ELSEVIER
Ecological Economics 30 (1999) 79–91

ECOLOGICAL ECONOMICS

ANALYSIS

Global environmental costs of beef production

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Received 28 July 1997; received in revised form 14 September 1998; accepted 28 September 1998

Abstract

This paper evaluates the impact on greenhouse gas emissions of beef produced under different management systems and compares these results with the estimated biophysical capital alteration of these same systems. The environmental impacts of a specific intensive US feedlot system and a traditional African pastoral system are calculated using a methodology that includes the major land-use and energy-related emissions. Although assessments of carbon dioxide emissions find much greater impacts related to the US feedlot mode, the methane intensity of the pastoral mode is much larger because of the lower productivity of these systems. It is found that when indirect sources, which include emissions from fossil fuels and foregone carbon storage on appropriated land, are considered as well as emissions from enteric fermentation and wastes, the social costs of the feedlot system at 15 kg CO_2 equivalent/kg beef are more than double that of the pastoralist system. Accordingly, the results of the more complete greenhouse gas emissions analysis were found to converge somewhat with the biophysical capital alteration approach in this example, although it is also argued that the entropy-based environmental indicators may have limited use in evaluating agro-ecosystems' contribution to climate change. Given an assumed, albeit uncertain, climate change impact value, a tax on beef production of about 9% of the unit price would represent the upper limit of the shadow costs of the associated greenhouse gas emissions flux from feedlot systems as estimated here, and a central value would correspond to a tax of about 4%.

Keywords: Agricultural emissions; Methane; Livestock assessments; Environmental indicators; Climate change costs

1. Introduction

Complex agricultural systems, such as the production of beef and other animal products, pose considerable challenges for environmental assessment. Ecologists recognize that environmental impacts related to these processes can involve detailed investigation of alternative uses of pastureland and the proximity and sensitivity of water bodies to related nitrogen pollution. Economists trying to assess a net social cost of

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0921-8009/99/$ - see front matter
PII: S0921-8009(98)00100-1

beef production are faced with an industry characterized by distortions such as the availability of land subsidies that reduce producer costs and labour not valued in the market economy. Efforts are under way to seek to limit some of the distortions that have led to the underpricing of an environmentally costly form of protein. Ideas for reducing livestock production have centred in the United States on proposals for limiting grazing rights on public lands (Repetto, 1992). Controls on related organic pollution are better established than land-use restrictions. In the UK, farmers are provided financial incentives to curb nitrogen runoff (MAFF, 1996). Farm effluent in the United States is controlled as a 'non-point' source under national Clean Water legislation (US EPA, 1972). In the Netherlands, farmers are fined if they do not use approved practices for disposing of livestock wastes (Wilkins, 1997)

Concern over the threats posed by long-term climate change has led to an interest in controlling emissions of the greenhouse gas methane, generated as a by-product of the digestive processes of livestock. Livestock are believed to be the most important source of anthropogenic methane internationally (Watson et al., 1992). Strategies to reduce greenhouse gas emissions from livestock production have centred largely upon increasing animal productivity, in part through higher-quality feeding (US EPA, 1994). These policies do not usually include consideration of indirect emissions related to energy used to produce stockfeed and changes in carbon fixation on land.

In this paper, several measures of the global environmental impacts of beef production are assessed for two contrasting production modes. Greenhouse gas emissions from beef production are assessed stepwise considering several boundaries of analysis for each of two systems—American feedlot and Sahelian pastoral beef production. A comprehensive approach to understanding greenhouse gas emissions from beef production is presented. This approach considers indirect emissions from livestock production and related land use. The approach includes the assessment of indirect sources—carbon dioxide flux related to embodied energy in on-farm use and stockfeed production, and the carbon storage potential foregone on land appropriated for raising livestock—in addition to direct sources—methane emissions from enteric fermentation and animal wastes.

The greenhouse gas emissions related to both pastoral and feedlot production modes are compared with other environmental impact indicators for these modes—both quantitatively and qualitatively with reference to their potential usefulness in assessing livestock systems generally. Greenhouse gas emissions are compared with a composite indicator of sustainability in agroecosystems, called biophysical capital alteration. Greenhouse gas emissions from each system are summarized for three boundaries of analysis: (1) direct methane emissions, (2) direct emissions plus embodied fuel combustion, and (3) direct methane and embodied fuel plus the carbon offset opportunity foregone in addition to the other emissions. The difference in estimated biophysical capital alteration and greenhouse gas emissions for the two systems are compared to reveal whether the environmental impacts as determined by each approach are similar.

These greenhouse gas emissions indices, when compared with market values per unit of beef, can be used to estimate a shadow price of an expected global warming impact as a proportion of the market value of the good. The comprehensive greenhouse gas approach can be expressed in climate change costs, taking the form \$/kg CO_2 equivalent. Measured as a proportion of the market value of beef, this measure can be used to determine the value of a tax on beef that would, in theory, be comparable with projected environmental impacts. The approaches compared are summarized in Table 1.

2. Methodology and results

Greenhouse gas emissions from two livestock production systems at opposite ends of the spectrum as regards energy inputs, are assessed according to a range of indicators—biophysical capital loss, topsoil loss, and greenhouse gas emissions. These systems have already been evaluated for topsoil loss and biophysical capital loss parameters by Giampietro et al. (1992). In this analysis, a comprehensive greenhouse gas emissions analysis of these systems is summarized based on the same specific livestock management practices assumed by Giampietro and colleagues. Details of the assumptions involved in assessing greenhouse gases from these particular feedlot and pastoral beef production modes can be found in Subak (1999). Other assessments of greenhouse gas intensity of livestock production involving embodied fossil fuel inputs have also been completed by Loethe et al. (1997), Ward et al. (1993) and Jarvis and Pain (1994).

Beef production systems vary greatly in their use of resources and labour and, spatially, the resource boundaries of intensive systems tend to be much greater than the immediate farm. Most feedlot systems rely on crops grown outside the cattle farm. Cattle diet and management differs in most respects between the feedlot and pastoral modes. The key assumptions for both beef production modes are presented in Table 2. In the pastoral example used here, stocking rates are assumed to be 18 ha per animal unit and forage grass is the only feed source in the African nomadic system. Details of daily gains are derived from Bremen and de Wit (1983) and de Leeuw and de Haan (1983). The US feedlot system includes a foraging phase for the young animals followed by a feedlot phase where animals consume a variety of crops grown on arable land. In the US feedlot system, all feed is produced on or in an area near a farm operating in New York State, displacing New York State's natural ecosystems. Diet composition and weight gain are based on data from Ensminger (1987) and the National Research Council (1989). Greenhouse gases are emitted in the US system through fossil fuel consumption embodied in the beef production process through on-farm energy use, and through energy use outside the farm for fertilizer manufacture and irrigation. In both the Sahelian and US systems, methane is released directly from the animals through enteric fermentation in the cattle rumen. Loss of carbon storage on land is also assessed for both systems. For the feedlot system, the opportunity cost of carbon uptake potential on cultivable land through foregone afforestation is considered. In the Sahel, periodic burning reduces the average standing biomass stock on pastureland and this is also calculated.

Greenhouse gas emissions are calculated on a common unit of measure—emissions per kg of beef on a carbon dioxide equivalent basis (see

Table 1
Costing production for 1 kg of beef

	Approach	Practitioner	Indicator
Agricultural economics	Expenditures of labour, capital and resources are assessed	Farmer Jones	Production costs: $ inputs of labour, capital, resources
Conventional pollution environmental analysis	Nitrogen pollution from wastes and fertilizers, conventional and toxic airborne pollutants from fuel combustion and pesticide applications; topsoil loss	National and state environmental and agricultural agencies	Nitrogen, sulphur, potassium, etc.
Biophysical capital alteration	All factors of production are assessed as energy inputs with reference to biomass stock and displacement	Giampietro from Odum	$(W/m^2)/(kg/m^2)$
Ecological economics	The total costs of production expressed in energy terms	e.g. Costanza, 1980	$\$/(W/m^2)$ or $\$/(W/kg)$
Climate change costs	Discounted expected impacts from global warming	e.g. Cline, 1992	$/tonne CO_2 equivalent
Greenhouse gas emissions analysis	Greenhouse gas emissions from production processes	Ward et al., 1993; Jarvis and Pain, 1994; Subak, 1997, 1999	CH_4, CO_2, N_2O emissions/kg animal product

Table 2
Diet and management assumptions for Sahelian pastoral and US feedlot beef production

	Pastoral/subsistence	Feedlot/forage
Lifetime (days)	1000	394
Time in forage (days)	1000	144
Time in feedlot (days)	0	250
Final weight (kg)	270	550
Beef yield (kg)	165	297
Diet (kg/head/day)		
Corn		7.1
Corn silage		11.5
Soya		0.45
Pasture	4.3	
Crop yield (kg/ha/yr)		
Corn		6500
Corn silage		26 000
Soya		2500
Pasture	1000	
Area required (ha/head/life)		
Fodder crops		0.41
Pasture	21	
Opportunity cost of fodder in net carbon uptake (kg C/ha/yr)		1000
Burning frequency of pasture land (%/year)	10%	0%
Carbon storage opportunity lost (kg/head/life)	409	430
Fertilizers for fodder (kg/N/ha)		206 (195 forage)
N_2O emission factor (kg N_2O/kg N fertilizer)		2%
Greenhouse gas embodied in fossil fuel for on-farm use, irrigation, fertilizer manufacture, fuel extraction (MJ/head)		24 167
CO_2/kg/head		463
CH_4/kg/head		2.9
N_2O/kg/head		0.1
Methane conversion	7.5%	4.5%
Digestability of feed	40%	75% (65% forage)
Enteric fermentation emissions factors (kg CH_4/head/year)	29	50
CH_4 from manure (kg CH_4/head/year)	1	2

Table 3). The results indicate that methane emissions from the pastoralist system are nearly twice that of the feedlot system. This is because the African cattle have a higher methane conversion rate from lower quality feed, live longer than feedlot animals, expend more energy eating over a larger range, and produce less meat. These factors compensate for the fact that the animals are eating less than the feedlot animals. However, when carbon dioxide embodied in fuel is considered as well, higher emissions are found in the feedlot system. In fact, the estimated level for the feedlot system is more than double that of the pastoralist system when carbon sink/stock losses are also considered.

It has been proposed that sustainability in agriculture can be evaluated according to changes in ‘biophysical capital’ in a system. Biophysical capital alteration describes an ecosystem’s ability to use solar energy to maintain the biosphere’s structure and function (Giampietro and Pimentel, 1991; Giampietro et al., 1992). Sustainability of human activities as proposed by Giampietro and colleagues is indicated by the stability of the

Table 3
Greenhouse gas emissions (kg CO_2 equivalent/kg beef)[a]

	Enteric fermentation and wastes (1)	(1)+embodied fuels (2)	(2)+sink/stock loss
Feedlot	3.6	9.1	14.8
Pastoralist	6.8	6.9	8.4

[a] Global warming potentials for methane of 24.5 and 320 for nitrous oxide, integrated over a 100-year time horizon, are used to derive CO_2 equivalence (IPCC, 1995).

dynamic equilibrium between biophysical and human–technological capitals. High levels of biophysical capital represent relatively high stocks of biomass, but significant alteration involves a diminishment in biomass stock, and loss of a flow of solar energy at a given density. Unsustainable alteration of biophysical capital may be seen as human exploitation of natural processes such that the flow of energy in the ecosystem is insufficient to maintain the original structures/functions. It has also been suggested that this indicator can be used to evaluate depletion of resources and species richness.

Biophysical capital alteration, according to this definition, can be quantified. Specifically, biophysical capital is determined by the quantity of solar energy, i.e. watts of solar energy (W), that is used in the work of self-organization (W/m^2) within a given biomass structure (kg/m^2), thereby indicating the level of energy dissipated to maintain 1 kg of biomass structure (W/kg). Emissions analysis can be compared with biophysical capital loss (W/kg), which has already been evaluated for the African and American beef production systems (Giampietro et al., 1992). Giampietro et al. (1992) concluded that the biophysical capital alteration (W/kg) for the US feedlot system is about twice that of the Sahelian pastoral system. The results of the most comprehensive greenhouse gas emissions analysis provide relative values that are similar to the sustainability value (W/kg), where the impact of the feedlot system is about double that of the pastoral mode (see Table 4).

A comparison of the relative environmental impact of the two beef production modes in topsoil loss, methane, biophysical capital alteration and total greenhouse gas emissions, appears in Table 5. Results of the comprehensive greenhouse gas emissions analysis and the biophysical capital alteration approach are similar, with environmental impacts of the feedlot system greater than that of the pastoral system in both approaches. Under the biophysical capital alteration measure, environmental impacts are 1.7 times greater for the feedlot mode, and considering comprehensive greenhouse gas emissions, the impact of the feedlot system is about 1.8 times greater than the pastoral mode. Further research would be needed to demonstrate whether these results would hold more generally.

3. Evaluating the environmental impacts

The foregoing quantitative assessment shows that there appears to be some convergence between comprehensive greenhouse gas emissions analysis and the biophysical capital alteration approach. However, it is important to consider the actual processes involved in both sets of transformations, and their usefulness as environmental indicators. The biophysical capital alteration value is based on the estimated flow of energy, which includes the energy spent in photosynthesis in the community plus the energy required to transport the water needed to carry nutrients from the roots to the rest of the plant as well as to cool the plant. This is a more comprehensive form

Table 4
Comparison of environmental parameters

	W/m^2	kg/m^2	W/kg
Feedlot	21.50	1.92	11.2
Pastoral	0.65	0.10	6.6

Source: Giampietro et al., 1992.

Table 5
Summary of results of environmental impacts (units as noted, per kg beef)

	Topsoil loss (t/ha/year)	Methane emissions (kg CO_2 equivalent)	Biophysical capital alteration $(W/m^2)/(kg/m^2)$	Greenhouse gas emissions (kg CO_2 equivalent)[a]
Feedlot	20–40	3.6	11.2	14.8
Pastoral	0	6.8	6.6	8.1

[a] CO_2 equivalents are based on a global warming potential integrated over a 100-year time horizon (IPCC, 1995).

of energy accounting than that of embodied energy analysis, which considers the heat energy of fuels and does not include environmental energies (Brown and Herendeen, 1996).

The biophysical capital alteration value (W/kg) involves high values in unstable situations such as immature plant communities or human-managed biotic communities. High values of energy dissipation are associated with high net primary productivity and low standing biomass, as characterize agriculture, plantation-forests and grasslands. Mature forests and suppression of burning are associated with areas of low energy dissipation (see Table 6). The principle behind the biophysical capital alteration measure is that, after alteration, a given land area is depleted in its ability to use energy to maintain its structures and functions and species diversity (Giampietro et al., 1992).

To serve as an indicator of biodiversity, however, the biophysical capital alteration approach would have to correlate with loss of diversity over a range of ecosystem types—including grasslands as well as forests. While the alteration measure would sometimes correspond to loss of species in cleared forests it would tend not to correspond with habitat changes in grassland and savannah ecosystems. Low energy dissipation (low W/kg) can mean the preservation of species-rich forests or it can mean the destruction through fire suppression of species-rich savannah. For some biomes, however, such as the fynbos shrubland of southern Africa, some of the most diverse plant communities in the world exist at a relatively low level of biomass stock and are maintained through periodic fire (Pyne, 1995). If these areas were planted with trees, the original flora and fauna would disappear but the W/kg indicator would be higher. In addition, the impact of the particular system alteration, i.e. deforestation at a site, has implications for the larger system and contribution towards total system value, but information on the scale of this contribution will not be available (Turner and Pearce, 1993). For this reason, biophysical capital alteration, as defined, should not be treated as a measure of biodiversity reduction.

In the natural capital approach, energy flows are calculated based on appropriation of photosynthesis, and expenditure of energy in the production of valued outputs. The energy calculated relates to production and expenditure of primary productivity, and therefore includes investments in carbon and carbohydrate production and its dissipation. Consequently, the energetic approach will undervalue processes that are not directly related to photosynthesis and transpiration. Methane production depends directly upon the presence of anaerobic conditions and microbial populations and, in some cases, upon the conditions for combustion, but not directly upon the sun's energy.

Without more detailed analysis of the relevant entropy processes and the implications of potential biomass accumulation on all related processes, the biophysical capital implications of

Table 6
Level of energy dissipation (W/kg)

	High W/kg	Low W/kg
High biomass stock		Mature forests; suppression of burning
Low biomass stock	Agriculture; plantation-forests; grasslands	

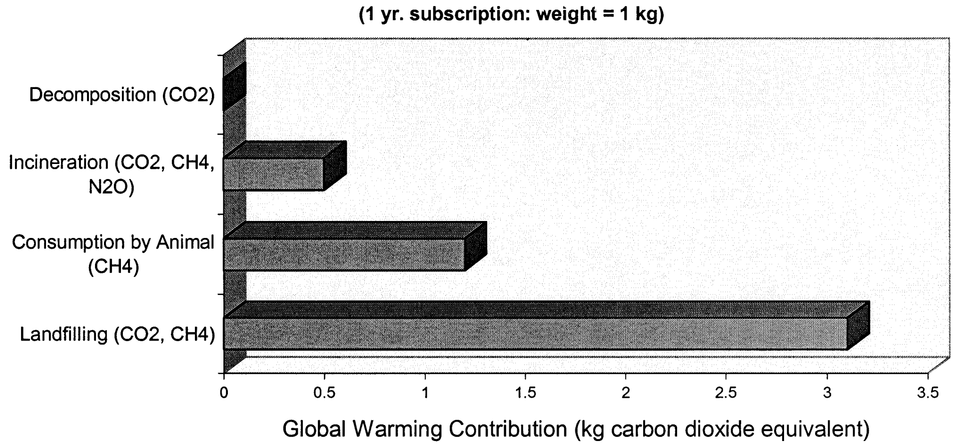

Fig. 1. Greeenhouse gases from different disposal routes of the journal *Ecological Economics* (1 year subsription:weight = 1 kg).

disposal systems will not be obvious. Even the direct impact on greenhouse gas emissions has not been widely known, although it can be summarized in brief. Whether organic matter decomposes aerobically, is burned, or decomposes anaerobically, represents large differences in greenhouse gas emissions. For instance, a given mass of paper will generate about six times the radiative forcing if it is left to decompose in a landfill than if it is burned, as indicated in Fig. 1. Similarly, if a ruminant animal eats the paper, the resulting greenhouse gas contribution will be much greater than if the paper is burned. If the fibre for paper is being grown at replacement, carbon dioxide emissions from decomposing paper represents a temporary flux only.

All of these waste disposal forms can provide energy for direct human use, except for disposal from decomposition and enteric fermentation. The fuel contribution of biomass combustion is well known. While emissions from enteric fermentation are too diffuse for energy recapture, animal wastes can be used in biogas digesters to produce fuel and concentrated fertilizers. Paper disposed in landfills can contribute to useful energy when methane emissions are recaptured on site.

At some levels, the entropic flow principle tells us very little about sustainability. We can imagine a planet of plant matter, cattle and humans thriving indefinitely if global warming does not adversely effect their survival. Humans and cattle can fertilize plants and plants provide humans and cattle with oxygen and food. Solar input continues to enable plant productivity. The second law of thermodynamics is not refuted, and yet a steady state is conceivable. The entropy principle does not appear to be useful in this example. At a given level of activity or a given climate sensitivity, however, the waste flows in this consumption cycle become critical. Whether the animal wastes decompose aerobically, producing carbon dioxide, or decompose anaerobically, producing the more potent methane, could make all the difference in the long-term survival of these species. The response of the atmosphere to greenhouse gas emissions, which is still quite uncertain, is important to long-term survivability of humans and other species, but this response is not captured in the concepts of irreversibility as developed by Georgescu-Roegen (1971) and others.

Nonetheless, it can be readily understood why there is some correspondence in the relationship between primary productivity and methane production for at least the bacterial sources. Higher methane emissions from enteric fermentation in cattle, for instance, are directly related to the digestion of plant matter. The correlation with primary productivity, however, would most likely be lower in livestock systems where factors like roughage quality, energy expended on feeding, and reproductive patterns, are important. Consequently, it may be that the biophysical capital alteration analysis would lead to the underestimation of the environmental impacts of beef production for those agricultural systems where animals rely on low quality feed and live longer than necessary.

4. Evaluating social costs

Environmental impacts can be assigned monetary values and evaluated as a social cost, although most such valuation exercises are viewed as crude attempts to compare disparate goods and damages. It has also been proposed that calculated energy values can provide a unit of currency for natural capital accumulation and its conversion. Odum (1971) pioneered an approach for analysing the dissipation of matter as an indicator of the 'cost' in resources of production processes. Costanza (1980) and others have developed an application of the energetic approach that expresses natural capital expenditures in terms of prices and economic values. They have transformed the W/m^2 into a value based on $\$/(W/m^2)$. The embodied energy approach to value is similar to neo-Ricardian economics where the exchange value of commodities in a determinate economy can be expressed in terms of a single 'standard commodity' (Judson, 1989). Costanza (1980) argues that for goods produced in a market economy, excluding primary energy, calculated embodied energy values show a very good empirical relation to market-determined dollar values if there are interdependencies among the primary factors.

In the case of beef production, there are some interdependencies between factors of labour, capital and land. In the pastoralist example, labour and land area replaces fossil fuel inputs, capital investments and topsoil that would be exploited in more intensive livestock production. In the more extensive forms of American and European beef production, land substitutes for capital and soil quality. The capital intensity of the feedlot system is, in part, a reflection of the relatively high costs of labour and land in these regions. In Costanza's analysis, however, primary agricultural products such as livestock and forest products were outliers in the original input–output analysis of market value as a function of embodied energy inputs (Costanza, 1980). This is believed to be because market values are low relative to calculated energy inputs (Costanza, 1980).

If we adjust the calculated W/m^2 values for each system—21.5 and 0.65, respectively—as the denominator of the US market values of \$1.50, we do not get remotely similar ratios: $\$1.50/21.5 = (\$0.07)$ and $\$1.50/0.65 = (\$2.31)$. However, when considering the \$/W/kg values, the resulting ratios for both livestock systems are closer in value: $\$1.50/11.2 = (\$0.13)$ and $\$1.50/6.6 = (\$0.23)$. Beef commodity prices have been relatively stable in the United States during the 1990s with only $\pm 5\%$ variation between 1991 and 1994 (IMF, 1996). In 1994, producer prices for beef were approximately \$1.50 per kg (FAO, 1995). Published beef prices in the Sahel have been more variable over time (FAO, 1995) and the exchange rate volatility often high (IMF, 1996). Taking producer price values of a range of Sahelian countries in 1994—Algeria, Ghana, Malawi, and Niger—we find a mean of approximately \$0.75 per kg. This comparison must be qualified by the usual points about differences in purchasing power parity and unfavourable exchange rate volatility is often high (IMF, 1996). Moreover, prices for beef are often set by the state and not by the market, and so will reflect costs to a lesser extent than will prices for US beef. These factors preclude a meaningful comparison between beef prices in the US and Sahelian regions. Nonetheless, using the US prices, energetic parameters do not provide any plausible unit of relative economic value for the agricultural systems considered here.

On the other hand, the biophysical capital alteration approach does show a potential for convergence. To reach actual convergence in the $\$/(W/kg)$ value, the unit price of Sahelian beef would need to be \$0.85 compared with \$1.50 for feedlot beef. Given that international prices of African beef are highly controlled, and the purchasing price disparities and exchange rate volatility are high, the presence of such a price cannot be established. The relevance of the comparison of the W/kg indices is tentative, however, given the limited number of cases considered here. Moreover, any value based solely on physical activities (W/kg) will neglect the influence of preferences on the demand, and hence on commodity price, for goods. This is a strong argument against the energy theory of value and would hold true for a monetary value based on the biophysical capital alteration concept.

The advantages of the physical measures of biophysical capital alteration and greenhouse gas emissions are that they reflect environmental impacts irrespective of preferences and price distortions. Local environmental impacts, as assessed here, can be used to derive global environmental impacts in monetary terms. Given rudimentary assessments of the potential economic impacts of climate change, the greenhouse gas emissions assessment unit can be translated into global environmental cost estimates. Although projected social costs of climate change are as uncertain as any quantification related to climate change, greenhouse gas emissions estimates can be used to attempt to provide some notion of the global environmental costs of beef production. Attempts at estimating the social costs of greenhouse gas emissions have been made by a number of economists.

If the greenhouse gas emissions are compared on a carbon dioxide equivalent basis, for example over a 100-year time horizon, the emissions values may be readily expressed within this range of costs related to climate change impacts. Because these estimated potential impacts are highly uncertain, one of the wider estimated ranges is noted here. The widest range in the recent literature has been published by Fankhauser (1994) at $6.20–45.20 tonne carbon (or $1.70–9.20 tonne CO_2) for emissions from the 1991–2000 period. These values are published as the estimated marginal social cost per tonne of emissions expected given a specific scenario of climate change, i.e. doubling of atmospheric CO_2 concentrations. Fankhauser's and other estimates are highly dependent on the discount rate assumed, i.e. the rate at which future impacts of climate change are discounted. Fankhauser's probabilistic approach to a range of discount rates between 0 and 3% accounts for the range of social cost estimates (Fankhauser and Tol, 1996). The climate change cost estimates can be compared against the market value of the producer value of the commodity evaluated. The social costs of greenhouse gas emissions are calculated at about 9% of the market price for beef as an upper limit of the estimated cost range, although a central value of $20 tonne/carbon suggests expected social costs equivalent to only 3–5% of the producer price of beef (Table 7).

One possible approach to accounting for the estimated global environmental impacts of beef production is to implement a tax on beef consumption. Beef is a luxury protein in many respects. Most regions that raise beef intensively have alternative sources of protein. Indeed, in Argentina and Uruguay, for instance, most of the vegetable protein raised on arable land is fed to beef cattle. The additional resources in land, energy and water inputs needed to produce animal protein are well known, estimated at about five-fold that of a comparable level of protein from grain, and the difference in greenhouse gas terms is even greater. An estimated 4.8 kg of grain is used to produce 1 kg of beef in the United States (Pimentel, 1980). Given the scale of livestock production, even small changes in management or consumption level can make a significant difference in environmental impact. Cattle and live-

Table 7
Economic impacts and environmental impacts (units as noted, per kg beef)

	Conventional costs ($)	Ecological economics ($/(W/kg))	Climate change costs[a] ($/kg beef)	Beef tax as % of value (%)
Feedlot	1.50	0.13	0.03–0.14 (0.08)	2–9% (5%)
Pastoral	? (1.50)	(0.23)	0.01–0.07 (0.04)	1–5% (3%)

[a] Expected social costs of climate change: $6.2–45.2/tonne C or $1.7–9.2 tonne CO_2 (Fankhauser, 1994).

stock are believed to graze over about half of the earth's land area (BOSTID and NRC, 1990). An estimated 38% of the world's grain is believed to be produced for livestock with the proportion as high as an estimated 70% in the United States (Durning and Brough, 1992).

In the longer term, tax measures that would address the persistent environmental externalities associated with beef production, such as greenhouse gas emissions, could be imagined, although they should be implemented only after subsidies are removed. Beef production in many countries has been characterized by distortions such as rangeland subsidies in North America and, through the Common Agricultural Policy, support for the intervention price of beef produced in Europe. Recent changes in the Common Agricultural Policy are aimed at eliminating these price supports (EEC, 1992), although subsidies are expected to persist in many instances, i.e. support for traditional grazing in water-logged soils and upland areas in some countries (MAFF, 1996). The large area of Bureau of Land Management pasturage in the United States is increasingly a target of criticism from US environmentalists and taxpayers. While many producers have enjoyed subsidies for generations, subsidies have distorted the market for food products that bear a lower environmental cost. As demonstrated in this study, greenhouse gas emissions per unit of beef vary considerably with different production modes. While this comparison included extremes in terms of energy and land intensity in two continents, greenhouse gas emissions per unit of product will tend to vary considerably within many countries. Optimally, a tax would be applied in recognition of the differential environmental impact of the beef sold. In practice, of course, a variable tax would be highly impractical.

The response to beef prices must be somewhat elastic if a tax on beef is to lower consumption, and not just add to government revenues. A negative price elasticity of demand indicates that people will reduce their consumption of beef when prices increase. Of course, different regions of the world are expected to respond differently to changes in prices for beef depending upon income level, preference for beef and availability of other meat protein. Price elasticities of demand derived from IIASA's Basic Linked Systems model for European Union countries are estimated at −0.04, with greater elasticities for Japan at −0.13 and Canada at −0.33 (Fischer et al., 1988). These estimated price elasticities are lower than most calculated price elasticities of demand related to fossil fuels. In addition, these elasticities are quite uncertain given the poor statistical efficiency that generally characterize beef demand and supply models (Subak, 1995). While a beef tax would primarily be expected to be a revenue-raising measure that would reflect environmental externalities associated with beef production, it could also lead to some reduction in beef consumption.

Another approach for internalizing costs related to the potential risks of global warming would be to tax livestock products in accordance with the estimated costs of abating greenhouse gas emissions from livestock production at a given level. Because demand for beef in industrialized countries is relatively inelastic, using revenue from taxation of livestock products for paying for the incremental costs of greenhouse gas emissions abatement would more effectively lead to lower emissions. For example, given an estimated 14.8 kg CO_2 equivalent related to producing 1 kg of beef, assuming sufficient information about abatement costs, the costs of reducing ruminant emissions in line with regional or national targets could be derived. Few studies of greenhouse gas abatement costs related to livestock systems are available. The US Environmental Protection Agency (US EPA) has been developing cost curves for reducing greenhouse gases from cattle through improved management (Clinton and Gore, 1993; Kruger, 1997). The ruminant emissions reduction programme includes chiefly information dissemination aimed at promoting improved reproduction, nutrition and grazing management. Estimated cost curves for reductions from dairy cattle relate a cut of 25% from total dairy cattle emissions in 2000 at about $20 per tonne of CO_2 equivalent reduced (derived from Kruger, 1997; US EPA, 1995) (see Table 8). Assuming that abatement costs are similar for beef cattle, if these costs were applied as a levy on beef

Table 8
Sample abatement costs for reducing greenhouse gases from dairy ruminants

Abatement costs (\$/t CO_2 equivalent)[a]	Abatement in 2000[b] (%)	Abatement in 2000 (Tg CH_4)	Abatement in 2020 (Tg CH_4)	Cost as % of unit price assuming beef
0	12	0.27	0.43	0
4	16	0.36	0.58	4
14	21	0.49	0.77	14
20	25	0.57	0.90	20
27	28	0.65	1.02	27

[a] Kruger, 1997.
[b] Estimated cuts from 1990 levels derived from Kruger (1997) and US EPA (1995) based on 1990 dairy ruminant emissions of 2.3 Tg CH_4.

consumption, the resulting tax would be about 20% of unit cost assuming \$1.50/kg of beef. As indicated in Table 8, if abatement targets were set further into the future, these costs would decline. Incidentally, the methane abatement levels projected by the US EPA may appear less impressive if related increases in carbon dioxide due to improvement in nutrition, as quantified in this study, were also considered.

Finally, the trade-offs between methane reduction and increases in carbon dioxide emissions may not be immutable. The energy productivity of agriculture has been dynamic and fossil fuel inputs have declined dramatically since the 1980s due to technical and managerial changes (Cleveland, 1995). Some of the reduction in fossil fuel use was due to upscaling to larger farm size (Cleveland, 1995), which may have actually boosted methane emissions from manures in intensive livestock systems. Also, greater reductions in fossil fuel inputs in intensive systems are conceivable for the future both in total requirement and in fuel type. A range of renewable fuels such as biogas, wind and solar would represent lower carbon alternatives for the agricultural sector. In the United States, the greatest reductions in energy intensity over recent decades have been accompanied by the introduction of technology that exploits less carbon-intensive fuel (Kaufmann, 1992). Changes in the respective methane carbon ratios of livestock systems would be expected to change as new technologies are developed and management of wastes improves.

5. Conclusions

Environmental assessments and pollution reduction strategies for livestock systems have chiefly focused on direct organic pollution from the animals in the form of nitrogen loadings to water bodies or upon methane emissions from enteric fermentation or anaerobic decomposition of manures. Efforts to reduce conventional pollution have targeted intensive systems, whereas efforts to lower methane emissions have focused on the more extensive systems. The conventional pollution assessment has tended to find that intensive agriculture is more polluting because of nitrogen runoff and emissions related to fuel and fertilizer inputs for stockfeed. Rangeland and pastoral agriculture tend to involve lower levels of conventional pollution. In contrast, most greenhouse gas emissions analyses completed in recent years assume that the emissions intensity related to traditional agriculture is much higher than the intensive form, because lower productivity translates into higher methane emissions per unit of product.

The livestock production comparison completed here shows that the greenhouse gas emissions and biophysical capital alteration results are very different from those of the conventional environmental impact analysis that would focus primarily on topsoil loss or individual species emissions, e.g. N (Nitrogen), P (Phosphorus) and S (Sulphur). For example, nitrogen impacts can be quite site-specific, but do not correlate with methane and carbon dioxide emissions related to the production of a given animal product. Methane emissions assessments and conventional environmental analyses of beef production are missing a large component of the environmental impact of beef production systems. A more complete assessment of the environmental impact of these systems is found when indirect emissions related to the carbon dioxide flux are considered as well. These conclusions underscore the need for policies that address the other environmental impacts of beef production.

The results of the complete greenhouse gas emissions analysis do converge to some extent with the results of the biophysical capital alteration approach. While fossil fuel inputs are often considered a good proxy for pollution loadings related to industrial production, the biophysical capital alteration approach appears to be a reasonable proxy for the full-greenhouse gas emissions implications of the two livestock production systems examined here. These results are tentative given the limited cases explored and the numerous assumptions made for the cases, particularly for the opportunity costs of the land.

These results indicate that the intensification of beef production systems may be counter-productive because net emissions of carbon dioxide as well as nitrogen and other pollutants would increase. Additional emissions of ammonia are also related to intensive production, although these emissions were not quantified in this analysis. Livestock are the main source of ammonia emissions (NH_3), which contribute to the acidification of lakes and forest soils (Asman, 1987; Roelofs and Houdijk, 1991). The impacts of different forms of nitrogen pollution, including ammonia, should be considered according to the sensitivity of a given locale to these non-point sources. Acidification from ammonia is caused indirectly through nitrogen deposition and directly by affecting vegetation in the vicinity of the source. Ideally, a range of livestock production systems will also be analysed comprehensively for greenhouse gas emissions as well as for conventional pollution. In practice, such assessments are complex to undertake, particularly because of the large range of agricultural systems and sensitivities concerned.

A more general point may be made that beef production has a more serious environmental impact than usually assumed. Greenhouse gas emissions related to producing a tonne of beef in feedlot systems appear to be two to three times greater in heating equivalent terms than the direct methane emissions involved. These impacts underscore the high environmental cost of producing beef protein as opposed to vegetable protein. The greenhouse gas analysis is more comprehensive than the biophysical capital (W/kg) measure and, in the long term, will be easier to calculate. The greenhouse gas assessment includes atmospheric impacts as well as impacts on standing biomass levels as related by the biophysical capital measure. Accordingly, economic instruments are more efficiently applied using greenhouse gas emissions analysis to estimate environmental damage. All estimates of the social costs of greenhouse gases are of course very uncertain, regardless of whether they come from agricultural systems or from energy use. The \$/kg CO_2 equivalence value estimated in this paper provides a social cost estimate that has an upper limit of about 9% of the current market value of beef and a central value of 3–5%. Given that the demand for beef is relatively inelastic to price in many instances, direct investment in low-cost greenhouse gas abatement strategies may be a sensible option in some regions.

Acknowledgements

The author is grateful to R. Brouwer, D.W. Pearce, D. Pimentel, and R.K. Turner for helpful comments on earlier versions of this draft.

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