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COMPREHENSIVE AND AGRICULTURAL GREENHOUSE GAS EMISSIONS INVENTORIES FOR NEBRASKA AND THE MIDWEST AS BASELINES FOR CLIMATE CHANGE MITIGATION

by

Eric R. Holley

A DISSERTATION

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COMPREHENSIVE AND AGRICULTURAL GREENHOUSE GAS EMISSIONS INVENTORIES FOR NEBRASKA AND THE MIDWEST AS BASELINES FOR CLIMATE CHANGE MITIGATION

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University of Nebraska, 2020

Advisors: Adam Liska and Michael Hayes

Climate change is the paramount challenge of today for a sustainable future. Mitigation of greenhouse gas (GHG) emissions is necessary to reduce the associated risks and impacts on society. Using the EPA's SIT and literature review, comprehensive GHG-emissions inventories were developed for the state of Nebraska over 25 years (1990-2015) and agricultural GHG emissions inventories were developed for the Midwest U.S for one year (2016). Nebraska's net emissions increased from 56.2 million metric tons of carbon dioxide equivalent (MMtCO_2e) in 1990 to 87.4 MMtCO_2e in 2016. Agriculture was found to be the sector with the most emissions (36 MMtCO_2e), primarily from beef cattle, followed by electricity generation (21 MMtCO_2e), primarily from coal. Total emissions in Nebraska were found to be 47.4 MtCO_2e per capita in 2015, compared to 20.6 in the U.S. due to concentrated agricultural emissions and low population. Total agricultural GHG emissions per state in the Midwest in 2016 were found to range from 10.3 MMtCO_2e (Michigan) to

41.0 $MMtCO_2e$ (Iowa), with an average of 23.3 $MMtCO_2e$. In 2016, Wisconsin was the least efficient state (0.86 $MtCO_2e$/kg product) and Illinois was the most efficient (0.34 $MtCO_2e$/kg product) in terms of emissions per product, which aligned with these states having the highest (71.5%) and lowest (21%) percentage of livestock out of total agriculture. Agricultural emissions per capita ranged from 1.0 $MtCO_2e$ (MI) to 26.2 $MtCO_2e$ (SD), driven by cattle and state population.

A review of literature was also conducted to explore the interactions between climate change and the insurance industry. Climatic events accounted for 91% of $1.05 trillion in insured costs for global catastrophic events from 1980 to 2016. Insurance feedbacks in response to disaster events caused by climate change include changes in 1) premiums and insurance policies, 2) non-coverage, and 3) policy making and litigation. Alongside a suite of strategies, including government policies, insurance feedbacks could be used to facilitate and manage climate change mitigation.

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Introduction

Climate change will have significant long-term effects on all aspects of climate, including changes in precipitation, temperature, and the frequency and severity of weather events and natural disasters, such as droughts, floods, hurricanes, heat waves, wildfires, and sea-level rise. Anthropogenic greenhouse gases (GHGs) are the cause for the observed warming of the Earth's average surface temperatures over the past century (IPCC, 2014). The observed higher average temperatures are the primary driver behind a changing climate and limiting the temperature increase is the goal of mitigation (reduction of GHG emissions). The sooner mitigation occurs, the greater the reduction of risks and impacts from climate change (IPCC, 2014). It is especially important to reduce GHG emissions and warming before compounding non-linear feedback effects occur from climatic tipping points, such as the thawing of arctic permafrost or ocean acidification (Alley, 2003). These tipping points represent paths where irreversible and extensive change to our climate is no longer avoidable and may accelerate change to other aspects of Earth's climate (Lenton, 2011).

Alongside changes in climate, there will be major impacts on society. Agriculture is the primary sector that will be affected in the near term due to its susceptibility to, and dependence on, weather and climate. Changes in weather patterns, climate, and increased risk of damages from extreme weather events generally occur over broad geographic areas and directly impact crops, livestock, and farm operations. Agriculture is an essential industry at the beginning of the supply chain for many other industries and indirectly impacts all people as they need food for survival. Changes to the agricultural industry can have downstream effects on other industries.

Categorizing and quantifying agricultural GHG emissions compared to overall GHG emissions is vital to help reduce the impacts the agricultural industry will face from climate change. Agriculture is estimated to cause ~11% of global GHG emissions while total food systems (agriculture, storage, packaging, transport, etc.) account for ~25%, although estimates vary (Tubiello et al., 2015; Vermeulen et al., 2012). Inventories of GHG emissions, such as those in this dissertation, help provide the basis necessary to develop GHG mitigation plans that have the lowest current impact on the profitability of the agricultural industry, while minimizing future impacts from climate change. Mitigation of GHG emissions in the agricultural industry may also have compounding benefits down the supply chain and provide further opportunities to reduce emissions. To address climate change, society should understand the mechanisms of how the discussed changes to climate and society will be impacted and what factors can be changed to reduce some of these impacts. Accurate and comprehensive GHG emissions inventories are the first step in mitigation of GHGs to address climate change. Knowing the quantity and sources of GHG emissions provides a baseline to understand what sources are the most impactful and where mitigation efforts can be concentrated to efficiently reduce GHG emissions. Inventories can also provide some insight into interactions of emissions sources and can help pinpoint the specific aspect of an emissions source that is the most impactful.

Policy and the structure of political systems are also likely to change. As society learns more about the impacts from climate change and as those changes start occurring, action becomes a necessity and no longer an option. Political issues such as migration of refugees from natural disasters or rising sea levels and economic or fiscal problems will become increasingly prominent. These issues will shape and change policy like environmental regulations of the past (O'Neill, 2002; Weiss and Jacobson, 2000). However, the scale and urgency of these changes will likely disrupt current systems and cause more abrupt changes in political structure, akin to the likely effects of COVID-19 on political and social systems in 2020 (Monbiot, 2020). Proper action to mitigate GHG emissions now, and better plans to address impacts from climate change, are likely to minimize or even prevent this disruption and ensure that our political and social systems continue to function.

The costs and risks associated with climate change will likely shift many economic subsystems. Changes in risk management, fiscal policy, work, payroll, and taxes are all likely to occur to varying degrees in response to climate change. These shifts will have a great impact on most social and political systems as economics is often intertwined with these other systems. Insurance may no longer be the most heavily used risk management tool, or the structure of insurance systems may look quite different than they do today (e.g. direct aid, public or partly public insurance, new insurance products).

Once factors or areas that will impact future changes are identified, effective mitigation plans can be developed that address specific impacts, reducing costs and resource investments in strategies with low return on investments. With limited resources, not every emissions source can or should be reduced. In some areas, the effort required to reduce GHG emissions below current levels will simply be too costly and in others not enough reductions will occur to justify the costs. The potential reduction of large sources of GHG emissions, however, has the added effects of singular focus (more resources to pool together to address one problem than split among many) and necessity (GHG emissions must be reduced by as much as possible to mitigate the impacts of climate change). Potential GHG emissions reductions change from location to location and scenario to scenario. Which GHG emissions sources are the best candidates for reduction efforts will change and depend on local factors and perspectives. Mitigation plans, then, should start with a GHG emissions inventory and then develop solutions that meet the specific needs to the area addressed.

This dissertation covers two separate groups of GHG emissions inventories and a closer look at developing mitigation strategies in the insurance sector. These are small, but important, steps in the long and arduous process of addressing the impacts of climate change. The chapters ahead help provide a base for efforts in the reduction of GHG emissions on a state, regional, national, and international scale. Continuing to develop GHG emissions inventories and discussing the impacts and effects on social systems from climate change is important in addressing the largest and most complex series of problems that humanity may ever see over the long term.

CHAPTER 1 - GREENHOUSE GAS EMISSIONS INVENTORIES FOR NEBRASKA

Anthropogenic GHG emissions and associated global climate change will increase the severity and destructiveness of heat waves, droughts, wildfires, floods, hurricanes, and sea-level rise. In the U.S., these impacts are expected to cost hundreds of billions of dollars annually by the end of the century if global GHG emissions are not substantially reduced (USGCRP, 2018). The cumulative economic effect of climate change from 2020 to 2300 has been estimated to be between $1,390 trillion, with high levels of mitigation, and $2,197 trillion for no mitigation ("business as usual") (Yumashev, 2019). Climate change impacts and economic losses could also increase significantly by compounding feedback effects from the melting of Arctic permafrost and other cryosphere elements, meaning projections probably underestimate costs (Yumashev, 2019). Over the next two decades actions to reduce anthropogenic GHG emissions have the potential to limit atmospheric temperature increases to only 2°C above the pre-industrial era, but extensive emissions mitigation must occur on an economy-wide and global scale (UNEP, 2017; Figueres et al., 2017; Millar et al., 2017; Xu and Ramanathan, 2017). As industrial-scale carbon sequestration technologies ('negative carbon emissions') are expected to cost many trillions of dollars to implement (Hansen et al., 2017), and as other potential solutions (e.g. geoengineering solar radiation) are excessively risky (Morton, 2016), the only practical and immediate approach to mitigate climate change is to reduce the annual rate of global anthropogenic GHG emissions alongside increased natural and, potentially, man-made carbon sequestration systems. Ultimately, a preponderance of high-emitting countries must reduce their emissions to limit increases in atmospheric CO_2 concentrations. This will probably occur with a binding international climate change agreement, which has yet to come to fruition. Even without such an agreement, many countries have set targets for emissions reductions and have begun transitions to low-carbon economies.

The first stage of emissions reduction requires identification of GHG emissions rates and their sources. While many country-level GHG emissions have been quantified since the signing of the Kyoto Protocol, based on data such as national aggregate energy use, GHG emissions inventories for sub-national regions (states, provinces, etc.) have been far less developed. Sub-national inventories can be key tools for mitigating emissions because local characteristics and associated GHG emissions reduction potentials vary. Regional socio-economic differences in fossil fuel production and use, in electricity generation, transportation, industry, forestry, and agriculture can present more specific and actionable GHG emissions reduction strategies.

Agricultural regions can have particularly high GHG emissions because 1) they can disrupt large amounts of carbon stored in soils, perennial plants, and forests, 2) livestock and rice are significant sources of methane (CH_4) emissions, which has a global warming potential 25 times more potent than CO_2, 3) nitrogen fertilizer and manure use produces nitrous oxide (N_2O), which has a global warming potential 298 times more potent than CO_2, and 4) the scale of agricultural systems needed to produce current food use exponentially amplifies inefficiencies and their resulting GHG emissions. As one of the leading agricultural economies and exporters of the U.S., the state of Nebraska has many characteristics of an agricultural region with potentially high GHG emissions. In 2018, Nebraska had the highest state-level commercial red meat production, highest beef exports among states, and the largest number of cattle on feed (NDA, 2019). The state is also the third largest producer of maize for grain in the U.S., according to state statistics. In 2012, the livestock industry in

Nebraska had annual sales of roughly $11.7 billion dollars (USDA NASS, 2019). Nebraska also has the largest area under irrigation among states in the U.S., which requires substantial amounts of energy (USDA ERS, 2012). In 2017, Nebraska had 47,400 farms and ranches with an average size of 386 hectares and a total of 18.3 million hectares of agricultural land (NDA, 2019). In 2017, Nebraska ranked second in maize-ethanol production capacity, with 25 operating biorefineries that have a production capacity of ~7.6 billion liters and utilize ~40% of the state's maize crop.

Livestock production is a significant source of GHG emissions. Livestock farming contributes ~14.5% of anthropogenic GHG emissions globally, although estimates vary (Gerber et al., 2013). A large portion of GHG emissions from livestock come from enteric fermentation, the digestive process in ruminant animals such as cattle, sheep, or goats. Due to their large population and size, cattle account for a majority of GHG emissions from enteric fermentation (ICF, 2004). Around 65% of global livestock-related GHG emissions are from cattle, and over 80% of livestock-related GHG emissions are from ruminants (Gerber et al., 2013). The effect of livestock on agricultural soils also plays a large role in emissions, through the spread of manure on fields and pastures and the leeching and runoff of nitrogen from manure into soil and water systems. Manure use and management from livestock accounts for 26% of global livestock-related emissions (Gerber et al., 2013). To reduce GHG emissions in Nebraska, significant attention will need to be paid to livestock.

A second significant source of emissions comes from electricity generation. Emissions of GHGs from electricity generation accounted for 28% of total emissions for the U.S. in 2016 (EPA, 2019). Electricity-related GHG emissions in Nebraska largely come from the fuel source in the generation of electricity, specifically coal powered plants.

Generation of electricity is dependent on demand for electricity, that is in turn dependent upon economic growth, relative energy prices, technological efficiency, and several other factors (EIA, 2014). If economic growth and energy demand continues to increase and relevant energy prices remain stable, electricity generation will need to either increase the efficiency of current technologies (which may already be at or near efficiency limits) or switch to zero or net-zero emissions sources for energy (e.g. renewables, nuclear, carbon-capture systems) to maintain or reduce GHG emissions. Addressing GHG emissions from electricity generation is vital to reducing Nebraska's contribution to climate change.

Emission inventories of GHGs are precursors for action. They allow comprehensive knowledge of a system and its emissions. Emission inventories are a building block upon which solutions can be tailored to reduce or even eliminate emissions dependent on the characteristics of the system. Regulation (e.g. cap-and-trade, carbon tax), market solutions (e.g. investments, incorporation of emissions costs into business plans and stock prices), and risk management systems (e.g. insurance, FEMA) all rely on inventories to provide a basis for resource allocation and management. State-specific inventories allow a more accurate and relevant analysis of state emissions compared to federal inventories and provide a framework for state-relevant solutions to climate change. Prior to this analysis, a comprehensive state specific GHG emissions inventory for Nebraska was unavailable. While default EPA model inputs could be used to estimate comprehensive GHG emissions for Nebraska, data were never coalesced into a publicly available report, as provided here; nor has a comprehensive analysis and comparison of the relevant systems been presented. This inventory uses non-default data where data were accessible: fossil fuel combustion, natural gas transmission and distribution, transportation (non-highway), and emissions from fires (2000-2016). Future comprehensive state GHG emissions inventories would benefit from the continuous evaluation of state-level emissions by governmental or non-governmental organizations.

Methods for Estimation of Greenhouse Gas Emissions

Emissions were estimated using the most recent version of the U.S. Environmental Protection Agency's (EPA) State Greenhouse Gas Inventory Tool (SIT) (downloaded December 1, 2019) using data specific for Nebraska where available (data sources detailed below). The calculation methods in the SIT are based on the August 2004 version of EPA's Emission Inventory Improvement Program guidance for GHGs (ICF, 2004). Default input values in the SIT were collected from relevant government or industry sources for each sector (i.e. US Geological Survey, Energy Information Administration, Nebraska Energy Office); details of the SIT's calculation methods are available in the SIT User Guide (EPA, 2019). The individual modules for each sector in the SIT are Excel workbooks populated with default emission factors (EF) and state-specific input values. Conversions from one unit to another were used in all calculations where appropriate. Emissions were calculated using available data for 26 years from 1990 to 2016 to keep annual comparisons as accurate as possible while still providing enough data to observe trends. The SIT estimates GHG emissions in million metric tons of CO_2 equivalent ($MMtCO_2e$) from eight major source sectors: agriculture, fossil fuel combustion, industrial processes, natural gas transmission and distribution, transportation, solid waste, wastewater treatment, and land use, land use change, and forestry (LULUCF). The global warming potentials (GWP) used for each GHG were 1 (CO_2), 25 (CH_4), and 298 (N_2O).

Emissions of GHGs from agriculture were calculated using the agriculture module of the EPA's SIT. The agriculture module calculates emissions for nine categories: enteric fermentation (CH_4), manure management (CH_4 and N_2O), residues and legumes from agricultural soils (N_2O), fertilizers applied to agricultural soils (N_2O), manure on agricultural soils (N_2O), liming of agricultural soils (CO_2), urea fertilization (CO_2) (fertilizer production), rice cultivation (CH_4), and burning of agricultural residues (CH_4). Rice cultivation and burning of agricultural residues were not included in these inventories as these are not practices that take place in Nebraska. Emissions from livestock were based on animal populations from the USDA's Quick Stats tool (USDA NASS, 2018) and corresponding annual EFs (kg CH_4 per head per year) from the SIT. These livestock categories, with enteric fermentation EFs, where appropriate, include: dairy cows (108.9-139.7), dairy replacement heifers (42.2-68.7), beef cows (86.5-92.01), beef replacement heifers (52.4-67.6), heifer stockers (50.4-58.9), steer stockers (53.1-56.9), bulls (88.3-95.1), feedlot heifers (37.2-43.4), feedlot steers (36.3-42.2), calves, breeding swine (1.5), market swine (four categories by weight; 1.5), layer chickens, broiler chickens, sheep (8), goats (5), and horses (18). Emissions from legumes and residues were estimated based on annual production of alfalfa, maize for grain, wheat, barley, sorghum for grain, oats, rye, millet, and soybeans (USDA NASS, 2018). Liming of agricultural soils is calculated by multiplying the total limestone or dolomite applied to soil by an EF (Mt C per Mt limestone or dolomite). Urea fertilization is calculated by multiplying total urea applied to soil by an EF (Mt C per Mt urea).

Historic (pre-1990) agricultural GHG emissions for Nebraska are estimated from historic cattle head counts and assumed EFs. Total cattle head count for Nebraska between 1920-2016 includes dairy cows, beef cows, stockers, calves, and bulls. Feedlot cattle data starts in 1965 for Nebraska (USDA NASS, 2018) so feedlot totals for years 1920-1964 were assumed to be the value for 1965. This assumption means pre-1965 values are slightly inflated and actual headcount was likely lower. Historic values were obtained by taking historic cattle head counts (USDA NASS, 2018) multiplied by the EF from 1990 (earliest calculated EF in the SIT) to give values in kilograms of methane. These values were converted to $MMtCO_2e$ to give historic emissions from enteric fermentation. Enteric fermentation accounts for 47.7% on average of total agricultural emissions from 1990-2016 so values were divided by 0.477 to give historic agricultural emissions in $MMtCO_2e$.

Emissions of GHGs from fossil fuel combustion were calculated in two main categories: residential, commercial, and industrial (RCI) emissions, and electricity generation from power plants. Emissions of GHGs for RCI were calculated using two SIT modules: CO_2FFC for CO_2 emissions and the Stationary Combustion module for CH_4 and N_2O emissions (ICF, 2004). Residential CO_2 emissions are calculated by multiplying consumption (billion BTUs) of a fuel type by the corresponding EF (kg C per million BTUs) for the following types: coal, distillate fuel, kerosene, liquefied petroleum gas (LPG), and natural gas. Commercial CO_2 emissions are calculated the same as residential emissions with the addition of two categories: motor gasoline, and residual fuel. Industrial CO_2 emissions are calculated by multiplying total energy consumption (billion BTUs) minus the result of non-energy related material consumption (billion BTUs) multiplied by a storage factor percentage, which yields net-combustible consumption (billion BTUs). The net-combustible consumption is then multiplied by an EF (kg C per million BTUs) for the following categories: coking coal, other coal, asphalt and road oil, aviation gasoline blending components, crude oil, distillate fuel, naphtha less than 401°F feedstocks, other oils greater than 401°F feedstocks, kerosene, LPG, lubricants, motor gasoline, motor gasoline blending components, miscellaneous petroleum products, petroleum coke, pentanes plus, residual fuel, still gas, special naphthas, unfinished oils, waxes, and natural gas. While transportation and bunker fuels are included in the CO_2FFC module, transportation emissions from mobile sources are included in the transportation sector and bunker fuel data were not available for Nebraska. Emissions of N_2O and CH_4 in the RCI module are calculated by multiplying energy consumption (billion BTUs) by corresponding EFs (metric tons of N_2O per billion BTUs and metric tons of CH_4 per billion BTUs) in the same manner as CO_2 emissions with the addition of wood as a category. Emissions from electricity generation were calculated using fuel consumption data for Nebraska available from the Energy Information Administration (EIA, 2018a & 2018b). While more site-specific emissions data are available from 2010 onward (EPA, 2019b), the SIT was used to calculate emissions to provide a consistent calculation for comparisons from 1990 to 2015. Consumption data (billion BTUs) for electricity generation is multiplied by the relevant EF for each fuel type, with factors and fuel types the same as residential for CO_2, N_2O, and CH_4 emissions.

The Industrial Processes module calculates emissions based on the amount of material produced in the state (ICF, 2004). In Nebraska, several categories were not included because the material is either not produced in the state or production data are unavailable: dolomite, magnesium, aluminum, nitric acid, adipic acid, and hcfc-22. Default production values for Nebraska present in the SIT were used for all other materials. Industrial processes emissions were calculated by multiplying production values by an EF (metric tons CO_2 emitted per metric ton of material produced) for the following materials: clinker cement, cement kiln dust, high-calcium lime, dolomitic lime, limestone, soda ash consumption, iron and steel production (basic oxygen furnace with coke ovens), iron and steel production (basic oxygen furnace without coke ovens), iron and steel production (electric arc furnace), ammonia production, urea production, and electric power transmission and distribution.

Lime is further multiplied by a CO_2 reabsorption factor (0.8) that accounts for the precipitation of calcium carbonate during the process. Ozone Depleting Substances (ODS) substitutes are calculated by multiplying national ODS emissions ($MtCO_2e$) by state population divided by national population for Nebraska's share of national emissions.

Emissions for natural gas transmission and distribution were calculated using the natural gas (NG) and oil systems module in the SIT. The emissions are broken down into five categories: NG production, NG transmission, NG distribution, NG venting/flaring, and petroleum systems. Default values from the SIT are used for the number of NG wells in Nebraska, number of gas transmission and storage compressor stations, and oil production. NG transmission and distribution were calculated using miles of pipeline and services (DOT, 2018). Production of NG is calculated by multiplying the total number of wells by an EF (metric tons CH_4 per year per activity unit) which varies annually. Emissions from NG transmission were calculated by multiplying an EF (metric tons CH_4 per year per activity unit) by each input value: miles of transmission pipeline, number of gas transmission compressor stations, and number of gas storage compressor stations. Emissions from NG distribution were calculated by multiplying an EF (metric tons CH_4 per year per activity unit) by each input value: miles of cast-iron distribution pipeline, miles of unprotected-steel distribution pipeline, miles of protected-steel distribution pipeline, mile of plastic distribution pipeline, total number of services, number of unprotected-steel services, and the number of protected-steel services. Emissions from NG venting/flaring were calculated by multiplying the total NG vented or flared in the state (billion BTUs) by an EF (metric tons CO_2 per year billion BTU). Petroleum systems were calculated by multiplying amount of oil in production, refining, and transportation in the state (per 1000 barrels) by an EF (kg CH_4 per year per 1000 barrels).

The transportation section of the SIT includes both highway and non-highway (e.g. aviation, marine vessels, locomotives, and tractors) vehicles. Default vehicle miles traveled (VMT) were used to calculate emissions for highway vehicles (FHWA, 2019) and petroleum consumption values were used for non-highway vehicles (EIA, 2019a). Highway vehicle N_2O and CH_4 emissions were calculated by multiplying VMT by an EF for each type of vehicle and emissions-control technology, then distributed by vehicle age. The types of vehicles are light duty gas vehicles (LDGV), light duty gasoline trucks (LDGT), heavy duty gas vehicles (HDGV), light duty diesel vehicles (LDDV), light duty diesel trucks (LDDT), heavy duty diesel vehicles (HDDV), and motorcycles (MC). Emissions-control technologies are: T2 three-way catalysts, T1 three-way catalysts, T0 early three-way, oxidation catalysts, non-catalysts, low emission vehicles, advanced, moderate, and uncontrolled. Non-highway N_2O and CH_4 emissions were calculated by multiplying fuel consumption by a density factor (kg/L) and by relevant EFs (g GHG per kg fuel, N_2O and CH_4) for aviation, boats, locomotives, and other (includes farm equipment, construction equipment, industrial, and snowmobiles). Carbon dioxide emissions in the transportation sector are calculated by the CO_2FFC module of the SIT and used instead of CO_2 emissions calculated using VMT in the transportation module because the method used in the CO_2FFC module is less uncertain (ICF, 2004). Transportation emissions are calculated by multiplying fuel consumption (billion BTUs) by an EF (kg C per million BTUs) for each of the following categories: aviation gasoline, distillate fuel, jet fuel kerosene, jet fuel naphtha, LPG, motor gasoline, residual fuel, and natural gas.

The Solid Waste module uses annual tons of solid waste landfilled and population as inputs to calculate emissions for municipal solid waste (MSW) landfills, minus any methane emissions flared. Default values present in the SIT were used to calculate emissions.

Combustion of municipal solid waste was not calculated for Nebraska due to lack of available data. Methane emissions from MSW landfills were calculated using a first order decay model from the SIT ($Q_{tx} = A * k * R_x * L_0 * e^{-k(T-x)}$) where Q_{tx} is the amount of CH_4 generated in a particular year, A is the normalization factor $(1-e^k)/k$, k is the CH_4 generation rate per year, R_x is the amount of waste landfilled for a particular year, L_0 is the CH_4 generation potential (m^3/Mt of refuse), T is the current year (i.e. 2019), and x is the year the waste was input into the system.

The Wastewater module of the SIT calculates emissions for both municipal and industrial wastewater. Emissions from municipal wastewater are calculated using state population values multiplied by a series of EFs to generate the amount of CH_4 produced per metric ton. This process does not account for collected CH_4 and assumes all CH_4 is released to the atmosphere. Industrial wastewater emissions are calculated by red meat production in the state. The SIT assumes a constant amount of emissions per metric ton of meat processed at meat processing facilities and deals only with the wastewater at those facilities. Municipal CH_4 emissions from wastewater are calculated by multiplying state population by per-capita 5-day biochemical oxygen demand (BOD_5, 0.09), the number of days in a year, an EF (0.6 Gg CH_4 per Gg BOD_5), and then the percentage of wastewater BOD_5 that is anaerobically digested. Direct wastewater N_2O emissions are calculated by multiplying population by the fraction of the population not on septic by an EF (g N_2O per person per year). Indirect wastewater N_2O emissions are calculated by multiplying population by the total annual protein consumption, the fraction of nitrogen content in protein, and the fraction of non-consumed nitrogen, minus the direct nitrogen emissions from wastewater, multiplied by the percentage of biosolids not used as fertilizer, and an EF (kg N_2O-N per kg sewage N-produced). Industrial wastewater from red meat production is calculated by multiplying metric tons of production by wastewater outflow (m^3 per metric ton), chemical oxygen demand (COD), an EF (g CH_4 per g COD), and the fraction of COD degraded.

The LULUCF module is composed of seven categories: settlement soils, urban trees, burning CH_4, burning N_2O, yard trimmings, forest carbon flux, and agricultural soil carbon flux. Default SIT values were used for all categories except for burning CH_4 and burning N_2O from 2000-2016. Data provided by the Nebraska Forest Service was used to calculate emissions from 2000-2016; data before 2000 was not available. Settlement soils are calculated by multiplying total synthetic fertilizer applied to settlements (Mt N) by an EF, and the molecular weight ratio (N_2O/N_2). Urban trees are calculated by multiplying total urban area (km^2) by the fraction of urban area with tree cover, and a carbon sequestration factor (Mt C per hectare per year). Burning CH_4 and N_2O were calculated by multiplying the area burned (ha) by the average biomass density for forests (kg dry matter per ha), the combustion efficiency for the type of forest, and an EF (g/kg dry matter burned). Yard trimmings were calculated by multiplying default assumed percentages of grass, leaves, and branches applied to the total landfilled yard trimmings and scraps by wet weight (state population multiplied by the national landfilled yard trimmings and food scraps per capita). Then, the amount of carbon for each category added to landfills annually is calculated by multiplying the landfilled materials wet weight by the initial carbon content percentage for grass, leaves, branches, and food scraps and by the dry-to-wet weight ratio for each category to get total mass additions (Gg C). The total annual stocks of landfilled carbon are then calculated by summing the carbon remaining from all previous years' deposits of waste. The stock of carbon remaining in landfills for any given year is calculated as follows: total mass additions multiplied by a term (percentage of C stored permanently + (1 - percentage of C stored permanently) multiplied by e ^(-ln(0.5)/half-life of degradable C)). The annual flux of carbon stored in landfills is then calculated by subtracting the current year's carbon stocks from the previous year's stocks. Forest carbon flux is calculated by multiplying outputs of the Carbon Calculation Tool (CCT) from the USDA Forest Service for carbon storage (million metric tons of carbon) and calculating the change in carbon storage over an inventory year. This change is then converted to $MMtCO_2e$ to give net sequestration or emissions from aboveground biomass, belowground biomass, dead wood, litter, and soil organic carbon. Carbon storage from wood products and landfills is calculated by multiplying estimates of harvested wood stocks from 1987, 1992, and 1997 and averaging change from 1987-1992 and 1992-1997 to get average annual change for each of those ranges. The average annual change for 1998-2016 is assumed to be the average annual change for 1992-1997. The average annual change was added to the net sequestration or emissions from the other categories to give total annual net sequestration or emission, or forest carbon flux. Agricultural soil flux is calculated in much the same way as forest carbon flux, but without wood products and landfills, for cropland remaining cropland, land converted to cropland, grassland remaining grassland, and land converted to grassland (EPA, 2019; USDA, 2016).

Aggregate State Emissions 1990-2016

Nebraska's net emissions increased from 56.2 $MMtCO_2e$ in 1990 to 87.4 $MMtCO_2e$ in 2016 with an average increase of 1.2 $MMtCO_2e$ per year (Table 1.1 & 1.2). For comparison, Iowa and Illinois (both comprehensive inventories) reported 131.8 and 119.8 $MMtCO_2e$, respectively, in 2015 for total emissions which includes non-energy sectors such as agriculture (Iowa DNR, 2018; ICF, 2018). Kansas, Texas, and Minnesota reported 63.1, 625.8, and 87.7 MMtCO$_2$ (EIA, 2018a) in 2015, respectively, but didn't include non-energy sectors or GHGs other than carbon dioxide. The largest increase in GHG emissions in Nebraska came between 2000 and 2001 with an increase of 10.35 MMtCO$_2$e. This difference is largely due to an estimated decrease in soil organic carbon under forests (the difference between the release of carbon by oxidation and the storage of carbon through photosynthesis), but these values are uncertain and could simply be the result of a change in methodology. While more carbon was sequestered in later years, this change was offset by increased demands for fossil fuels in electricity production and transportation (Table 1.2). There were also small increases in emissions produced throughout most industries between 1990-2016, probably due to an increase in population size (Table 1.1) placing higher demands on those industries. The overall trend is an increase of 0.41 MtCO$_2$e per person per year (Fig. 1.1). Increasing trends for per capita emissions are from emissions growth beyond what can be accounted for by population growth. From 1990 to 2016, significant increases in emissions are primarily from agriculture (increasing by 8.2 MMtCO$_2$e) and electricity (increasing by 7.5 MMtCO$_2$e), which accounted for ~50% of the increase together, with lesser increases in other sectors (Table 1.2, Fig. 1.2).

Table 1.1 Emissions per capita for Nebraska and the U.S. (MtCO$_2$e).

Category	1990	2016	Change	% Change
Nebraska Population	1,578,385	1,893,765	315,380	20%
U.S. Population	249,620,000	321,040,000	71,420,000	29%
Nebraska Net Emissions, MMtCO$_2$e	56.2	87.4	31.2	56%
U.S. Net Emissions, MMtCO$_2$e	5,564	5,913	349	6%
Fraction NE of U.S. Population	0.006	0.006	-	-
Nebraska Per Capita Emissions, MtCO$_2$e	35.6	46.2	10.6	30%
U.S. Per Capita Emissions, MtCO$_2$e	22.3	18.4	-3.9	-17%

Sources: Nebraska Energy Office; United Nations Population Division, 2018; U.S. Census Bureau, 2018; EPA, 2019.

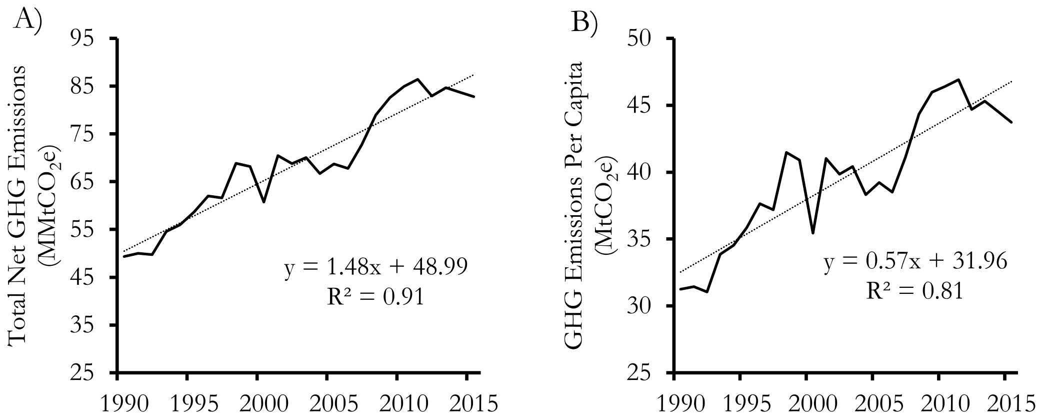

Figure 1.1 A) Total net emissions for Nebraska 1990-2016 (MMtCO_2e), and B) emissions per capita for Nebraska (MtCO_2e), 1990-2015.

Source: Nebraska Energy Office (NEO), 2018a.

Table 1.2 Inventory of GHG emissions from Nebraska by sector ($MMtCO_2e$), 1990-2016.

Emissions ($MMtCO_2e$)	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2016**
Agriculture	27.85	28.84	37.17	32.94	35.35	36.79	36.01
Enteric Fermentation	9.91	11.15	17.75	12.74	13.06	13.03	13.38
Manure Management	2.55	2.45	2.88	2.54	2.75	2.84	2.90
Ag Soils	15.26	15.10	16.35	17.53	19.34	20.74	19.55
Liming	0.08	0.09	0.11	0.03	0.10	0.04	0.04
Urea Fertilization	0.04	0.05	0.07	0.09	0.10	0.13	0.13
Agricultural Residue Burning	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Power Plants	13.53	16.94	19.00	21.19	22.94	23.27	21.04
Electric Power (CO_2)	13.47	16.86	18.90	21.08	22.83	23.15	20.93
Coal	13.26	16.67	18.55	20.63	22.59	22.90	20.60
Petroleum	0.01	0.03	0.05	0.03	0.02	0.01	0.01
Natural Gas	0.19	0.16	0.30	0.43	0.21	0.24	0.33
Electric Power (CH_4)	0.00	0.00	0.01	0.01	0.01	0.01	0.01
Coal	0.00	0.00	0.00	0.01	0.01	0.01	0.01
Petroleum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood	—	—	—	—	—	—	—
Electric Power (N_2O)	0.06	0.08	0.09	0.10	0.11	0.11	0.10
Coal	0.06	0.08	0.09	0.10	0.11	0.11	0.10
Petroleum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood	—	—	—	—	—	—	—
RCI	9.02	10.46	10.25	10.06	12.41	13.42	13.45
Residential (CO_2)	2.51	2.69	2.77	2.51	2.67	2.34	2.20
Coal	0.00	0.00	—	0.00	—	—	—
Petroleum	0.34	0.34	0.50	0.48	0.53	0.39	0.35
Natural Gas	2.17	2.34	2.27	2.03	2.14	1.94	1.86
Residential (CH_4)	0.03	0.03	0.03	0.02	0.02	0.02	0.02
Coal	0.00	0.00	—	0.00	—	—	—
Petroleum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.01	0.01	0.00	0.00	0.00	0.00
Wood	0.03	0.03	0.02	0.02	0.02	0.02	0.01
Residential (N_2O)	0.01	0.01	0.01	0.00	0.01	0.00	0.00
Coal	0.00	0.00	—	0.00	—	—	—
Petroleum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Commercial (CO_2)	2.13	2.20	1.77	1.62	1.86	1.96	1.82

Coal	0.01	0.02	—	0.01	—	—	—
Petroleum	0.22	0.10	0.23	0.15	0.16	0.30	0.30
Natural Gas	1.90	2.08	1.54	1.47	1.70	1.65	1.52
Commercial (CH_4)	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Coal	0.00	0.00	—	0.00	—	—	—
Petroleum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Commercial (N_2O)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal	0.00	0.00	—	0.00	—	—	—
Petroleum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Industrial (CO_2)	4.32	5.51	5.65	5.87	7.82	9.06	9.38
Coal	0.21	0.63	0.76	0.74	1.21	2.01	1.90
Petroleum	2.79	2.60	2.46	2.96	2.16	2.35	2.46
Natural Gas	1.32	2.28	2.43	2.16	4.45	4.71	5.02
Industrial (CH_4)	0.00	0.01	0.01	0.01	0.01	0.01	0.01
Coal	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Petroleum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood	—	0.00	0.00	0.00	0.00	0.00	0.00
Industrial (N_2O)	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Coal	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Petroleum	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wood	—	0.00	0.00	0.00	0.00	0.00	0.00
Industrial Processes	0.99	1.47	2.13	2.12	1.94	2.19	2.23
CO_2 Emissions	0.83	1.14	1.56	1.45	1.06	1.24	1.26
Cement Manufacture	0.32	0.60	0.69	0.71	0.41	0.52	0.52
Lime Manufacture	—	0.07	0.06	0.09	0.09	0.11	0.11
Limestone and Dolomite Use	—	0.05	0.03	0.03	0.08	0.09	0.08
Soda Ash	0.02	0.02	0.02	0.02	0.01	0.01	0.01
Iron & Steel Production	—	—	0.55	0.41	0.28	0.28	0.28
Ammonia Production	0.49	0.40	0.21	0.18	0.19	0.22	0.24
Urea Consumption	0.01	0.01	0.01	0.01	0.01	0.02	0.02
HFC, PFC, and SF6 Emissions	0.15	0.32	0.57	0.67	0.87	0.95	0.97
ODS Substitutes	0.00	0.20	0.48	0.61	0.83	0.92	0.94
Electric Power Transmission and Distribution Systems	0.15	0.13	0.09	0.06	0.05	0.03	0.03
LULUCF	0.31	0.33	0.34	0.34	0.38	0.39	0.39

Forest Fires	—	—	0.01	0.00	0.00	0.00	0.00
CH_4	—	—	0.01	0.00	0.00	0.00	0.00
N_2O	—	—	0.00	0.00	0.00	0.00	0.00
N_2O from Settlement Soils	0.31	0.33	0.33	0.33	0.38	0.39	0.39
Natural Gas T&D	2.77	1.00	1.07	4.03	3.73	3.74	4.74
Natural Gas	2.65	0.92	1.01	3.97	3.68	3.71	4.71
Oil	0.12	0.08	0.06	0.06	0.05	0.03	0.03
Transportation	11.86	12.80	13.16	13.99	15.17	15.23	15.25
CO_2	11.36	12.20	12.59	13.60	14.93	15.08	15.10
Gasoline Highway	5.81	6.11	6.74	7.33	6.52	6.68	7.13
Diesel Highway	1.70	2.08	2.40	2.13	3.01	2.93	2.72
Non-Highway	3.85	4.01	3.44	4.12	5.39	5.46	5.24
Alternative Fuel Vehicles	0.00	0.00	0.00	0.00	0.01	0.01	0.01
CH_4	0.06	0.06	0.05	0.04	0.03	0.03	0.03
Gasoline Highway	0.05	0.05	0.04	0.02	0.02	0.01	0.01
Diesel Highway	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-Highway	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Alternative Fuel Vehicles	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N_2O	0.44	0.54	0.52	0.36	0.21	0.13	0.12
Gasoline Highway	0.40	0.50	0.49	0.32	0.16	0.08	0.08
Diesel Highway	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-Highway	0.03	0.03	0.03	0.03	0.04	0.04	0.04
Alternative Fuel Vehicles	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste	0.86	1.01	1.19	1.37	1.60	1.65	2.66
Solid Waste	0.53	0.65	0.78	0.97	1.18	1.21	2.21
Wastewater	0.33	0.36	0.41	0.40	0.42	0.44	0.45
Municipal CH4	0.13	0.13	0.14	0.14	0.15	0.15	0.15
Municipal N2O	0.05	0.05	0.05	0.05	0.05	0.06	0.06
Industrial CH4	0.15	0.18	0.22	0.21	0.22	0.23	0.24
Total Gross Emissions	67.20	72.84	84.31	86.03	93.51	96.69	95.77
Carbon Stored in LULUCF	-10.95	-8.16	-13.46	-11.11	-2.91	-7.67	-8.35
Forest Carbon Flux	-6.80	-4.38	-4.38	-9.50	-1.76	-1.76	-1.76
Aboveground Biomass	-2.63	-1.05	-1.05	-1.98	-0.92	-0.92	-0.92
Belowground Biomass	-0.50	-0.20	-0.20	-0.36	-0.18	-0.18	-0.18
Dead Wood	-0.35	-0.43	-0.43	-0.47	-0.27	-0.27	-0.27
Litter	-0.30	-0.25	-0.25	-0.58	-0.10	-0.10	-0.10
Soil Organic Carbon	-2.59	-2.31	-2.31	-5.96	-0.15	-0.15	-0.15
Total Wood Products and Landfills	-0.43	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15
Urban Trees	-0.11	-0.12	-0.13	-0.14	-0.15	-0.16	-0.16
Landfilled Yard Trimmings and Food Scraps	-0.15	-0.08	-0.07	-0.06	-0.06	-0.06	-0.06

Agricultural Soil Carbon Flux	-3.89	-3.57	-8.88	-1.41	-0.94	-5.69	-6.37
Total Net Emissions	56.24	64.68	70.85	74.92	90.60	89.02	87.43

Note: A dash denotes zero attributed emissions or unavailable data, whereas 0.00 denotes values less than 0.005 but greater than zero

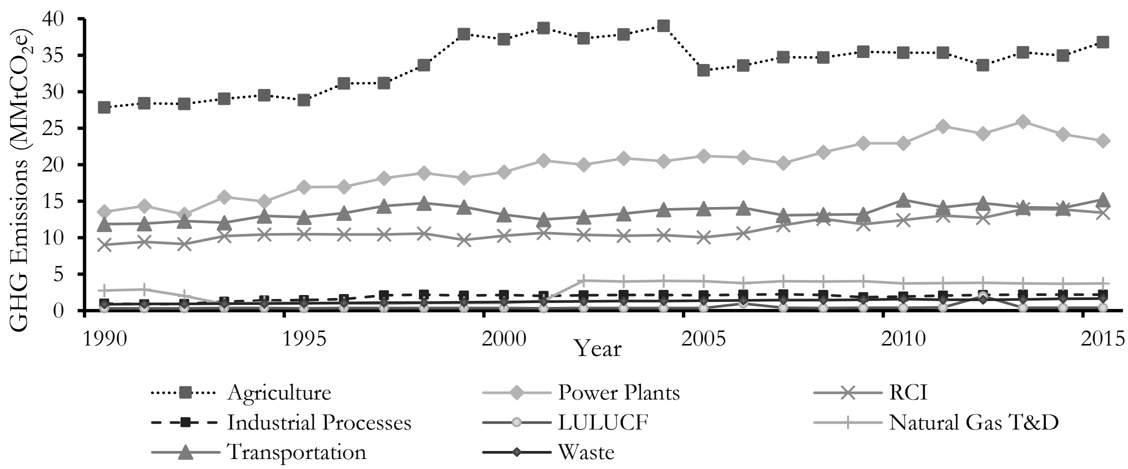

Figure 1.2 Nebraska gross GHG emissions by sector ($MMtCO_2e$), 1990-2016.

Emissions of GHGs by Sector

The majority of emissions between 1990-2016 in Nebraska were from the agriculture, electric power, transportation, and RCI sectors (Fig. 1.2). In 1990, these sectors made up 92.6% of total emissions (Fig. 1.3A). By 2016, these sectors decreased slightly to 90.5% of state emissions (Fig. 1.3B). The relative proportion of emission sectors changed from 1990-2016, with a much larger share of emissions stemming from energy production and industry compared to agriculture (Fig. 1.3).

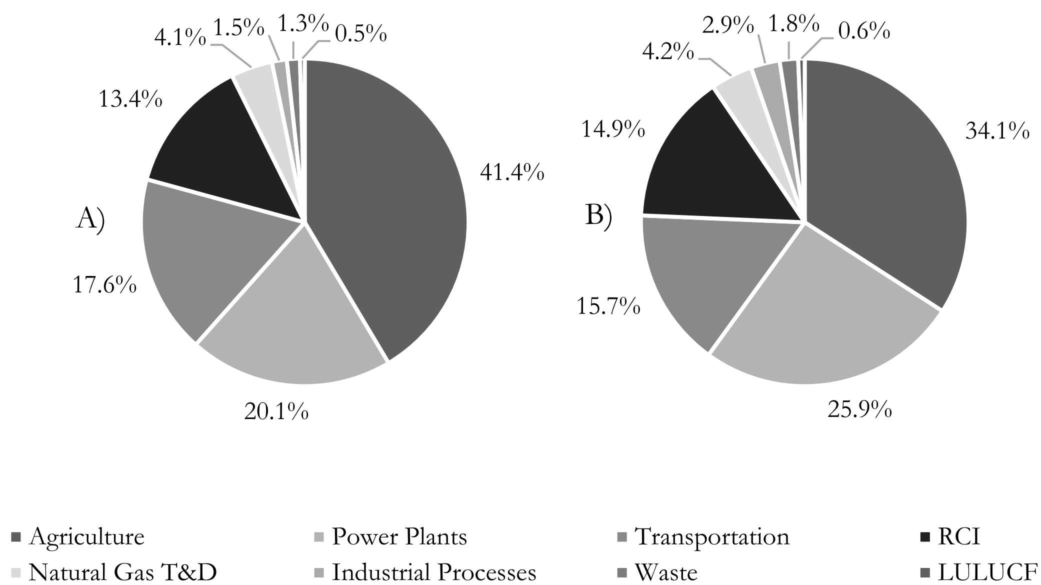

Figure 1.3 Percentage of Nebraska gross GHG emissions by sector: A) 1990 and B) 2016.

Agriculture

The agriculture sector is comprised of emissions from livestock and crop production through the processes of enteric fermentation, manure management (CH_4), manure management (N_2O), residues and legumes in agricultural soils (N_2O), fertilizers on agricultural soils (N_2O), animals on agricultural soils (N_2O), liming of agricultural soils (CO_2), and urea fertilization (CO_2) (Fig. 1.4). Enteric fermentation emissions are the emissions given off by ruminant animals (including cattle) from their digestive processes. Agricultural soil management includes emissions from fertilizers, runoff, plant residues, and cultivation of highly organic soils. Emissions from field equipment (e.g., tractors, harvesters) are included in the transportation sector. Agricultural emissions increased by nearly 30% from

1990-2016 with a nominal increase of 8.2 $MMtCO_2e$, the second largest increase of all sectors (Table 1.3).

Table 1.3 Emissions of GHGs from agriculture ($MMtCO_2e$).

Category	1990	2016	Change	% Change
Ag Soils	15.26	19.55	4.28	28%
Enteric Fermentation	9.91	13.38	3.47	35%
Manure Management	2.55	2.90	0.35	14%
Urea Fertilization	0.04	0.13	0.09	219%
Liming	0.08	0.04	-0.04	-54%
Agricultural Residue Burning	0.00	0.01	0.00	111%
Total	27.85	36.01	8.16	29%

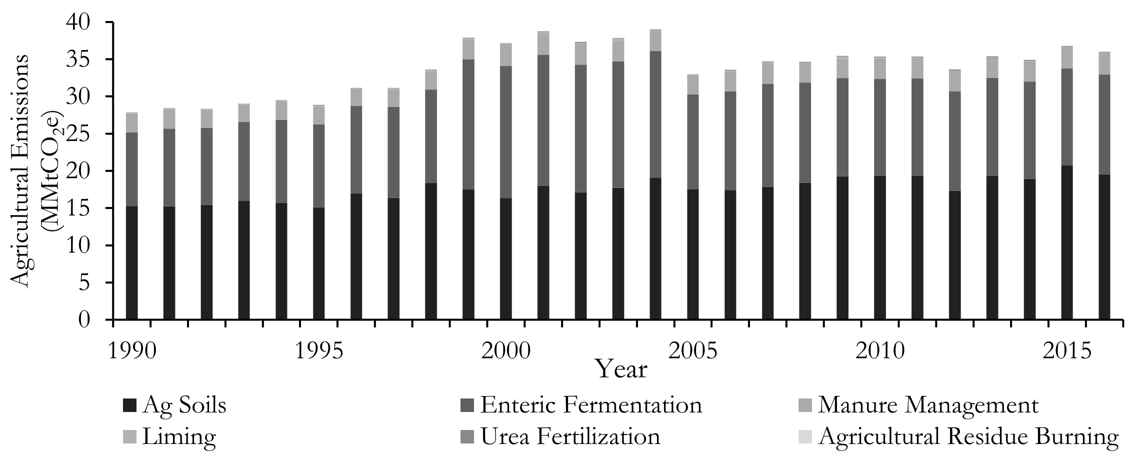

Figure 1.4 Nebraska agricultural emissions by category, 1990-2016.

Historic Agricultural Emissions in Nebraska

Historic agricultural emissions for Nebraska from 1920-1989, based on cattle headcount, were compared to emissions calculated in the GHG inventory from 1990-2016 (Figs. 1.5 & 1.6). Emissions from cattle alone made up, on average, 77.8% of total agricultural emissions from 1990-2016 and 25.8% of total Nebraska GHG emissions during the same time period. The characteristics and landscape of agriculture changed significantly between 1920 and 2016 and these changes are not accounted for through this method. This approximation of historical agricultural emissions can still give insights into how agriculture has developed over time.

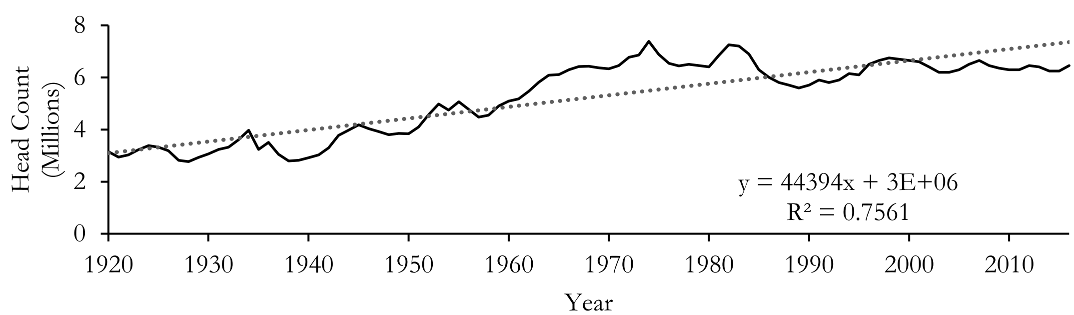

Figure 1.5 Total beef head count in Nebraska, 1920-2016.

Source: USDA NASS, 2018.

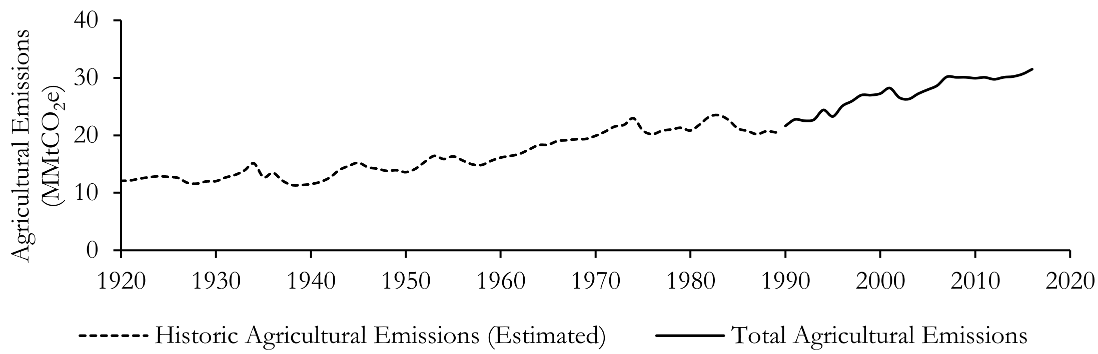

Figure 1.6 Estimated historic agricultural GHG emissions (1920-1990) and agricultural emissions (1990-2016).

Fossil Fuel Combustion

This sector is comprised of GHG emissions from four categories: power plants, residential emissions, commercial emissions, and industrial emissions (Table 1.4). These last three categories are often labeled under one category, RCI. Combined, these four categories account for ~40% of total net emissions in 2016. Industrial emissions had the highest increase, largely due to increased natural gas consumption (NEO, 2018b). The decrease for the residential and commercial sectors is due to a decrease in direct fuel consumption (i.e. wood or natural gas burned for heating homes or businesses) and probably due to a higher reliance on electric tools, appliances, and other home goods (NEO, 2018b).

Emissions from power plants for electricity had the largest increase of any of the sectors in the inventory, followed by agriculture. Emissions from electricity generation come from the increased use of coal, which was 98.4% of Nebraska's electricity emissions and 23.7% of Nebraska's net GHG emissions in 2016 (Table 1.5, Fig. 1.7). Increases in state emissions of GHGs have been growing at a steady rate since 1990, increasing by 56% (Table 1.1). These steady increases are primarily attributable to increases in electricity generation (Table 1.2). Electricity consumption in Nebraska has increased by 69% from 1990-2016 (NEO, 2019a). The largest increase in electricity use came from industry (146.8%), compared to the residential (42.2%) and commercial (44.1%) sectors. Increased energy demand in Nebraska may be explained by increases in ethanol production in new biorefineries and from transition of pumps for irrigation wells from diesel to electricity, among other factors (Liska and Perrin, 2011; NEO, 2018b).

Table 1.4 Emissions of GHGs from fossil fuel combustion excluding transportation (MMtCO_2e).

Category	1990	2016	Change	% Change
Power Plants	13.5	21.0	7.5	55%
RCI	9.0	13.5	4.4	49%
Industrial	4.3	9.4	5.1	117%
Residential	2.5	2.2	-0.3	-13%
Commercial	2.1	1.8	-0.3	-15%
Total	22.6	34.5	11.9	53%

Table 1.5 Coal-based electricity generation (million MWhrs) and emissions (MtCO_2e) in Nebraska.

Category	1990	2016	Change	% Change
Coal Electricity Generation	12,661,150	21,897,715	9,236,565	73.0%
Total Electricity Generation	21,633,587	36,524,869	14,891,282	68.8%
Percentage Coal of Total Energy Generation	58.5%	60.0%	0.01	2.4%
Coal Emissions	13.3	20.7	7.4	55.3%
Total Electricity Emissions (TEE)	13.5	21.0	7.5	55.5%
Nebraska Total Net Emissions	56.2	87.4	31.2	55.4%
Percentage Coal of TEE	98.5%	98.4%	-0.001	-0.1%

Source: EIA, 2018c.

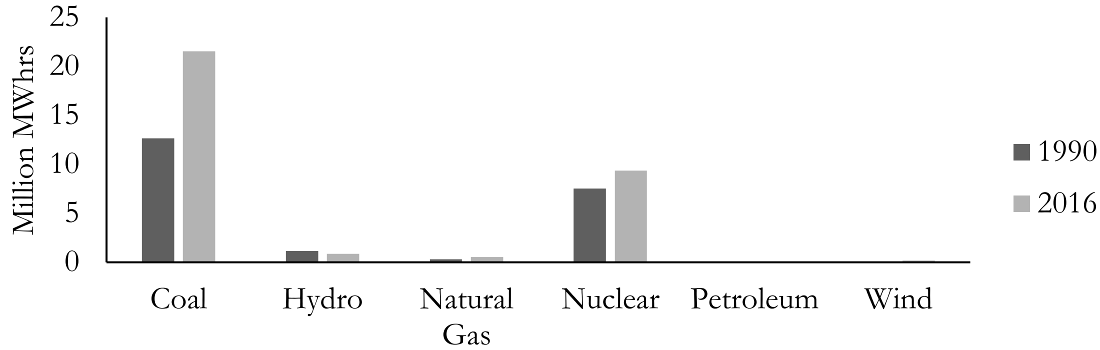

Figure 1.7 Nebraska electricity generation by energy source, 1990 and 2016.

Source: Energy Information Administration, 2018c.

Industrial Processes and Natural Gas Transmission and Distribution

The Industrial Processes sector includes non-combustion GHG emissions from a variety of processes including cement production, lime manufacture, limestone and dolomite use, soda ash use, iron and steel production, ammonia production, nitric acid production, substitutes for ozone depleting substances (ODS) and electric power transmission and distribution. Individual categories vary from 1990-2016, but the overall trend was an increase by 1.24 $MMtCO_2e$. Industrial processes only account for 1.4% of total Nebraska emissions for 2016 (Fig. 1.3). Included in emissions from this sector are natural gas transmission and distribution (T&D) systems. The increase in T&D comes from an increase in services and renovations for existing systems (Table 1.6).

Table 1.6 Emissions of GHGs from industrial processes and natural gas transmission and distribution ($MMtCO_2e$).

Category	1990	2016	Change	% Change
ODS Substitutes	-	0.94	0.94	-
Cement Manufacture	0.32	0.52	0.20	63%
Iron & Steel Production	-	0.28	0.28	-
Ammonia Production	0.49	0.24	-0.25	-51%
Lime Manufacture	-	0.11	0.11	-
Limestone and Dolomite Use	-	0.08	0.08	-
Electric Power T&D Systems	0.15	0.03	-0.12	-77%
Urea Consumption	0.01	0.02	0.02	284%
Soda Ash	0.02	0.01	0.00	-27%
Industrial Processes Total	0.99	2.23	1.24	126%
Natural Gas	2.65	4.71	2.06	78%
Oil	0.12	0.03	-0.09	-75%
Natural Gas T&D Total	2.77	4.74	1.97	71%

Transportation, Waste, and Land Use, Land Use Change, and Forestry

Transportation includes both highway and non-highway vehicles in GHG emissions calculations with planes, trains, tractors, boats, utility vehicles, and alternative fuel (biofuels, etc.) counted as non-highway vehicles. Emissions from highway vehicles are calculated based on total vehicle miles traveled and emissions from non-highway vehicles are based on fuel consumption. Increase in locomotive activity accounts for most of the change from 1990-2016 alongside a small increase in total miles driven (NEO, 2018c) and number of licensed drivers in the state (NEO, 2018d).

The waste sector incorporates GHG emissions from solid waste landfills and the treatment of municipal and industrial wastewater. Emissions from solid waste increased at a much higher rate than population growth (Table 1.1), but wastewater emissions increased at a rate more similar to population growth, though still higher. These emissions only account for 3.1% of total Nebraska GHG emissions in 2016.

The LULUCF sector accounts for GHG emissions from liming and fertilization of agricultural and residential soils (e.g. golf courses, landscaping) as well as settlement soils. The sector also includes carbon sequestered by forests and urban trees, yard waste, and food scraps in landfills. Negative numbers represent net sequestration (taking in more carbon than giving off through combustion and other processes) and a positive change and percentage change represent less sequestration than previous years.

Table 1.7 Emissions of GHGs from transportation, waste, and LULUCF (MMtCO_2e).

Category	1990	2016	Change	% Change
Transportation	11.0	15.3	3.4	29%
Solid Waste	0.5	2.2	1.7	314%
Wastewater	0.3	0.5	0.1	36%
Waste Total	0.8	2.7	1.8	208%
N_2O from Settlement Soils	0.3	0.4	0.1	26%
Forest Fires	-	0.002	0.002	-
Landfilled Yard Trimmings and Food Scraps	-0.1	-0.1	0.1	-59%
Urban Trees	-0.1	-0.2	0.0	44%
Forest Carbon Flux	-6.8	-1.8	5.0	-74%
Agricultural Soil Carbon Flux	-3.9	-6.4	-2.5	64%
LULUCF Total	-10.5	-8.0	2.7	-25%

Emissions of GHGs by Pollutant

Emissions of GHGs accounted for in the EPA's SIT tool include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFC), hydrofluorocarbons (HFC), and sulfur hexafluoride (SF_6). The LULUCF sector is included in this section to account for the different type of pollutants, but the carbon sinks for LULUCF are not included, so gross emissions are presented in this section rather than net emissions (Table 1.2). Carbon dioxide is the highest emitted GHG for Nebraska at 60.1% of total emissions in 1990 and 58% of total emissions in 2016 (Figs. 1.8-1.10). Nearly all CO_2 emissions are from combustion or transportation with some coming from industrial processes. A large majority of CH_4 and nearly all N_2O emissions are from the agriculture sector. Natural gas transmission and distribution contributes ~20% of CH_4 emissions with most of the rest coming from waste. A small percentage of N_2O emissions are from non-agricultural sectors, under 4% of total N_2O emissions. The distribution of GHG emissions for Nebraska did not change significantly from 1990-2016, but the largest increases came from increased CO_2 emissions from electricity and increases in GHG emissions from agriculture. Increases from agriculture were roughly half from N_2O and half from CH_4.

Table 1.8 Gross emissions of GHGs by pollutant and sector ($MMtCO_2e$).

GHG and Sector ($MMtCO_2e$)	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2016**
CO_2	34.9	40.8	43.5	46.3	51.4	53.0	50.9
Power Plants	13.5	16.9	18.9	21.1	22.8	23.2	20.9
Transportation	11.4	12.2	12.6	13.6	14.9	15.1	15.1
RCI	9.0	10.4	10.2	10.0	12.3	13.4	13.4
Industrial Processes	0.8	1.1	1.6	1.4	1.1	1.2	1.3
Agriculture	0.1	0.1	0.2	0.1	0.2	0.2	0.2
Natural Gas T&D	0.1	0.1	0.1	0.1	0.1	0.0	0.0
CH_4	16.0	15.6	22.9	20.7	21.1	21.3	23.7
Agriculture	12.5	13.6	20.6	15.3	15.8	15.9	16.3
LULUCF	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural Gas T&D	2.7	0.9	1.0	4.0	3.7	3.7	4.7
Transportation	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Power Plants	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RCI	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.8	1.0	1.1	1.3	1.5	1.6	2.6
N_2O	16.1	16.3	17.5	18.5	20.3	21.6	20.4
Agriculture	15.3	15.2	16.5	17.6	19.5	20.9	19.7
LULUCF	0.3	0.3	0.3	0.3	0.4	0.4	0.4
Transportation	0.4	0.5	0.5	0.4	0.2	0.1	0.1
Power Plants	0.1	0.1	0.1	0.1	0.1	0.1	0.1
RCI	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HFC, PFC, SF_6	0.2	0.3	0.6	0.7	0.9	1.0	1.0
Industrial Processes	0.2	0.3	0.6	0.7	0.9	1.0	1.0
Total Gross Emissions	67.2	73.0	84.5	86.1	93.7	96.9	95.9

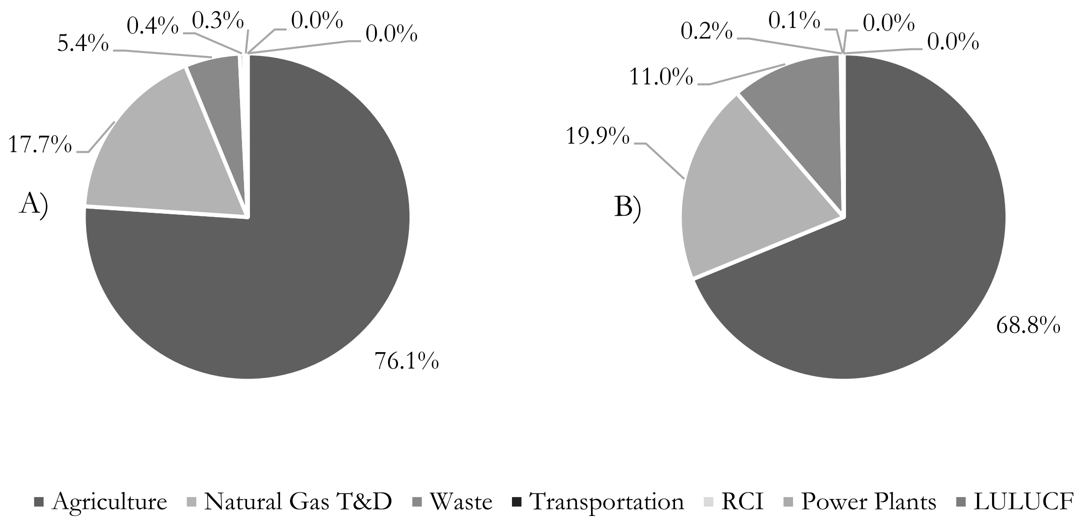

Figure 1.8 Percentage of carbon dioxide emissions by sector in Nebraska: A) 1990 and B) 2016.

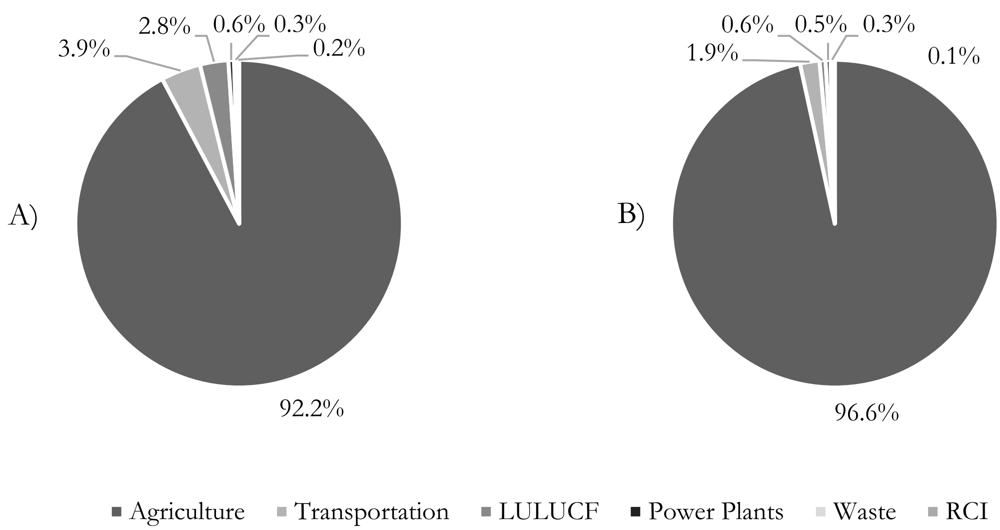

Figure 1.9 Percentage of methane emissions by sector: A) 1990 and B) 2016.

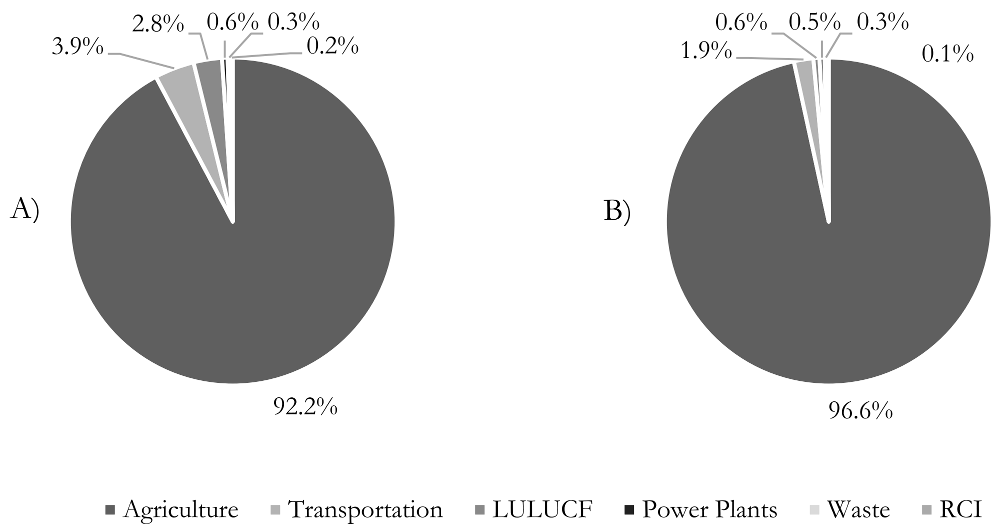

Figure 1.10 Percentage of nitrous oxide emissions by sector: A) 1990 and B) 2016.

Comparison of State, U.S., and Global Emissions

Nebraska's share of total GHG emissions in the U.S. increased from 1.05% in 1990 to 1.46% in 2016 (Table 1.9). Yet, Nebraska's portion of the U.S. population decreased slightly from 0.63% in 1990 to 0.59% in 2016 in comparison (Table 1.1). Agricultural emissions account for a significantly higher proportion of Nebraska emissions than U.S. emissions, which is consistent with Nebraska's extensive agricultural economy. Emissions from Power Plants, RCI, Natural Gas Transmission and Distribution, and Transportation sectors were combined into the energy sector for comparison with U.S. emissions, which use the IPCC sectors for the national GHG inventory (IPCC, 2006; Fig. 1.11). Data for U.S. and global emissions comes from the Climate Watch service provided by the World Resources Institute, which only has data to 2014 (Table 1.10). The U.S. share of global emissions decreased from 1990 to 2014, while Nebraska's share increased during the same time period.

Table 1.9 Emissions for Nebraska and the U.S. by IPCC sector category (MMtCO_2e), 1990 and 2016.

IPCC Sector	NE 1990	U.S. 1990	NE 2016	U.S. 2016
Energy	37.2	5339.8	54.5	5,465.3
Agriculture	27.8	490.2	36.0	541.2
Waste	0.9	198.9	2.7	131.1
Industrial Processes	1.0	342.1	2.2	354.6
Total	66.9	6371.0	95.4	6492.2

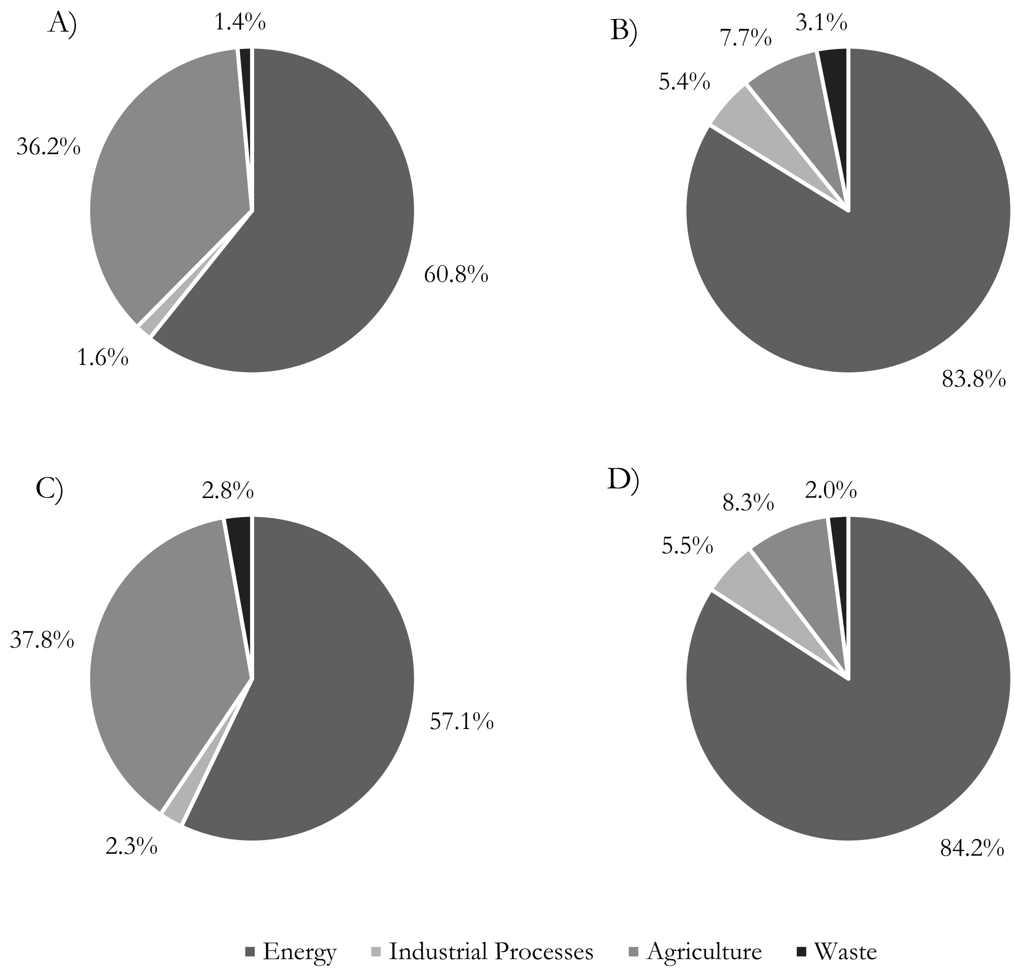

Figure 1.11 Percentage of GHG emissions by sector: A) NE 1990, B) U.S. 1990, C) NE 2016, D) U.S. 2016.

Table 1.10 Emissions of GHGs (MMtCO_2e) by geographic area, 1990 and 2014.

Category	1990	2014	Change	% Change
Global	33,823	48,892	15,069	45%
U.S.	5,564	6,090	526	9%
Nebraska	56.2	87.9	31.7	56%
Nebraska Share of U.S.	1.01%	1.44%	0.004	43%
U.S. Share of Global	16%	12%	-0.04	-24%
Nebraska Share of Global	0.2%	0.2%	0.0001	8%

Source: World Resources Institute, 2018.

Although Iowa has a higher amount of agricultural emissions compared to Nebraska, more of Nebraska's emissions come from livestock, specifically cattle, with 23.7% of net emissions in Nebraska compared to 10% of net emissions in Iowa (Table 1.11). Beef cattle were found to contribute 22.6% of Nebraska's net emissions (Table 1.11). A larger portion of Iowa's agricultural emissions come from the manure management of swine and poultry, which do not contribute to enteric fermentation. Iowa's swine and poultry populations vastly outnumber Nebraska's populations (USDA NASS, 2018) and thus require more manure management. Along with a higher crop output, Iowa's agricultural composition leads to more emissions, but also a larger agricultural economy (USDA ERS, 2019).

Table 1.11 Avg. GHG emissions from livestock in Nebraska and Iowa, in 2016 and 2014-2016.

Category	NE 2016	IA 2016	NE 3-year AVG	IA 3-year AVG
Gross Emissions	95.8	126.6	95.8	132.5
Net Emissions	87.4	126.6	88.1	132.2
Enteric Fermentation	13.4	8.4	13.2	7.4
Manure Management	22.4	10.96	22.6	9.0
Agricultural Soils	0.2	20.09	0.2	20.3
Total Agricultural Emissions	36.0	39.5	35.9	36.7
Percent Livestock of Agricultural Soils	78.2%	12.2%	47.8%	12.2%
Emissions from Livestock	36.0	21.8	35.8	18.9
Percent Livestock of Gross	37.5%	17.3%	37.4%	14.3%
Percent Livestock of Net	41.1%	17.3%	40.7%	14.3%
Total Cattle Emissions	20.7	12.7	20.5	12.5
Percent Cattle of Gross	21.6%	10.0%	21.4%	9.4%
Percent Cattle of Net	23.7%	10.0%	23.2%	9.4%
Total Beef Cattle Emissions	19.8	10.1	19.4	9.7
Percent Beef Cattle of Gross	20.6%	7.9%	20.3%	7.4%
Percent Beef Cattle of Net	22.6%	7.9%	22.1%	7.4%

Comprehensive state-level GHG inventories are not common among states in the U.S., but some states report gross emissions based on some of the available data for their state. Nebraska has the highest per capita gross emissions based on available data, with Iowa and Texas both higher than U.S. average emissions (Table 1.12). Nebraska emissions per capita are higher than other states partly due to having a sparse population with a relatively large geographic area devoted to high-emissions agriculture. Texas's estimated value is not comprehensive and thus underestimates gross GHG emissions as it only accounts for energy-related carbon emissions and cattle emissions. Texas's emissions were estimated by taking energy-related carbon emissions data from the EIA and cattle head count data from the USDA and, assuming the largest sources were also energy and agriculture (specifically cattle), applying the same ratio of cattle head count to emissions in Nebraska to Texas to get an estimated gross emissions value, which may overestimate Texas's cattle emissions (Table 1.12). Texas is included because it is the largest emitting state in the U.S. (EIA, 2018a). Other states were included primarily due to availability of gross emissions data (DEWA, 2018; DECV, 2018; DEPM, 2019; DEPNJ, 2017; DEQO, 2018; UHERO and ICF, 2019). Nebraska per capita emissions have increased from 38.2 in 1990 to 47.4 in 2015, or 24.1% over the time frame. Nebraska's 2015 per capita emissions total more than either the U.S. or global averages (Fig. 1.12).

The states' emissions per capita also do not consider exports of products. In Nebraska, beef production is high but most of that beef is not consumed in the state. Thus, many people argue there exists a 'shared responsibility' among states that produce a product and consume that product for the emissions that occur in the transaction between them.

Table 1.12 Per capita gross GHG emissions for the U.S. and relevant states, 2015*.

State	Gross Emissions	Population	Emissions Per Capita, $MtCO_2e$
Nebraska	89.9	1,896,190	47.4
Iowa	131.8	3,123,899	42.2
Texas	668.9[1]	27,469,114	24.4
U.S.	6616.8	321,418,820	20.6
Vermont	10.0	626,042	16.0
Oregon	63.0	4,028,977	15.6
Maine	19.8	1,329,328	14.9
Washington	97.4	7,170,351	13.6
New Jersey	109.0	8,958,013	12.2
California	441.0	39,144,818	11.3
Hawaii	15.3	1,431,603	10.7

[1]Estimated value, *Several states have not updated to 2016, so 2015 values were used for comparison

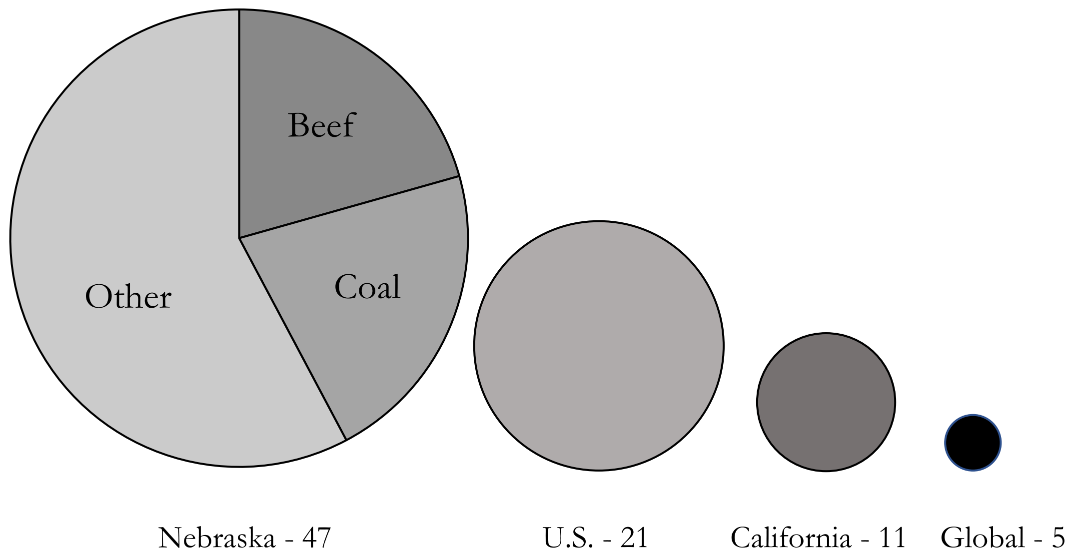

Figure 1.12 Relative per capita gross GHG emissions (MtCO_2e) for selected regions and emissions sources, 2015.

Uncertainties and Limitations to Emissions Estimation

The accuracy of the EFs calculated by the SIT is the main source of uncertainty for the inventory. EFs are aggregations of measurements, calculations, studies, surveys, and reporting. Even relatively small amounts of uncertainty for each of these elements adds to the uncertainty of a given EF and the calculated EF is quite dependent on the accuracy of the methods that go into estimating it. The mixture of national, regional, and state data also adds some uncertainty to calculations.

The amount of CH_4 emissions due to enteric fermentation from livestock is dependent on the accuracy of the animal population estimates and the EFs used for each animal type. Animal populations vary throughout the year, which will affect annual total emissions and is not accounted for by the SIT (ICF, 2017a). EFs used have inherent uncertainty due to differences in production, environment, diet, and genetics of the animal (ICF, 2017a). Like enteric fermentation, manure management is subject to uncertainty in livestock populations and EFs. The largest source of uncertainty in manure management, however, comes from EFs of manure management systems. The SIT does not account for Nebraska-specific facilities and relies on regional estimates of emissions for manure management systems. While the SIT does sub-categorize animal groups to some extent, there is insufficient data and infrastructure to accurately measure differences in animal types and diet and how they affect the constants used in the SIT (ICF, 2004). Nitrogen emissions from soils are dependent on many factors other than nitrogen input, including soil moisture, type, pH, temperature, organic carbon content, oxygen's partial pressure, and soil amendment. The SIT uses only nitrogen input as a factor in calculating N_2O emissions and does not account for these other variables or their interactions. The combination of type of soil, climate, and management conditions changes nitrogen output and this highly variable system is simply too complex to accurately determine (ICF, 2004). Fertilizer usage includes only synthetic fertilizers applied to crops and does not use organic fertilizers (such as manure) due to a lack of Nebraska-specific data for the application of fertilizers.

The Fossil Fuel Consumption section includes GHG emissions from the consumption of fossil fuels in four main categories: power plants, residential, industrial, and commercial (i.e. RCI). The category of power plants includes direct emissions from electricity generation but not indirect emissions from imported electricity. Fossil Fuel Consumption also does not include fuel combusted from mobile sources. These are included in the "Transportation" section.

The amount of CO_2 emitted from fossil fuel consumption depends on the type and amount of fuel that is consumed, the carbon content of the fuel, and the fraction of the fuel that is oxidized. The SIT uses national default values for these variables in calculating emissions, which may differ from Nebraska-specific values. Carbon content and oxidization of fuels are more consistent between states (aside from coal) and the higher variability of coal is accounted for by state in the SIT. Sharing electricity between states adds complexity because it is difficult to track specific fuel mixes for generated or consumed electricity and a regional average is often used. EFs for CO_2 may be generated from relatively uncertain emission monitors rather than carbon content. The amounts of CH_4 and N_2O emitted depend on the amount and type of fuel used, the technology in which it is combusted, and the type of emission control used. The contribution of these emissions to the total GHG emissions is small, however, and estimates are highly uncertain (IPCC, 2006; UNEP, 2017). Energy consumption and end-use estimates are also uncertain and some small source emissions may not be included in state-specific or national data (e.g. wood burning in fireplaces, stoves, campfires).

Most of the uncertainty associated with the industrial processes section pertains to the use of national averages and default data within the SIT. State-specific and site-specific data allow for more accurate estimations of GHG emissions. Other sources of uncertainty include inherent uncertainty in geologic composition of raw materials, use of population in calculating emissions, and use of sales rather than consumption in some categories.

The largest sources of uncertainty for transportation are the activity data and the EFs used in calculations. Methods of measurement for VMTs and the application of national factors to state-specific data creates variability in the total VMTs used. EFs also may not be reflective of conditions in Nebraska. For those parts that use fuel consumption to calculate emissions, it is assumed that all fuel purchased is consumed in the same year.

Emissions of CH_4 from landfills are impacted by several factors at individual sites that cannot be accounted for by the SIT. The time period that CH_4 is emitted is also uncertain and is affected by the factors listed at the beginning of this section. The amount of CH_4 oxidized during diffusion through soil cover over landfills will also affect the net CH_4 emissions and is not accounted for by the SIT.

Uncertainty in municipal wastewater is dependent largely on the uncertainty in activity data and EFs. State-specific and site-specific data can reduce this uncertainty to an extent but is still subject to the variation in process and conditions. Uncertainty in industrial wastewater comes from the lack of available data for wastewater outside of red meat production and in the differences between assumed production values and factors on a national scale and site-specific factors for facilities in Nebraska.

There is significant uncertainty in the LULUCF section from the methodologies for EFs and state data. SIT defaults cannot account for the wide variation in tillage practices, landfill composition, fires, and survey methodologies between states. There is inherent uncertainty in estimation methods of land use and land use change as well as geospatial variability. Agricultural soil organic carbon flux has a particularly high associated uncertainty and could affect the values presented in this section significantly. It was included, however, because it tends to overestimate sequestration and underestimate net emissions.

Despite the uncertainties discussed above, the SIT provides a standardized procedure that estimates sector emissions with relatively small errors compared to the absolute amount of emissions and compared to the conclusions that can be interpreted from these sector emission estimates.

Mitigation of Greenhouse Gas Emissions in Nebraska

To reduce emissions without reducing consumption, decoupling GHG emissions associated with higher levels of consumption per capita has been identified as the paramount engineering challenge of today and the future; emissions could be drastically reduced with combinations of energy efficient technologies and renewable energy sources available today (Lovins, 2011; Pacala and Socolow, 2004). Technological changes such as switching from fossil fuels to renewables, reduction in potent GHG emissions, and carbon sequestration could reduce emissions to keep atmospheric warming below a 2°C increase by 2100 (Xu & Ramanathan, 2017; Miller et al., 2017). Globally, fossil fuel emissions are dominated by electricity and heat, transportation, manufacturing, and construction. Nebraska's annual GHG emissions per capita (43.7 $MtCO_2e$) are more than twice as high as average U.S. emissions per capita (18.4 $MtCO_2e$), and far larger than most regions globally. In 2014, people in the U.S. and Canada emitted an average of ~16 metric tons of CO_2 per capita per year from fossil fuels, compared to an average of 6.7 metric tons in China, 6 in European countries, 4.5 per capita on average globally, 1.6 in India and other Asian countries, and only 1 metric ton per capita in African countries (IEA, 2016). Inclusion of other GHGs, primarily CH_4 and N_2O, would increase these emissions but the relative trends would probably remain the same. For example, U.S. emissions were found to be 18.4 $MtCO_2e$ per capita where all GHGs were considered, which is slightly higher than the 16 $MtCO_2$ per capita per year from fossil fuels alone. Higher emissions in the U.S. and Canada are largely due to higher consumption rates, but also geographical differences in heating and cooling needs.

Emissions per capita can vary significantly depending on the methods used for estimations. Emissions in the SIT are calculated from production values of products or resources rather than from demand, which is a valid alternative metric. Production values are used, however, because they are often readily available and significantly easier to measure than demand (consumption). Areas with high production but low demand (large amounts of exports of a product) will have higher emissions per capita values than those based on consumption in an area. For Nebraska, per capita emissions based on consumption could be significantly lower than the values presented above (Table 12), as most of the beef produced in the state is exported rather than consumed by the population. Per capita production emissions can be interpreted as state activity that is attributed to the population in that state, as that population is ultimately responsible for the economy and laws that facilitate those emissions. Thus, the production based per capita GHG emissions values for Nebraska presented above should accurately represent the population's impact on climate change.

A GHG emissions inventory for Nebraska is an important and feasible endeavor to track emissions to provide a framework for evaluating state-specific solutions and inform climate change mitigation decisions. Nebraska's GHG emissions and its share of national GHG emissions have steadily increased since 1990 (Table 1.10). Emissions growth has outpaced population growth, meaning Nebraska emits more per person in 2016 than in 1990 (Table 1.1). The distribution of Nebraska's GHG emissions are much different compared to the national level, with over 37% of emissions from agriculture compared to 8% nationally (Fig. 1.11). Agriculture and electricity were found to be the two highest emissions sectors in

Nebraska (Table 1.2), and thus require the greatest attention to significantly reduce state emissions in the near term.

The largest category of agricultural GHG emissions in Nebraska is from beef cattle, where feedlots are a major contributor with a population of ~2.7 million head in 2016 (Fig. 1.13). Where agricultural emissions reductions are sought, the most direct action would be to reduce the population of beef cattle in the state. The IPCC recently suggested that changes in diet, including reduced meat consumption and increased use of agricultural products from resilient, sustainable, low-GHG emission systems, have a high potential for GHG emissions mitigation and improvement of human health globally (IPCC, 2019). But such a reduction in beef cattle will not be easily achieved as the livestock industry in Nebraska had annual sales of roughly $11.7 billion dollars in 2012 (USDA NASS, 2019), which means there are extensive social, economic, and political interests that complicate such reductions. One potential and perhaps equitable solution to reduce livestock populations would come from a carbon tax on the consumption or production of beef and other animal products. A carbon tax of $248 per ton of CO_2e could increase the price of beef by as much as 41% in the supermarket, which reflects the external costs of climate change (Coniff, 2018). Current carbon prices are as high as $139 per ton of CO_2e in Sweden and $101 in Switzerland and Liechtenstein, but most plans propose to price carbon at $55 per ton of CO_2e or lower (World Bank and Ecofys, 2018). An increase in the price of beef would probably lower demand and consumers would probably substitute some of the beef they consume for lower cost options such as pork, poultry, or plant-based proteins. As monograstic animals, pork and poultry are considerably less GHG-intensive compared to beef. Based on life cycle assessments of meat production, emissions from pork are ~21% of those from beef and poultry are ~18% (Fig. 1.14). The production of pork and poultry also requires less water, is associated with less nitrogen pollution, and requires less land area (Fig. 1.14). Substitutions away from beef could cause state-level reductions in GHG emissions. If all beef (9.6 kg CO_2e/Mcal) were substituted with pork (2.03 kg CO_2e/Mcal), Nebraska emissions would be lowered by 15.64 MMtCO_2e based on emissions per unit energy in meat (Fig. 1.14), or 17.9% of Nebraska's net emissions in 2016.

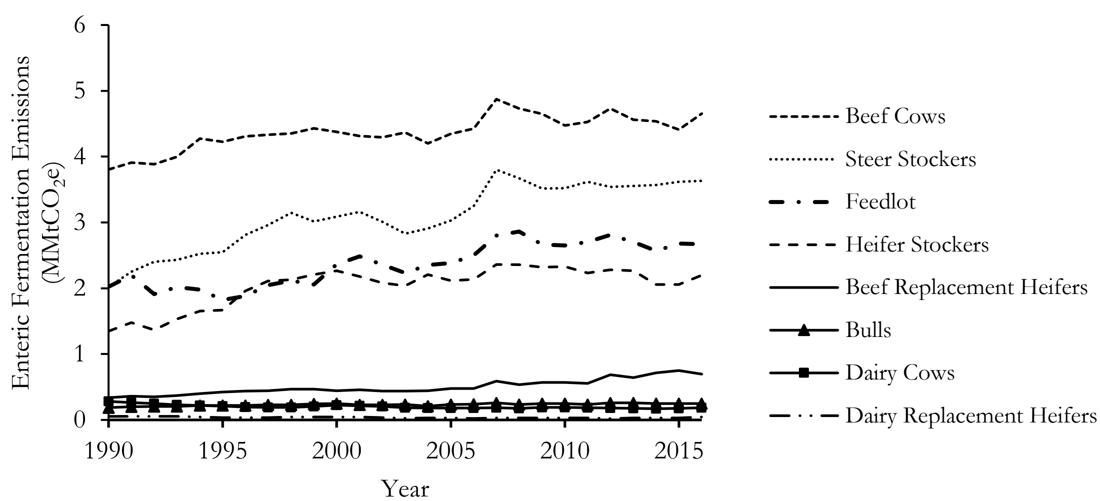

Figure 1.13 Enteric fermentation emissions by cattle category, 1990-2016.

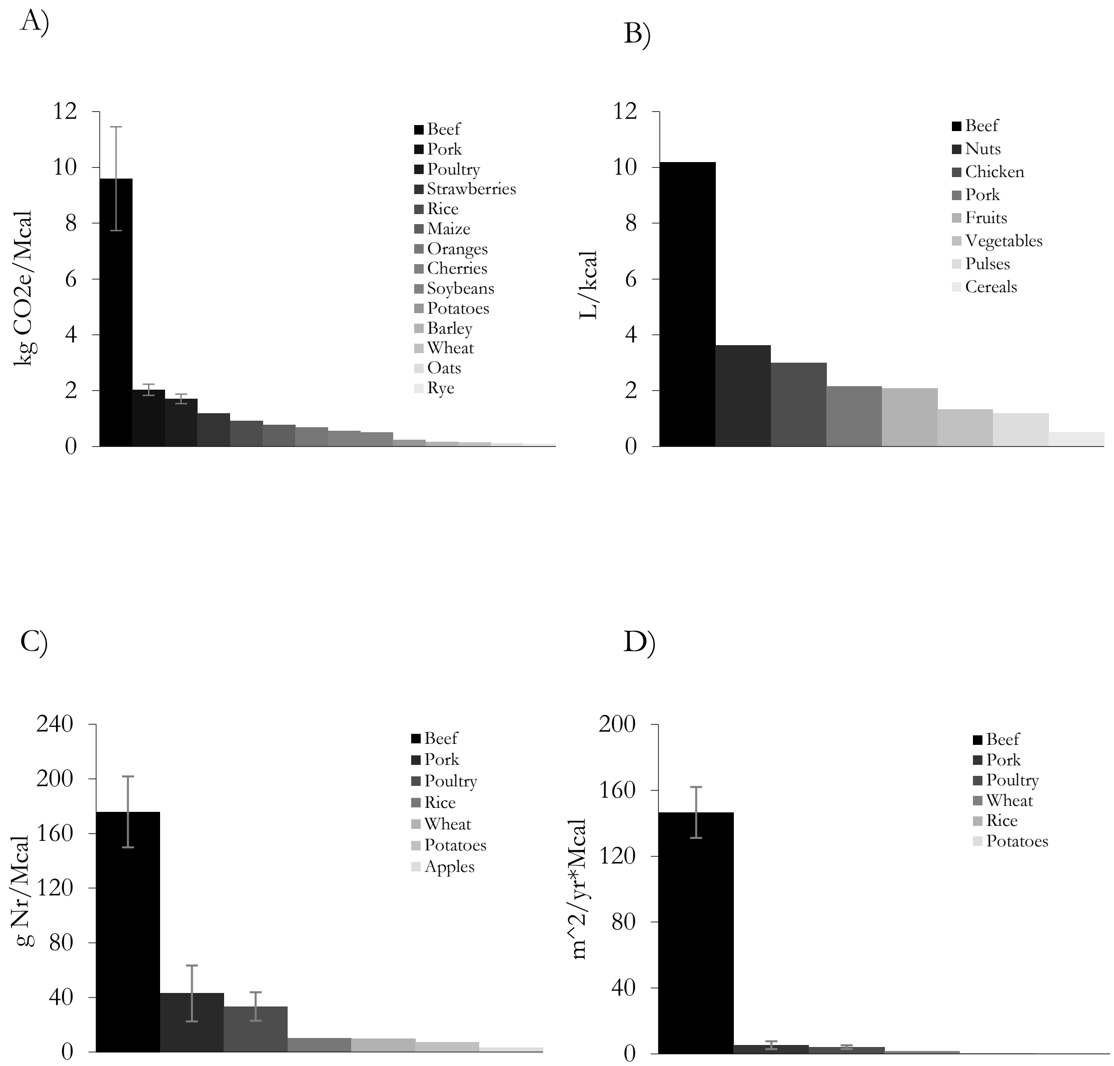

Figure 1.14 Environmental impacts of livestock and common food crops in the U.S. (A, C, and D) and globally (B).

A) Greenhouse gas emissions (González et al., 2011; Eshel, Shepon, Makov, & Milo, 2014); B) Total water use (Mekonnen & Hoekstra, 2012); C) Reactive nitrogen use; D) Arable land use (Eshel et al., 2014). Note: Environmental impacts of beef, pork, and poultry include results from other life cycle assessments compiled by Eshel et al. (2014) including: de Vries and de Boer (2010); Phetteplace, Johnson, & Seidl (2001); Pelletier et al. (2008; 2010a, 2010b). Thus, they are plotted as averages with standard deviations here.

Actions that reduce agricultural emissions without reducing livestock populations are also viable and can be used in conjunction with reduction of consumption of livestock. There is a significant amount of variance among farms due to agricultural practices, geography, temperature, and many other factors (Poore and Nemecek, 2018). Solutions to address these emissions (e.g. multi-variate, ground-up approach to quantify impacts; setting and incentivizing mitigation targets; reducing impacts through choices upstream in the supply chain; dietary changes; food supply and waste changes; communication and cooperation between entities in the supply chain to reduce impacts) are as varied as the factors themselves and the complexity is such that a potential solution addressing the same product in similar conditions across multiple farms may not be effective for all of those farms. With proper localized data and analysis, however, a portfolio of solutions can greatly reduce variability and lower emissions for producers of agricultural products (Poore and Nemecek, 2018). A multivariate approach could reduce environmental impacts and allow policymakers and producers more options in how they address agricultural emissions (Pacala and Socolow, 2004).

Conversion of grasslands to agricultural land could also significantly contribute to emissions in Nebraska. From 2006 to 2011, expansion of maize area in the central U.S. resulted in 530,000 hectares converted from grassland to row crops (Wright and Wimberly, 2013), which is associated with extensive carbon emissions from the disruption of soils (Fargione, et al. 2008). Increasing ethanol production and demand increases crop prices, which correspondingly drives conversion of grasslands to maize; the ethanol industry in Nebraska consumes ~40% of the state's annual production of maize. Cropland can be converted back to grassland, but this is unlikely to occur unless ethanol demand and maize prices are also reduced, or relevant policy is implemented. Reduced demand for grain could cause a corresponding reduction in the acreage of maize, with corresponding reductions in nitrogen use and land conversion, and thus reductions in GHG emissions.

The second largest sector of emissions in Nebraska comes from electricity generation (Table 1.2). Reducing GHG emissions from electricity, like many other mitigation scenarios, will require a portfolio of solutions (Pacala and Socolow, 2004). There are several strategies that can be used to reduce emissions from electricity including reducing demand, changing fuel sources, and increasing the efficiency of the electrical system. Reducing electricity demand can be done through increasing efficiency of electric devices (e.g. LED lighting, appliances, phones, electric cars) or by using less energy intensive processes for manufacturing or in the home, such as turning the lights off when not in use. The most direct way to reduce emissions from electricity use is to change fuel sources for electric plants from fossil fuels to zero or net-zero emission sources such as nuclear, solar, or wind (Tollefson, 2018). Changing fuel sources requires investment in new infrastructure among other issues (Davis et al., 2018), but integration of these sources into existing structures is already occurring and decreasing prices for these alternative energy sources makes incorporation increasingly feasible (Tollefson, 2018). Lastly, increasing the efficiency of Nebraska's electric infrastructure and reducing electrical waste can reduce emissions. Nearly 5% of electricity T&D is lost annually in the U.S. (EIA, 2019b).

The incorporation of external costs from climate change into fossil fuels can help put into perspective the actual costs of fossil fuels compared to zero or net-zero emission sources. Coal currently costs the second least per kilowatt-hour in Nebraska for direct-fuel costs ($0.60 more than nuclear per million BTUs; NEO, 2019b), but if the costs of carbon emissions were included in the cost of electricity, the higher price of coal would probably be less competitive compared to the initial infrastructure costs of renewable and/or net zero GHG emission sources. A carbon tax, much as with livestock, is a potential way to quantify these external costs. Tax breaks, subsidies, and other incentives can also be used to increase the use of zero or net-zero emission energy sources; unlike most states, Nebraska currently does not have a renewable portfolio standard, energy efficiency resource standards, or energy efficiency resource goals (DSIRE, 2019). Potential solutions will need to consider the effect that they might have economically as well as related repercussions. While a change might reduce emissions in the short term (probably by reducing consumption), production or use may simply shift elsewhere and increase net emissions.

Carbon taxes or cap-and-trade systems are an indispensable strategy for the reduction of GHG emissions efficiently across sectors (HLCCP, 2017). While the two largest emissions sectors in Nebraska are agriculture and energy, carbon pricing should be applied to all sectors. Carbon pricing is used internationally, nationally, regionally, and subnationally to help reach environmental and social objectives (HLCCP, 2017; World Bank and Ecofys, 2018). Revenue generated from a carbon tax can be redistributed back to citizens on a per capita basis (a "climate dividend"), which could limit government holdings of climate revenue and keep average tax burdens largely unchanged (Carattini et al., 2019). Most people, however, tend to overestimate the costs of carbon pricing and underestimate its benefits which can impede implementation of carbon prices (Carratini, et al., 2018). Yet, research has shown that once a carbon price is enacted, public support increases over time. Ultimately, there will be no single solution for significant GHG emissions reductions. A diverse set of technologies and policies will be essential for meeting adaptation and mitigation goals (Pacala and Socolow, 2004; HLCCP, 2017; World Bank and Ecofys, 2018). Furthermore, to avoid some of the worst impacts of a rapidly changing climate, action will need to be taken sooner rather than later (Figueres et al., 2017; IPCC, 2006; Tollefson, 2018).

CHAPTER 2 - AGRICULTURAL GREENHOUSE GAS EMISSIONS IN THE MIDWEST

Inventories of GHG emissions generally focus on national emissions rather than state emissions. Emissions inventories at the state level often do not include agricultural emissions except for Iowa, Illinois, and recently, Nebraska (Iowa DNR, 2018; ICF, 2018; see Chapter 1). Agricultural emissions account for ~9% of U.S. emissions, but can account for as much as ~40% of state level emissions (see Chapter 1). The difference between national and state emission sources highlights the need for state specific GHG emissions inventories to help develop solutions tailored to the specific issues of each state (Poore and Nemecek, 2019). Agricultural regions can have particularly high GHG emissions compared to other regions and have a higher variability in site-specific emissions (see Chapter 1; Poore and Nemecek, 2019). Understanding and accounting for agricultural emissions is essential for comprehensive GHG emissions inventories.

This chapter calculates and compares agricultural GHG emissions for the Midwest region of the U.S. using the EPA's SIT. Comparing agricultural GHG emissions across states can provide insights into what agricultural products may contribute more to overall emissions and what factors can be addressed when developing GHG emissions reduction plans. A comparison of inventories also emphasizes how agricultural industries differ amongst states and how specific agricultural products may interact. A deeper understanding of agricultural emissions can help to pinpoint potential emissions reductions that minimize the overall impact on an agricultural industry while still meeting GHG emissions reduction goals.

Agriculture is an important aspect of state economies in the Midwest. Agriculture accounts for over two thirds of land use in the Midwest and ~40% of U.S. agricultural land is in the Midwest (Pryor et al., 2019). Farms directly contribute ~1% of U.S. GDP through sales and operations (USDA ERS, 2020a). Indirectly, farms contribute a much higher amount to U.S. GDP as many other industries rely on agricultural inputs to generate economic value (e.g. biofuels, restaurants, and tourism). Additionally, agriculture- and food-related industries represent over 11% of employment in the U.S. with ~22 million jobs (USDA ERS, 2020b). Agriculture is the beginning of the food supply chain and potential changes will be amplified throughout the chain. Potential GHG emissions reduction strategies could be particularly effective within the agricultural industry, but care is needed as disruptions may also be amplified. State specific (or even farm specific) solutions alleviate some of the risk of change as they can minimize changes within the agricultural industry to lower the risk of disruption and maximize potential benefits.

As emission sources may vary significantly between states or equivalent sources within a state (e.g. farm to farm), the more detailed and "ground up" a GHG emissions inventory is, the more comprehensive and effective plans to address GHG emissions can be developed. Detailed and exhaustive GHG emissions inventories are resource and time intensive, however, and may be too costly for sectors or sources with relatively low GHG emissions. A balance must be struck between too broad a scope and too much cost for not enough benefit. State level GHG emissions inventories can often be the best of both, with specificity that leads to better solutions for an area and identifying key sectors for more detailed analysis to reduce the cost-to-benefit ratio of more thorough GHG emissions inventories. This chapter serves as an example of such an inventory by refining the scope of the inventory as well as identifying important interactions and emissions sources for future, more exhaustive GHG emissions inventories in the Midwest.

Methods

Emissions were estimated using the most recent version of the EPA's SIT (downloaded December 1, 2019). The calculation methods in the SIT are based on the August 2004 version of EPA's Emission Inventory Improvement Program guidance for GHGs (ICF, 2004). Default input values in the SIT were collected from relevant government or industry sources (e.g. USDA); details of the SIT's calculation methods are available in the SIT User Guide (EPA, 2019). The global warming potentials (GWP) used for each GHG were 1 (CO_2), 25 (CH_4), and 298 (N_2O).

Emissions of GHGs from agriculture were calculated using the agriculture module of the EPA's SIT. The agriculture module calculates emissions for nine categories: enteric fermentation (CH_4), manure management (CH_4 and N_2O), residues and legumes from agricultural soils (N_2O), fertilizers applied to agricultural soils (N_2O), manure on agricultural soils (N_2O), liming of agricultural soils (CO_2), urea fertilization (CO_2) (fertilizer production), rice cultivation (CH_4), and burning of agricultural residues (CH_4). Emissions from livestock were based on animal populations from the USDA's Quick Stats tool (USDA NASS, 2019) and corresponding annual emission factors (EF; kg CH_4 per head per year) from the SIT. These livestock categories, with enteric fermentation EFs where appropriate, include: dairy cows (108.9-139.7), dairy replacement heifers (42.2-68.7), beef cows (86.5-92.01), beef replacement heifers (52.4-67.6), heifer stockers (50.4-58.9), steer stockers (53.1-56.9), bulls (88.3-95.1), feedlot heifers (37.2-43.4), feedlot steers (36.3-42.2), calves, breeding swine (1.5), market swine (four categories by weight; 1.5), layer chickens, broiler chickens, sheep (8), goats (5), and horses (18). Emissions from legumes and residues were estimated based on annual production of alfalfa, maize for grain, wheat, barley, sorghum for grain, oats, rye, millet, rice, soybeans, peanuts, dry edible beans, dry edible peas, Austrian winter peas, lentils, and wrinkled seed peas (USDA NASS, 2019). Liming of agricultural soils is calculated by multiplying the total limestone or dolomite applied to soil by an EF (Mt C per Mt limestone or dolomite). Urea fertilization is calculated by multiplying total urea applied to soil by an EF (Mt C per Mt urea).

GHG emissions from the SIT are then used to generate comparison values for each animal and crop tracked by the SIT (Table 13). GHG emissions are often reported as million megatons of carbon dioxide equivalent (MMtCO_2e) but may also be reported as megatons of carbon dioxide equivalent (MtCO_2e) in some emissions comparisons for ease of reporting. There are no comparisons between these units; all comparisons are made using one or the other. To calculate MtCO_2e per unit, the total emissions for each type of animal and crop is divided by the number of units (the type of unit is dependent on how emissions are tracked in the SIT) of that animal or crop (default values are present in the SIT and are taken from the USDA NASS), which are summed to give a total for the state then multiplied by one million to convert to MtCO_2e for comparison. To calculate MtCO_2e per kilogram of agricultural product, average mass per head or bushel (estimated by the SIT) is multiplied by the number of heads or bushels to get total mass for each agricultural product (Table 5). Some products are already reported by weight in the SIT and total weight for these products is converted to total mass. Total emissions are multiplied by one million to convert to MtCO_2e, which are then divided by total mass to get MtCO_2e per kilogram for each agricultural product, which can be summed to provide totals by state. To calculate MtCO_2e per hectare total emissions are multiplied by one million and then divided by the total number of hectares of agricultural land in the state. Total crop emissions are the sum of emissions from direct and indirect fertilizers, crop residues, nitrogen fixing crops, fertilizer leaching and runoff, rice cultivation, liming of agricultural soils, urea fertilization, and agricultural residue burning. Total livestock emissions are the sum of emissions from enteric fermentation, manure management, direct and indirect livestock agricultural soils emissions, and livestock leaching and runoff.

Table 2.1 Calculations of comparison units.

$MtCO_2e$/unit = (GHG emissions from SIT x 1,000,000)/# of units in SIT
$MtCO_2e$/kg product = (GHG emissions from SIT x 1,000,000)/ (avg. mass per head or bushel x number of head or bushels or total mass from SIT)
$MtCO_2e$/hectare = (GHG emissions from SIT x 1,000,000)/total hectares of agricultural land

Results

Agricultural GHG emissions are an impactful and underrepresented part of GHG emissions inventories, particularly in the Midwest region of the U.S. Total agricultural GHG emissions in 2016 were found to range from 10.3 $MMtCO_2e$ (Michigan) to 41.0 $MMtCO_2e$ (Iowa), with an average of 23.3 $MMtCO_2e$ (Table 2.2). These data are also shown in a stacked bar chart (Fig. 2.1). Agricultural emissions for most states are dominated by three categories: enteric fermentation, ag soils, and manure management (Fig. 2.1). Both enteric fermentation and manure management are exclusive to livestock, while ag soils include fertilizer use, residues and legumes for crops, as well as effects from livestock on agricultural soils. Nebraska and

Kansas have the largest amount of emissions from enteric fermentation (Table 2.2). While these two states have a substantial amount of beef cattle, South Dakota and Missouri have comparable herds, with Missouri having the largest amount of beef cattle (as categorized by the SIT) in 2016 (USDA NASS, 2019).

Nebraska, Kansas, and Iowa have much more stocker cattle than other states and more cattle in feedlots. Nebraska and Kansas have approximately double the total amount of cattle (beef, stocker, dairy etc.) as Iowa, South Dakota, and Missouri, thus having nearly double the enteric fermentation emissions. Iowa's "enteric fermentation" emissions are higher than expected following this trend due to the vast swine population in the state (Iowa DNR, 2018). Sheep, goats, swine, and horses are monogastric animals that don't have enteric fermentation as part of their digestive process, but GHG emissions from their digestive processes are accounted for by the enteric fermentation section of the SIT (ICF, 2004). Iowa and Wisconsin have the highest emissions in manure management (Table 2.2), due to Iowa's large swine population and Wisconsin's large dairy cattle population. Swine have a higher methane conversion factor (MCF), or the percentage of waste that degrades to methane, than other livestock because of their manure management systems (ICF, 2004). Dairy cattle have a higher rate of volatile solids (VS), or the amount of waste that could potentially be converted to methane, produced than other livestock. Both MCF and VS are used by the SIT to calculate emissions from manure management and are values calculated by the EPA. Manure management emissions in other states are largely dependent on the amount of dairy cattle and swine in that state.

Table 2.2 Agricultural GHG emissions (MMtCO_2e) by state and category, 2016.

Category	IA	NE	KS	IL	MN	SD	MO	WI	ND	IN	OH	MI
Enteric Fermentation	8.45	13.40	12.16	2.29	4.65	7.57	6.65	7.36	3.35	1.90	2.59	2.68
Manure Management	7.23	3.06	3.17	2.06	3.65	1.25	1.91	4.60	0.18	2.06	1.86	2.40
Ag Soils	25.01	18.47	13.68	21.20	15.95	13.21	12.45	7.37	13.85	12.08	8.99	5.09
Rice Cultivation	0.00	0.00	0.00	0.00	0.00	0.00	0.55	0.00	0.00	0.00	0.00	0.00
Liming	0.13	0.26	0.02	0.51	0.02	0.00	0.17	0.11	0.00	0.49	0.12	0.04
Urea Fertilization	0.14	0.13	0.21	0.06	0.47	0.52	0.17	0.20	0.52	0.09	0.05	0.07
Ag Residue Burning	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Total	40.98	35.33	29.25	26.13	24.75	22.57	21.91	19.65	17.90	16.61	13.61	10.29

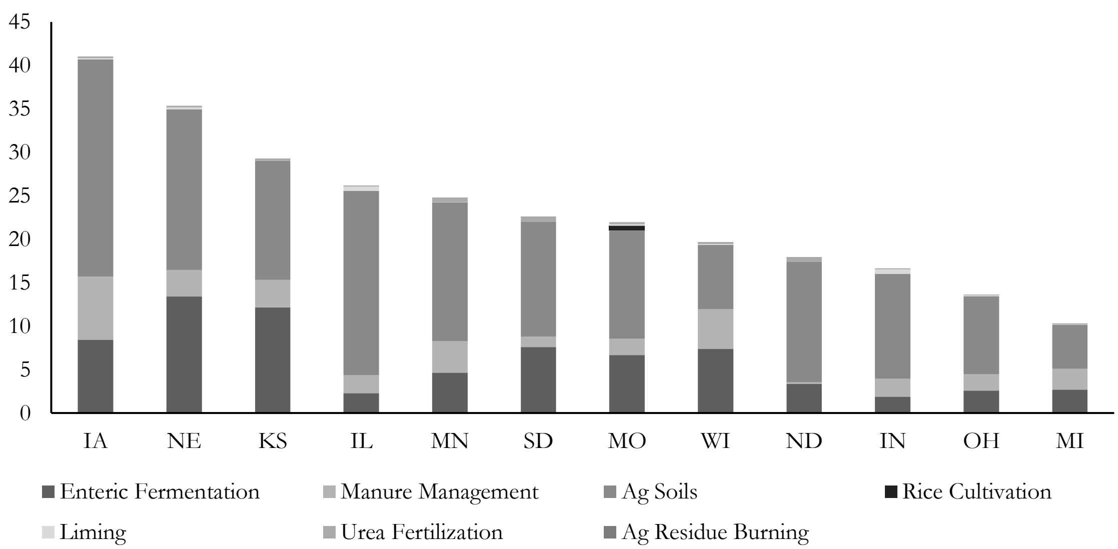

Figure 2.1 Total state agricultural GHG emissions by category, 2016.

Agricultural soils in the SIT are categorized into residues and legumes, fertilizers, and animals. These categories are further broken down into more specific categories for summary purposes in the SIT (Table 2.3). These data are also shown in a stacked bar chart (Fig. 2.2). Fertilizers, crop residues, N-fixing crops, and fertilizer runoff/leached are the sub-categories under crops and comprise the majority of GHG emissions from agricultural soils in the Midwest (Fig. 2.2). Livestock and manure runoff/leached GHG emissions are the sub-categories under livestock and their proportion of total agricultural soils emissions varies by state. Ag soils-animals consists of direct and indirect emissions from unmanaged manure on fields and soils. Iowa, Nebraska, and Kansas had the highest ag soils-animals emissions due to their respective cattle populations. Residues and legumes emissions are dependent mostly on the amount of soybeans produced in a state, with Illinois producing the most (USDA NASS, 2018). Fertilizer use depends on many factors, many of which aren't captured by the SIT, but are primarily associated with corn production. Iowa and Illinois had the highest uses of fertilizers in 2016 (Table 2.3). Missouri is the only state in the Midwest that grows rice, so GHG emissions from rice cultivation in other states are non-existent.

Table 2.3 Agricultural soils emissions ($MMtCO_2e$) by subcategory and state, 2016.

Category	IA	IL	NE	MN	ND	KS	SD	MO	IN	OH	WI	MI
Direct	21.4	18.4	15.9	13.8	11.7	11.8	11.5	11.0	10.4	8.0	6.2	4.4
Fertilizers	5.9	5.1	4.2	3.5	4.0	2.8	2.7	2.2	2.9	1.7	1.7	1.1
Crop Residues	5.1	5.0	3.1	3.4	2.4	2.5	2.2	2.0	2.5	1.9	1.0	0.9
N-Fixing Crops	7.2	7.4	4.3	5.3	3.8	2.7	3.6	3.4	4.1	3.4	1.7	1.6
Histosols	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Livestock	3.2	1.0	4.2	1.6	1.5	3.8	3.0	3.3	0.9	1.0	1.8	0.7
Indirect	3.6	2.8	2.6	2.1	2.2	1.8	1.7	1.4	1.7	1.0	1.2	0.7
Fertilizers	1.0	0.9	0.7	0.6	0.7	0.5	0.5	0.4	0.5	0.3	0.3	0.2
Livestock	0.2	0.1	0.2	0.1	0.0	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Leaching/Runoff	2.3	1.8	1.7	1.4	1.5	1.2	1.1	0.9	1.1	0.7	0.7	0.5
Fertilizer Runoff/Leached	2.1	1.8	1.5	1.2	1.4	1.0	1.0	0.8	1.0	0.6	0.6	0.4
Manure Runoff/Leached	0.2	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1
Total	25.0	21.2	18.5	15.9	13.8	13.7	13.2	12.4	12.1	9.0	7.4	5.1

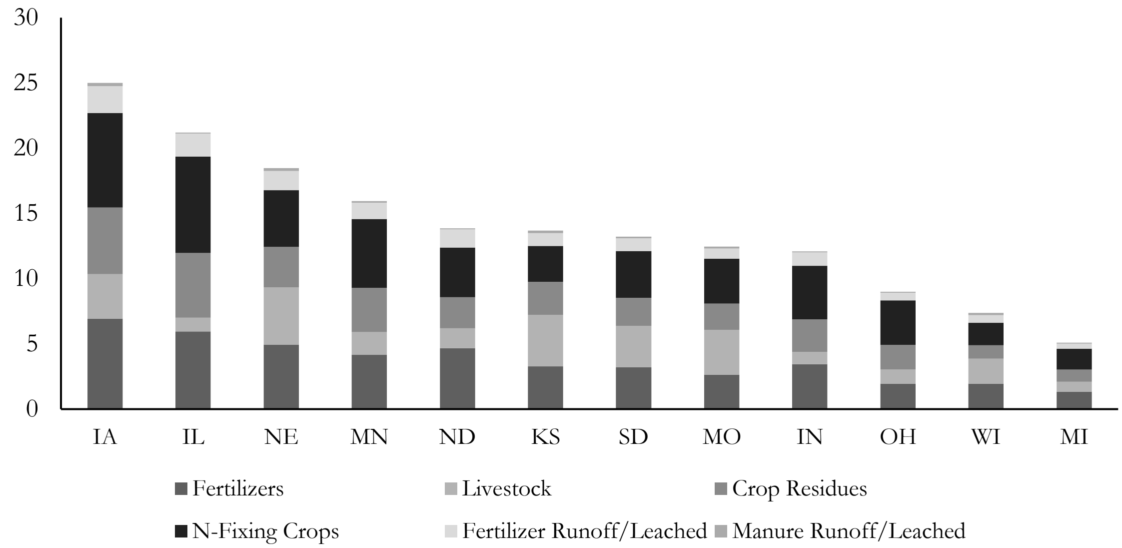

Figure 2.2 Direct and indirect agricultural soils emissions (MMtCO_2e) by category and state, 2016.

The percentage crop and livestock are the respective percentages out of total agricultural GHG emissions (Fig. 2.3). The ratio of livestock to crop emissions varies by state, with half of states with more livestock emissions and half with more crop emissions (Fig. 2.3). The average ratio for the Midwest is 47.7% livestock emissions to 52.3% crop emissions. Wisconsin has the highest proportion of agricultural GHG emissions associated with livestock (71.5%) and Illinois has the lowest (21%).

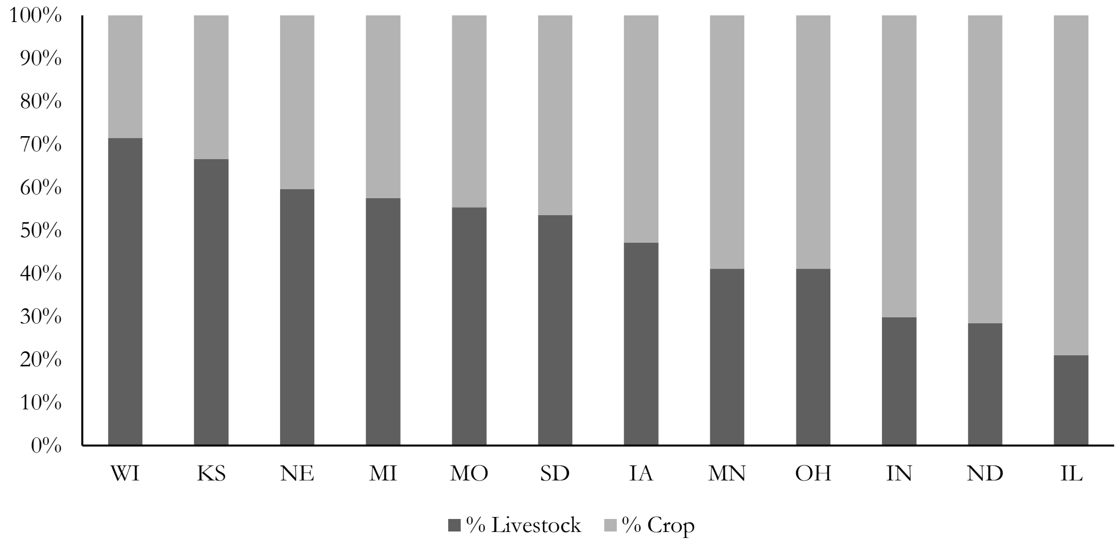

Figure 2.3 Percentage total livestock vs percentage total crop GHG emissions by state, 2016.

Emissions per state can also be compared using intensity metrics, such as GHG emissions per kilogram product and GHG emissions per area. Calculation of comparison metrics as described in the methods is summarized below (Table 2.4). Total emissions and total units are summed from values taken from the SIT. Total mass is derived from average mass per head or bushel which are values also present in the SIT (Table 2.5). Total agricultural land is provided by the USDA, which is the sum of pastureland, cropland, and woodland (Table 2.6).

Table 2.4 Calculation of emissions per unit, kg product, and hectare by state, 2016.

Category	IA	NE	KS	IL	MN	SD	MO	WI	ND	IN	OH	MI
Total Emissions ($MMtCO_2e$)	41.0	35.3	29.3	26.1	24.7	22.6	21.9	19.6	17.9	16.6	13.6	10.3
Units (millions)	3.4	2.1	1.6	2.9	2.1	1.2	1.0	0.7	1.2	1.4	0.9	0.5
Total Mass (Gg)	90.8	61.4	48.9	76.2	57.0	36.8	26.8	22.9	34.3	35.2	23.9	15.1
Ag Land (million hectares)	12.2	18.1	18.4	10.8	10.0	17.3	11.6	5.7	15.7	5.9	5.6	3.8
$MtCO_2e$/Unit	12.0	16.5	17.8	9.0	12.0	18.3	22.3	26.9	15.2	12.3	15.2	20.0
$MtCO_2e$/kg product	0.45	0.58	0.60	0.34	0.43	0.61	0.82	0.86	0.52	0.47	0.57	0.68
$MtCO_2e$/hectare	3.4	2.0	1.6	2.4	2.5	1.3	1.9	3.5	1.1	2.8	2.4	2.7

Table 2.5 Average mass per head, bushel, and unit for agricultural products, 2016.

Category	Unit	Average Mass (kg)/head or bushel	Average Mass (kg)/unit
Dairy Cows	1000 Head	679.8	679,770
Dairy Replacement Heifers	1000 Head	406.5	406,510
Beef Cows	1000 Head	610.9	610,890
Beef Replacement Heifers	1000 Head	405.5	405,540
Heifer Stockers	1000 Head	321.8	321,820
Steer Stockers	1000 Head	324.3	324,340
Feedlot Heifers	1000 Head	443.4	443,370
Feedlot Steer	1000 Head	470.6	470,550
Bulls	1000 Head	916.3	916,340
Calves	1000 Head	122.5	122,530
Sheep on Feed	1000 Head	55.8	55,791.8
Sheep Not on Feed	1000 Head	55.8	55,791.8
Goats	1000 Head	64	64,000
Breeding Swine	1000 Head	198	198,000
Market Under 60 lbs	1000 Head	15.9	15,880
Market 60-119 lbs	1000 Head	40.6	40,600
Market 120-179 lbs	1000 Head	67.8	67,820
Market over 180 lbs	1000 Head	90.8	90,750
Horses	1000 Head	450	450,000
Layers			
Hens > 1 yr	1000 Head	3.1	3,066.3
Pullets	1000 Head	3.1	3,066.3
Chickens	1000 Head	3.1	3,066.3
Broilers	1000 Head	2.9	2,898.5
Alfalfa	'000 tons	-	907,185
Corn for Grain	'000 bushels	25.4	25,401.2
All Wheat	'000 bushels	27.2	27,215.5

Barley	'000 bushels	21.8	21,772.4
Sorghum for Grain	'000 bushels	25.4	25,401.2
Oats	'000 bushels	14.5	14,514.9
Rye	'000 bushels	25.4	25,401.2
Millet	'000 bushels	22.7	22,679.6
Rice	'000 hundredweight	-	50,802.3
Soybeans	'000 bushels	27.2	27,215.5
Peanuts	'000 lbs	-	453.6
Dry Edible Beans	'000 hundredweight	-	50,802.3
Dry Edible Peas	'000 hundredweight	-	50,802.3
Austrian Winter Peas	'000 hundredweight	-	50,802.3
Lentils	'000 hundredweight	-	50,802.3
Wrinkled Seed Peas	'000 hundredweight	-	50,802.3

Table 2.6 Agricultural land (million hectares) by category and state, 2016.

Category	**IA**	**NE**	**KS**	**IL**	**MN**	**SD**	**MO**	**WI**	**ND**	**IN**	**OH**	**MI**
Pastureland	0.96	8.92	6.32	0.46	0.64	9.18	3.64	0.64	4.25	0.29	0.53	0.21
Cropland	10.75	9.01	11.80	9.72	8.82	8.02	6.32	4.08	11.32	5.23	4.44	3.21
Woodland	0.45	0.14	0.26	0.60	0.56	0.12	1.65	0.93	0.08	0.42	0.59	0.40
Total	12.15	18.07	18.38	10.77	10.03	17.32	11.60	5.66	15.66	5.94	5.57	3.82

Source: USDA NASS, 2020.

Agricultural emissions per kilogram of agricultural product by state were found to vary between 0.86 (Wisconsin) and 0.34 (Illinois) (Fig. 2.4). Kilograms of agricultural product are based on mass estimates of crops and livestock amounts reported to the USDA and don’t reflect changes throughout the year or actual agricultural products derived from livestock or crops (e.g. steaks).

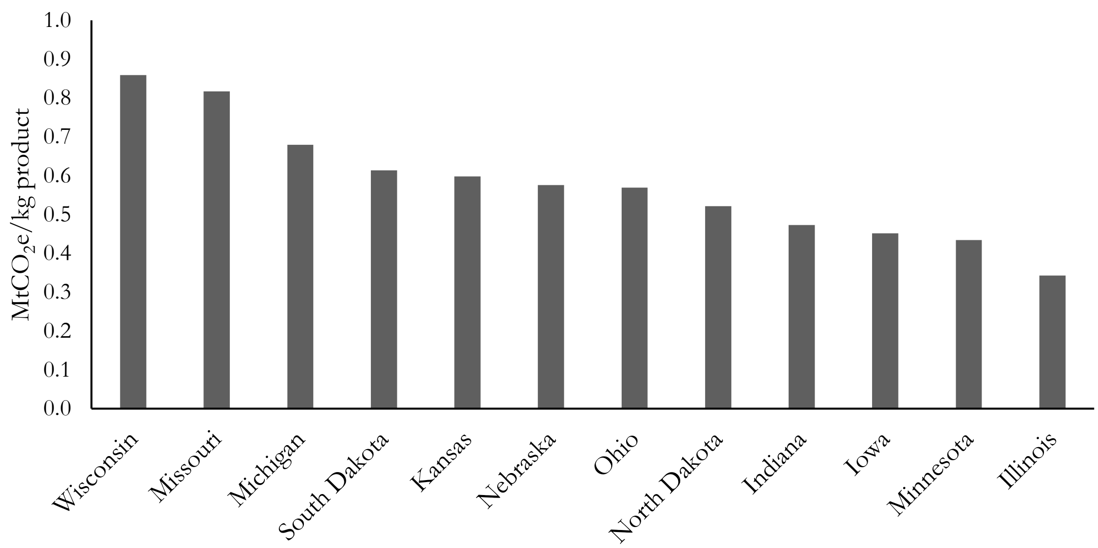

Figure 2.4 Agricultural emissions ($MtCO_2e$) per kilogram of product by state, 2016.

Plotting percentage livestock versus GHG emissions per kilogram of agricultural product helps to determine if there is a correlation between the amount of GHG emissions by mass and the ratio of livestock and crops in a state (Fig. 2.5). This comparison provides context for what insights emissions per mass can give as a basis of comparison between states. The percentage livestock or crop of total agricultural emissions is relatively correlated with $MtCO_2e$/kg product, meaning that the ratio of livestock to crop emissions in a state is indicative of the emissions efficiency of a state's agricultural sector, with livestock having higher emissions and crops having lower emissions (Fig. 2.5). As there are only two categories (livestock or crop), the effects are inversed, but the correlation is the same for both percentage crop and percentage livestock. The amount of emissions per kg agricultural product is correlated with whether a state is primarily livestock or crop based, which suggests that the equivalency assumption (the mass of crop and livestock are treated the same) may accentuate differences in emissions per kilogram product for livestock and crops, and should be considered in comparisons. While the ratio of livestock to crop emissions likely matters in emissions per mass, emissions per mass still captures both livestock and crop emissions though one likely has more influence than the other.

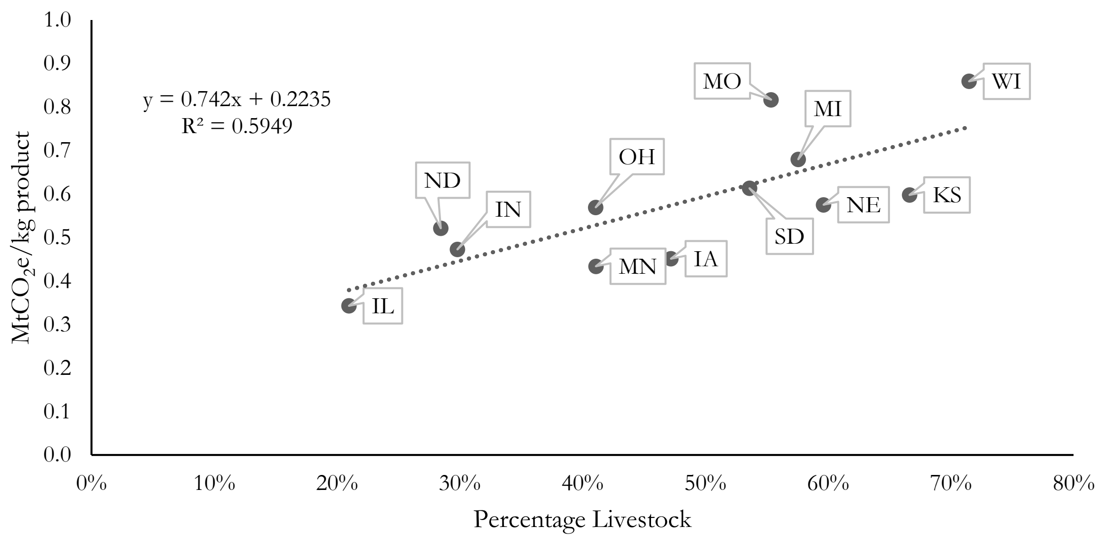

Figure 2.5 Emissions in $MtCO_2e$ per kilogram of product vs. percentage livestock, 2016.

Emissions per kilogram plotted against total livestock and total crop emissions of product provides insight into whether livestock or crop emissions are correlated with emissions per mass and which may have more influence (Fig. 2.6, Fig. 2.7). Emissions per mass do not change with increasing livestock emissions, but emissions per mass were moderately correlated with crop emissions ($R^2 = 0.59$). This suggests the high emissions variability among types of livestock in a state (e.g. dairy cattle versus swine) complicates the relationship with efficiency, whereas efficiency is more linearly related to crop emissions, with more crops leading to greater efficiency. Livestock emissions may have a greater influence on emissions per mass in some states and not others, whereas crop emissions likely have similar influence amongst states.

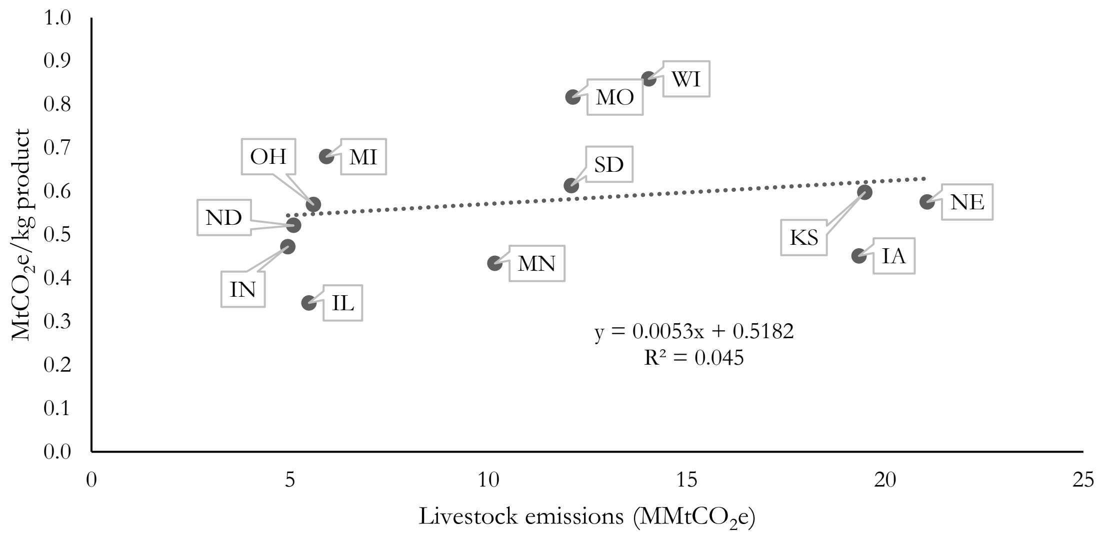

Figure 2.6 Emissions in MtCO$_2$e per kilogram product vs. total livestock emissions, 2016.

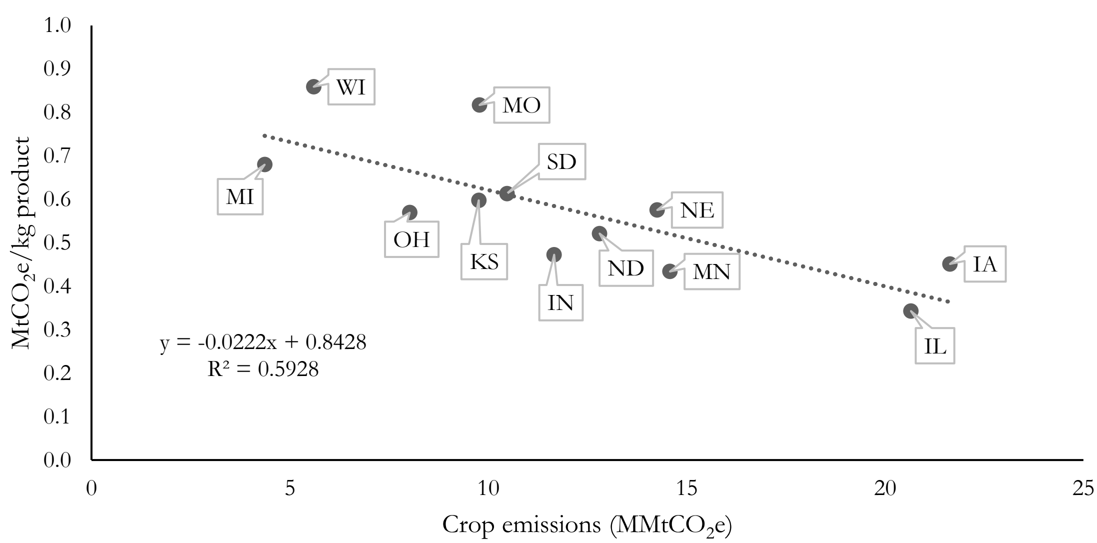

Figure 2.7 MtCO$_2$e per kilogram product vs. total crop emissions vs, 2016.

Total agricultural GHG emissions plotted against total agricultural land provides insight into if and how the size of agricultural land use influences total agricultural emissions (Fig. 2.8); intuition would suggest a linear correlation. Total agricultural emissions are somewhat correlated with total agricultural land (R^2 = 0.39). Livestock, particularly cattle, use a large amount of land with relatively low agricultural productivity and the differences in land use amongst livestock (e.g. pasture-raised, feedlot, CAFO) introduce variability.

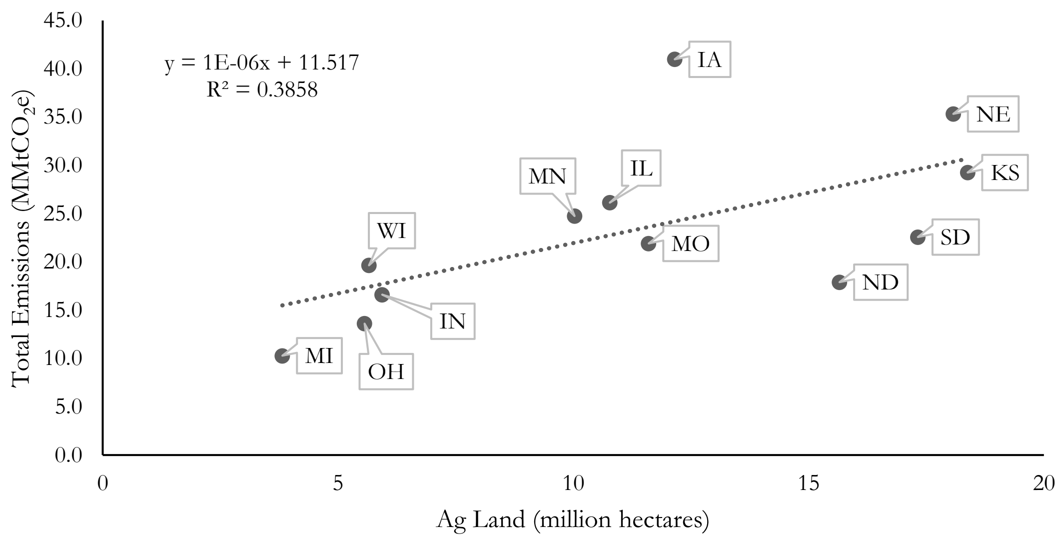

Figure 2.8 Total agricultural emissions vs total agricultural land, 2016.

Plotting total livestock or cropland GHG emissions against total pastureland or cropland, respectively, provides insights into how either category of emissions is correlated with the amount of land dedicated to that category (Fig. 2.9, Fig. 2.10). Similar to efficiency, pastureland has less of a linear relationship with livestock emissions (R^2 = 0.29) than cropland does with crop emissions (R^2 = 0.48). Livestock land use is more dependent on type of livestock and how the livestock are raised (e.g. pasture-raised beef cattle versus dairy cattle). Crops have less variability in their land use, although type of crop is likely to still affect total crop emissions, with corn having significantly more emissions than soybeans per unit area, due to fertilizer application in the former.

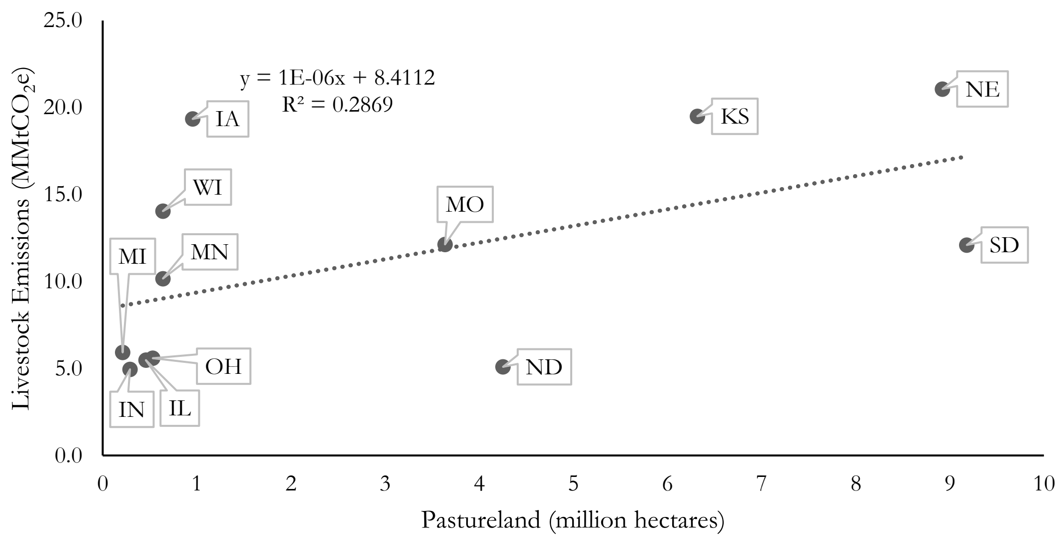

Figure 2.9 Pastureland vs total livestock emissions, 2016.

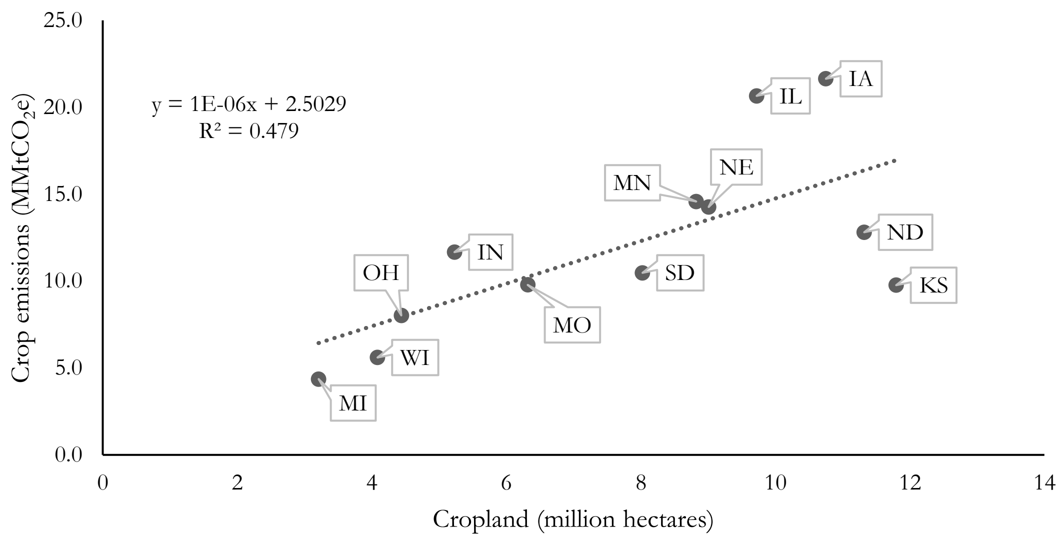

Figure 2.10 Cropland vs total crop emissions, 2016.

Plotting emissions per hectare against total agricultural land provides insights into whether agricultural land might be a good predictor of the efficiency of agricultural emissions (Fig. 2.11). The total amount of agricultural land in a state is somewhat correlated with the emissions efficiency of that agricultural land ($R^2 = 0.52$), suggesting that as agricultural land use increases, so does agricultural efficiency to a moderate degree. This relationship is probably due to the fact that cropland increases when agricultural land increases in size, which increases overall efficiency, and lowers emissions per hectare; yet, the four states with lowest emissions per hectare have high amount of pasture relative to cropland (Fig. 2.11).

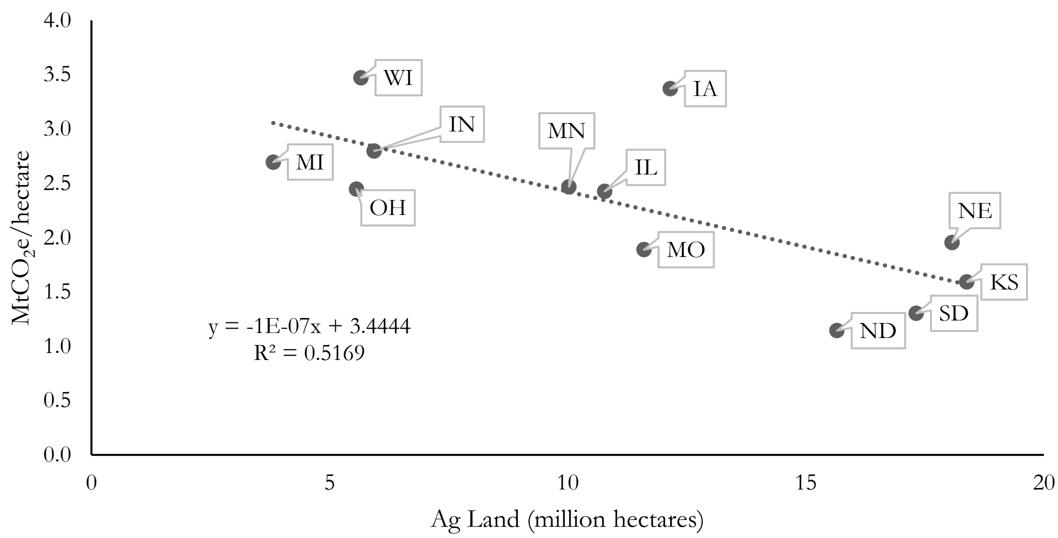

Figure 2.11 GHG emissions per hectare of agricultural land ($MtCO_2e$/hectare) vs total agricultural land (million hectares), 2016.

Plotting emissions per hectare of agricultural land against total pastureland or cropland land can indicate whether cropland or pastureland might have a larger effect on land-based efficiency (Fig. 2.12, Fig. 2.13). Pastureland has a relative negative correlation with overall emissions per hectare, which is probably due to the diluting effects of low-emission pastures, which have a less intensive operation (Fig. 2.12); the same relationship may hold for Figure 2.11. The differences in type of cattle and the amount of space given to each type of cattle likely have a large effect on emissions per hectare. Cropland has a relatively small negative correlation with overall emissions per hectare, meaning as cropland increases so does the agricultural land-based efficiency (Fig. 2.13). The smaller correlation is likely due to less variability in land use amongst crops, which are primarily corn and soybean in the Midwest.

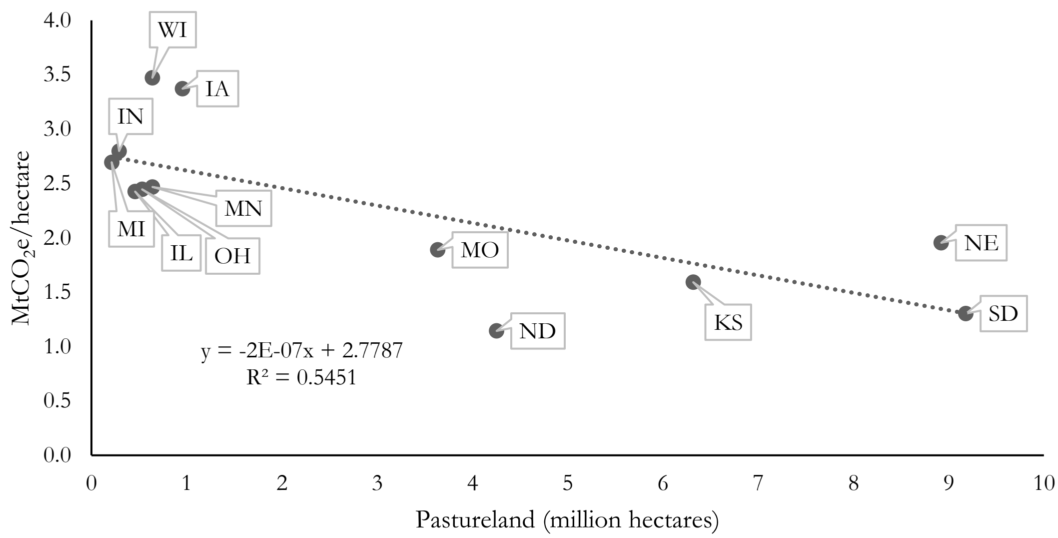

Figure 2.12 GHG emissions per hectare of agricultural land ($MtCO_2e$) vs pastureland (million hectares), 2016.

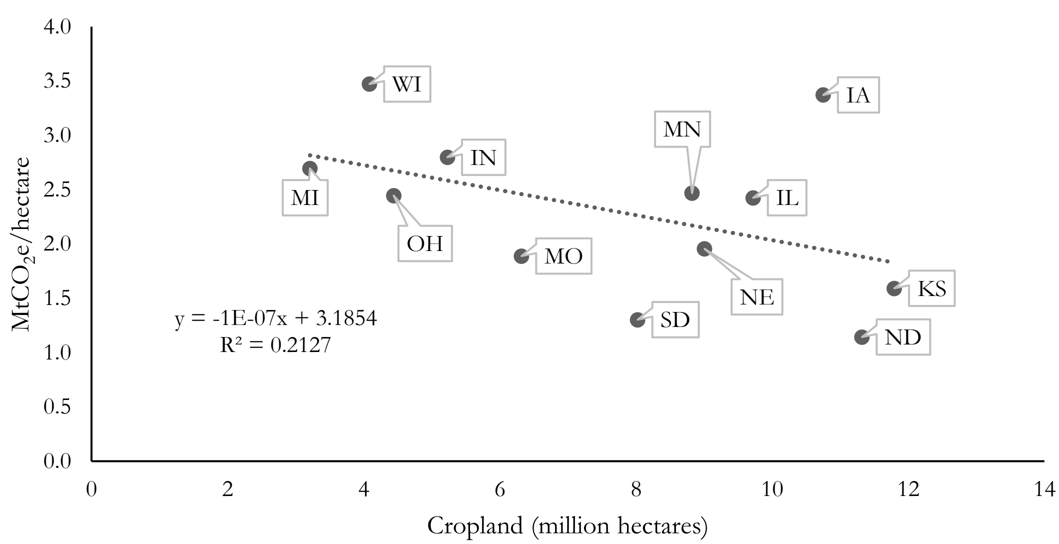

Figure 2.13 GHG emissions per hectare of agricultural land ($MtCO_2e$) vs cropland (million hectares), 2016.

Although per capita agricultural GHG emissions may not be the best comparator for states, it can still provide insight into the scope and nature of agricultural emissions. The highest emitting states per capita for agricultural emissions all have relatively low populations (Table 2.7). Four of these states (SD, NE, IA, and KS) have a strong livestock component of their agricultural industry, particularly cattle (Fig. 2.3). North Dakota does not have a particularly large livestock component but emissions per capita is high, while states like Missouri and Wisconsin do have large livestock components but per capita emissions are low. This emphasizes the issue with per capita emissions that population is too dominant of a factor and further work is necessary to improve per capita emissions as a comparator. However, these results suggest that livestock may be a significant factor in total emissions per capita and that these relationships would be useful to further characterize.

Table 2.7 Agricultural emissions per capita, 2016.

Category	SD	ND	NE	IA	KS	MN	MO	WI	IN	IL	OH	MI
Ag Emissions	22.6	17.9	35.3	41.0	29.3	24.7	21.9	19.6	16.6	26.1	13.6	10.3
Population (millions)	0.9	0.8	1.9	3.1	2.9	5.5	6.1	5.8	6.6	12.8	11.6	10.0
$MtCO_2e$/capita	26.2	23.7	18.5	13.1	10.1	4.5	3.6	3.4	2.5	2.0	1.2	1.0

Source: U.S. Census Bureau, 2020.

Uncertainties

The accuracy of the EFs calculated by the SIT is the main source of uncertainty for the inventory. EFs are aggregations of measurements, calculations, studies, surveys, and reporting. Even relatively small amounts of uncertainty for each of these elements adds to the uncertainty of a given EF and the calculated EF is quite dependent on the accuracy of the methods that go into estimating it. The mixture of national, regional, and state data also adds some uncertainty to calculations.

The amount of CH_4 emissions due to enteric fermentation from livestock is dependent on the accuracy of the animal population estimates and the EFs used for each animal type. Animal populations vary throughout the year, which will affect annual total emissions and is not accounted for by the SIT (ICF, 2004). EFs used have inherent uncertainty due to differences in production, environment, diet, and genetics of the animal (ICF, 2004). Like enteric fermentation, manure management is subject to uncertainty in livestock populations and EFs. The largest source of uncertainty in manure management, however, comes from EFs of manure management systems. The SIT does not account for state-specific facilities and specific management practices but relies on regional estimates of emissions for manure management systems. While the SIT does sub-categorize animal groups to some extent, there is insufficient data and infrastructure to accurately measure differences in animal types and diet and how they affect the constants used in the SIT (ICF, 2004). Nitrogen emissions from soils are dependent on many factors other than nitrogen input, including soil moisture, type, pH, temperature, organic carbon content, oxygen's partial pressure, and soil amendment (ICF, 2004). The SIT uses only nitrogen input as a factor in calculating N_2O emissions and does not account for these other variables or their interactions. The combination of type of soil, climate, and management conditions changes nitrogen output and this highly variable system is simply too complex to accurately estimate (ICF, 2004). Fertilizer usage includes only synthetic fertilizers applied to crops and does not use organic fertilizers (such as manure) due to a lack of state-specific data for the application of fertilizers.

In addition to the uncertainties present in the SIT calculations, there are uncertainties associated with generating the comparison units for states. Emissions per unit has a small amount of uncertainty from animal population estimates as head counts get rounded at various stages in reporting. Emissions per kg of animal product introduces uncertainty through the assumed average masses of livestock and crops. The SIT uses regional data to estimate average masses for each animal type. Many factors not accounted for by the SIT impact animal mass including type of feed, breed of livestock, variability of mass throughout the year, and activity level. For crops, there is less uncertainty as some products are reported in weight (which can be converted to mass with relatively low uncertainty) and others are reported volumetrically, with relatively low changes between one bushel of corn, for instance, and another. Emissions per hectare also introduces some rounding uncertainties in reporting as well as total agricultural land includes land for products not accounted for by the SIT.

Despite the uncertainties discussed above, the SIT provides a standardized procedure that estimates sector emissions with relatively small errors compared to the absolute amount of emissions and compared to the conclusions that can be interpreted from these GHG emission estimates. While the uncertainties discussed here can be reduced with refined methodology to provide a more accurate estimation of GHG emissions the results of this inventory provide the basis for planning and decision making. Future refinements of methodology improve estimations but do not discount the validity of previous inventories.

Discussion

Agriculture is an important sector for the Midwest U.S. and is a vital sector for the success of many states in the region. Understanding and properly addressing GHG emissions associated with agriculture is especially important in a varied region such as the Midwest, or the "Corn Belt". Crop emission percentages range from 28.5% to 79% of total state agricultural emissions and livestock emissions percentages range from 21% to 71.5%, emphasizing the diversity of agricultural industries among states in the Midwest and the need for more state-specific solutions to reduce agricultural emissions. Problems with the agricultural industry aren't necessarily the same from farm to farm, much less from state to state or beyond (Poore and Nemecek, 2019). Tailored solutions will require a more robust understanding of differences amongst state's agricultural industries and the causes of those differences. Agricultural GHG emissions inventories are the basis for developing tailored solutions.

The efficiency of an agricultural system regarding emissions can be measured by the amount of GHG emissions for every unit of agricultural product (e.g. bushel of corn, head of cattle). In 2016, Wisconsin was the least efficient state (0.86 $MtCO_2e$/kg product) and Illinois was the most efficient (0.34 $MtCO_2e$/kg product) (Fig. 2.4, Table 2.1). Dairy cattle have a high amount of emissions compared to their lower mass per animal, likely due to the production of milk over their lifetimes; yet, dairy cattle generally have higher emissions than beef cattle because they have a higher fraction of roughage in their diet, which leads to increased enteric fermentation emissions (as shown in the Methods). The SIT does not include milk production in its calculations and much of the mass produced by dairy cows is not accounted for in final weight, which decreases the perceived efficiency. However, the separate supply chains for milk and milk products versus the use of meat from dairy cows is also not considered which offsets the loss of mass to an unknown degree. Illinois has the highest ratio of crop to animal emissions, and most of its agriculture is based on crops (i.e. corn and soybean), which are more efficient than livestock in those areas (Fig. 1.14).

Using mass as a basis for comparison has several advantages when comparing agricultural emissions over more common comparisons like per capita or per GDP that are used when comparing overall emissions. Per capita emissions are useful when emissions are dependent on the consumption of a product (e.g. fuel use), or production of products that are constrained to the geographic area of the population considered (e.g. electricity disregarding exports, see Chapter 1). State-level, per GDP comparisons are particularly useful when the manufacture of a product is concentrated in an area and demand is elsewhere (e.g. exports). Per capita comparisons can give some insight into non-economic factors for comparison (e.g. laws) but fall short of direct comparisons as GHG emissions aren't dependent on the population of a region (Table 2.7), as agricultural products are often exported (see Chapter 1). Per GDP comparisons are better for agricultural products as emissions are tied to the production, rather than the consumption, of livestock and crops, but the highly variable nature of agricultural pricing makes direct comparisons difficult. Emissions per unit mass produced allows direct comparisons based on production and allows insights into agricultural efficiency. The drawback to emissions per unit mass is that the comparison assumes that a unit mass of one product is the same as a unit mass of another product and doesn't account for differences in economic or social value. As an example, a kg of corn has separate nutritional value, pricing, and inputs (e.g. labor, nitrogen) than a kg of beef but these differences are mostly ignored when comparing emissions per unit mass. With per capita and per GDP comparisons, however, most of these factors are also ignored aside from the relevant factors for each specific comparison. Comparing emissions across agricultural land ($MMtCO_2e$/million hectare) is similar to emissions per kg product in that it allows direct comparisons but makes the assumption that a hectare of land devoted to crops is the same as a hectare of land devoted to pasture.

Future state agricultural GHG emissions comparisons should try to account for the large differences amongst types of livestock, as well as incorporating more agricultural products. A more detailed statistical analysis would allow some of the comparisons and interactions discussed to be more certain and may highlight more complex interactions that aren't captured through scatterplots. Incorporation of agriculture in national GHG emissions reduction plans can help provide the necessary resources to reduce agricultural GHG emissions without disrupting current agricultural systems in unnecessary ways.

CHAPTER 3 - CLIMATE CHANGE AND MARKET-BASED INSURANCE FEEDBACKS

Introduction

Government policies have been a predominant approach to adapt to and mitigate climate change impacts (Drouet et al., 2015; Stern, 2015). Yet past political agreements have been largely unsuccessful in reducing carbon emissions necessary to avert probable widespread catastrophic effects (Stern, 2015). Changes in insurance coverage has been identified as an important external factor in driving adaptation and mitigation measures, among many other factors (USGCRP, 2018). Where future binding agreements are slow to develop (Stern, 2007; Lomborg, 2010), insurance feedbacks are under-recognized mechanisms and incentives to induce climate change adaptation and mitigation (Mills, 2005; Mills, 2012; Kunreuther et al., 2013; Botzen, 2013; Attali, 2006; IPCC, 2014). Market-based insurance feedbacks that are systemic, forceful, and knowledge-driven may become more active and apparent as the percentage of insured claims increases from natural catastrophes (Fig. 3.1). Alongside other factors, market-based insurance feedbacks provide a framework to recognize the challenges posed by climate change and incorporate the problem and potential solutions into existing structures (USGCRP, 2018). Each factor has its limitations, and must be part of a larger, coordinated effort to address climate change adaptation and mitigation.

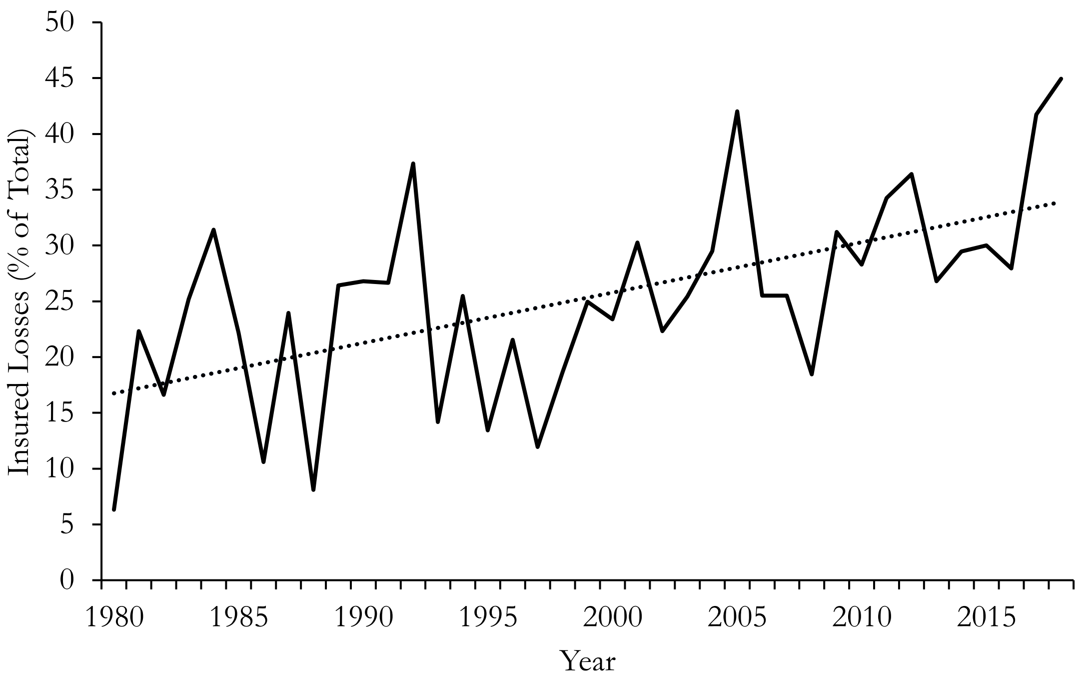

Figure 3.1 Insured losses as fraction of overall losses from natural catastrophes, 1980 to 2018.

Source: Munich Re, 2020.

In 2019, the World Economic Forum ranked extreme weather events, failure of climate change mitigation and adaptation, and natural catastrophes as the first, second and third most probable (respectively) and the third, second, and fifth most impactful economic risks to occur in the next 10 years (WEF, 2019). Downside risks associated with weather-related events are increasingly managed by the insurance industry, the largest global economic sector, with revenue of $4.6 trillion or 7% of the global economy in 2011 (Mills, 2012). Climatic events have accounted for 91% of the $1.05 trillion in insured losses concerning property and casualty insurance claims from 1980 to 2016 for global catastrophic events, and average costs per event have been steadily increasing (Fig. 3.2); Hurricanes Harvey, Irma, and Maria in 2017 further add to this trend. Mounting external costs are also not included on corporate balance sheets or asset prices (Dietz et al., 2016). But businesses, governments, and financially concerned organizations are increasingly incorporating externalities in their plans and are making climate risk management a higher priority (Chestney, 2016).

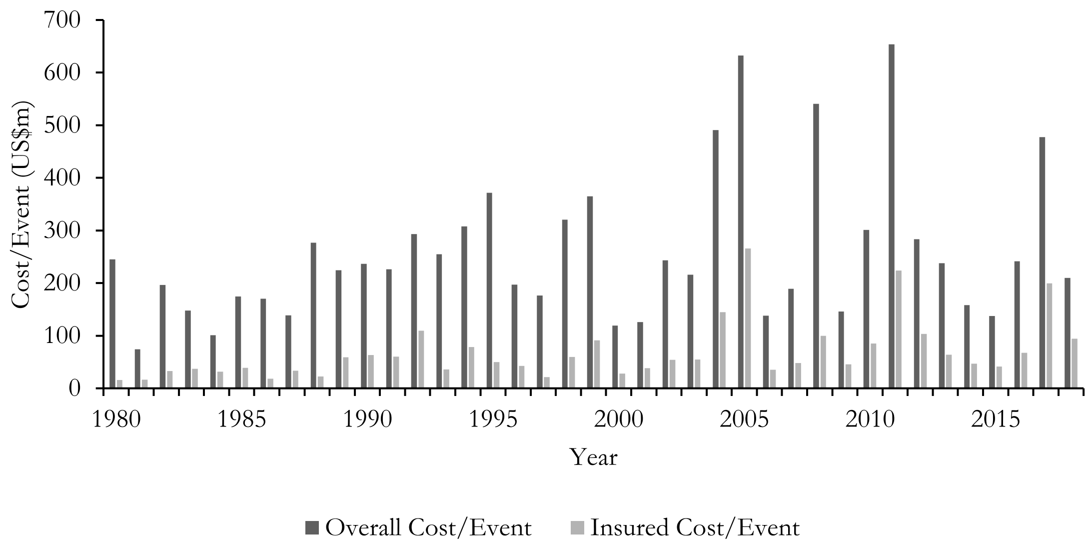

Figure 3.2 Overall and insured costs per event globally from 1980 to 2018 for relevant events only.

(At least 1 death and/or produced normalized losses ≥ US$ 100k, 300k, 1m, or 3m (depending on the assigned World Bank income group of the affected country). Source: Munich Re 2016.

The following sections describe the forceful and extensive mechanisms by which the insurance industry manages its role in adaptation and mitigation in market-based insurance markets. While some of our specific examples may cite the United States, these mechanisms and feedback processes are fundamental features of market-based insurance markets. Although the United States has the largest single share, the ten largest non-life insurance markets include Germany, the United Kingdom, France, Japan, Korea, Canada, Spain, Italy and Switzerland (OECD, 2016). Moreover, the most rapid percentage growth in private non-life insurance markets is occurring in Ecuador, Nicaragua, Columbia, Finland, Singapore, Poland, Israel, Portugal, Mexico and South Africa (OECD, 2017). Thus, the mechanisms described in our paper already operate in many developed countries (excluding public-private markets) and are rapidly expanding in a number of developing countries with market-based insurance. The descriptions following serve as a basis to understand the crucial interactions between the public and the insurance industry and to provide a framework for future research.

Premiums and Insurance Policy Feedbacks

Insurance premiums act as a signal of the average probability of a loss, and high initial premiums generally deter customers (Höppe and Gurenko, 2006; Kunreuther et al., 2013). Insurers will only offer catastrophe insurance if premiums can be priced sufficiently and where risks are not excessively uncertain (Jaffee and Russell, 1997; Kunreuther and Michel-Kerjan, 2007; Ferguson, 2008). Premiums often reflect one-year contracts between the insurer and insured. This time frame allows premiums to be adjusted in response to new information about the expected value of future losses in the short or long term. An increase in premiums to cover the newly realized costs and unknown risks from climate change may leave previously insured assets without insurance and exposed to financial losses (Mills, 2005; Kunreuther and Michel-Kerjan, 2007; Young and Schwartz 2014). Financial viability of policies also relies on applying differential pricing to coverage limits and deductibles (Höppe and Gurenko, 2006). Individual actions can lead to policy benefits, such as premium discounts or higher levels of coverage due to increased risk reduction behaviors (Botzen et al., 2009), which may also reduce post-disaster risk associated with structural failures or environmental contaminants.

High premiums signal there is a large amount of uncertainty, or that more risk management techniques by at-risk parties are needed (Höppe and Gurenko, 2006). Individual adaptation or societal mitigation can lead to decreased risk and cost savings for society (Ferguson, 2008; Young and Schwartz, 2014; Michel-Kerjan and Kunreuther, 2011; Aerts and Botzen, 2011). For example, in a hard-market scenario, where events lead to higher premiums and full adaptation, annual premium costs were projected to decrease to $5-6 billion after adaptation compared to $10-14 billion with existing building status in Florida (Young and Schwartz, 2014). More proactive engagement of risk management is a valuable investment that builds resilience and ultimately reduces insured losses (Jaffee et al., 2008). However, the cost of risk reduction may offset the effectiveness of risk-based pricing (Surminski, 2016) as those most vulnerable to risks may not be able to afford risk-based premiums or have the means to reduce their risk. This equity-efficiency tradeoff (Picard, 2008) might be bridged through subsidies for risk-reduction measures, subsidized insurance, cost-effective technology, or a guaranteed reduction in premiums to offset the initial or recurring costs of adaptation and mitigation efforts (Botzen et al., 2009; Surminski, 2016).

But empirical studies show that people do not voluntarily invest in adaptation measures even when they are cost effective (Kunreuther et al., 2011, Bouwer et al., 2007). The theory of moral hazard suggests that those with a risk sharing mechanism such as insurance may be more likely to engage in risky behavior due to the protection provided by that risk sharing mechanism (Hölmstrom, 1979). However, Hudson et al. (2017) found that in some catastrophe insurance markets moral hazard is not present, due likely to the internal characteristics of individual policyholders and the low-probability/high-impact nature of catastrophe events. Strong market pressure and marketable solutions, such as catastrophe bonds that transfer peak risks to capital markets, are proven incentives to adopt adaptation measures (Michel-Kerjan and Kunreuther, 2011). Multi-year contracts could also make the benefits of adaptation clearer, as the probability of a disaster during the time frame would be higher (Dlugolecki and Hoekstra, 2006; Kunreuther et al., 2011; Michel-Kerjan and Kunreuther, 2011). Incentives that both limit damage and reduce the probability of natural catastrophes have been the most effective way to reduce extreme costs (Aerts et al., 2008).

Premiums reflect the direct demand and supply of insurance policies between customers and the insurance industry (Surminski et al., 2016). High premiums signal limited coverage availability, or low supply, due to high uncertainty or risk. These high premiums decrease the demand for coverage as many cannot afford it. Subsidizing premiums allows for more affordable premiums but ultimately fails to reduce risk and reduces the effectiveness of feedback between insurer and insured. While climate insurance can enhance resilience by providing post-disaster liquidity (World Bank, 2012), this requires affordable coverage. Lowering premiums to reward mitigation and adaptation behavior can help bridge the gap between higher premiums and affordable coverage for policyholders (reflecting reduced risk of loss and greater certainty, resulting in lower premiums).

Non-Coverage Feedbacks

Inaction is a major factor contributing to negative economic impacts from climate change (Tucker, 1997). The undesired result of inaction is non-coverage, consisting of two subtypes: (1) insurance premiums do not reflect true risk, leading insurers to not offer a policy and (2) premiums are allowed to reflect true risk, but the premiums and deductibles (out-of-pocket costs for a claim) are too costly for the consumer to purchase the policy (Kunreuther et al., 2013; Botzen et al., 2009; Tucker, 1997). Non-coverage occurs when the insurance supply is low and premiums are high (Surminski, 2016). Non-coverage is a deterrent to compounding harmful behaviors related to climate change such as rebuilding in catastrophe zones and failing to improve preparation or response to catastrophes (Mills, 2005; Aerts and Botzen, 2011; Tucker, 1997). Non-coverage also pressures public organizations to assume more climate risks, which may lead to more federal debt. When the National Flood Insurance Program (NFIP) insured damages from Hurricanes Katrina, Rita, and Sandy, the NFIP incurred $24 billion in debt from these hurricanes alone (Kunreuther et al., 2013; Kunreuther and Michel-Kerjan, 2007). Other examples include hurricane protection in Florida, earthquake protection in California, and the crop insurance system in the United States (Kousky and Kunreuther, 2017).

Risk financing comes from a variety of sources (Fig. 3.3). The primary source is the party itself through a deductible (where losses are paid through savings or working capital) for events that are below a threshold of cost and are usually frequent and not severe. Insurance protects against events that are somewhat frequent and severe enough that equity alone cannot cover the losses. Reinsurance, state-aid, and tort law cover rare events that have high financial impacts which an insurance company's equity alone cannot cover. These methods transfer risks from an insurer to a third-party, protecting them in the case of a catastrophic event. Tort law is rare but may increase in the future if significant disagreements over liability continue.

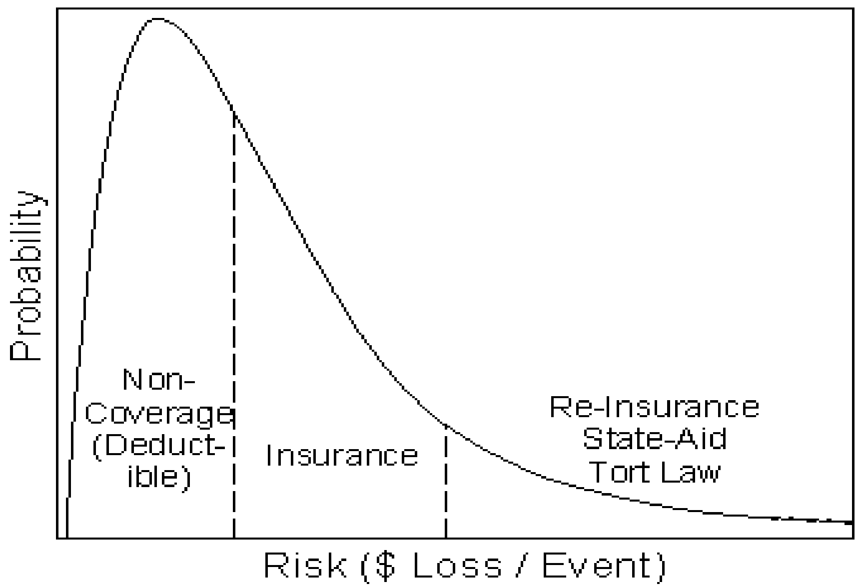

Figure 3.3 Financing climatic loss at different levels of risk.

Events leading up to non-coverage and the effects of non-coverage can be seen in the Saint Bernard Parish district of New Orleans after Hurricane Katrina (Ferguson, 2008). Total insured losses of at least $41 billion occurred; the risk to insure parts of New Orleans is extremely high and lack of understanding of these risks also plays a part in keeping premiums too high to afford (King, 2008). Contrasting interpretations of significant natural catastrophe risk, due to differences in assumptions and design of catastrophe models and minimal understanding of catastrophes, can lead to a large amount of uncertainty (King, 2008). Many insurance agencies chose not to provide coverage in New Orleans as a result; a similar situation could occur in other places as more extreme events occur and flood plain maps are redrawn. The probability of non-coverage will be reduced with mutual adaptation and communication as well as increased understanding of the impacts of climate change.

Policymaking and Litigation Feedbacks

The insurance industry has a role in influencing public policy (McCormick, 2018; Kunreuther, 2013; Attali 2006; Kleindorfer and Kunreuther, 1999). Government policies affect the industry directly by exempting parties from liability, subsidizing insurance deductibles or premiums, engaging in reinsurance, or providing coverage that competes with private sector insurance (Mills, 2005). The role of government has decreased over the last 20 years as insurance coverage of natural disaster relief has increased from 20% to 40% in developed countries (Kunreuther and Michel-Kerjan, 2007). While developed economies have a buffer from widespread loss, the ability of this buffer to protect nations from crippling loss effects is dwindling as the rate and severity of natural disasters increases (Kunreuther et al., 2013; Kunreuther and Michel-Kerjan, 2007). As the need for more effective relief becomes apparent, many governments are using insurance to provide a reliable system for their citizens (Kunreuther et al., 2013; Kunreuther and Michel-Kerjan, 2007; Tucker, 1997). The insurance industry interacts with the public sector in providing protection against risks, although there is always disagreement over the allocations of costs (Mills, 2005). The lack of cohesion in the response to Hurricane Katrina is one example of non-optimized risk allocation that resulted in $109 billion in post-disaster assistance and $8 billion in tax relief provided by the government (McCoppin, 2014). For insurance and government to be more efficient and effective at disaster adaptation, mitigation, and relief, there must be more highly coordinated policy. Due to the immense costs from climate change, significant disagreements over the distribution of costs between the two sectors are not in the best interests of either party (Piketty, 2014).

Litigation from insurance to government has been the result of ineffective policy or failure to reasonably foresee and adapt to the impacts of climate change. In 2013, The Farmers Insurance Co. sued the city of Chicago, Illinois for damages caused by storm water and sewage overflow because local municipalities knew that the drainage systems were inadequate but failed to take reasonable action to prevent damages (Sullivan, 2014). The suit was eventually withdrawn, stating that the important issues were brought to the attention of the respective cities and counties and with the hope that policyholders' interests will be protected in the future (Sullivan, 2014). As climate change impacts are further researched and understanding grows, more government entities and businesses may be held responsible via similar lawsuits for damages caused by climate change if proactive action is not taken to increase system resiliency (Sullivan, 2014; Sustainable Brands, 2017).

Coordination of efforts between government and insurers is crucial in developing a strong plan to provide affordable, adequate insurance coverage in the face of increasing risk from climate change (Glaas et al., 2016). Collaboration of building codes and standards, sharing of data, and better communication are all examples of action that can provide the knowledge and means necessary for policy-holders to adopt mitigation and adaptation measures and allow insurers to offer rewards or lower premiums for these measures. These actions can also provide direct feedback between the public, the government, and private insurers on how best to reduce risk and decrease costs for all stakeholders involved.

CONCLUSIONS

The first step towards reduction of society's contribution to climate change is understanding the state of emissions today. A comprehensive GHG emissions inventory is necessary to understand where mitigation efforts could have the greatest impact and future inventories will allow maintenance and adjustment of these strategies as needed. Agriculture and electric power were found to be the two largest sectors of emissions in Nebraska and any plans to reduce GHG emissions in Nebraska should prioritize these categories, with specific attention to beef cattle and coal. Nebraska may yet be an important example for the U.S. and the world that significant reductions of GHG emissions are possible, if the state's population accepts its responsibility to address climate change and acts accordingly.

Agricultural GHG emissions are an important aspect of comprehensive GHG emissions inventories, particularly in an agricultural region such as the Midwest U.S. region. Comparing agricultural GHG emissions between states provides more detailed inventories as well as identifying GHG emissions sources that could be reduced more effectively within the agricultural landscape of a state, rather than regionally or countrywide. The agricultural industry is crucial for many economies in the Midwest and emissions reduction strategies should seek to reduce the impact on agriculture as much as possible when changes are considered. More detailed and comprehensive GHG emissions inventories can pinpoint where GHG emissions reduction strategies would be most impactful on emissions and least impactful on the profitability of industry. Livestock, particularly beef, is a high intensity source of emissions in the agricultural sector and states that rely on livestock for their agricultural economies should focus on ways to reduce this impact, such as technological advancements (e.g. methane capture), feed or lifestyle changes, and diversification of agricultural products. Future GHG emissions inventories should consider a focus on incorporating more interactions and more state-specific data to better inform research, development, and policy.

Increased losses from climatic catastrophes will challenge insurance systems to adapt and offer affordable coverage (Botzen, 2013). Risk financing systems, including insurance, will need to be cautious of downside risks that can cause disincentives, market failures, and decrease equity (Botzen, 2013). Market-based insurance and its associated feedbacks are not a panacea, should not be expected to work well in all circumstances, and may even produce negative outcomes. Like all firms, insurance companies are vulnerable to agency problems and conflicts of interest that may interfere with the effectiveness of the sector (Jensen and Meckling 1976). While mechanisms exist within firms to reduce such conflicts, they are imperfect and sometimes the social costs of a firm's actions outweigh the benefits. In addition, there are numerous contexts in which insurance markets simply fail to form despite the fact there are real human needs or problems to be addressed. The failure to form can arise from problems such as adverse selection (Rothschild and Stiglitz, 1976), moral hazard (Smith and Stutzer, 1995), or even a lack of perceived risks on the part of the public. In the absence of market-based insurance, the feedback mechanisms described in this dissertation (excluding litigation) will fail to develop. In these instances, alternative mechanisms must be established, which may include mutual aid or cooperative insurance arrangements (Smith and Stutzer, 1995), public-private partnerships, or direct government intervention among many other novel solutions. In addition, the scale of insurance feedbacks affects their viability as a factor in adaptation and mitigation measures. Some risks need to be addressed on a larger than individual scale and the feedbacks discussed will be less effective without external forces and other factors than individuals can provide alone (USGCRP, 2018).

Through improved research, the interactions between the insurance industry and society can create more efficient and effective risk management strategies for public and private interests to address the challenges associated with climate change (Botzen 2013). Future avenues of research should include the complexity of these feedback loops and insurers' response to the discussed risk factors, including both climate and other risks. Specific interactions among these risks is not well understood and further empirical work on the dependencies of these risk factors is necessary. Another key challenge facing insurers is how to integrate climate change into their existing business models and including underwriting procedures that help to integrate these climate risks. Similarly, the dissertation did not look at specific methods for incentivizing risk reduction, and empirical analysis of the efficacy of practices on risk reduction will help to provide a more detailed understanding of which elements of the feedback processes work best. Encouraging proactive cooperation between private insurers and government can increase the probability that mitigation techniques and adaptation can align incentives to protect assets. The insurance industry will continue to be a forceful and systemic mechanism to drive adaption and mitigation to climate change impacts in the absence of, and alongside, effective government policies, but further research is needed to clarify these relationships. Insurance can serve as a market-based approach to climate change that exists alongside policy-based approaches, providing a diversity of approaches that can shore-up the weaknesses of policy-based approaches and provide new and potent avenues for climate change adaptation and mitigation.

It is the responsibility of society to ensure the sustainability of Earth's systems into the future. Inaction results in the disruption and restructuring of humans as a species as Earth's climates and systems change in a manner that even humanity cannot adapt to quickly enough (Alley et al., 2003). Reducing GHG emissions and concentrations in the atmosphere is the paramount challenge of today and requires all the knowledge, understanding, and effort that can be mustered. Climate change impacts all facets of society and all societal systems so there must be a collective effort to reduce our impacts to the environment and to help reduce the environment's impact on society. Research must be simultaneous with action from local and world leaders to realize solutions. All GHG emissions reductions allow more time to develop effective, sustainable, long term solutions to climate change. By incentivizing, developing, and funding each small step in addressing climate change, humanity may not only survive but thrive in a sustainable world.

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APPENDIX A: LIST OF ABBREVIATIONS

Name	Abbreviation
5-Day Biochemical Oxygen Demand	BOD_5
Carbon Calculation Tool	CCT
Carbon Dioxide	CO_2
Chemical Oxygen Demand	COD
Concentrated Animal Feeding Operation	CAFO
Database of State Incentives for Renewables and Efficiency	DSIRE
Department of Ecology State of Washington	DEWA
Department of Environmental Conservation Air Quality and Climate Division State of Vermont	DECV
Department of Environmental Protection State of Maine	DEPM
Department of Environmental Protection State of New Jersey	DEPNJ
Department of Environmental Quality State of Oregon	DEQO
Department of Transportation	DOT
Economic Research Service	ERS
Emissions Factor	EF
Energy Information Agency	EIA
Environmental Protection Agency	EPA
Federal Emergency Management Agency	FEMA
Federal Highway Administration	FHWA
Global Domestic Product	GDP
Global Warming Potential	GWP
Greenhouse gas	GHG
Heavy Duty Diesel Vehicles	HDDV
Heavy Duty Gas Vehicles	HDGV
High-Level Commission on Carbon Prices	HLCCP
Hydrofluorocarbons	HFC
Insurance Information Institute	III
Intergovernmental Panel on Climate Change	IPCC
International Energy Agency	IEA
Land Use, Land Use Change, and Forestry	LULUCF
Light Duty Diesel Vehicles	LDDV
Light Duty Gas Vehicles	LDGV
Liquified Petroleum Gas	LPG
Methane	CH_4
Methane Conversion Factor	MCF
Metric tons of carbon dioxide equivalent	$MtCO_2e$
Million metric tons of carbon dioxide equivalent	$MMtCO_2e$
Motorcycles	MC
Municipal Solid Waste	MSW

National Agricultural Statistics Service	NASS
National Flood Insurance Program	NFIP
Natural Gas	NG
Nebraska Department of Agriculture	NDA
Nebraska Energy Office	NEO
Nitrous Oxide	N_2O
Organization for Economic Co-operation and Development	OECD
Ozone Depleting Substance	ODS
Perfluorocarbons	PFC
Residential, Commercial, and Industrial	RCI
State Greenhouse Gas Inventory Tool	SIT
Sulfur Hexafluoride	SF_6
Transmission and Distribution	T&D
United Nations Environment Programme	UNEP
United States Department of Agriculture	USDA
United States Global Change Research Program	USGCRP
Vehicle Miles Traveled	VMT
Volatile Solids	VS
World Economic Forum	WEF
World Resources Institute	WRI