energy inputs}\right) / \text{permanent pasture} \quad [3]$$

In addition to calculating total energy of the cow-calf production phase, a separate calculation was made to estimate energy required to transport marketed calves from the cow-calf production site to a feedlot. Travel was based on distance to Amarillo, Texas (Google Maps; http://maps.google.com). For this calculation, all marketed calves were assumed to weigh 240 kg. Energy required for transportation to feedlot was calculated as:

$$\mathrm{FT}\left(\mathrm{MJ \cdot calf^{-1}}\right) = \text{calf weight(kg)} \times \text{distance(km)} \times 0.00177\ \mathrm{MJ \cdot kg^{-1} \cdot km^{-1}} \quad [4]$$

where FT is feedlot transportation. Percentage of energy due to transportation to feedlot was calculated as:

$$\mathrm{FTP}(\%) = 100 \times \left(\mathrm{FT \cdot calf^{-1}}\right) / \left(\mathrm{FT \cdot calf^{-1}} + \text{Total energy} \cdot \mathrm{calf^{-1}}\right) \quad [5]$$

where FTP is feedlot transportation percentage, and Total energy $\cdot calf^{-1}$ was calculated as:

$$\text{Total energy} \cdot \mathrm{calf^{-1}(MJ)} = \text{calf weight(kg)} \times \mathrm{MJ \cdot kg^{-1}} \text{ liveweight marketed} \quad [6]$$

Table 1. Mean annual temperature, precipitation, and elevation for 11 cow-calf systems in nine ecological regions in the United States (Data from the National Oceanic and Atmospheric Administration [NOAA] 2002a, 2002b, 2002c, 2002d).

System[1]	Temperature, °C			Mean annual precipitation, mm	Elevation, m
	Minimum	Mean	Maximum		
TX-winterpasture	13	19	25	1 149	165
TN-highlandrim	9	15	21	1 377	282
IA-southeast	5	11	16	911	253
TX-centralimproved	11	17	24	754	393
SD-silage	−1	7	14	471	561
SD-distillers	−1	7	14	471	561
TX-coastalbend	16	22	29	698	60
TX-centralrange	11	17	24	754	393
TX-rollingplains	10	17	24	705	386
TX-highplains	6	14	22	526	1 041
TX-transpecos	10	19	27	357	900

[1]Climate data in each region is from the following locations: TX-winterpasture: Tyler, Texas; TN-highlandrim: Winchester, Tennessee; IA-southeast: Ottumwa, Iowa; TX-centralimproved and TX-centralrange: Stephenville, Texas; SD-silage and SD-distillers: Highmore, South Dakota; TX-coastalbend: Alice, Texas; TX-rollingplains: Seymour, Texas; TX-highplains: Tulia, Texas; TX-transpecos: Ft. Stockton, Texas.

Locations

The 11 systems in nine ecoregions were selected to represent diverse ecological zones where cow-calf production occurred, with management ranging from extensive rangeland systems based on native and naturalized forages to intensive pastureland systems based on introduced forages (Fig. S1). Stocking rates ranged from 0.04 to 1.65 cows $\cdot$ ha^{-1} $\cdot$ yr^{-1} (Table S1; available online at http://dx.doi.org/10.2111/REM-D-10-00190.s1). Mean annual temperatures and precipitation across all regions ranged from 7°C to 22°C and 357 to 1 377 mm (Table 1). Within two locations (South Dakota and central Texas), two alternative production systems were evaluated to determine management effects on energy use without the confounding impact of environmental differences. Seven budgets, including six locations, were based on Texas cow-calf operations. Texas is the largest cow-calf producing state in the United States, with more than twice as many beef cows as Oklahoma, the second largest producing state (National Agricultural Statistics Service [NASS] 2010). The ecological zones represented by Texas' seven budgets were diverse, with the range in annual precipitation across Texas sites almost as broad as the range among the four states in this study (Table 1). Other states in this analysis were also among the largest cow-calf producing states in the United States, with national ranking as follows: South Dakota, 5; Tennessee, 9; and Iowa, 12 (NASS 2010).

Cow-Calf Systems

Stocking rate, mean cow size, breed type, calving season, and primary forage species differed among cow-calf systems (Table S1), as did inputs such as fertilizers and mechanical operations (Table 2). The principal energy-dependent categories of inputs were common across most systems, although quantity sometimes varied greatly. The Tennessee system produced hay on land that was also grazed, but supplemental forage for all other systems was purchased from offsite (nongrazed) land. All systems provided salt and mineral supplement to cows to meet nutritional requirements. Further details and unique aspects of each system are described below. Systems are ordered from highest to lowest stocking rate, except for the central Texas region, which included two systems with different stocking rates.

Eastern Texas (TX–Winterpasture). This intensive pasture system assumed autumn-calving cows remained on well maintained bermudagrass (*Cynodon dactylon* L.) at a moderate stocking rate throughout the year. In autumn, annual ryegrass (*Lolium multiflorum* Lam.) was interseeded into about 17% of the bermudagrass area to provide higher quality winter grazing. Bermudagrass hay was also fed during winter.

Tennessee Highland Rim (TN-Highlandrim). During spring and summer, cows grazed in "Max Q" novel-endophyte tall fescue (*Festuca arundinacea* Schreb.) pasture interseeded with red (*Trifolium pratense* L.) and white (*Trifolium repens* L.) clovers. Calving occurred in late winter to early spring. One hay cutting occurred on selected pastures in late spring, forage was stockpiled for autumn grazing on half of the area, and fescue-clover hay was fed to cows during winter to supplement grazing as needed.

Southeastern Iowa (IA-Southeast). Spring-calving cows grazed in improved (0.2 ha $\cdot$ cow^{-1} $\cdot$ yr^{-1}) and unimproved pastures (0.8 ha $\cdot$ cow^{-1} $\cdot$ yr^{-1}) for 5 to 5.5 mo (from about 1 May to about 1 October) and corn stalks (0.88 ha $\cdot$ cow^{-1}) for 2 to 2.5 mo. Alfalfa (*Medicago sativa* L.)-bromegrass (*Bromus inermis* L.) hay and corn grain were fed during winter. Limited quantities of herbicides and fertilizers were applied to improved pastures but not to unimproved pastures.

Central Texas (TX-Centralrange and TX-Centralimproved). Budgets were developed for two spring-calving systems in central Texas. The first was a low-input system (TX-centralrange) that depended primarily on rangeland grazing. Cows were fed a small amount of hay (136 kg $\cdot$ cow^{-1} $\cdot$ yr^{-1}), and provided a 20% crude protein (CP) supplement made from corn and cottonseed (*Gossypium hirsutum* L.) meal.

In the second system (TX-centralimproved), a combination of bermudagrass (0.7 ha $\cdot$ cow^{-1} $\cdot$ yr^{-1}) and rangeland (0.8 ha $\cdot$ cow^{-1} $\cdot$ yr^{-1}) was used. Cows were fed a relatively large amount of hay (1 123 kg $\cdot$ cow^{-1} $\cdot$ yr^{-1}) with a lesser quantity of 40% CP cottonseed meal.

Table 2. Selected energy-dependent inputs in 11 cow-calf systems. Systems include rangeland and pastureland systems selected to represent a range of stocking rates across diverse ecosystems.

System	Fertilizer applied to pasture, $kg \cdot ha^{-1} \cdot yr^{-1}$	Supplemental forage, $kg\ cow^{-1} \cdot yr^{-1}$	Additional supplementation, $kg \cdot cow^{-1} \cdot yr^{-1}$	Mechanical operations in pasture	Pickup truck, $km\ cow^{-1} \cdot yr^{-1}$	Fencing, $km\ cow^{-1} \cdot yr^{-1}$
TX-winterpasture	Bermudagrass: 101 N, 25 P_2O_5, 51 K_2O, 740 lime; ryegrass: 202 N, 56 P_2O_5, 112 K_2O, 740 lime	Hay,[1] 1 361	Salt and mineral, 30	Bermudagrass establishment, herbicide application, fertilizer application, shredding, no-till planting rye/ ryegrass, disking	31	0.06
TN-highlandrim	34 N, 15 P_2O_5, 22 K_2O, 448 lime	Hay,[2] 1 814	Salt and mineral, 45	Tall fescue establishment, shredding, no-till planting clover, fertilizer application, hay harvest	64	0.08
IA-southeast	Improved pasture: 67 N, 22 P_2O_5, 22 K_2O; unimproved pasture: none	Hay,[1] 1 905; corn stalks,[1] 0.87 ha	Salt and mineral, 27; corn, 102	Fertilizer application	30	0.14
TX-centralimproved	Bermudagrass: 86 N, 20 P_2O_5, 45 K_2O; unimproved pasture: none	Hay,[1] 1 122	Salt and mineral, 22; 40% crude protein, 68	Bermudagrass establishment, herbicide application, fertilizer application	44	0.16
SD-silage	None	Hay,[1] 588; corn silage,[1] 2 939	Salt and mineral, 9	None	91	0.14
SD-distillers	None	Hay,[1] 624; baled corn stover,[1] 1 578	Salt and mineral, 20; distiller's grains, 254	None	110	0.14
TX-coastalbend	Bermudagrass: 101 N, 22 P_2O_5, 45 K_2O; unimproved pasture: none	Hay,[1] 479	Salt and mineral, 31; 40% crude protein, 85	Bermudagrass establishment, herbicide application, fertilizer application	29	0.16
TX-centralrange	None	Hay,[1] 136	Salt and mineral, 22; 20% crude protein, 227	None	77	0.22
TX-rollingplains	None	None	Salt and mineral, 14; 20% crude protein, 227	Brush control	110	0.21
TX-highplains	None	Hay,[1] 127	Salt and mineral, 23; 40% crude protein, 159	None	62	0.26
TX-transpecos	None	Hay,[1] 3	Salt and mineral, 23; 40% crude protein, 109; oats, 0.04	None	266	0.56

[1]Forage harvested off-site.
[2]Forage harvested from pasture.

South Dakota (SD-Silage and SD-Distillers). Two system budgets, differing little except in winter feed type, were developed for late winter to early spring-calving cows in central South Dakota. Cows in both systems grazed native and naturalized forages for 203 d during spring, summer, and autumn. Both operations fed cattle an average of 162 d during winter, from 1 December to 10 May. In SD-silage, cows were fed a mixture of corn silage and triticale (*X Triticosecale* W.) hay during winter. All forages were grown on the farm with low levels of inputs. In SD-distillers, winter feed was baled corn stover, alfalfa hay, and distiller's grains.

Gulf Coast of Texas (TX-Coastalbend). Similar to TX-centralimproved, this system included bermudagrass (0.4 $ha \cdot cow^{-1} \cdot yr^{-1}$) and rangeland (3.6 $ha \cdot cow^{-1} \cdot yr^{-1}$) for late winter to early spring-calving cows. Intermediate quantities of 40% CP cottonseed meal and bermudagrass hay were fed to supplement grazing during winter.

Texas Rolling Plains (TX-Rollingplains). Cattle in these winter-calving systems grazed in unimproved pastures year-round and were fed a 20% CP supplement over winter. Unique to this system were mechanical brush control (0.13 $ha \cdot cow^{-1} \cdot yr^{-1}$ at \$173 $\cdot ha^{-1}$) and controlled burning (0.37 $ha \cdot cow^{-1} \cdot yr^{-1}$ at a rate of \$49 $\cdot ha^{-1}$). Controlled burning was assumed to have a negligible energy cost and was not included in the energy analysis.

Texas High Plains (TX–Highplains). Like TX-rollingplains, cows in this system grazed unimproved forages year-round but calved in spring. During winter, cows were fed a 40% CP cottonseed meal supplement to compensate for low protein value of dormant native forage. A small amount of purchased bermudagrass hay was budgeted for weather-related emergencies.

Trans Pecos Region of Southwestern Texas (TX–Transpecos). This system had the lowest stocking rate in the analysis. Besides rangeland grazing, spring-calving cows were supplemented with a 40% CP cottonseed meal. This was the only system that budgeted a small amount of purchased bermudagrass hay and oats (*Avena sativa* L.) for horse feed. Horses were used due to the rugged terrain and extensive nature of the system. Horse-use incurred very little energy cost but may have reduced pickup truck use. Nevertheless, pickup trucks were used more in this system than any other.

Energy Values

Total energy cost of an agricultural input is the sum of direct and indirect energy used in its fabrication, packaging, transportation, and when appropriate, consumption. Direct energy "is used as an immediate input in the production of a given good or service," whereas indirect energy is "required to produce other inputs (e.g., materials, equipment, etc.)" (Gardner and Robinson 1993, p. 2). Thus, depreciable assets (e.g., tractors and barns) constitute use of indirect energy. Many inputs to cow-calf operations require both direct and indirect energy inputs. For instance, haying requires use of diesel fuel (direct energy) and haying equipment (indirect energy). Thus, the total energy cost of hay is the sum of direct and indirect energy cost. All energy consumption values are expressed as the sum of direct and indirect energy inputs unless specified otherwise.

Energy values for many inputs used in farming and livestock production including seed, feed, buildings, fuel, fertilizer, pesticides, and machinery operations were available from the literature (Table S2; available online at http://dx.doi.org/10.2111/REM-D-10-00190.s2). In some cases, input values were estimated by the authors (Table 3) because necessary values were unavailable in the literature or were not specific enough for this analysis. One example was hay, which varied greatly in energy intensity across regions and production practices (Table 3). Energy required to produce polyethylene haywrap and silage bags was estimated using the energy value for low density polyethylene (Thompson and Sorvig 2000). Energy required to establish forages was included. For perennial forages, establishment cost was divided by the anticipated stand life to obtain an annual energy cost. Energy values for miscellaneous costs, including veterinarian supplies, salt, minerals, and seed were estimated using the dollar-to-energy conversion methodology (Heichel 1973), based on a value of 7.29 $MJ \cdot US\$^{-1}$ for 2008 (US Energy Information Administration [EIA] 2009; Bureau of Economic Analysis [BEA] 2011). The dollar-to-energy conversion methodology was used in conjunction with estimated energy input in fencing (Cook et al. 1980) to calculate energy embodied in regional fences of different expenses and styles. No energy value was assigned to human labor.

Direct and indirect energy use by field equipment was estimated based on machinery weight, anticipated useful life, repair bills, and in-field fuel consumption (Bowers 1992). Coefficients for energy sequestered in repairs can be found in Bowers (1992), Doering (1980), and American Society of Agricultural Engineers (ASAE; 2000). Useful life values were provided by Bowers (1992, 1994), ASAE (2000), and Donald Zilverberg (personal communication, October 2009). Following Bowers (1992), data from Pimentel et al. (1973, as cited by Bowers 1992) were used for $MJ \cdot kg^{-1}$ of farm equipment and Loewer et al. (1977, as cited by Bowers 1992) for $MJ \cdot kg^{-1}$ for transportation and distribution of manufactured products. Estimates of in-field fuel consumption were based on Bowers (1992, 1994), West and Marland (2002), Cook (1980), Fluck (1992), and Donald Zilverberg (personal communication, October 2009).

Agricultural By-Products and Coproducts. Coproducts are multiple final products generated by a single production process. In this analysis, total energy required to produce all coproducts from a given field was estimated and then allocated among coproducts in proportion to each product's contribution to total monetary revenue. We followed Pimentel et al. (2007) to calculate energy cost of corn grain in Iowa and dried distiller's grains in South Dakota, except for excluding human labor energy.

Carbon Values

C emission values for agricultural activities came from West and Marland (2002) or were estimated by the authors based on West and Marland's (2002) coefficients. This method assigns a specific C emission value for each type of energy source. For operations for which the fossil fuel source was not known, we assumed the source was 50% diesel fuel and 50% electric. C emissions from soils and biota were not included in the analysis.

Correlations

Correlation coefficients were calculated using the CORREL function in Microsoft Excel. Excel was also used to fit curves to data. Curves were drawn using R (R Development Core Team 2008).

RESULTS

Total Energy Use

As stocking rate increased, energy input ha^{-1} and cow^{-1} increased (Figs. 1A and 1B). Extensive, low-stocking rate systems that grazed native range (TX-centralrange, TX-rollingplains, TX-highplains, TX-transpecos) used the least energy ha^{-1} because of their large land area, and had the lowest energy use cow^{-1} (Table 4), with the exception of TX-transpecos. The highest stocking rate system (TX-winterpasture), based on bermudagrass and annual ryegrass, used more than twice as much energy ha^{-1} (20 700 MJ) as any other system. In general, systems with bermudagrass as the primary forage (TX-winterpasture, TX-centralimproved, and TX-coastalbend) used disproportionally high amounts of energy relative to stocking rates, primarily due to fertilization of bermudagrass pastures. Energy use ha^{-1} (coefficient of variation [CV]: 1.46) varied more than energy use cow^{-1} (CV: 0.46); energy use ha^{-1} also had a wider range of values (ratio of maximum to minimum values was 80:1) than

Table 3. Energy costs and carbon emissions from inputs required by 11 cow-calf systems. Systems include rangeland and pastureland systems selected to represent a range of stocking rates across diverse ecosystems. Not all systems used all inputs.

Input item	Unit	MJ · unit^{-1}	kg C · unit^{-1}	Sources
Hay				
Bermudagrass hay (Texas)	kg	2.23	0.036	1
Alfalfa-brome hay (Iowa)	kg	0.91	0.018	1
Alfalfa hay (South Dakota)	kg	0.58	0.0125	1
Triticale hay (South Dakota)	kg	1.41	0.024	1
Barley hay (South Dakota)	kg	1.67	0.029	1
Corn products				
Corn	kg	3.28	0.056	1,2
Corn (South Dakota)	kg	1.84	0.030	1
Corn stover (baled, South Dakota)	Mg	516.44	8.351	1
Corn stalks (grazed, Iowa)	ha	292.71	4.918	1,2
Corn silage	Mg	1 092.02	—	3
Corn silage (South Dakota)	Mg	540.01	10.388	1
Dried distiller's grains	Mg	948.77	19.362	1,2
Supplements				
Cottonseed meal (40% crude protein)	kg	3.84	0.065	1,4
Cottonseed meal/corn (20% crude protein)	kg	3.88	0.063	1,4
Salt	kg	1.76	0.035	5
Mineral	kg	5.78	0.113	5
Oats	kg	4.32	0.084	6
Other				
Miscellaneous	$ unit	7.29	0.142	5
Veterinary	hd	167.67	3.277	5
Transportation	kg · km	0.00177	0.00004	7
Netwrap (Alfalfa)	bale	13.95	0.306	1
Netwrap (Small grains)	bale	22.83	0.501	1
Silage bag (3 × 75 m)	Mg silage	35.96	0.789	1
Annual depreciation				
Pickup	km	0.82	0.017	1
Service buildings	m^2	35.33	0.691	8
Barbed wire fence (8 strands, steel and cedar)	km	1 998.24	39.059	3,5
Barbed wire fence (5 strands, steel and cedar)	km	1 808.36	35.347	3
Barbed wire fence (3 strands, steel posts)	km	1 085.02	21.208	3,5
Hay feeding wagon	yr	6 638.78	137.711	1
Tractor with loader	hr	56.90	1.180	1
Tractor and mixer wagon	hr	156.53	3.247	1
Herd bull	hd	150.00	2.932	1

[1]Calculated by the authors; [2]Pimentel et al. 2007; [3]Cook et al. 1980; [4]National Cottonseed Products Association 2002; [5]Estimated by the authors using the dollar to energy conversion value of 7.29 MJ · US$$^{-1}$ for 2008 (US Energy Information Administration [EIA] 2009; Bureau of Economic Analysis [BEA] 2011). For a discussion of the method, see Heichel 1973; [6]Weaver 1980; [7]Fluck 1992; [8]Doering 1980.

energy use cow^{-1} (ratio of maximum to minimum values was 4.1:1). Energy consumed kg^{-1} liveweight marketed had a CV (0.48) and maximum to minimum ratio (3.6:1) similar to cow^{-1} values. In addition, the relationship between stocking rate and total energy kg^{-1} liveweight marketed (correlation: 0.69) was similar to the relationship between stocking rate and energy use cow^{-1}.

Direct vs. Indirect Energy

Averaged across the 11 cow-calf systems, direct energy accounted for 78% of total energy used, ranging from a low of 69% to a high of 91% (Table 4). Direct energy cow^{-1} ranged from 2 100 to 11 400 and was highly correlated (0.99) with total energy. In contrast, indirect energy cow^{-1} had a narrower range, from 800 to 1 700, and was poorly correlated with total energy (0.18). Direct energy, as a percentage of total energy, was positively correlated with total energy (0.75) and stocking rate (0.37). Thus, indirect energy costs cow^{-1} tended to be proportionately greater for low intensity and low stocking rate systems. This suggests omission of indirect energy inputs could lead to biased results when comparing relative energy use of alternative cow-calf production systems across a range of energy intensities and stocking rates.

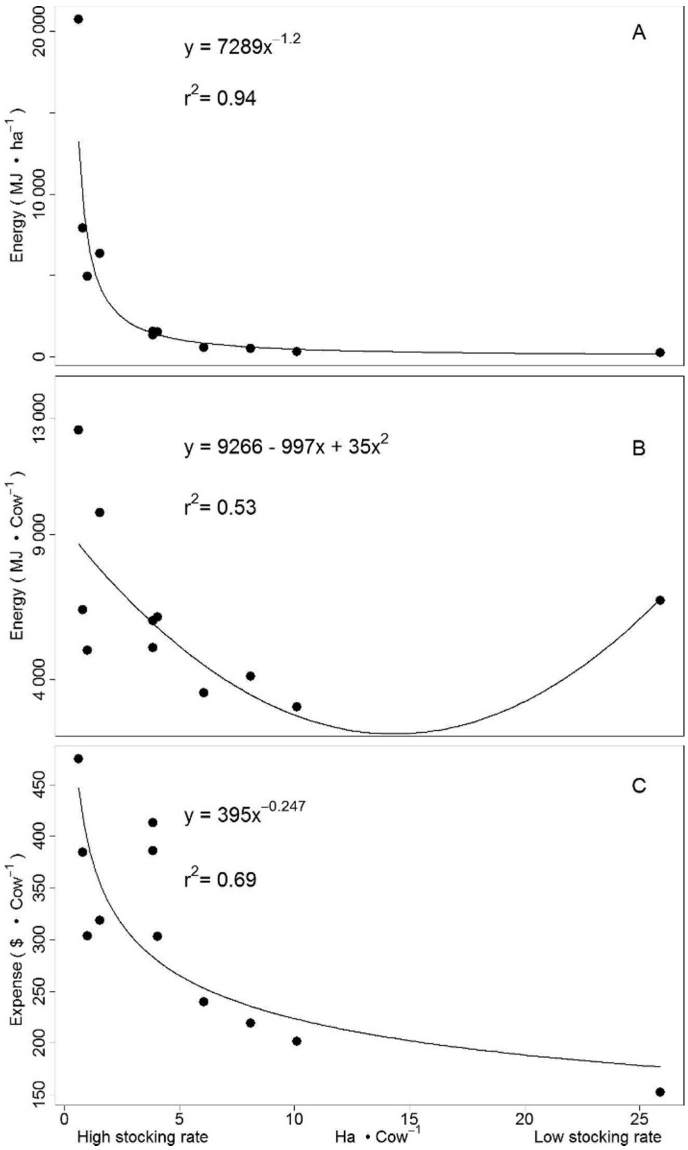

Figure 1. The relationship between stocking rate of 11 cow-calf systems and **A**, megajoules (MJ) · ha^{-1}; **B**, MJ · cow^{-1}; and **C**, expense of land rent, land inputs, and feed ($ · cow^{-1}). Systems include rangeland and pastureland systems selected to represent a range of stocking rates across diverse ecosystems. The x-axis uses the inverse of stocking rate, rather than stocking rate, because it provides a clearer visual representation of the data.

Relative Contribution of Energy Components

Relative proportions of energy components (fertilizer, fuel and machinery, pesticides, fencing, CP supplement, and other) remained the same for a system whether calculated on a cow^{-1} or ha^{-1} basis. However, there were large differences within and across systems when total energy was evaluated on a cow^{-1} or ha^{-1} basis (Table 4; Figs. 1A and 1B).

The major energy consuming components of most agricultural systems include irrigation, fertilizer, fuel, and machinery. While irrigation was not used in any of the cow-calf systems in this analysis, fertilizer, fuel, and machinery together accounted for more than half of energy used cow^{-1} by all systems except TX-highplains and TX-centralrange (Fig. 2A). Fertilizer alone accounted for most of the difference in total energy intensity among the 11 systems analyzed (Fig. 2A). Correlation between total energy cow^{-1} and fertilizer energy was 0.91. Little or no fertilizer was used in the low-stocking rate systems. Fertilizer use increased in the more intensive systems, especially in those systems that included bermudagrass (TX-coastalbend, TX-centralimproved, and TX-winterpasture).

Fuel and machinery were a large component of energy use in all systems but was poorly correlated with total energy cow^{-1} (0.26; Fig. 2A). The system requiring the most energy cow^{-1} for fuel and machinery was TX-transpecos, the system with the lowest stocking rate. The high use of fuel and machinery in the TX-transpecos system was primarily due to the need to cover the large land area typical of operations in that region. Energy consumed by pesticide use was a relatively small amount of the total system energy and was used primarily in the higher stocking rate systems (Fig. 2A). In contrast, energy in fencing cow^{-1} was inversely related to stocking rate. As with fencing, CP supplementation was generally higher in the low stocking rate systems that depended on grazing low-protein forages during winter.

Energy in the "other" category was not highly correlated with stocking rate (Fig. 2A). Veterinary costs, repairs, and salt and mineral supplements were the primary components of the "other" category. Salt and mineral supplementation cow^{-1} were similar among all systems except TN-highlandrim, which used larger quantities (45 kg · cow^{-1}) than other systems (9 to 30 kg · cow^{-1}). Also included in the "other" category was seed, a cost for TX-winterpasture (472 MJ · cow^{-1}) and TN-highlandrim (278 MJ · cow^{-1}) because a portion of their grazing was provided by annuals or short-lived perennials.

Winter Feeding Strategies

Feeding hay and grain during winter can account for nearly half of a ranch's energy expenditure (Table 5). Energy required for wintering cattle depended on energy cost of the inputs used and length of the feeding period. Primary energy costs for hay, grain, and silage production were fertilizer, mechanical operations, seed, and pesticides (data not shown).

Wintering cows in northern states (Iowa and South Dakota) included more feeding days than southern states (Texas and Tennessee), as would be expected due to the colder climate (Table 5). Despite feeding for fewer days, two of the southern production systems used similar quantities of energy on feed and supplements cow^{-1} as northern systems due to type of feedstuffs used. Percentage of total annual energy expended on winter feed was greater for northern systems than for southern systems. Southern systems that included supplemental winter feeding used more energy d^{-1} of feeding than northern systems. In one system, TX-winterpasture, ryegrass was planted to provide high quality winter grazing for its fall-calving cows. This cost 2 100 MJ · cow^{-1}, of which 1 400 MJ · cow^{-1} was for fertilizer and lime, and 600 MJ · cow^{-1} was for seed and mechanical operations.

Carbon Efficiency

C emissions cow^{-1} and ha^{-1} varied across systems (Table 6), similar to the variation in total energy use. Total energy cow^{-1} was closely correlated with kg C · cow^{-1} (0.99). Therefore, conclusions regarding energy use generally apply to C emissions as well.

Table 4. Energy expenditure of 11 cow-calf systems. Systems include rangeland and pastureland systems selected to represent a range of stocking rates across diverse ecosystems, ordered from highest to lowest stocking rate.

	Stocking rate	Total energy[1]			Direct energy[2] only	
System	$Cow \cdot ha^{-1} \cdot yr^{-1}$	$MJ \cdot ha^{-1} \cdot yr^{-1}$	$MJ \cdot cow^{-1} \cdot yr^{-1}$	$MJ \cdot kg^{-1}$ liveweight marketed	$MJ \cdot cow^{-1} \cdot yr^{-1}$	Direct energy as a percentage of total
TX-winterpasture	1.65	20 700	12 600	49	11 400	91%
TN-highlandrim	1.24	7 900	6 400	25	4 700	74%
IA-southeast	0.99	4 900	5 000	20	3 400	69%
TX-centralimproved	0.65	6 300	9 800	42	8 500	87%
SD-silage	0.26	1 600	6 000	19	5 100	84%
SD-distillers	0.26	1 300	5 100	16	4 300	84%
TX-coastalbend	0.25	1 500	6 200	24	5 300	86%
TX-centralrange	0.16	580	3 500	15	2 600	73%
TX-rollingplains	0.12	510	4 100	15	2 800	69%
TX-highplains	0.10	300	3 000	14	2 100	69%
TX-transpecos	0.04	260	6 700	26	5 000	74%

[1]Total energy includes both direct and indirect energy.

[2]Direct energy "is used as an immediate input in the production of a given good or service," whereas indirect energy is "required to produce other inputs (e.g., materials, equipment, etc.)" (Gardner and Robinson 1993, p. 2).

Economic Impacts

Economic returns to land and labor ranged from $-\$145$ cow^{-1} (TX-winterpasture) to \$208 cow^{-1} (SD-silage), with a mean of \$95 cow^{-1} (CV: 1.17; Table S3; available online at http://dx.doi.org/10.2111/REM-D-10-00190.s3). Returns to land and labor cow^{-1} were negative for the systems with the highest energy use cow^{-1} (TX-winterpasture and TX-centralimproved). As land and feed expenses increased, gains in stocking rate $\$^{-1}$ of expenditure decreased (Fig. 1C). Energy intensive operations were more vulnerable to fluctuations in input expenses than extensive operations (Table S3). To estimate short-term response to changing input prices, feeds were assumed to be purchased at constant prices across all scenarios, while the prices of fuel, transportation, electricity, and custom operations varied. The greatest proportional increase in expenses occurred in the TN-highlandrim system, where doubling the price of the specified inputs resulted in an 18% increase in expense cow^{-1}. More than half of the systems experienced an increase of 5% or less. The TX-transpecos and TX-rollingplains systems experienced some of the highest percentage increases (12% and 10%, respectively) in expenses because of greater quantities of gasoline or diesel fuel used cow^{-1}, due to the large land area cow^{-1} in these systems.

Expense cow^{-1} also responded differently across systems to an increase in fertilizer price (Table S3). Doubling fertilizer price increased expenses for two of the most intensive operations (TX-winterpasture and TX-centralimproved) by more than 15% cow^{-1}, whereas most operations experienced no impact due to not applying fertilizers. The implication is not only that market price fluctuations have differential impacts on cow-calf producers, but also that policies designed to limit greenhouse gas emissions by increasing fossil fuel expense would reduce some systems' profitability more than others.

DISCUSSION

The 11 systems included in the analysis represented cow-calf production systems that varied with regard to the intensity of energy use and geographic location. Each system represented a single, plausible cow-calf production system reflecting regional opportunities and constraints; however, within a given location, many alternative systems are possible. The results presented addressed the objective of determining fossil fuel energy input and C emissions for a diverse set of cow-calf production systems that represented a range of stocking rates, management strategies, and environmental conditions.

In general, the results suggested that increasing fossil fuel energy use ha^{-1}, especially by using nitrogen (N) fertilizer on improved pastures, permitted increased stocking rates but also increased energy use cow^{-1}. Systems that relied on native range grasses as primary forage generally had lower energy use ha^{-1} and cow^{-1}. As total energy expense increased, the proportion of total energy due to indirect expenses (e.g., tractors, barns, and fences) decreased. Vulnerability to shocks in energy prices increased with energy use cow^{-1}. The relationship between energy use and C emissions was highly correlated (0.99); therefore, practices that increased energy use also increased C emissions.

Energy use of systems in our analysis was similar to values reported in previous studies. Averaged over the 11 sites, total energy was 6 100 $MJ \cdot cow^{-1} \cdot yr^{-1}$. When the five systems that used fertilized pastures were removed, mean total energy (4 800 $MJ \cdot cow^{-1}$) was similar to the 5 142 MJ cultural (total) energy cow^{-1} reported by Heitschmidt et al. (1996) for cows grazing unfertilized pastures in Montana. Ward et al. (1977) cited efficiency values ranging from 22 to 133 $MJ \cdot kg^{-1}$ liveweight marketed for western US systems, compared with 14 to 49 $MJ \cdot kg^{-1}$ liveweight marketed in our analysis. Cook et al. (1980) found that a range-sorghum cow-calf system in the central Great Plains required 4 346 $MJ \cdot cow^{-1}$, or 23.5 $MJ \cdot kg^{-1}$ liveweight marketed, whereas a range-only system required 3 364 $MJ \cdot cow^{-1}$, or 19.8 $MJ \cdot kg^{-1}$ liveweight marketed. Energy values cow^{-1} cited by Cook et al. (1980) were similar in magnitude to those of rangeland systems in our analysis, but energy usage kg^{-1} liveweight marketed was greater in Cook et al. (1980) than our rangeland systems.

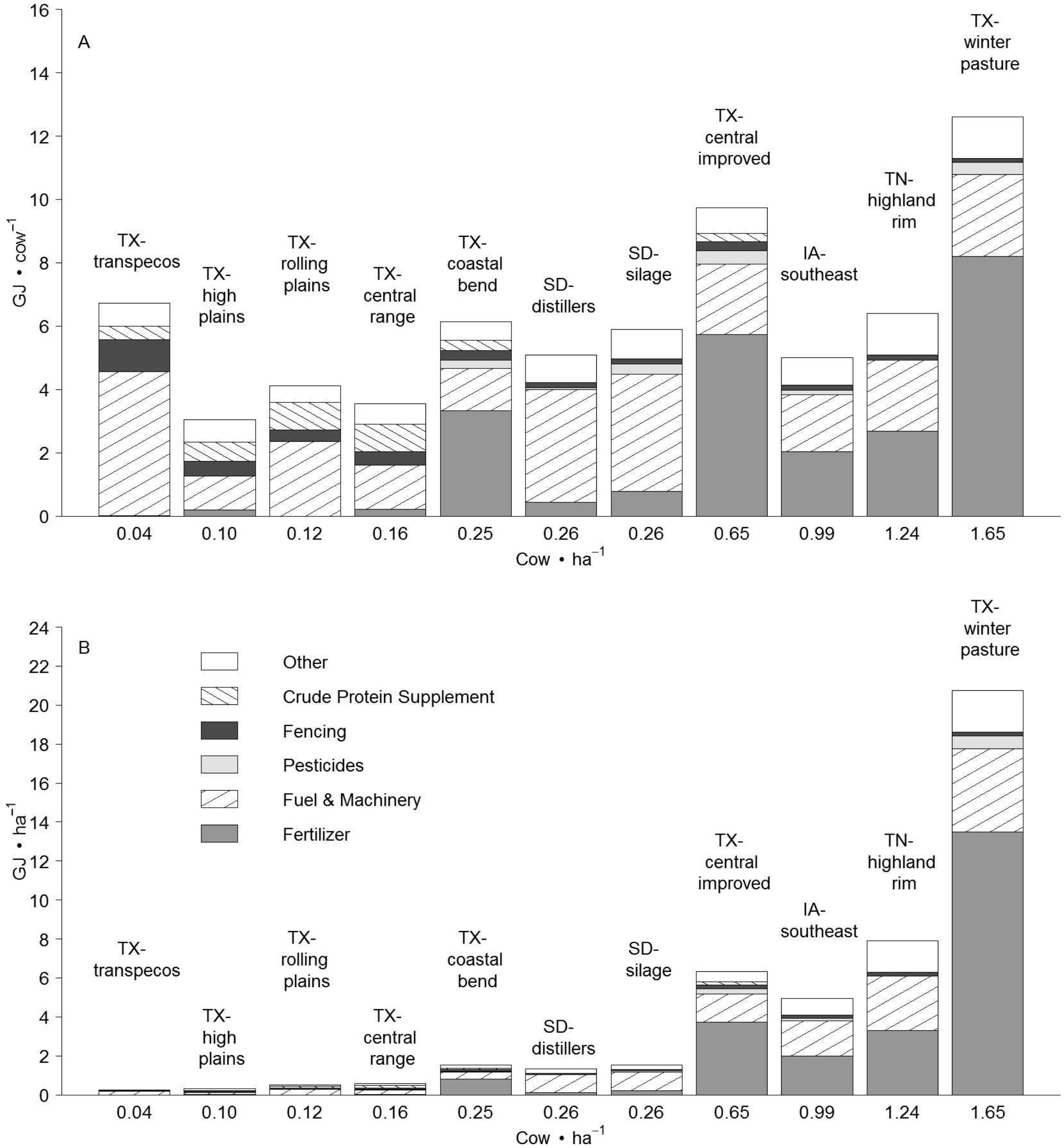

Figure 2. Energy (GJ) used by fossil-fuel derived inputs **A**, cow^{-1}, and **B**, ha^{-1} for 11 cow-calf systems. Systems include rangeland and pastureland systems selected to represent a range of stocking rates across diverse ecosystems.

Fertilizer Use

Increasing stocking rates generally required more fertilizer to increase forage growth and hay production. Increased synthetic fertilizer use, especially N, increased expenditure of fossil fuel energy based on energy cow^{-1}, ha^{-1}, and kg^{-1} of liveweight marketed, largely because natural gas is a feedstock for production of most commercial nitrogenous fertilizers. Systems in the central Texas region illustrated tradeoffs between productivity and energy efficiency. The low stocking rate system (TX-centralrange) relied entirely on native grass pastures, while the more intensive system (TX-centralimproved) relied on a combination of native grass pastures and bermudagrass pastures. In this case, increasing stocking rate 300% led to an approximate 175% increase in energy expenditure cow^{-1} (Table 4), two-thirds of which was due to inclusion of bermudagrass pasture with its higher fertilizer requirements. The remaining third was attributed to increased hay feeding, which required additional fertilizer, fuel, and mechanical operations. It has long been recognized that bermudagrass yield and protein concentration respond to high rates of N fertilization (Burton and DeVane 1952), but it was energetically expensive compared with hay from the South Dakota and Iowa systems. Incorporating N-fixing legumes into a system is an alternative to synthetic N fertilization, but might disrupt system functioning (Allen et al. 1992) and require additional energy costs, such as periodic reseeding, additional phosphorous and potassium fertilizers, irrigation, and soil amendments to adjust pH.

Fuel and Feeds

Transitioning from intensive to extensive cow-calf production reduced total energy use cow^{-1} less than expected due to greater requirements for CP supplementation and fencing, as well as the relatively large expenditure on fuel, machinery, and "other" costs made by all systems in the analysis (Fig. 2). Low

Table 5. The relationship between winter feeding and total energy use for 11 cow-calf systems. Systems include rangeland and pastureland systems selected to represent a range of stocking rates across diverse ecosystems.

System	Days of winter feeding	MJ of feed and supplements $\cdot$ cow^{-1} $\cdot$ yr^{-1}	MJ hay, grain, and silage $\cdot$ cow^{-1} $\cdot$ yr^{-1}	MJ hay, grain, and silage $\cdot$ cow^{-1} $\cdot$ d^{-1} feeding	% of total energy spent on winter feed (hay, grain, and silage)[1]
TX-winterpasture	100	3 200	3 000	30	24%
TN-highlandrim	115	1 500	1 300	11	20%
IA-southeast	138	2 500	2 300	17	46%
TX-centralimproved	94	2 900	2 500	27	26%
SD-silage	162	2 500	2 400	15	40%
SD-distillers	162	1 500	1 400	9	27%
TX-coastalbend	37	1 500	1 100	29	18%
TX-centralrange	11	1 300	300	28	8%
TX-rollingplains	0	900	0	—	0%
TX-highplains	10	1 000	300	28	10%
TX-transpecos	0	500	0	—	0%

[1]Includes energy in feed only. Does not include fuel costs for feeding.

stocking rate systems made greater use of pickup trucks for routine operations such as inspecting herd health and water. Our results agree with Ward et al. (1977, p. 267) who suggested over 30 yr ago that use of pickup trucks meant that range-produced beef was "no longer a low-energy operation since the cow pony has been replaced by the pickup truck and the cattle are driven by transport trucks."

A Montana system (Heitschmidt et al. 1996) spent 40% of its energy on winter feeds, similar to the nearby SD-silage system in this analysis. SD-silage, which used 2 400 MJ $\cdot$ cow^{-1} for corn silage and triticale hay (Table 5), expended more energy on winter feed than SD-distillers, where cows were fed dried distiller's grains, baled corn stalks, and alfalfa that totaled 1 400 MJ $\cdot$ cow^{-1}. Based on an output-to-input ratio of 0.70 (Pimentel et al. 2007), we calculated an energy cost of 1.04 MJ $\cdot$ kg^{-1} for dried distiller's grains. If ethanol output-to-input production efficiency ratios were assumed greater than 1.0, the only energy cost of dried distiller's grains would be transportation to the site of feeding, and SD-distillers energy use would be reduced an additional 200 MJ $\cdot$ cow^{-1}. As a low energy-cost alternative to feeding hay, grain, or silage during winter, the most extensive systems (TX-centralrange, TX-rollingplains, TX-highplains, and TX-transpecos) supplemented standing dormant forage with feeds high in CP (Table 5).

Table 6. Carbon expenditure from 11 cow-calf systems. Systems include rangeland and pastureland systems selected to represent a range of stocking rates across diverse ecosystems.

System	Cow $\cdot$ ha^{-1} $\cdot$ yr^{-1}	kg C $\cdot$ cow^{-1} $\cdot$ yr^{-1}	kg C $\cdot$ ha^{-1} $\cdot$ yr^{-1}
TX-winterpasture	1.65	219	360
TN-highlandrim	1.24	123	152
IA-southeast	0.99	94	93
TX-centralimproved	0.65	168	109
SD-silage	0.26	119	31
SD-distillers	0.26	101	26
TX-coastalbend	0.25	107	26
TX-centralrange	0.16	68	11
TX-rollingplains	0.12	83	10
TX-highplains	0.10	59	6
TX-transpecos	0.04	136	5

Carbon Emissions

Concerns regarding climate change have made understanding C emissions a societal priority. This analysis showed that C emissions in cow-calf production, other than emissions from soils and biota, are closely related to energy use. Environmental conditions at a production site can influence energy use and result in increased or decreased C emissions. Transportation from the site of cow-calf production to the next phase of production (assumed to be Amarillo, Texas), whether stocker farm or feedlot, emits relatively little C compared with annual emission by cow-calf operations (Table S4; available online at http://dx.doi.org/10.2111/REM-D-10-00190.s4). Above all, management practices, which are dictated by markets, environment, and personal preference, exert great influence over C emissions and energy use.

Management also impacts soil C sequestration, although our understanding of the processes involved and our ability to predict C sequestration on grazing lands is limited (Follet and Reed 2010). A summary of soil C sequestration on rangeland revealed relatively high rates of C accumulation on recently restored rangelands (up to 2.75 Mg C $\cdot$ ha^{-1} $\cdot$ yr^{-1}), and lower rates of accumulation (0 to 1.6 Mg C $\cdot$ ha^{-1} $\cdot$ yr^{-1}) on long-term rangelands (Follett and Reed 2010). Compared to haying, grazing has been shown to return more organic residue to the soil and increase soil organic C (Schnabel et al. 2001). In the Northern Great Plains, Liebig et al. (2010) analyzed N fertilizer production and application, enteric fermentation, soil organic C accumulation, and CH_4 and NO_2 flux from soils, and found unfertilized native vegetation was a net sink for CO_2 equivalents, but fertilized crested wheatgrass (*Agropyron desortorum* [Fisch. ex. Link] Schult.) was a net source.

Compared to field crops, most cow-calf operations in the current analysis emitted less C $\cdot$ ha^{-1} due to energy consumption. Based on average US agricultural input use, West and Marland (2002) found that conventional till corn, soybeans (*Glycine max* L.), and winter wheat (*Triticum aestivum* L.), emitted 253, 118, and 176 kg C $\cdot$ ha^{-1}, respectively, compared with cow-calf production systems in this study, where 9 of the

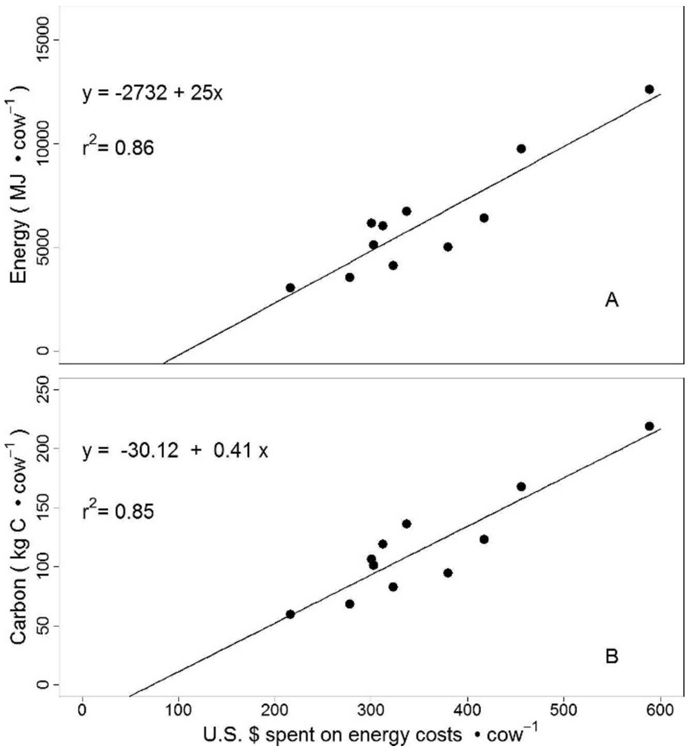

Figure 3. Simple linear relationships between energy use (**A**, megajoules [MJ] $\cdot$ cow^{-1}) or carbon use (**B**, kg C $\cdot$ cow^{-1}) and cost (US\$ $\cdot$ cow^{-1}) of energy inputs (does not include land rent, labor, marketing, or interest) for 11 cow-calf systems.

11 (82%) systems emitted less than 118 kg C $\cdot$ ha^{-1} (range: 5 to 360 kg C $\cdot$ ha^{-1}). Only one cow-calf system, TX-winterpasture, emitted more C $\cdot$ ha^{-1} than average conventional till corn. The simple linear relationship between energy use and money spent on energy inputs (Fig. 3) suggested that reasonable energy and C use estimates could be made based on money spent on fossil fuel-derived inputs (everything except land rent, labor, marketing, or interest in this analysis). This is appealing because input prices are more readily available than energy or C values.

MANAGEMENT IMPLICATIONS

Use of fossil fuel energy temporarily relaxed locations' ecological constraints by permitting higher stocking rates and by allowing herds to overwinter in harsh environments. Producers who reduce fossil fuel input use might experience declines in productivity per unit area. However, opportunities exist to improve energy use efficiency; Provenza (2008) suggested that energy efficiency could be improved by recognizing production limits of harsh environmental conditions and selecting for locally adapted animals, in contrast to current practices that preferentially select for animals that do well in feedlots. Locally adapted animals may reduce need for protein supplementation (Distel et al. 1994; Wiedmeier et al. 2002), but might also cause inefficiencies downstream from the cow-calf phase of production. Additional options to improve energy use efficiency include selecting forages with high N use efficiency, using locally adapted plants, and replacing hay with dormant forage and CP supplementation. Finally, if regulations to reduce C emissions are imposed, policy-makers should recognize that the impact on cow-calf producers will differ substantially across regions and among systems.

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