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ABSTRACT—Recent international agreements for controlling emissions of greenhouse gases have focused the attention of both the climate research and policy communities on strategies for reducing the production and emission of these radiatively active substances. Most approaches have adopted a "top down" perspective, where mitigation strategies are framed at the level of national governments. However, emissions occur at local, rather than national scales. We describe a study aimed at documenting greenhouse gas emissions from a local area in the High Plains of southwestern Kansas that is currently undergoing marked economic change and population increase in response to restructuring of the meat packing industry. We estimate volume and source of emissions for three greenhouse gases, carbon dioxide, methane, and nitrous oxide, and contrast the relative importance of gas emissions at the local, state, and national level. The relative amounts of greenhouse gas emissions and the processes that produce them were found to vary considerably across these three geographic scales. In the study area, agribusiness is the leading source of methane and the greatest overall contributor to greenhouse gas emissions. Utilities and the natural gas industry contributed the largest amounts of carbon dioxide, ranking second and third in overall contribution to greenhouse gas levels, respectively. The proportion of total global warming potential (GWP) contributed by CH_4 is somewhat higher at the local level than at the state or national levels. Contribution to total GWP by N_2O in the local area is roughly equivalent to the larger geographic areas. Overall, the relative importance of various emission sources shows considerable contrasts across scale.

Introduction

Within the climate research community, there is growing consensus that the combined effect of human emissions of greenhouse gases, land cover change, and other impacts on the Earth-atmosphere system are forcing

change in the global thermal equilibrium (Pielke and Avissar 1990; Dickinson et al. 1996). Although the magnitude and spatial expression of climatic change due to this enhanced greenhouse effect are still controversial, concern about anthropogenic climate change has stimulated international efforts to reduce emissions of greenhouse gases. With striking similarities to the Montreal Protocol and Chloroflourocarbon production, the agreements reached in Kyoto, Japan, in December of 1997 are the most recent examples of international efforts to to curb greenhouse gas production. Under the terms of the Kyoto agreement, participating nations must meet individual emissions reduction goals within a specified time period. If ratified by congress, the Kyoto agreement will require the United States to reduce its emissions to 7% below 1990 levels by the year 2012. The Kyoto agreement has already sparked discussion within both the scientific and policy communities as to how emissions goals can be met (Romm et al. 1998). Lost in this debate, however, are fundamental questions of scale and the relative impact of emissions reduction locally.

The scientific debate over global warming and consideration of its policy implications are examples of the prevailing tendency toward a "top-down" approach to global climate change issues. Climate change scenarios derived from global-scale models serve as the starting point for regional impact analysis (Hubbard and Flores-Mendoza 1995; Mendolsohn and Rosenberg 1994; Easterling et al. 1993). These analyses in turn stimulate global-to-national scale responses such as the Kyoto agreement, where governments or governmental consortia (e.g., the European Union) are the fundamental organizing units. Yet greenhouse gas emissions and other changes in radiative forcing do not originate at the national scale. Emissions typically originate from discrete point sources, mobile sources such as vehicles, or from spatially distributed processes such as agriculture. These sources rarely exceed the local spatial scale and are distributed heterogeneously throughout countries. Their number and type in any particular region depends on a complex series of factors reflecting the economic, political, social, and historical development of the local area. Although goals and policies may be formulated at the national level, actual reduction of emissions must occur at a more localized scale. Mitigation strategies based on national-level assumptions about the relative importance of various emissions sources may not adequately reflect the individual character of the local areas at which both the emissions themselves and the efforts to mitigate them actually occur. Thus, the goals and policies should also be related to the unique characteristics of the area in question.

In this paper, we consider an alternative to the prevalent top-down approach by studying greenhouse gas emissions from a local area. This investigation is part of a larger research initiative dubbed "Global Changes in Local Places" (Kates and Torrie 1998). The protocol of this initiative includes four study areas, located in the Blue Ridge/Appalachian Piedmont of North Carolina, Central Pennsylvania, the Great Lakes/Manufacturing Belt of Northwestern Ohio, and the High Plains/Ogallala Aquifer area of southwestern Kansas. Each site is approximately one equatorial degree in area, a spatial dimension chosen to coincide with an individual grid cell in many global climate and integrated assessment models. The "Global Change in Local Places" program is a three year effort to assess the links between local areas and global change processes: assessing local greenhouse gas emissions, social and economic driving forces and, especially, mitigation and adaptation capacities. In order to evaluate mitigation strategies for local areas, estimates of greenhouse gas emissions must first be available. Here, we present the results and analysis of a greenhouse gas emission inventory for the southwest Kansas study site. Our objectives are threefold: (1) to describe the study area and methods, (2) to present local emissions estimates and contrast them with comparable values estimated at state and national scales, and (3) to consider the significance of these results in light of policy considerations and mitigation strategies.

Study Area

The study was conducted in a six county area located in the High Plains of southwestern Kansas (Figure 1), an approximately 10,000 km^2 area. Due to the prevalence of counties as data reporting units, individual county boundaries, were used to delimit study site boundaries. The High Plains are a region of relatively high elevation (1500-1600 m) but little topographical relief. Natural vegetation is mixed or short grass prairie with few trees (Küchler 1974). The climate is characterized by a continental temperature regime with mean monthly temperatures in the range 5-22° C. Precipitation averages less than 45 cm per year, most of which falls as spring or summer rain (Goodin et al. 1995). The precipitation total exceeds that of true desert, but it is insufficient to support intensive grain production without irriga-tion.

Although often perceived as an area stagnant or in decline, the human dynamic in the High Plains is far more complex. The gloomy picture of depopulation and neglect painted by some (e.g., Popper and Popper 1987)
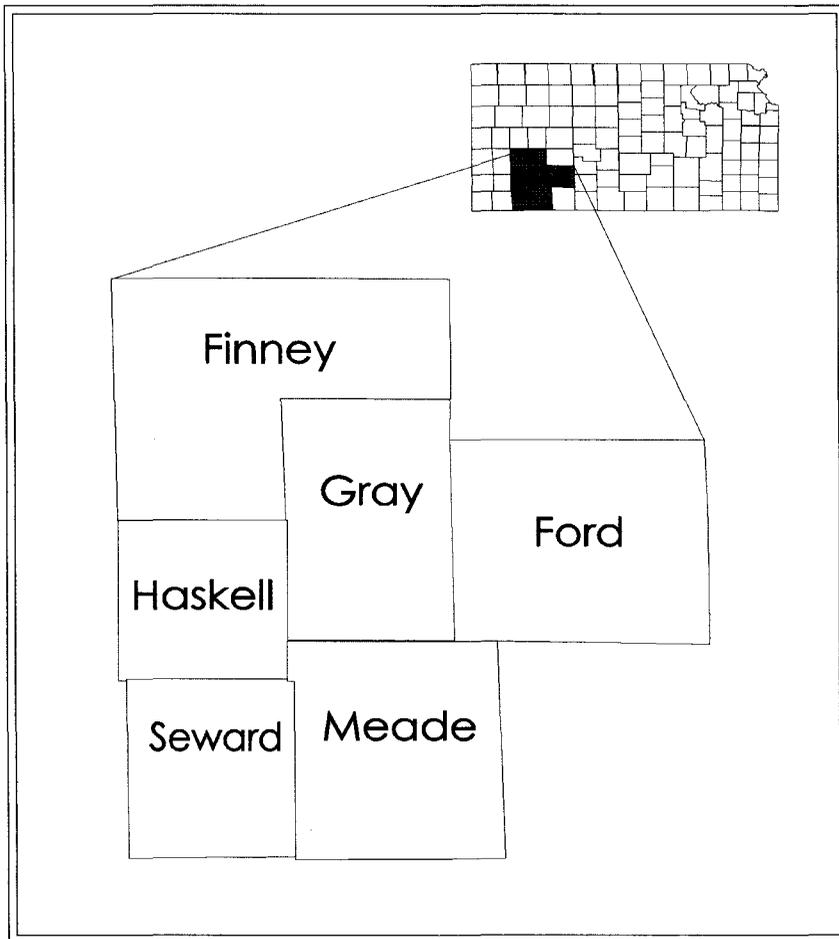
Figure 1. The six county study area by authors.

contrasts with an alternate view in which some High Plains areas are declin-
ing, while others are experiencing fundamental economic restructuring and
rapid population growth. Because these more vital areas of the plains are
closely tied to groundwater resources such as the Ogalalla aquifer system,
White (1994) has termed them "Ogalalla Oases." Within these oases, a viable
and dynamic agribusiness economy has flourished, including a healthy meat
packing industry. Easy access to groundwater coupled with improved irriga-
tion technology has resulted in supplementation of rangeland and dryland
crops by irrigated feedgrain production (Kromin and White 1992). Census
of Agriculture data for 1969 and 1992 indicate that irrigated land in the study

area increased from 200,000 ha to over 450,000 ha (National Agricultural Statistics Service 1969; National Agricultural Statistics Service 1992). Large feedlots, some with annual capacities exceeding 50,000 cattle, were introduced to exploit this proximity to feedgrain. Beef processing plants have shifted to southwest Kansas from their traditional Midwestern locations to capitalize on access to grain fed beef.

The study site was chosen to provide an example of the economic and environmental dynamic occurring in response to changes in the meat packing industry in the High Plains. Five large packing plants now operate within the study area. The largest, an Iowa Beef Packers (IBP) facility near Garden City, can process over 6,200 animals per day. The expansion of beef packing has been accompanied by a number of supporting industries, including package and container plants, fertilizer and agricultural chemical manufacturing, and transportation (mostly trucking). The expansion of the beef packing industry has increased the local demand for labor, resulting in a significant increase and redistribution of population. Farm consolidation and improved technology have decreased the demand for on-farm labor, hence many rural areas are depopulating through migration to local urban centers. The demand for laborers in factories and packing plants, however, has increased beyond what the local labor pool can supply. As a result, a substantial in-migration of workers, many of them Hispanic or Southeast Asian, has occurred.

Changes in the agribusiness sector of the study site's economy have been superimposed on the natural gas production industry that has been active in the region since the early 1930s. Portions of three study-area counties, Finney, Haskell, and Seward, overlie the Hugoton gas field, the largest natural gas field in North America (Carr and Sawin 1997). This complex of gas fields supports over 11,000 wells in Kansas (2,579 in the study area), and has extracted nearly 800 billion m^3 of gas in its production history. Supporting gas transportation activities, such as pipeline and compressor companies, accompany the gas production sector and contribute significantly to the economy of the study area and the region as a whole (Carr and Sawin 1997).

Emission Estimates

Although direct measurement of greenhouse gas flux is possible, such instrument-intensive measurements are impractical on the time and space scale needed to assess total emissions of greenhouse gases from even a

modest sized area. In addition, the necessary retrospective data for temporal trend analysis and cross-site comparison are not available. Emission values suitable for analysis of local greenhouse gas production must therefore be estimated by other means. An Environmental Protection Agency (EPA) workbook of methods is available for state-level emission estimates (United States Environmental Protection Agency 1995).

One of the central challenges in this research has been to adapt the EPA protocol to estimate emissions from a smaller geographic area. Much of the data needed to estimate emissions are obtained from the censuses of agriculture and population. Since these censuses are conducted at regular but infrequent intervals, the years for which emissions estimates can be made are similarly restricted. In this study, we used data from the 1990 Census of Population (United States Census Bureau 1990) and the 1987 Census of Agriculture (National Agricultural Statistics Service 1987). The 1987 agricultural census was chosen over the 1992 version in order to maintain uniformity with the other "Global Change in Local Places" sites.

The inventory of emissions concentrated on three major greenhouse gases, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O). These three gases together are estimated to contribute over 75 percent of the anthropogenic greenhouse effect (Houghton et al. 1996). Absent from our study is any consideration of chlorofluorocarbons (CFCs). These industrial chemicals are radiatively active and contribute significantly to the global greenhouse effect. We omit them because their emissions are already controlled by international treaty (i.e., the Montreal Protocol), and their atmospheric contributions are declining (Elkins et al. 1993; Cunnold et al. 1994). Water vapor is also not included in our study because no methodology exists for estimating its emission and because atmospheric residency time is relatively short. We should also note that non-controlled halocarbons, such as CFC substitutes that do not deplete stratosphesic ozone, are powerful greenhouse gases, and their contribution to global warming potential is growing rapidly, perhaps filling the void left by the declining contribution of the controlled halocarbons. However, we retain our focus on only those gases for which accepted estimation protocols are available to accord with **IPCC** (Intergovernmental Panel on Climate Change) guidelines regarding greenhouse gas inventories.

The three gases under consideration are not equal in their capacity to absorb longwave radiation and warm the lower atmosphere. Because of the disparity in efficiency, it is convenient to consider each gas in terms of its global warming potential, defined as the cumulative radiative forcing be-

TABLE 1

GLOBAL WARMING POTENTIAL (GWP) FOR EACH GREENHOUSE
GAS, ASSUMING 100 YEAR TIME HORIZON*.

GAS	GWP
Carbon Dioxide (CO_2)	1
Methan (NH_4)	21
Nitrous Oxide (N_2O)	310

* From Houghton el al. 1996.

tween the present and some chosen time horizon caused by a unit mass of greenhouse gas, expressed relative to CO_2 (Houghton et al. 1996; see Table 1). All global warming potential values in this study use a 100 year time horizon.

The Environmental Protection Agency protocol organizes emission estimates into a number of major categories, of which five are relevant to the study area. A summary of these categories and subcategories, together with relevant greenhouse gas in each category, is given in Table 2. The data used to estimate fossil fuel emissions vary somewhat depending on subcategory. Fossil fuel emissions from commercial-institutional sources, industry and manufacturing, and utilities were derived from the Aerometric Information Retrieval System, a self-reported database collected by the US EPA. The aerometric data consist of gas emissions (in tons/year) organized according to the U.S. Census Bureau's Standard Commercial Classification code. Activities associated with the code often differed somewhat from our major emissions categories and subcategories. Data from the Bureau's relevant code therefore had to be identified and aggregated to match the categories used here. Three subcategories of fossil fuel consumption—transportation, residential, and production and distribution—were not available from the aerometric database. Emissions from production-distribution and residential sources were estimated from the state energy report (Energy Information Administration 1995b). These data are reported in energy units (BTU) that were converted to tons/year of gas emission. Gas emissions associated with use of fossil fuels for transportation were estimated using data on vehicle

TABLE 2

GASES PRODUCED BY EMISSIONS CATEGORY

Emission Source Category	CH_4	CO_2	N_2O
Fossil Fuel Consumption			
Commercial/Institutional	X	X	X
Industrial/Manufacturing	X	X	X
Residential	X	X	
Transportation	X	X	X
Production/Distribution	X	X	X
Utilities	X	X	X
Production Processes (includes chemical)	X		X
Agricultural and Livestock Production			
Domestic Animals	X		
Animal Manure Management	X		
Game Animals (Deer)	X		
Fertilizer Use/Agricultural Liming	X		
Waste Disposal, Treatment, & Recovery			
Landfills	X		
Waste Incineration	X	X	
Burning of Agricultural Waste	X		X
Sewage Treatment	X		
Human Emissions	X	X	

miles traveled per length and class of road obtained from the Kansas Department of Transportation, and converted to tons/year of GHG emissions, using the Environmental Protection Agency's Mobil5a emissions model (United States Environmental Protection Agency 1995).

Emissions of methane and nitrous oxide from agriculture and livestock production were estimated via animal counts extracted from the 1987 U.S. Census of Agriculture (National Agricultural Statistics Service 1987). Conversion of animal counts to emissions was done using a validated mechanistic model (Crutzen et al. 1986), which took into account species, mass, gender, and age to estimate per-animal greenhouse gas production. Type of animal within a species is also taken into account. For example, beef and

dairy cattle emit differing amounts of greenhouse gases and are therefore considered separately. Ruminant game animals (i.e., deer) were also included in this category, and were treated as cattle. Also included under this general heading were emissions resulting from the management of animal manure. Again, these estimates were derived from validated emissions formulae, using agricultural census data on animal count, species, gender, and mass.

Waste disposal, treatment, and recovery processes produce methane and nitrous oxide in direct proportion to human population. Emissions from these activities were therefore estimated using total population numbers from the decennial census of population, using an Environmental Protection Agency conversion formulae (United States Environmental Protection Agency 1995). Landfill emissions, a major emission source in-this category, depend on volume of material deposited, and also on precipitation. Areas such as the study site, which receive less than 63.5 cm of rain annually, require an estimation formula different from that of more humid areas. Direct human emission, comprising biological production of CO_2 and CH_4 by respiration and digestive processes, is also a direct function of population. Agricultural waste burning (i.e., the burning of crop residue) is not population dependent, and emissions were estimated from EPA formulae based on crop type and acreage data derived from the agricultural census. Methane emissions associated with agricultural chemical production processes, such as the production of fertilizer, anhydrous ammonia, and ethanol, were estimated using U.S. Census Bureau Standard Commercial Classification data and Environmental Protection Agency conversion formulae.

Accuracy and reliability of greenhouse gas emissions estimates are a significant concern in research of this type. For this study, the relative proportions of various gases were more important than their absolute volumes. Nevertheless, some assessment of accuracy is needed. Emissions estimates must be made using data and methods from a variety of sources. For many of these methods, quantitative estimates of accuracy are not available, making it difficult to assign definitive error estimates to these emissions estimates. The Energy Information Agency, which inventories nationwide emissions using methods and data similar to those used here, estimated that the overall reliability of its inventory depends on the type of emission. Estimates of CO_2 values were accurate to within 5-6%, whereas methane figures are less reliable, with uncertainty estimates at 25-30%. Nitrous oxide estimates are considered accurate to within an order of magnitude (Energy Information Administration 1995a).
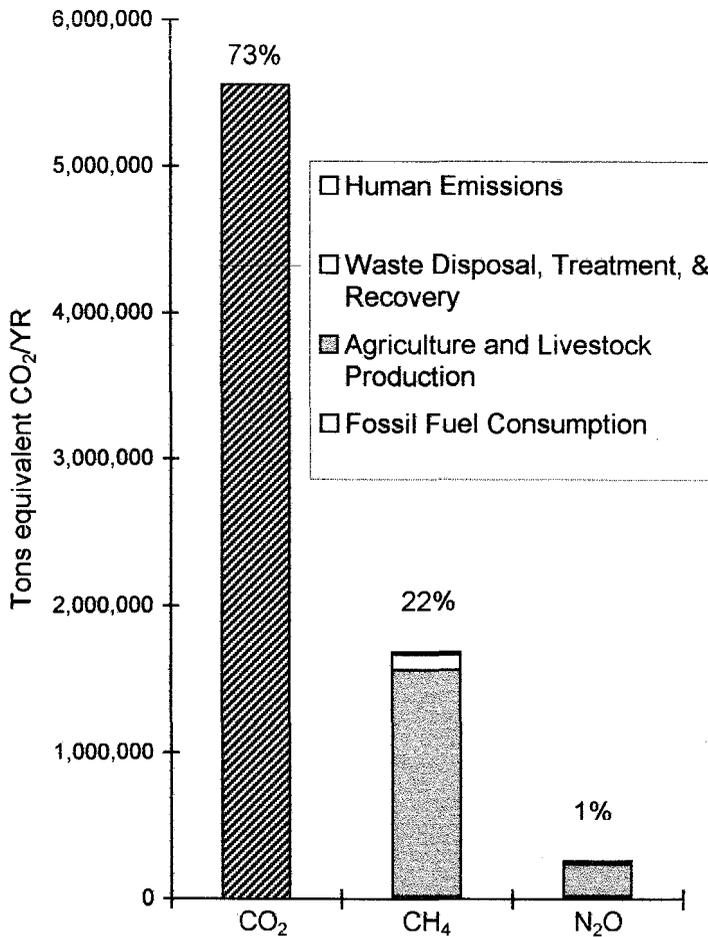
Figure 2. Total emissions of all greenhouse gases from major souce categories in the study area, expressed as global warming potential (GWP) of emissions estimates in this study.

Analysis of Emissions

Examination of estimates for local production of each greenhouse gas showed that CO_2 dominated emissions from the study area, in both total emission mass and global warming potential (Figure 2). Methane is second in overall contribution, followed by N_2O. This ranking is the same at all scales from global to local. However, there are notable differences in the percentage of global warming potential accounted for by each gas at the

various scales. Emission-producing activities at the local scale, such as the study area, differ from those at the state and national scales. To illustrate these differences, we consider each gas individually using local area emissions estimated by the methods outlined above. These local emissions are compared to state and national emissions extracted from either the EPA national survey (United States Environmental Protection Agency 1996), or the third annual Energy Information Administration report (Energy Information Administration 1995a).

Carbon Dioxide

In the study area slightly more than 5.5 million tons of CO_2 were emitted in 1990, accounting for 73% of all local global warming potential (Figure 2). For comparison CO_2 accounted for 81% of global warming potential emitted by the state of Kansas and about 86% of nationwide emissions. At the state and national scales, these US figures exceed the world average contribution by CO_2 to total global warming potential, estimated to be about 72% (Houghton el al. 1996). Contribution by CO_2 in the study area closely agrees with the global figure, suggesting that in terms of relative GHG contibution, the six counties in southwest Kansas more closely resemble a less-industrialized country. Although it is proportionally the largest contributor to global warming potential in the study area, the number of activities that emit CO_2 are relatively few (Table 2). In these 1990 estimates, fossil fuel use was the major emission category, accounting for over 99% of CO_2 emissions (see Figure 2). The small remaining fraction of CO_2 was directly emitted in the respiratory processes of humans and animals. Given the comparatively small population in the study area, the insignificance of direct emission of CO_2 is not surprising.

Although the predominance of fossil fuel combustion as a source of CO_2 is consistent across all scales of consideration, the contribution of various economic activities responsible for these emissions differ (Figure 3). At each level, utilities lead all emission categories, accounting for nearly 40% of local global warming potential compared to about 36% for the state and 34% at the national scale. The majority of fossil fuel emissions from the utility category originated from electrical generation facilities at all levels. In the local study area, most of these emissions are attributable to a single source, the coal-fired Sunflower-Holcomb Station power generation facility located west of Garden City. Two other small municipal power generation plants, one in Meade, the other in Dodge City, account for some utility
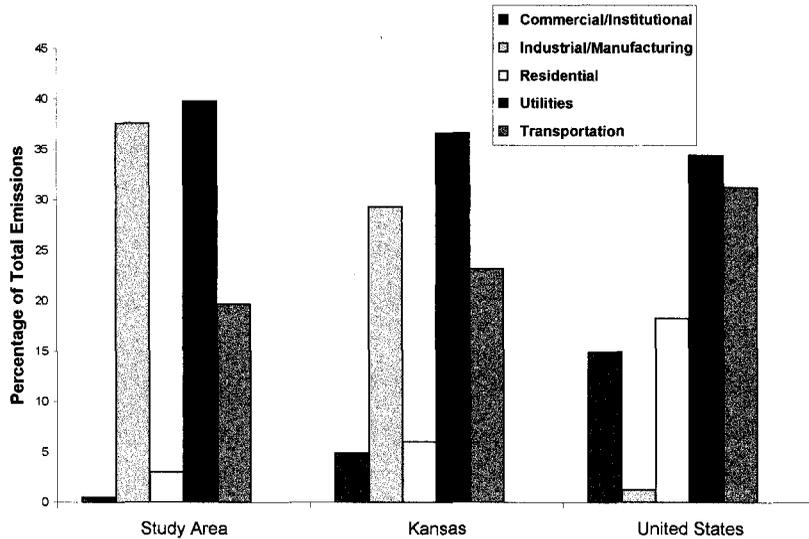
Figure 3. Percentage of global warming potential (GWP)produced by fossil fuel consumption at the local (study area), state, and national scale. Local area and state estimates from this study, national estimates from Energy Information Administration (1995a).

emissions, albeit a much smaller amount. The Holcomb Station has been in operation only since 1983. Prior to this time, the fraction of study site CO_2 emissions associated with utilities would have been much less. This illustrates the significance of scale in emissions calculations. As spatial scale becomes finer, individual sources of greenhouse gas-producing activities take on greater importance, and relative percentages associated with various sources are more likely to change over time.

The greatest contrast between local and nationwide emissions rates occurred in the-industrial and manufacturing subcategory, which accounted for about 38% of the total study area CO_2 emissions compared to less than 3% nationally. The major source of emissions within this category was somewhat surprising. Although the most visible economic activities within the study area are irrigated agriculture and beef processing, the majority of industrial and manufacturing emissions originated from compressor engines associated with the natural gas industry, not from these agribusiness activities. In the Hugoton gas field, the pressure of gas at the well-head was less than 80 psi. In order to transport the gas via pipeline, it has to be pressurized

to about 300-350 psi. To do this, there are 64 compressor stations in the study area, each with one to eight engines burning locally tapped natural gas and emitting CO_2. Collectively, these compressor engines account for over 70% of the total CO_2 emissions in the industrial and manufacturing category. Emissions from natural gas production were grouped in the industrial and manufacturing category (rather than utilities) because the gas was extracted locally, but distributed to other areas for consumption.

The remaining CO_2 emissions in the industrial-manufacturing subcategory were attributable to agribusiness sources. Irrigation wells in the study area used locally tapped natural gas to fuel the pump engines. While these smaller engines did not emit the volume of gas typical of compressor engines, they were numerous in the study area (approximately 1,250 scattered throughout the six counties), and thus a significant source of emissions. The beef packing plants themselves accounted for some CO_2 production, mostly emitted by the rendering process and power generation. The remaining industrial/manufacturing emissions were produced by a small factory which manufactures plastic chemical tanks. The high percentage of CO_2 emissions associated with the natural gas industry also highlights the need to understand the local activity. Prior to the start-up of Holcomb station, this subcategory was the largest in the study area, yet its importance as an emission source is not immediately obvious to an observer.

Residential emissions is another category where the contrast between the local and national level was marked. This category accounted for only about 3% of fossil fuel emissions in the study area, compared to over 5% at the state level and almost 20% nationally. This disparity reflects the sparse population of the study area. Because the total number of both persons and households in the study area was small compared to the state or national average, the residential category accounted for a smaller proportion of CO_2 compared to other source categories. Similarly, there was great contrast between the study area and state and national emssions in the commercial-institutional sector. Commercial and institutional activities accounted for over 15% of national and 5% of statewide fossil fuel emissions, but contributed negligibly to study area emissions.

Methane

Methane emissions accounted for nearly 1.8 million tons of equivalent CO_2, 22% of the global warming potential from the study area (Figure 2). This percentage exceeds both state and US values, which are about 17% and
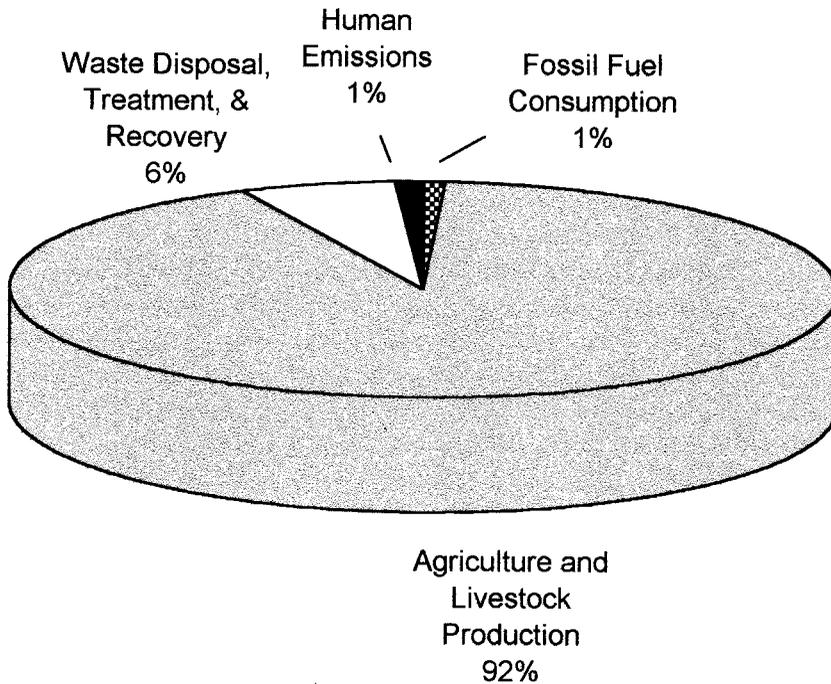
Figure 4. Methane emissions by major source category, espressed in percentage of global warming potential.

12%, respectively. Worldwide, CH_4 accounts for about 18% of global warming potential (Mintzer 1992). Although the total contribution was small locally, sources and production processes for methane emission in the study area were more numerous and more complex than those for CO_2. Unlike CO_2 emissions, agribusiness sources dominated methane production. Emissions associated with agriculture and livestock production accounted for 92% of the total global warming potential from CH_4 in the study area (Figure 4). The largest proportion of these emissions, 49% of the study area methane total, are directly associated with the metabolic processes of cattle. The enteric fermentation carried on by anaerobic bacteria in the forestomachs of ruminant animals, such as cattle, produces large amounts of methane, which are subsequently exhaled or eructed by the animal. A well-fed ruminant in a temperate climate typically converts about 5.5-6.5% of its feed intake into CH_4 (Johnson et al. 1993). The actual amount of gas emitted by an animal depends on its mass, gender, and age, but typically averages about 3.7 kg of

CH_4 per day (United States Environmental Protection Agency 1995). During 1987, an average of 73,000 feeder cattle were present in the study area at any given time, accounting for the overwhelming majority of direct animal methane emissions. Ruminant game animals were also present, but accounted for only 7,000 tons of CH_4 during 1990.

Management of the manure produced by domesticated animals accounted for the remaining 43% of total CH_4 emissions attributable to agribusiness. Methane emissions from animal manure occur when microorganisms metabolize organic material in the manure under anaerobic conditions. The mass of CH_4 produced depends on the oxygen, water, and organic matter content in the waste, and also on climatic factors such as temperature and moisture (from rainfall and humidity). The strategy used to manage the manure also affects emission amounts. Within the study site, there are two manure management strategies, each producing differing amounts of CH_4 per unit of waste. Pasture or range management is used for free grazing animals. It is not a true manure handling system, in that the waste is simply left to decompose in place. Since there are relatively few pastured cattle in the study area, this practice contributed little. The so-called "daily spread" system is the more commonly used manure management system, especially for feedlot waste. In this system, manure is collected in solid form by simply scraping it from the animal pens. It is then spread onto fields as fertilizer. Emissions per unit mass of manure for the daily spread method are slightly higher than for pasture or range management. However, both of these methods produce far less methane compared with other available manure managements systems, such as slurrying or lagoons.

Landfills account for the majority of methane emissions in the waste disposal, treatment, and recovery subcategory (Figure 4). Like emissions from animal waste, landfill emissions originate from anaerobic decomposition of organic material. The moisture content of the landfill is a factor in controlling conditions for anaerobic decomposition. Because the study area climate is semiarid, landfills were drier and anaerobic conditions less common than average. The decomposition of waste material therefore produced less CH_4 per unit mass of solid waste relative to more humid climates. Landfills in the study area emitted about 4.3 kg/yr of CH_4 per capita, compared to approximately 5.5 kg/yr in more humid areas. Landfills in the study area accounted for 61% of CH_4 from waste, lower than the corresponding figure of 68% for the state. Since crop residue burning is not as widely used in the study area, the proportion of CH_4 from agricultural burning was slightly lower compared to the average for the entire state.

Together, waste processing and agriculture-livestock production accounted for 98% of methane emissions. The remaining two percent originated via direct human emission and from the burning of fossil fuels. Interestingly, the natural gas industry did not appear to contribute greatly to methane emission, despite the high methane content of natural gas. However, the apparent lack of CH, emissions from the gas industry may be somewhat misleading. Using the Environmental Protection Agency workbook methodology for fugitive discharge, we obtained a rather small value for pipeline loss. However, examination of data reported by gas production companies suggests that about 6% of all extracted gas was lost somewhere in production or transport (Energy Information Administration 1995a). The Hugoton field is long established; and, it has an aging infrastructure, with old lines for gas collection. It is therefore reasonable to assume that our inventory slightly underestimated the amount of methane reaching the atmosphere directly from gas collection pipelines or venting of gas in the study area. Without a verified method for estimating these emissions, however, we continued to use the Environmental Protection Agency method in our inventory. A refined methodology for estimating pipeline fugitive emissions could substantially decrease the uncertainty of estimates for this category.

Nitrous Oxide

Compared to CO_2 and CH_4 nitrous oxide is a minor component of total greenhouse gas emissions from the study area. Although total volume of emissions is small, the global warming potential of N_2O is significantly higher than that of either CO_2 or CH_4 (see Table 1). Hence, its potential as a significant greenhouse agent is great. Nitrous oxide is the only gas for which the equivalent CO_2 contribution of the study area (3%) matches that of the state and the U.S. Worldwide, the proportional importance of N_2O in global warming potential is about 7%. Total volume of emissions in the study area is very small, only 842 tons during 1990, equivalent to 227,460 tons of CO_2 (Figure 3).

About 83% of agricultural N_2O emissions in the study area originated from the use of nitrogen-based fertilizers. Nitrous oxide is not directly emitted by fertilizer use. It is produced by the process of denitrification, which occurs naturally through microbial action in soils. Addition of more nitrogen to the soil, as from use of nitrogen-based fertilizers, increases the output of N_2O. Fertilizer use was heavy in the study area, particularly for grain production in irrigated fields. The enhanced moisture content of the

irrigated fields, coupled with the characteristically high growing-season temperatures in the study area, enhance the action of nitrogen fixing bacteria in the soil, increasing N_2O production. The 17% of N_2O not produced by agricultural fertilization originated mostly as a by-product of fossil fuel consumption. Most of the N_2O released by fossil fuel consumption came from internal combustion engines, compressor stations and irrigation well pumps, and the coal-fired power plant. The low contribution to total local global warming potential by N_2O was somewhat surprising. This may be a consequence of uncertainty in the emission estimates. A refined emission methodology, capable of better estimating emissions from fossil fuel burning, might suggest greater significance for this category.

Discussion

In analyzing the results of this study, we observed variation and contrast in the relative significance of various emission types and categories at the local, state, and national levels. Although this observation is noteworthy, it is not surprising from a geographic perspective. For the pattern to be consistent across scales, with similar proportions forming total emissions, the economic structure of the population must be similar at each hierarchical level with a similar mix of industrial, residential, and agricultural activities. Clearly, this is not the case in the local study area relative to the other levels, nor would it be the case in most similar sized areas in the United States. As the scale at which processes are considered becomes coarser, internal variability is hidden. It is only when regions are resolved at finer scales that the differences between them become apparent. This aspect of spatial hierarchies can be observed in multiple applications and settings (e.g., Gehlke and Biehl 1934; Clark and Avery 1976; Openshaw and Taylor 1981).

Our findings indicate that CO_2 emissions were the largest contributor to global warming potential from the study area, followed by CH_4, with N_2O accounting for a very small fraction. In this ordering of contributions to global warming potential, uncertainty in the accuracy of gas emission estimates increases as the relative contribution gets smaller. We therefore conclude that the method has done a reasonable job of documenting major characteristics of greenhouse gas emissions in the study area.

An unexpected observation arising from our study concerns the relative contribution to greenhouse gas emissions by key economic sectors. The most visible and dynamic element of the regional economy is the agribusiness sector. The restructuring of the local cattle industry from pasturing to feed-
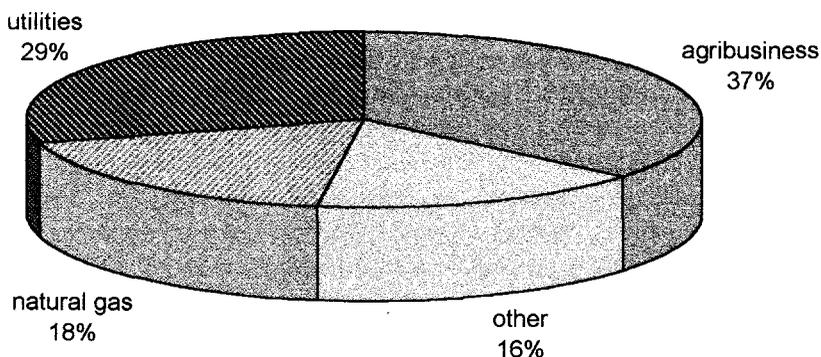
utilities
29%

agribusiness
37%

natural gas
18%

other
16%

Figure 5. Relative contibution of natural gas production, agriculture/agribusines, utilities and other total greenhouse gas emissions in the study area. The agriculture/agribusiness category incorporates all aspects of the beef packing industry including feedlots and waste management. The 'other' category includes sources for which the data are not detailed enough to assign to one of the above categories (e.g., vehicle emissions).

lots, accompanied by expansion of irrigated grain production and relocation of packing plants, has produced marked change in the local economy. The feedyards, irrigated fields, packing plants, and other elements of this agribusiness complex are the dominant visible elements on the landscape. Simple observation might therefore suggest that the majority of greenhouse gas emissions must be directly linked to agribusiness. While agribusiness was the leading source of CH_4 emissions, utilities and the gas industry accounted for the majority of CO_2 emissions. Together the utilities and gas industries lead agriculture-related industries in contribution to total global warming potential, despite the smaller total number of emissions sources (Figure 5). Changes in the agribusiness sector of the economy led to an increase in greenhouse gas production in the study area, but this increase was superimposed on an already high level of emissions from the gas fields and their associated collection and transmission system. Addition of the single large utility in the study area further altered the relative impact of food production on total global warming potential. From the perspective of global warming potential, it appears that agriculture-related changes in greenhouse gas production might not be as significant we first thought. Clearly, retrospective studies are needed in order to more fully explore patterns of greenhouse gas production over time.

One of the overarching concerns of the "Global Change in Local Plains" project, of which this research is a component, has been the implications of scale of greenhouse gas emissions in the formulation of mitigation policy. Environmental impacts of human activities are often conceptualized as the product of population size, affluence, and technological attainment—the so-called "IPAT" relationship introduced by Ehrlich and Holdren (1971) and widely used in the human impacts literature (Kates et al. 1990; Meyer 1996). Although the IPAT model is not universally accepted, we use it here since it provides a framework for cross-site comparisons. However, it is clear that local population has little effect on total greenhouse gas production within the study area. Here, a local area with a population of slightly more than 90,000 produced a greater quantity of global warming potential than urban areas over three times as populous (International Council for Local Environmental Initiatives 1996). The role of population in the IPAT formulation has been questioned (Hynes 1993). In this study, it would seem that the key issue is not the size of the human population. While emissions from the study area were certainly tied to affluence and technology, local population and local consumption clearly were not dominant forces driving these emissions. In our study area, emissions mainly resulted from production of food and natural gas, which were consumed externally by a prosperous, technologically advanced society. Population was certainly a force driving the demand for both food and energy (gas), but it was external, rather than internal population. The demand areas for commodities and products exported from the study area are mainly large and growing urban areas in the upper midwestern, western, and eastern United States. Considered on a national level, a form of the IPAT model in which population is a key term might appropriately conceptualize human environmental impacts, but when resolved to the finer scale of our study area, this model as it is currently defined is inappropriate for conceptualizing anthropogenic environmental impacts.

Thus the key question remains: what is an appropriate scale at which to create policies designed to implement mitigation of greenhouse gas emissions? Consider, for example, the effect on both the study area and the state if mitigation policy decisions were made based on relative emissions data gathered at the national, or even the state, level. From our data it can be surmised that there are substantial differences in the relative significance of various emissions categories between the state of Kansas (as a whole) and one six-county subset. Consequently, policy based on state-level data may be ineffective or even counterproductive for mitigating greenhouse gas pro-

duction in local areas. Policy based on national level emissions estimates would be even more inappropriate. Our study demonstrates that local data are crucial as a basis for local decisions on greenhouse gas mitigation measures. Our results also demonstrate to local, state, and national decision makers the need for better information with which to make informed decisions as to appropriate scales for mitigating greenhouse gas emissions.

The results of this study may also help resolve equity issues across geographical scales. For example, should local, or even state, resources be used to comply with federally mandated greenhouse gas reductions on emissions resulting from natural gas production and transmission (if such regulations were put in place) or would it be more equitable to place the burden on those consumers outside the local area who benefit from exploitation of the resource? Similar consumption-based equity arguments could be made about the costs of mitigating emissions from agricultural production or cattle feeding operations. Understanding functional links between producers of emissions and the end users of their products is vital if questions of this type are to be resolved fairly.

Future research should include looking beyond simple estimates of gas production to consider the proximate causes and driving forces behind the emissions. These human activities and their drivers must be identified and understood before the full suite of physical and economic factors controlling greenhouse gas production can be unified into an integrated assessment. The findings presented here are a step toward a more complete understanding of human-environment interaction, as well as a guide for further investigation.

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