Ecosystems, Sustainability, and Animal Agriculture[1,2]

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ABSTRACT: The long-term sustainability of animal agriculture is examined in an ecological context. As an aid to defining agriculture, animal agriculture, and sustainable agriculture, a broad overview of the structural and functional aspects of ecosystems is presented. Energy output/cultural energy input ratios were then calculated for 11 beef cattle management systems as relative measures of their long-term sustainability. Energy output was estimated by direct conversion of whole body mass of steers to caloric values. Cultural energy inputs were estimated using published forage and cereal grain production budgets in combination with estimated organic matter intakes. Cultural energy inputs included raw materials, manufacturing, distribution, maintenance, and depreciation of all equipment and products used in a 250-animal cow-calf farm/ranch operation. Management systems evaluated included 1) spring calving with slaughter beginning at either weaning (age of calf ≈ 6 mo) or after 84, 168, or 252 d in postweaning finishing lot; 2) spring calving with slaughter beginning at about 18 mo of age after either 0, 42, 84, or 126 d in finishing lot; and 3) fall calving with slaughter beginning at about 14 mo of age after either 63, 126, or 189 d in finishing lot. Estimated efficiencies were < 1.0 in all treatments, even when assumed marketed calf crop was 100%. Product energy output/cultural energy input ratios ranged from a high of .40 in the spring calving → stocker → 126 d in finishing lot treatment to a low of .23 in the spring calving → slaughter at weaning treatment. The low levels of efficiency were found to be largely the result of the interaction effects of the high levels of cultural energy required to maintain a productive cow herd and grow and finish calves in the rather harsh environment of the Northern Great Plains. Results pointedly reveal the high level of dependency of the U.S. beef cattle industry on fossil fuels. These findings in turn bring into question the ecological and economic risks associated with the current technology driving North American animal agriculture.

Key Words: Ecological Efficiency, Sustainable Agriculture, Beef Cattle, Ecosystem, Energy Flow

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J. Anim. Sci. 1996. 74:1395–1405

Introduction

Sustainable agriculture is a subject of great interest and lively debate in many segments of the world. The debates stem largely from differing viewpoints as to what is sustainable agriculture (USDA, 1980; Lowrance et al., 1986; Dover and Talbot, 1987; Keeney, 1989; Crews et al., 1991; Science Council of Canada, 1992; Lehman et al., 1993). The resulting effect is that no concise, universally acceptable definition of sustainable agriculture has yet emerged. This is in part because sustainable agriculture is viewed more often as a management philosophy rather than a method of operation (MacRae et al., 1993), and as such acceptance or rejection of any definition is linked to one's value system (Clark and Weise, 1993). But regardless of its precise definition, most agriculturalists agree that the concept of sustainable agriculture is of paramount importance to the sustainability of our biosphere and its ever-increasing human population.

There is a wide array of response variables that can be used to examine the potential long-term sustainability of various agricultural practices; one of the most useful methods is energy output/input ratios. Such analyses are performed to quantify the energy return from products produced relative to the cultural energy invested to produce the product. Energy outputs are

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[1] Presented at a symposium titled "Toward Sustainability: Animal Agriculture in the Twenty-First Century" at the ASAS 86th Annu. Mtg., Minneapolis, MN.

[2] This research was conducted under a cooperative agreement between USDA-ARS and the Montana Agric. Exp. Sta. and is published as contribution no. J-3009 from the Montana Agric. Exp. Sta. Mention of a proprietary product does not constitute a guarantee or warranty of the product by USDA, Montana Agric. Exp. Sta., or the authors and does not imply its approval to the exclusion of other products that may also be suitable. USDA-Agricultural Research Service, Northern Plains Area, is an equal opportunity/affirmative action employer and all agency services are available without discrimination.

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Received October 6, 1994.

Accepted September 6, 1995.

estimated by the direct conversion of product yields of mass (e.g., pounds or kilograms) to energy yields (e.g., kilocalories or megajoules). For example, a corn grain yield of 7,000 kg/ha is equivalent to a yield of about 24.5 million kcal/ha because 1 kg of corn grain contains about 3,500 kcal of energy (Pimentel and Burgess, 1980). However, in contrast to estimating outputs, assessing energy inputs is a much more difficult task because 1) the array of kinds of inputs included in the production of a product is extremely diverse (e.g., human labor, transportation, fertilizer, machinery, fuels, etc.) and 2) detailed estimates of energy inputs associated with the manufacturing and operation of all the equipment and products used in an agricultural enterprise are highly variable and difficult to quantify. But regardless of these difficulties, energy output/cultural energy input estimates are of considerable value because they provide an estimate of our level of dependence on exogenous energy sources to meet established production goals. Moreover, such estimates provide insight into agriculture's dependence on inexpensive fossil fuels to meet established economic goals. This information is important if it is assumed that adequate supplies of alternative energy sources may not be readily available when the world's finite sources of fossil fuels are exhausted.

The broad objective of this paper is to examine the potential role of animals in sustainable agriculture systems. Because this objective necessitates that we define sustainable agriculture in a clear, unambiguous manner, we will first present, as an aid to developing this definition, a fundamental overview of the structural and functional attributes of ecological systems. Next, we will examine agriculture from an ecological perspective with emphasis on sustainability. We will then present a case study to examine the sustainability features of several Northern Great Plains beef cattle management systems. We will then conclude the paper by tying these findings back to our original objective.

The Ecosystem Concept

The ecosystem concept is fundamental to understanding what agriculture generally, and animal agriculture specifically, is all about. An **ecosystem** is simply an assemblage of organisms and their associated chemical and physical environment (Briske and Heitschmidt, 1991). A fishbowl is an ecosystem, as is a vegetable garden, a field of corn, a pasture, an entire ranch or farm, a city, a state, a country, or the entire world. In other words, an ecosystem can be essentially anything we desire providing we can define its boundaries.

The structural organization of all ecosystems can be described as consisting of four components, one nonliving and three living. The **abiotic** (i.e., non-living) component defines the chemical and physical environment of the biotic (i.e., living) component. It includes such things as climate, atmosphere, and soils. It is the water in the fishbowl and the soil, air, and sunlight in the garden, cornfield, and pasture.

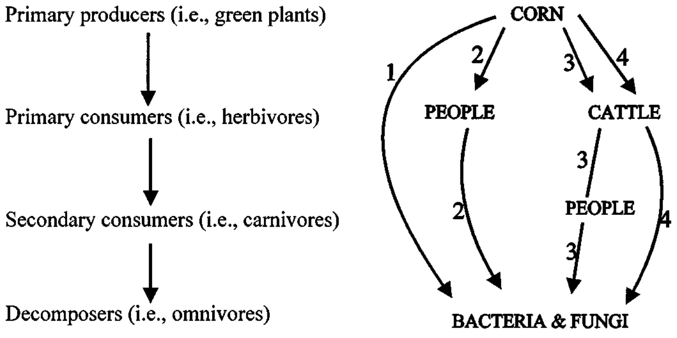

Figure 1. Schematic diagram of four potential food chains.

The three **biotic** components are producers, consumers, and decomposers. **Producers** are organisms that capture solar energy. They are the phytoplankton in the fishbowl, the vegetables in the garden, the corn in the cornfield, and the grasses, forbs, and shrubs growing in the pasture. **Consumers** are organisms that obtain their energy by consuming other organisms. Consumer organisms are animals except in very rare instances (e.g., the Venus fly trap). Consumers that consume plants are called herbivores, those consuming other animals are called carnivores, and those consuming both plants and animals are called omnivores. Cattle are herbivores, coyotes are primarily carnivores, and people are omnivores. **Decomposers** are the final or last consumers of organic matter. They are the microorganisms, primarily bacteria and fungi, that complete the decomposition process.

The integrity of an ecosystem is dependent on the efficient flow of energy through the system and the efficient cycling of the raw materials required to capture and process solar energy. **Food chains** are energy processing pathways that determine the pattern of energy flow through an ecosystem (Figure 1). There are two types of food chains, **detrital** and **grazing.** In both chains, the first **trophic level** consists of the primary producers or green plants. The difference between the chains comes at the second trophic level in that if the primary consumers are decomposers, then the food chain is a detrital food chain (e.g., chain #1, Figure 1), otherwise that defined food chain is called a grazing food chain (e.g., chains #2, 3, and 4, Figure 1).

Regulation of energy flow through an ecosystem via various food chains is governed by the first two laws of thermodynamics. In their simplest form, these laws state that although energy can be transformed from one form to another, it can never be created or destroyed, nor can any transformation be 100%

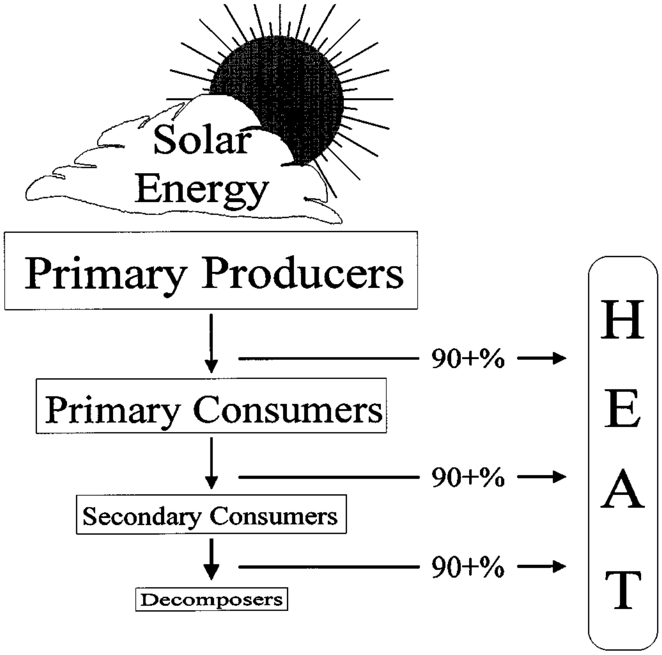

Figure 2. Simplified illustration of energy flow through a four trophic level food chain.

efficient. The impact of these laws on energy flow through an ecosystem is that they dictate that the amount of energy that will flow through an ecosystem is set by the primary producers, and that a portion of this energy, usually greater than 90%, will be lost each time the energy is transferred from one trophic level to another. These concepts are depicted in Figure 2 wherein the largest energy store is the primary producers and the amounts of energy stored in each successive trophic level becomes smaller at every step.

The second indispensable function performed by ecosystems is the cycling of nutrients. Nutrients are the abiotic raw materials required by organisms to capture and process solar energy. Carbon, nitrogen, oxygen, and water are examples of nutrients that are continually cycled by ecosystems (Figure 3). The cycle revolves around the assimilation of nutrients by the primary producers followed by the sequential reduction of complex organic compounds by consumers to simpler, less complex forms.

The Ecosystem Concept and Agriculture

Agriculture is traditionally defined as the business of producing food and fiber. But a basic understanding of the structure and function of ecosystems reveals that **agriculture** can be defined also as the business of managing resources to capture solar energy and transfer it to people for their use. It can be reasoned then that success in agriculture is closely linked to the employment of management tactics that either 1) enhance the efficiency with which solar energy is captured, and(or) 2) the efficiency with which captured solar energy is harvested, and(or) 3) the efficiency with which harvested solar energy is assimilated.

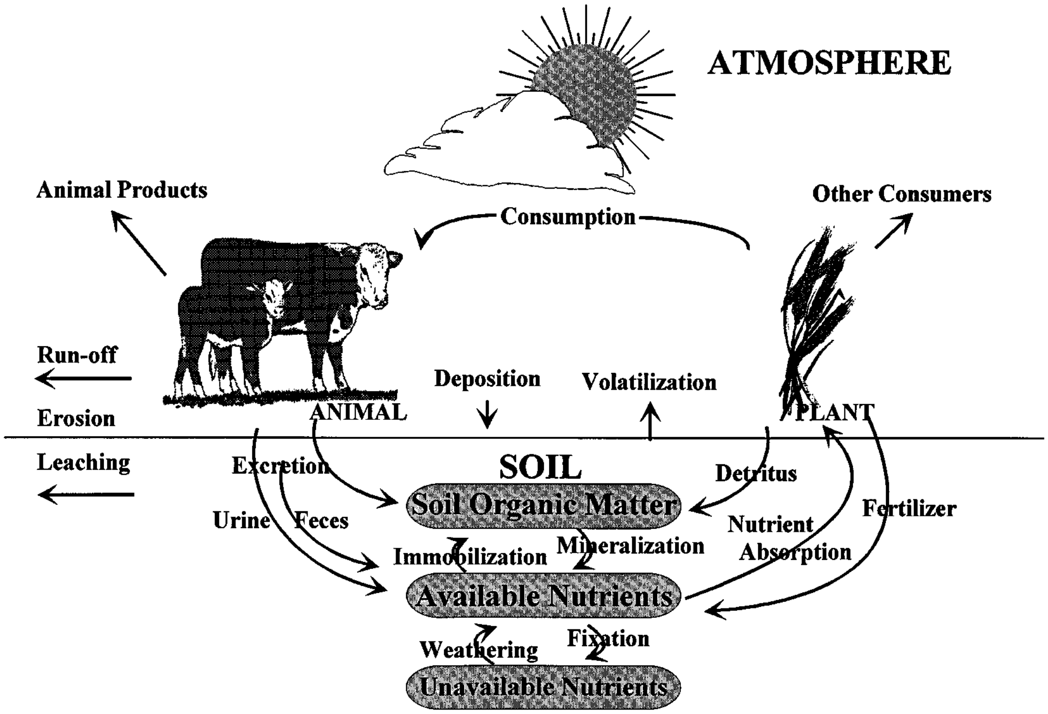

Figure 3. Simplified illustration of ecosystem level nutrient cycle (after Wilkinson and Lowery, 1973; from Briske and Heitschmidt, 1991).

Examples of management practices attempting to improve the efficiency with which solar energy is captured, harvested, and assimilated are numerous. For example, irrigation, fertilization, and the planting of hybrid seeds are common tactics used to enhance efficiency of solar energy capture. Two examples of tactics used to improve the efficiency with which captured solar energy is harvested are the use of insecticides and livestock grazing of post-harvest residue. In these instances, the insecticides are employed to shift the flow of captured solar energy from food chains that do not include people (e.g., rangeland forage → grasshoppers → decomposer) to those that do include people (e.g., rangeland forage → livestock → people → decomposer). This shift is achieved by simply eliminating the competing consumer. Likewise, livestock grazing of post-harvest residue works in a similar fashion in that it shifts the flow of energy from a detrital food chain (e.g., corn stalks → decomposers) to a grazing food chain that includes people (e.g., corn stalks → livestock → people → decomposers).

Similarly, many different types of tactics are employed to improve the efficiency with which harvested solar energy is assimilated. Two examples of tactics commonly used to directly enhance assimilation efficiency are the feeding of mineral supplements and doctoring sick animals. Often feeding just a small amount of a deficient nutrient or vaccinating to eliminate disease will dramatically improve an animal's performance. But the most common factor affecting assimilation efficiencies is quality of foodstuff. In fact, **food quality** can be defined relative to its effect on assimilation efficiencies in that high- and low-quality foods are those that result in high and low net energy gains to consuming organisms. For example, rangeland forages are deemed a low-quality human foodstuff but a high-quality ruminant livestock foodstuff. The reason for this disparity is that ruminant digestive systems are such that they can process range forages in a manner whereby they can derive most of their life-giving nutrients from the forage. This is in contrast to human digestive systems, which are incapable of effectively digesting these same forages. Thus, the assimilation efficiency of range forages is low for humans and high for ruminants.

Even the efficient production of fiber (e.g., cotton, timber, and wool) is dependent on the efficient capture of solar energy and its subsequent harvest. That is why cotton, for example, is often irrigated and fertilized (i.e., increase efficiency of solar energy capture). But in contrast to food production practices, post-harvest processing of fibers is designed primarily to interrupt food chains and prevent consumption of the fiber (e.g., termites consuming wood).

Sustainable Agriculture

A fundamental problem with the questions associated with sustainability stems in part from our inability to define what sustainability is or what it is not. An understanding of how ecosystems function provides an additional means of defining sustainable agriculture. As such, **sustainable agriculture** may be broadly defined as ecologically sound agriculture and narrowly defined as eternal agriculture, that is, agriculture that can be practiced continually for eternity. It is those forms of agriculture that do not necessarily require exogenous energy subsidies to function. For example, grazing of indigenous grasslands is one of the most sustainable forms of agriculture known. This is because no other form of agriculture is less dependent on external finite resources, such as fossil fuels, and(or) external, potentially environmentally sensitive resources such as fertilizers, pesticides, and so on, than grazing of native grasslands.

But the issue of sustainable agriculture goes beyond the idea that it is eternal agriculture because without the use of fossil fuels, it is not possible for agriculturalists to feed and clothe the world's human population. Fossil fuel technology is a major reason that agriculturalists can produce an abundance of food and fiber. This is reflected in Table 1, which shows that as use of fertilizers and other products (i.e., fossil fuels) are increased, yields increase also. Unfortunately, these data also reveal that the efficiency of production, as measured by energy output/input ratios, decreases as yields increase, and therein lies the dilemma. So what is the issue of sustainable agriculture all about? It is about the issue of how we can maintain high yields of agricultural products while maintaining high levels of ecological efficiencies. The challenge to agricultural scientists is to develop the technology that will allow us to maintain and(or) increase product yields while increasing ecological efficiencies.

Table 1. Energy output/cultural energy input ratios for corn production systems in Mexico (manpower only) and the United States (conventional)[a]

	Management system	
Item	Mexico	United States
	kcal/ha	
A. Cultural energy inputs	553,678	8,390,750
	kg/ha	
B. Grain yield		
1. Weight	1,944	7,000
	kcal/ha	
2. Energy	6,901,200	24,500,000
C. Energy output/input ratio	12.5	2.9

[a] Pimentel, 1984.

Materials and Methods

Study Area

Research was conducted from 1990 to 1993 at the 22,250-ha Fort Keogh Livestock and Range Research Laboratory near Miles City, MT. The regional natural vegetation is a mixed grass dominance of grama-needlegrass-wheatgrass (*Bouteloua-Stipa-Agropyron*) (Kuchler, 1964). Annual precipitation averages 338 mm with about 60% received during the 150-d, mid-April to mid-September growing season. Average daily temperatures range from a low of –10°C in January to a high of 24°C in July.

Treatments

Spring Calving → Finishing Lot. Crossbred cows were bred by AI to high-index Charolais or average-index Hereford sires to calve in April. Cow-calf (steers only) pairs grazed perennial planted pastures, primarily crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.) and Russian wildrye (*Psathyrostachys juncea* [Fisch.] Nevski), during May and June and native rangeland thereafter. Calves were weaned in early October and either slaughtered immediately or fed a corn silage (64%) and barley grain (30%) finishing diet for 84, 168, or 252 d before slaughter. Cows remained on rangeland until early February, when they were placed on a full-feed diet of alfalfa hay (23%), grass hay (72%), and barley grain (5%) until calving and returning to tame pasture. Cows were fed a soybean meal-based 32% CP supplement every 3 d at a rate of .9 kg/d from mid-December to early February.

Spring Calving → Stocker → Finishing Lot. Cows were bred and managed the same as those on the spring calving → finishing lot treatment. However, following weaning in early October, calves grazed wheatgrass-ryegrass-dominated tame pastures for about 75 d before entering drylot. Calves were fed a silage (78%)—grass hay (20%)-based growing diet thereafter until returning to the tame pasture—native rangeland grazing treatment with the cow herd in early May. These stocker cattle were then either slaughtered off grass in early October or placed in finishing lots for 42, 84, or 126 d before slaughter. Diet fed in feedlot was a corn silage (39%) and barley (56%)-based mix.

Fall Calving → Stocker → Finishing Lot. Cows were bred and managed the same as spring-calving cows except they were bred to calve in early October. They calved on native rangeland and were placed on full feed from mid-November until calves were weaned in mid-April. The full feed diet was the same as that fed spring-calving cows during late winter and early spring. After weaning, the cows were moved to tame pasture. Management thereafter was the same as that of the spring-calving cows. Calves were creep-fed a grain-based pellet throughout winter. After weaning, the calves were managed the same as the cow herd, grazing tame pasture during May and June and native rangeland thereafter. All calves entered the finishing lot in early October for 63, 126, or 189 d before slaughter. Diet fed was same as that fed to finish the spring calving → stocker → finishing lot treatment cattle.

Data Set

Organic matter intakes (**OMI**) of all animals (Table 2) were estimated using either unpublished study data or literature values. Key intake estimates (forage + supplemental feeds) derived from concurrent unpublished grazing studies were as follows: 1) cows = 1.9% BW/d; 2) spring-born suckling calves = 1% BW/d; 3) spring-born stocker steers = 1.65 to 1.75% BW; and 4) fall-born stocker steers = 2.0% BW. Estimates of OMI of cows on full feed were developed from standard diet procedures, whereas estimates for weaned calves were the average for the Charolais and Hereford crosses as measured using individual feeding pens. Estimated OMI of calf creep feed was 0.5% BW/d.

Energy budgets for cultural energy inputs (Table 3) were derived from Cook et al. (1980) with some modifications. These budgets included all energy inputs associated with the operation, manufacturing, distribution, maintenance, and depreciation of equipment (e.g., farm machinery, vehicles, etc.) and products (e.g., fertilizer, herbicides, etc.) used in the farm/ranch operation. These budgets were based on inputs required to attain predicted yields (Table 3). Energy inputs/hectare were then divided by yields/hectare to attain energy inputs/yield estimates (Table 4). These estimates were then multiplied by OMI estimates (Table 2) to attain cultural energy input/animal estimates (Table 5). Body composition of marketed calves (Table 6) was based on whole-body grinding following the procedures outlined by Short et al. (1993). Energy output/input ratios were derived by dividing yields (Table 5) by energy inputs (Table 4).

Results

Study results pointedly revealed the heavy reliance of these 12 beef cattle management systems on energy subsidies. Specifically, results (Table 6) showed energy output/cultural energy input ratios 1) averaged .31 and .28 when marketed calf crops were assumed to be 100% and 80%, respectively; 2) varied little among management systems ranging from a low of .18 for the 80% calf crop, spring calving → 0 d in finishing lot system to .40 for the 100% calf crop, spring calving → stocker → 126 d in finishing lot system; and 3) increased within a management system as days in finishing lot increased.

Table 2. Estimated organic matter intakes for cows and steer calves

Feedstuff	Spring calving→finishing lot					Spring calving→stocker→finishing lot					Fall calving→stocker→finishing lot			
		Calf					Calf					Calf		
	Cow	0[a]	84[a]	168[a]	252[a]	Cow	0[a]	42[a]	84[a]	126[a]	Cow	63[a]	126[a]	189[a]
	kg/yr	kg/lifetime				kg/yr	kg/lifetime				kg/yr	kg/lifetime		
A. Grazable forages														
1. Native rangeland	2,093	147	147	147	147	2,093	740	740	740	740	1,773	507	507	507
2. Tame pasture	585	30	30	30	30	585	706	706	706	706	444	287	287	287
B. Hay														
1. Alfalfa	283	—	—	—	—	283	—	—	—	—	474	—	—	—
2. Tame pasture	739	—	—	—	—	739	252	252	252	252	1,243	—	—	—
C. Corn silage	—	—	349	765	1,287	—	983	1,224	1,391	1,542	—	377	568	795
D. Barley grain	60	—	164	359	603	60	—	346	579	802	199	541	716	1,141
E. Supplements														
1. Calf creep	—	—	—	—	—	—	—	—	—	—	—	118	118	118
2. Protein	89	—	—	—	—	89	—	—	—	—	89	—	—	—
3. Finishing	—	—	33	62	102	—	25	56	77	97	—	48	73	102
Total	3,849	177	723	1,363	2,169	3,849	2,706	3,324	3,745	4,139	4,222	1,878	2,269	2,950

[a] Days in finishing lot.

The underlying reason for these results is related largely to the interaction effects of low product output (i.e., small body mass) and the high cultural energy inputs required to maintain a productive cow and a growing or finishing calf in the rather harsh environment of the Northern Great Plains. For example, when minimal cultural energy was expended to grow and finish a weaned calf (Table 4), as was the case for the spring calving → 0 d in finishing lot system (8 Mcal), energy outputs (Table 5) were too low (280 Mcal) to offset the energy inputs (Table 4) required to maintain the cow-calf pair up to time of slaughter (1,237 Mcal). However, when product outputs were increased, the energy required to grow or finish the calves offset gains in size. For example, in the spring calving → stocker → 0 d in finishing lot treatment, an additional 894 Mcal were invested (902 − 8 = 894; Table 5) to increase product output from 280 Mcal to 523 Mcal (Table 6) with a resulting increase in efficiency of .02 (.23 vs .25) with a 100% calf crop and .03 (.18 vs .21) with an 80% calf crop. Likewise, by investing an additional 1,355 Mcal in the finishing lot (2,257 − 902 = 1,355; Table 5) to increase product output from 523 Mcal to 1,390 Mcal (Table 6), we were able to increase efficiency from .25 to .40 for a 100% calf crop and from .21 to .37 for an 80% calf crop. Although these increases were relatively large (≈ 60%), the absolute increase was very small (.16).

A point of initial concern in the analyses was the magnitude of the textbook (Cook et al., 1980) cultural energy inputs estimate for general operations (Table 3). This estimate (567,642 $\mathrm{kcal \cdot cow^{-1} \cdot yr^{-1}}$) seemed excessive because at an assumed low rate of stocking of 20 $\mathrm{ha \cdot cow^{-1} \cdot yr^{-1}}$, cultural energy inputs/hectare for native rangeland would be only slightly less than that for irrigated corn (7,096 vs 7,862 kcal). Granted, a portion of these general operations energy inputs could be allocated to the various cropping enterprises (e.g., pickup and fencing), but even so these estimates seemed extremely high. However, a reduction in these estimated inputs did not change the efficiency estimates as greatly as originally expected. For example, when the general operations cultural energy input estimate was reduced 50%, from 568 to 284 Mcal cow year, estimated efficiencies for the spring calving → finishing lot treatment increased a maximum of only .07 with a 100% calf crop. This was because the general operations inputs were < 50% of the total annual inputs/cow, thereby emphasizing again that the fundamental reason for the low efficiencies is simply that considerable cultural energy inputs are required in this region to maintain a biologically efficient "factory" (i.e., cow).

Discussion

The results of this study bring to question the long-term sustainability issue as it relates to currently accepted beef cattle production systems. The beef

Table 3. Energy budgets used to estimate cultural energy inputs (after Cook et al., 1980), yields, and output/input ratios for various feedstuffs

	Treatment									
	General operations		Alfalfa hay (irrigated)		Corn silage (irrigated)		Barley grain (dryland)		Perennial pasture (dryland)	
Item	Quantity	Mcal/yr	Quantity	Mcal/ha	Quantity	Mcal/ha	Quantity	Mcal/ha	Quantity	Mcal/ha
A. Inputs										
Labor, h	3,170	7,925	11.4	29	112.6	281	5.1	129	1.9	5
Machinery, h	—	—	3.8	1,092	3.6	1,301	2.5	918	.2	78
Pickup, km	20,000	83,660	—	—	—	—	—	—	—	—
Transportation, km×kg	573	1,662	238	690	317	920	1.5	4	—	—
Fertilizer, kg	—	—	123	332	262	2,623	—	—	—	—
Pesticides, kg	—	—	.6	8	2.2	54	—	—	.5	12
Seed, kg	—	—	1.1	68	25	625	67	201	.8	3
Irrigation, cm	—	—	25	1,262	50	2,058	—	—		
Fence, km	80	34,856	—	—	—	—	—	—	—	—
Water, AUM	3,000	13,815	—	—	—	—	—	—	—	—
Total		141,918		3,481		7,862		1,252		98
			kg output/ha							
B. Yields	250-head cow herd		9,945		12,750		1,427		350	
	kcal/cow		kcal input/kg output							
	567,672		350		617		877		280	
			kcal/kcal[a]							
C. Output/input ratio			11.4		6.4		4.6		14.3	

[a] At 4,000 kcal/kg.

cattle industry's heavy reliance on fossil fuels to maintain a productive cow herd in regions where nutrient shortfalls are common and to market a product acceptable to consumers carries with it some ecological and economic risks. These risks arise from the historical perspective that agriculture's continued success (i.e., sustainability) is tied to developing the technology needed to "control" nature as opposed to "living with" nature. Because the integrity of natural ecosystems is dependent on the efficient capture and processing of solar energy, ecosystem control strategies that alter natural flows of energy often require large inputs of exogenous energy. Risks accompany these control strategies because of future uncertainties about 1) the availability of cheap sources of exogenous energy (e.g., fossil fuels), and 2) the potential disruption of critical life-supporting ecological systems due to the continued generation of control strategy by-products (i.e., pollutants).

Central to the sustainability debate are the omnipotent technology and ecological constraint hypotheses. The omnipotent technology hypothesis embraces the fundamental concept that resource depletion (e.g., fossil fuels) automatically sets into motion a series of economic forces that alleviate the effects of depletion on society as a whole (Cleveland, 1987). On the other hand, the omnipotent ecological constraint hypothesis (Heitschmidt, 1991) is the underlying hypothesis supporting biophysical economic theory. Biophysical economics differ from standard economics in that they attempt to more fully factor the role of natural resources into the economic process (Pearce, 1987). The focus is on merging ecology and economics so as to ensure that what is economically sound on the short-term is ecologically sound on the long-term. In this sense, it is important we recognize that economics is simply a measure of the intensity of society's beliefs rather than a measure of the merits of those beliefs (Sagoff, 1981). As such, some argue that "economics can no longer afford to ignore, downplay or misrepresent the role of natural resources in the economic process. In the final analysis, natural resource quality sets broad but distinct limits on what is and what is not economically possible. Ignoring such limits leads to the euphoric delusion that the only limits to economic expansion exists in our own minds" (Cleveland, 1987).

Table 4. Cultural energy inputs/product output

	kcal input/kg output
I. Feedstuff	
A. Grazable forages	
1. Native rangeland	0[a]
2. Tame pasture	280[b]
B. Hay	
1. Alfalfa	350[b]
2. Tame pasture	280[c]
C. Corn silage	617[b]
D. Barley grain	877[b]
E. Supplements	
1. Calf creep	885[c,d]
2. Protein	1,546[c,e]
3. Finishing	1,023[f]
	kcal input$\cdot$cow$^{-1}\cdot$yr^{-1} [b,g]
II. General operations	
1. Ranch-farm	567,642
	kcal input$\cdot$animal$^{-1}\cdot$d^{-1} [c,h]
2. Feedlot	1,862

[a] Energy inputs are embedded in II.1.

[b] See Table 3.

[c] After Cook et al. (1980).

[d] 877 kcal for barley grain base + 84 kcal for pelleting.

[e] 1,462 kcal for soybeans + 84 kcal for pelleting.

[f] Ration = 63% barley, 20% soybean meal, 6% urea, and 11% minerals and vitamins.

[g] Based on 250-head cow herd.

[h] Based on 1,000-head feedlot.

These economic-ecological debates are central to the development of agricultural management strategies that are both ecologically and economically sustainable. Surely the results of our study provide some motivating interest to closely examine the general direction of agriculture research and specifically animal agriculture research. Our industry's heavy reliance on cheap fossil fuels is obvious and currently quite profitable. But is it the way of the future, and if not, what technology are we developing to meet this challenge? If we accept the premise that sustainable agriculture is eternal agriculture (i.e., agriculture that can be practiced forever), then what forms of animal agriculture might we consider sustainable?

The fundamental characteristic of sustainable animal agriculture systems must be that animals act as "energy brokers," that is, they convert low-quality human feedstuff (e.g., corn stalks, spoiled grains, waste products, etc.) into high-quality human feedstuff for their consumption (e.g., meat, milk, eggs, etc.) (e.g., see Oltjen and Beckett, 1996). For example, livestock grazing of indigenous grasslands is fully sustainable in many regions of the world where level of cultural energy inputs required to maintain a productive herd of animals is low. Rangeland agriculture is grazing, and when properly managed, rangeland agriculture is fully sustainable, having gone on long before the discovery of fossil fuels, and it will, without doubt, go on long after the depletion of fossil fuels.

Any discussion concerning the long-term sustainability of animal agriculture would be shallow and incomplete without some consideration given to the ecological relationship between human population food demands and livestock production systems. From an ecological perspective, humans are consumers that most often either solely occupy the second (herbivorous) or third (carnivorous) trophic level of food chains or concurrently occupy both the second and

Table 5. Cultural energy inputs/animal (from Tables 1 and 3)

	Treatment													
	Spring calving→finishing lot					Spring calving→stocker→finishing lot					Fall calving→stocker→finishing lot			
		Steer					Steer					Steer		
Item	Cow	0[a]	84[a]	168[a]	252[a]	Cow	0[a]	42[a]	84[a]	126[a]	Cow	63[a]	126[a]	189[a]
	Mcal/yr	Mcal/lifetime				Mcal/yr	Mcal/lifetime				Mcal/yr	Mcal/lifetime		
A. Grazable forages														
1. Native rangeland[b]	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2. Tame pasture	164	8	8	8	8	164	198	198	198	198	124	80	80	80
B. Hay														
1. Alfalfa	99	—	—	—	—	99	—	—	—	—	166	—	—	—
2. Tame pasture	207	—	—	—	—	207	71	71	71	71	348	—	—	—
C. Corn silage	—	—	215	472	794	—	607	755	858	951	—	233	350	491
D. Barley grain	53	—	144	315	529	53	—	303	508	703	175	474	628	1,001
E. Supplements														
1. Calf creep	—	—	—	—	—	—	—	—	—	—	—	104	104	104
2. Protein	138	—	—	—	—	138	—	—	—	—	138	—	—	—
3. Finishing	—	—	34	63	104	—	26	57	79	99	—	49	75	104
F. General operations														
1. Ranch-farm[c]	568	—	—	—	—	568	—	—	—	—	568	—	—	—
2. Feedlot[d]	—	—	156	313	469	—	—	78	156	235	—	117	235	352
Total	1,229	8	557	1,171	1,904	1,229	902	1,462	1,870	2,257	1,519	1,057	1,472	2,132

[a] Days in finishing lot.
[b] Cultural energy inputs are embedded in F. 1.
[c] Includes energy inputs required to maintain and manage 250-head cow herd.
[d] Based on number of days in 1,000-head feedlot.

Table 6. Whole body weight and composition, energy yield animal and energy output/cultural energy input ratios

	Treatment										
	Spring calving→finishing lot				Spring calving→stocker→finishing lot				Fall calving→stocker→finishing lot		
Item	0[a]	84[a]	168[a]	252[a]	0[a]	42[a]	84[a]	126[a]	63[a]	126[a]	189[a]
	kg										
A. Composition											
1. Protein	23.0	29.5	38.0	46.0	41.0	51.0	54.0	60.5	38.5	44.5	50.0
2. Fat	16.0	35.0	62.5	91.5	31.0	60.0	89.0	111.5	39.5	76.0	105.0
Total	39.0	64.5	100.5	137.5	72.0	111.0	143.0	172.0	78.0	120.5	155.0
	Mcal										
B. Energy yield											
1. Protein[b]	130	167	215	260	232	288	305	342	218	251	283
2. Fat[c]	150	329	587	860	291	564	837	1,048	371	714	987
Total	280	496	802	1,120	523	852	1,142	1,390	589	965	1,270
C. Output/input ratios											
1. 100% calf crop	.23	.28	.33	.36	.25	.32	.37	.40	.23	.32	.35
2. 80% calf crop[d]	.18	.24	.30	.33	.21	.28	.34	.37	.20	.29	.32

[a] Days in finishing lot.
[b] At 5.65 Mcal/kg.
[c] At 9.40 Mcal/kg.
[d] 80% Calf output/100% cow input + 80% calf input.

third trophic levels (omnivorous). Occupation of trophic levels greater than the second is in many instances a luxury afforded to only a privileged few, that being those living in an environment where human food demand is well below supply. However, when human food demand begins to exceed supply, the laws of thermodynamics dictate that humans occupy the second trophic level to the maximum extent possible, and as such, the role of animal agriculture is relegated to that of an "energy broker" (i.e., converting low-quality foodstuff, such as rangeland forages, into high-quality meat). Thus, the challenge to animal agriculturalists in a world with an ever-increasing human population is to develop technology that will enhance animal conversion efficiencies of both high- (e.g., cereal grains) and low- (e.g., rangeland forages) quality foodstuff into high-quality products that meet human expectations (e.g., tender, flavorful, etc.). Historically, North American animal agriculturalists have done a commendable job developing technology and associated seedstock that perform well in converting feed grains into meat products acceptable to consumers. But because most selection criteria have focused largely on offspring's performance in feedlot environments, it is not surprising that these same seedstocks do not generally do an acceptable job of converting grazable forages and other low-quality roughages (e.g., straw) into highly desirable meat products. The fact of the matter is little effort has been expended in North America developing this ruminant animal production technology, and yet it is this technology that will ensure that North American animal agriculture will continue to play a critical and important role in sustaining the burgeoning human population inhabiting our biosphere.

Finally, we hope the contents of this article provide readers with insight as to why we believe the long-term health of modern-day animal agriculture is highly dependent on the long-term health of this biosphere's human population and its associated ecological life support systems. Contrary to popular belief, the ecological ills of this biosphere are largely the result of human rather than livestock production activities. Thus, the long-term health of animal agriculture is as dependent on focused, problem solving social science research activities as it is on traditional animal science research activities. Together we can overcome; apart we limit our options.

Implications

Results show that accepted Northern Great Plains beef cattle management systems rely heavily on exogenous sources of cultural energy, primarily in the form of fossil fuels. Thus, the long-term survival of this industry seems to be largely dependent on 1) the continued availability of cheap, traditional and(or) new sources of energy, and(or) 2) increased revenue to offset increased energy costs, and(or) the development of new animal production technology to increase the ecological efficiency of production. The analyses also reveal that a major factor threatening the long-term sustainability of modern U.S. animal agriculture systems is human population growth.

Literature Cited

Briske, D. D., and R. K. Heitschmidt. 1991. An Ecological Perspective. In: R. K. Heitschmidt and J. W. Stuth (Ed.) Grazing Management: An Ecological Perspective. p 11. Timber Press, Portland, OR.

Clark, E. A., and S. F. Weise. 1993. A forage-based vision of sustainable agriculture. p 95. American Society of Agronomy, Madison, WI.

Cleveland, C. J. 1987. Biophysical economics: Historical perspective and current research trends. Ecol. Model. 38:47.

Cook, C. W., J. J. Combs, and G. M. Ward. 1980. Cultural energy in U.S. beef production. In: D. Pimentel (Ed.) Handbook of Energy Utilization in Agriculture. p 475. CRC Press, Boca Raton, FL.

Crews, T., C. Mohler, and A. Power. 1991. Energetics and ecosystem integrity: The defining principles of sustainable agriculture. Am. J. Alter. Agric. 6(3):146.

Dover, M., and L. Talbot. 1987. To Feed the Earth: Agro-Ecology for Sustainable Development. World Resources Institute.

Heitschmidt, R. K. 1991. Ecology, economics and ethics in range management. Proc. 4th Int. Rangeland Congr. 2:927.

Keeney, D. R. 1989. Toward a sustainable agriculture: need for clarification of concepts and terminology. Am. J. Alter. Agric. 4(3&4):101.

Küchler, A. W. 1964. Potential natural vegetation of the conterminous United States. Am. Geog. Soc. Spec. Publ. 36. American Geographic Society, New York.

Lehman, H., E. A. Clark, and S. F. Weise. 1993. Clarifying the definition of sustainable agriculture. J. Agric. Environ. Ethics 6(2):127.

Lowrance, R., P. F. Hendrix, and E. P. Odum. 1986. A hierarchical approach to sustainable agriculture. Am. J. Alter. Agric. 1(4): 169.

MacRae, R. J., J. Henning, and S. B. Hill. 1993. Strategies to overcome barriers to the development of sustainable agriculture in Canada: The role of agribusiness. J. Agric. Environ. Ethics 6(1):21.

Oltjen, J. W., and J. L. Beckett. 1996. Role of ruminant livestock in sustainable agricultural systems. J. Anim. Sci. 74:1406.

Pearce, D. 1987. Economic values and the natural environment. Discussion paper in economics no. 87-08. Dept. of Econ., University College, London.

Pimentel, D. 1984. Energy flow in agroecosystem. In: R. Lowrance, B. Stinner, and G. House (Ed.) Agricultural Ecosystems: Unifying Concepts. p 233. John Wiley & Sons, New York.

Pimentel, D., and J. Burgess. 1980. Energy inputs in corn production. In: D. Pimentel (Ed.) Handbook of Energy Utilization in Agriculture. p 67. CRC Press, Boca Raton, FL.

Sagoff, M. 1981. Economic theory and environmental law. Mich. Law Rev. 79:1393.

Science Council of Canada. 1992. Sustainable Agriculture: The Research Challenge. Report 43, July. Science Council of Canada, Ottawa, ON.

Short, R. E., E. E. Grings, J. H. Killen, G. L. Bennett, and R. K. Heitschmidt. 1993. Effects of genotype and management system on postweaning production efficiency and composition of beef. World Conf. on Anim. Prod. p 362. Edmonton, Alberta, Canada.

USDA. 1980. Report and Recommendations on Organic Farming. U.S. Gov. Printing Office, Washington, DC.

Wilkinson, S. R., and R. W. Lowery. 1973. Cycling in mineral nutrients in pasture ecosystems. In: G. W. Butler and R. W. Bailey (Ed.) Chemistry and Biochemistry of Herbage. Vol. 2. p 247. Academic Press, New York.