Resilient Agroecosystems: Reducing Greenhouse Gas Emissions in Beef and Ethanol Production Amidst Climate Change

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Abstract

The agricultural sector is a significant contributor to climate change, accounting for around 20 to 25% of global greenhouse gas (GHG) emissions–including methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). This literature review investigates selective breeding, optimized cattle diets, methane capture, and agrivoltaics. Selective breeding works to produce low-emitting cattle using recent technology in genetics without compromising productivity. Dietary additives such as red seaweed, oils, and fats also can reduce CH_4 emissions by up to 82%. Another viable method involves adopting bioenergy technologies through the use of a CH_4 capture system using anaerobic digesters, which convert waste into biogas energy. Similarly, agrivoltaics is a burgeoning area of research with rapidly evolving technology and policy that supports global food and energy security. We also discuss precision agriculture as an innovative strategy to mitigate ethanol production emissions by integrating Geographic Information Systems (GIS), remote sensing technologies, robotics automation, and GPS field mapping for efficient fertilizer application and crop monitoring. Moreover, the implications of cellulosic ethanol include using leftover corn stover, chemical pretreatments, and enzymatic hydrolysis to enhance ethanol yields while minimizing waste. We examine the production systems' environmental impact and current mitigation strategies–aligning with United Nations (UN) Sustainable Development Goals (SDGs) such as Affordable and Clean Energy (7), Responsible Consumption and Production (12), Climate Action (13), Life on Land (15), and Partnership among Stakeholders (17). Our study integrates USDA National Institute of Food and Agriculture (NIFA) Topics, including Environment, Farming and Ranching, Animals, Advanced Technology, Plants, Business and Economics, and Natural Resources. Our findings emphasize the need for continued innovation and policy support engagement to achieve a more sustainable agricultural industry. In addition, this research contributes to the broader understanding of how integrated approaches in agriculture can lead to significant environmental benefits and co-benefits among sectors of the Water-Energy-Food (WEF) Nexus. Policy support from the Bioenergy Technologies Office (BETO), Farm Bill, Inflation Reduction Act (IRA), as well as Renewable Energy Certificates (RECs), and carbon credits are just a few of the programs that help fund research and implement solutions.

Introduction

The Greenhouse Effect is one of the leading atmospheric phenomena responsible for global warming amidst climate change; however, this naturally occurring process of trapping heat within the atmosphere is essential to maintain a relative surface temperature of 15°C to support life on Earth (NASA, 2024). Issues arise when certain GHGs–including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) continue to be heavily emitted via anthropogenic activities at unprecedented levels that have consequently expedited and exacerbated the effects of climate change. Since the mid-19th century, average global temperatures have risen by 1.0°C and are projected to increase by at least 2.8°C by the year 2050 without climate action (Lindsey & Dahlman, 2023). For projected global temperatures and carbon emissions, see *Figure 1* in the Appendix. In 2015, 196 international parties signed the Paris Agreement to limit global warming to a 1.5°C temperature increase in alignment with the United Nations (UN) Sustainable Development Goals (SDGs) for Clean Energy (7), Responsible Production (12), Climate Action (13), Improved Life on Land (15), and International Partnership (17). The Paris Agreement mandates minimizing economic and social losses, increasing capacity and technology, and furthering education and awareness in relation to climate change (UNCC, n.d.). To accomplish these goals, we must significantly reduce anthropogenic GHG emissions and promote cleaner, more sustainable solutions in each major economic sector: transportation, electricity, industry, commercial, residential, and agriculture. According to the Environmental Protection Agency (EPA), agriculture–alongside forestry–contributed about 22% of global GHG emissions in 2019. However, such statistics do not account for agriculture's carbon sequestration potential through the soil and retention of GHGs with proper regenerative strategies. Therefore, the scope of our study includes the importance of maintaining healthy, resilient agroecosystems affected byclimate change. Through scientific discussion, significant strides toward international and national emission reduction goals can be made.

This paper will cover some of the primary sources of and solutions to GHG emissions pertaining to the beef cattle and corn-sourced bioethanol industries, such as cattle diet, feed production, manure management, meat processing, corn cultivation, and energy usage. We hope to propose practical solutions that promote sustainable animal production management, optimize corn cultivation and harvest, and encourage the widespread adoption of cleaner, renewable energy like solar and bioenergy. At the federal level, these solutions are connected to various USDA NIFA Topics including Bioenergy, Biotechnology, Climate Change, Sustainable Agriculture, Natural Resources Economics, and Farmer Education. In addition, they promote discussion regarding the Paris Agreement subjects for adaptation and resilience, climate finance and technology, innovation, mitigation, and cooperative science. Most importantly, the study's implications extend beyond agriculture and into the energy and transportation sectors with the adoption of renewable energy and biofuels. Climate change is a complex, "wicked" problem, meaning it requires multi-faceted and scientifically informed thinking to solve. Without meaningful action and global collaboration, climate change will continue to threaten global supply chains, food security, water security, and agroecosystems critical to sustaining a human population of ten billion by 2050.

Problem Statement

Reducing CO_2, CH_4, N_2O, and other GHG emissions within agriculture and agroecosystems is essential to mitigate climate change and ensure a resilient, sustainable future. Analyzing sources of GHGs in beef and ethanol production, we evaluated science-based emission solutions–discussing practical, cost-effective management strategies for farmers and businesses to meet UN SDGs in renewable energy, responsible production, climate action, life on land, and partnership; USDA National Institute in Food and Agriculture (NIFA) topics for advanced technology, animals, business and economics, environment, farming and ranching, natural resources, and plants; and Paris Agreement issues in adaptation and resilience, climate finance, climate technology, SDGs, land use, innovation, mitigation, and science.

Methods

In a non-systematic process, we reviewed literature on agroecosystems and climate change–emphasizing intersections with U.S. federal policy, beef cattle industry, renewable energy, bioenergy, and precision agriculture. We used databases such as Google Scholar, Journal Storage (JSTOR), Google, Gale, EBSCOHost, and Wiley Online Library. We reviewed 45 articles using keywords such as selective breeding of beef cattle, beef cattle diet, methane capture, and enteric fermentation. We used sources such as articles, journals, media, PDFs, and government reports. We used a fishbone diagram, flow charts, and force field analysis to organize our research and manage the time we had to complete our investigation. Each of these tools was used as an organization resource. They helped us to contain our thoughts and ideas and also plan out how we were going to complete our project. They also helped decide who would be completing what section.

Background

The relationship between beef cattle production, corn feeding practices, and ethanol production significantly impacts GHG emissions–especially CH_4, CO_2, and N_2O. Despite CO_2 being less potent per molecule than CH_4 and N_2O, CO_2's high concentration in the atmosphere makes it the most substantial GHG in terms of overall climate impact. With a global warming potential (GWP) approximately 25 times greater than CO_2 over 100 years, CH_4 emissions primarily originate from enteric fermentation in ruminant animals and the anaerobic decomposition of organic matter in manure management systems (IPCC, 2014). Although CH_4 has a shorter atmospheric lifespan than CO_2, its high GWP makes it a potent contributor to climate change. N_2O has a GWP nearly 300 times that of CO_2 and is primarily emitted through agricultural soil management practices, such as the application of synthetic and organic fertilizers, as well as the decomposition of crop residues. Additionally, soil microbial processes like nitrification and denitrification are impactful sources of N_2O emissions (Smith et al., 2003).

The beef cattle sector is a significant source of CH_4 emissions due to enteric fermentation. The digestive process of ruminants produces CH_4, which is then belched into the atmosphere. Each cow emits approximately 154–264 pounds of CH_4 per year during enteric fermentation, a process integral to their digestive system (Quinton, 2019). In the United States, beef production accounts for 3.7% of total agricultural GHG emissions. The life cycle annual GHG emission related to beef production and consumption in the U.S. is about 250 teragrams (Tg). Of this total, about 80% is related to producing cattle; within that about 58% is from enteric emissions, 23% is in feed production, and 7% is related to manure management (Clarence, 2023). Moreover, corn ethanol production, in addition to emitting N_2O, its production contributes to CH_4 emissions during the conversion process in biorefineries, or processing facilities.

Corn plays a dual role in GHG emissions. The interconnection between beef cattle production and corn ethanol production is primarily through the use of corn as cattle feed. In beef cattle production, corn-based diets influence CH_4 emissions due to their impact on digestive processes (Jaborek, 2022). The cultivation of corn involves considerable N_2O emissions due to fertilizer use. Moreover, the byproducts of corn ethanol production, such as distillers grains, are often used as feed for cattle, creating a full circle relationship between the two sectors (Liska et al., 2009).

In ethanol production, corn contributes to CO_2 emissions during fermentation and fuel combustion. While ethanol production aims to reduce overall fossil fuel dependence and mitigate CO_2-equivalent emissions compared to gasoline, the agricultural practices associated with corn production contribute to GHG emissions (Sarisky-Reed, 2022). Lifecycle assessments have shown that corn ethanol can reduce GHG emissions by about 20-50% compared to gasoline, but that depends on the production practices (Wang et al., 2015).

Recent studies have focused on quantifying and mitigating GHG emissions in beef and ethanol production systems. In terms of beef production, research highlights significant CH_4 emissions from enteric fermentation and manure management. These mitigation strategies include dietary supplements and manure management practices (Hristov et al., 2013). Ethanol production life cycle assessments of corn ethanol production emphasize the importance of reducing N_2O emissions. On the other hand, when it comes to ethanol production recent studies focus on fertilizer usage and improving energy efficiency in biorefineries. To make significant changes, advanced agricultural practices, and renewable energy integration are critical strategies (Wang et al., 2015). As a prominent global leader in both beef and ethanol production, the United States plays a pivotal role in pioneering these efforts. Educating producers on these methods ensures innovative and environmentally friendly practices are adopted.

Points of Emission

Enteric Fermentation

Enteric fermentation plays a crucial role as a natural part of the digestive process in ruminants and in methane emitted from beef cattle production. “Methane is produced when microbes digest food during a process called enteric fermentation inside the stomach or rumen. It is estimated that enteric fermentation accounts for nearly 30% of all anthropogenic methane emissions” (Climate & Clean Air Coalition, 2018). The diet of cattle, therefore, is one of the key contributors to GHG emissions. Cattle diet is mainly forages and legumes. “Cattle can lose between 2-12% of their energy intake to enteric fermentation because of the process of methane emission into the atmosphere” (Climate & Clean Air Coalition, 2018). There are many solutions to help with enteric fermentation, including optimizing cattle diet and availability. “Additives like oils and fats, red seaweed, and ionophores can reduce these methane emission levels from the very beginning of the process" (Alward, 2024). There are many other strategies to reduce methane emissions, like altering the environment of the rumen with a new diet.

Feed Production

Feed production is another major point of emissions for beef cattle production. Specifically, CO_2 and N_2O emissions from fertilizer use, pesticide application, and land use changes are ways CH_4 is emitted into the atmosphere. Interestingly, Amanda Garris states that "Methane pollution from ammonia fertilizer plants is 100 times higher than what the industry reports, and substantially above what the EPA estimates for all industrial processes in the United States" (Garris, 2019). These alarming statistics illustrate the importance of reducing such emissions to mitigate global warming. By 2030, the UN has a goal of ensuring sustainable consumption and production patterns. Their main target for this goal is to achieve sustainable management and efficient use of natural resources. To reach this goal, producers need to control the CH_4 emitted from their productions through solutions such as methane capture, selective breeding, and adjusting the diet of their cattle herd.

Methane Management

Livestock waste–and its derivative fertilizers–is the largest emitter of N_2O in agriculture (Chen, 2018). and about 16% of global agricultural emissions originate from livestock manure management. Generally, manure is removed from the bovine living area and into a slurry container. It is then separated into a solid pile and a lagoon. CH_4 originates from the anaerobic lagoon and slurry tank. Further, the corral and slurry produce significant amounts of N_2O. Because dairy cattle are raised on feedlots, they contribute more significantly to manure emissions than beef cattle (Owen et al., 2015). In New Zealand, 63% of N_2O emissions came from livestock excretion (Chen, 2018). Often, this manure is reused in organic fertilizers. During this process, the manure is processed, stored, transported, and then applied to a field. For organic fertilizers like this, the amount of emissions during use depends on the substrate used to produce it, the efficiency of the system, the soil type, and the soil management (Walling, 2020).

Meat Processing

115, 100, 38 and 65 Megatons (Mt) of pork, chicken, other animals, and cattle produced globally. The approximate GHG emissions from processing cattle are 4.6 Mt of CO_2, and 5.1 Mt from slaughtering. Cattle have the largest total and per capita amount of GHG emissions arising from the processing stage compared to other meat animals (Aan et al, 2017). Large amounts of energy are used in the beef packing industry. Pasteurization, sterilization, evaporation, and cooling are identified as the main processes in which this energy is used. Additionally, a significant amount of GHGs are emitted by the beef packaging industry. A study on energy efficiency in Australia measured the energy use of various processes in a beef packing plant. It found that the largest source of energy usage was refrigeration, followed by packaging (Li et al., 2018). Cattle slaughtering is estimated to consume 26% of the energy put into producing a pound of meat. In order to transport the beef for slaughter, the farmers must travel 120 miles three or four times a year. In addition, the beef must be stored with refrigeration throughout the whole process and while in stores (Mainville et al., 2005).

Corn Cultivation

Corn cultivation significantly contributes to GHG emissions from soil preparation and planting to soil management. Soil preparation, including plowing, tilling, and other mechanical disturbances, disrupts the soil structure. This disruption increases the oxidation of soil organic matter, releasing CO_2 into the atmosphere (Koushki et al., 2023). These activities are energy-intensive and typically powered by fossil fuels, further contributing to CO_2 emissions. The tillage process enhances microbial activity in the soil, leading to the production of N_2O. Tilling breaks down soil aggregates, which exposes organic matter to microbial decomposition, increasing the availability of nitrogen for microbial processes. This is conducive to the production of N_2O through nitrification and denitrification (Koushki et al., 2023). Emissions from these processes are a significant concern due to the high global warming potential of N_2O.

Planting is another early stage in corn cultivation that contributes to GHG emissions. The machinery used for planting seeds, often powered by diesel, emits CO_2. The operation of planting equipment, including seed drills and planters, requires considerable amounts of fuel, thus adding to the carbon footprint of the cultivation process (Koushki et al., 2023).

Fertilizer Application

It does not stop there for producing nitrogen, to meet the high demand, farmers rely heavily on nitrogen-based fertilizers to enhance crop yields. Nitrogen is a critical nutrient for plant growth, influencing protein synthesis and energy metabolism in plants (Robertson & Vitousek, 2009). However, the intensive use of nitrogen fertilizers has significant environmental repercussions. Particularly concerning N_2O emissions from agricultural soils primarily arising from microbial processes, notably nitrification and denitrification. Nitrification is the aerobic conversion of ammonium (NH_4^+) to nitrate (NO_3^-), while denitrification is the anaerobic reduction of NO_3^- to nitrogen gases (N_2 and N_2O). The application of synthetic fertilizers significantly increases the availability of ammonium and nitrate in the soil, enhancing the rates of nitrification and denitrification (Snyder et al., 2009). Studies have shown that up to 1-2% of the applied nitrogen can be emitted as N_2O, depending on the type of fertilizer and soil management practices (IPCC, 2014).

Ethanol Production

When making ethanol, the first step is milling the starches into smaller pieces. Then, it undergoes a series of heating and cooling vats until it enters fermentation, during which an enzyme is added to the heated mixture. From this, ethanol is secreted and then distilled and molecularly sieved for a purer product. The remaining mixture enters a centrifuge to become distiller grains and corn oil either for feed or biodiesel (Renewable Fuels Association, n.d.). During fermentation, carbon dioxide is released, which is often captured and recycled in other products, like dry ice and soda. According to the Renewable Fuel Standard (RFA) 2.6 million tons of CO_2 from biorefineries were captured in 2023 for use in byproducts, yet only about 30% of dry mills do this. Therefore, encouraging and incorporating CO_2 capture technologies can offset emissions directly tied to ethanol production.

There are additional ethanol processing methods, such as wet versus dry milling and first-generation (starch), compared to second-generation (corn stover or cellulosic) sourced ethanol; each system varies in its GHG emissions. Dry mill production is the most common method due to being cost-effective for producers and efficient in producing ethanol.

Alternatively, wet mill refining treats the mixture with a diluted sulfuric acid solution to separate corn into starch, germ, fiber, and protein, which produces more byproducts, including citric acid, xanthan gum, and high fructose corn syrup; however, it requires additional treatment and drying, and ethanol yields may vary (Mosier & Ileleji, 2006). In *Table 2* and *Table 3* of the Appendix, carbon intensity is compared for wet mill, dry mill, corn-based ethanol, and cellulosic – or plant sugar-based – ethanol. The report concluded that emissions in biofuels have exceeded reduction goals set by the EPA and RFA. In addition, for carbon intensity by corn ethanol production and fuel type, dry mill's carbon intensity is lower compared to wet mill methods, with the least being dry mill biogas-powered ethanol refineries. On the other hand, cellulosic ethanol has lower emissions per spent energy compared to other first-generation sourced ethanol. (Unnasch & Parida, 2021).

In terms of GHG emissions, ethanol fuel production is the largest emitter throughout the lifecycle. According to past models, it also demonstrated the most reduction potential in a growing industry; from 2005 to 2015, US ethanol production rose from 3.9 to 14.8 billion gallons per year, yet estimates for life-cycle emissions continue to decline (*USDA Factsheet: Lifecycle Greenhouse Gas Emissions of Corn-Based Ethanol*, n.d.). For more, *Figure 4* compares the GHG balance of gasoline and corn ethanol. Despite concerns about rising demand associated with a rapidly growing population, the technological advancements being made within the industry depict an optimistic future for biofuels that can actively compete with fossil fuels to drive down emissions.

A study by the Office of Energy Efficiency and Renewable Energy found that from 2005 to 2019, corn ethanol emissions were reduced by 20% because of better management strategies in farming, fertilizer, and ethanol production (Sarisky-Reed, 2,022), yet more can be done holistically regarding ethanol production and energy use. A study by the USDA in Iowa, depicted in *Table 5*, found that most emissions originate from energy use in ethanol production that is largely sourced from natural gas; therefore, transitioning to renewable energy may help to lower emissions, such as through biogas (e.g., methane and carbon dioxide capture), photovoltaics (PV), and more.

In 2022, the EPA found that natural gas-powered corn ethanol refineries emitted about 21% less GHGs than gasoline in 2005 – as shown in *Figure 6* – thus reaffirming ethanol as a feasible solution to reduce GHGs in agriculture with the additional benefit of prospective improvements in production and land use ("A Life-Cycle Analysis of the Greenhouse Gas Emissions of Corn-Based Ethanol," 2017).

Within the scientific community, one pushback to the viability of ethanol biofuel as a solution to climate change concerns land use change (LUC), or the concept of converting carbon sinks like forests and precious farmlands into ethanol fields that compete with food supply. However, numerous studies show that LUC emissions are often not the best way to analyze emissions and play a much less significant role. A 2015 study demonstrated that increased ethanol demand resulted in less-than-expected land use changes. Instead, more intensive farming practices were introduced, and new technologies were introduced to raise supply (Babcock, 2015). It is also believed that LUC emission analyses underestimate reduction percentages originally given by the USDA (21%), with some journals instead estimating between 43 to 48% reductions compared to gasoline in 2005 (*Building the Evidence on Corn Ethanol's Greenhouse Gas Profile*, n.d., Eranki et al., 2019, & Lewandrowski et al., 2019). Rather, focusing on the adoption of best management practices and precision agriculture during corn production plus introducing new technologies, fuel sources, or processes in ethanol production may optimally reduce emissions not only in agriculture but also within the transportation and energy sectors globally. Furthermore, emerging ethanol production from corn stovers (leftovers) and cellulose could further reduce land competition between food and fuel production systems.

Solutions

Cattle Production

Selective Breeding

Researchers and scientists have been searching for ways to reduce CH_4 emissions for years: one solution that is slowly helping is selective breeding. Breeders have handpicked certain traits for hundreds of years, but now they have found out ways to selectively breed cattle for reduced CH_4 emission. "The study, published in the Journal of Dairy Science, shows that cows with low emission levels tend to be smaller and house different microbial communities, and these differences were not associated with reduced milk production or altered milk composition" (Wait, 2023). This knowledge allows farmers to breed cattle for low CH_4 emissions while still being able to have the efficiency of their herd that they had beforehand. Pitta, who works in the Center of Stewardship Agriculture and Food Security states that, "low CH_4 emitters are more efficient cows" (Wait, 2023). Selective breeding is a burgeoning area of research; some of the solutions that scientists are looking at relate to DNA and genetics. This is specifically done through the isolation of embryonic stem cells, which leads to ethical concerns. "With the use of iPSCs, gene editing can be performed using technologies such as the CRISPR/Cas9 tool to out the genes relevant to high CH_4 production. This enables a decrease in the CH_4 production of the animal" (Climate Alliance, n.d.). With policy-allocated funding and cooperative resources to help producers mitigate CH_4 emissions, selective breeding can promote a more sustainable future.

Cattle Diet

Cattle consume various types of grass–like hay, alfalfa, and silage–creating a globally significant amount of CH_4 through enteric fermentation. Forages like this take around two to three days to fully digest in the rumen of the stomach (Project Drawdown, 2022). Occasionally, producers will include feed and other additives to their cattle's diet if they are specifically growing them for meat production. Cattle produce energy from the food they digest, "but between 2-12% of that energy intake is lost to enteric fermentation because of the process of CH_4 emission into the atmosphere" (Climate & Clean Air Coalition, 2018). There are many solutions to help with enteric fermentation, including optimizing cattle diet and availability. Many different additives like “oils and fats, red seaweed, and ionophores can be fed in their diet to reduce the CH_4 emission levels from the very beginning of the process” (Alward, 2024). In fact, a little bit of red seaweed can go a long way in mitigating emissions. These additives can reduce as much as 82% of all CH_4 emissions from beef cattle. “There is considerable evidence suggesting that even the addition of limited fat and oil supplements–particularly polyunsaturated fats sourced from plants–to the diet of beef cows will also reduce the level of methane emissions from beef cattle’’ (Comerford, 2023). This means that you can improve your cattle herd’s productivity, the composition of the herd, and altering the microbial environment of the rumen, all while being able to lower the levels of CH_4 emitted.

Methane Capture

Livestock manure produces approximately 240 million metric tons of CH_4 globally. Although most of it arises from enteric fermentation, this CH_4 is difficult to capture, so it is not as feasible to find a mitigating solution for, thus putting it outside the scope of this investigation. Methane capture–which is a catch-all term to describe methods of preventing CH_4 from going into the atmosphere–has a diverse array of strategies, such as cryogenics, fungal catalyzation, and sorbents. In China, India, and Southeast Asia, anaerobic digesters are commonly used to turn CH_4 from a waste product of manure into bioenergy. This method is relatively accessible and can potentially generate revenue for large-scale producers. The product is created using a substrate to cause microbial reactions (Tauseef et al., 2013). Another strategy for CH_4 capture is using a sorbent to purify the gas, liquify it, and then collect it for energy. This technology has a higher energy yield than oxidizing the CH_4, making it more desirable (Kim et al., 2013). Using a type of fungus (*Ganoderma lucidum*) is another potential CH_4 capture strategy, as it effectively biodegrades hydrophobic compounds and helps microbes capture CH_4 more efficiently. *Ganoderma lucidum* has been shown to have a 79% removal efficiency relative to activated carbon (Liew et al., 2020). Sequestering CH_4 using coolant devices produces bioenergy with 99.3% purity. The gas is treated with temperatures that use boiling points to separate and liquefy the bioethanol fuel. This method is understudied but has the potential to be a viable method of methane capture (Pethani et al., 2024).

Agrivoltaics

Agrivoltaics play a crucial role in the Water-Energy-Food (WEF) Nexus by allowing the dual use of agroecosystems for energy and food security. A study by the National Renewable Energy Lab (NREL) highlighted additional benefits of agrivoltaics, which include higher crop yields, improved soil moisture retention, and increased Power Conversion Efficiency (PCE) due to plant-understory thermal regulation. In other words, planting around the PV panels is beneficial not only for plants and pollinators but also for farmers wishing to optimize their renewable energy yields (Benefits of Agrivoltaics across the Food-Energy-Water Nexus, n.d.). However, there are some limitations in terms of crop cultivation because of the shade it produces. Some plants are shade tolerant while others are not; for example, corn requires direct sunlight for at least six to eight hours (Kogut, 2023). In addition, the effect of PV on the soil microenvironment and carbon exchange is yet to be fully understood. Without a developed plant understory, the panels may also undergo a Heat Island Effect and contribute to thermal pollution via runoff into streams as the sun heats the PV panel surface. Therefore, combining plants with agrivoltaics in crop fields and pasture lands is essential to, not only to buffer such issues, but also to promote biodiversity and manage habitat for pollinator species in agroecosystems (Nuria Gomez-Casanovas et al., 2023). For cattle, agrivoltaics provide shade that increases herd productivity, yet it may also limit cattle grazing. A Canterbury study emphasized that more research is needed in order to inform the use of PV Best Management Practices (BMPs) in the beef industry–including potential effects on livestock behavior and raw product yields (Vaughan et al., 2019).

Ethanol Solutions

Emerging Technologies and Techniques

To reduce emissions in ethanol production, promising strategies include combined heat and power (cogeneration) systems–switching from natural gas (NG) to renewable natural gas (RNG) as well as carbon capture, utilization, and storage (CCUS) technology. Large-scale cogeneration systems use natural gas to not only provide heating and cooling, but also enough thermal energy to generate electricity for ethanol biorefineries–providing a cost-effective way to mitigate emissions. Furthermore, using renewable biomass energy sourced from residues like wood chips, corn stover, and manure can offset CH_4 emissions from natural gas. It is estimated that 1 megajoule (MJ) of natural gas is equivalent to 1.2 MJ of wood chips and manure RNG may result in a net negative of 100 kg of carbon dioxide-equivalent emissions per million British thermal units (MMBtu). In addition to this, ethanol refineries are located close to corn fields to save on transportation costs; corn stovers are also an accessible fuel source that provides further incentives for producers (Xu et al., 2022). One study found that a minimum of 60% RNGs with 40% NG may result in net zero emissions (GHG Analysis of Dry Mill for Corn Ethanol Production under IRA, 2022). Another solution is CCUS technology that captures and either recycles (CCU) or subterraneously stores carbon (CCS). However, CCS is generally limited by geography, and its seismic effects are not yet fully understood; therefore, CCU is more commonly used to produce carbon byproducts or to convert carbon dioxide into methanol for further production (Xu et al., 2022).

Bioenergy

Biomass and bioenergy reduce the carbon footprint of corn ethanol through various mechanisms. Biomass includes agricultural residues, such as corn stover (the leaves, stalks, and cobs left after harvesting corn), which present an opportunity to reduce waste and provide additional energy sources without cultivating more agricultural land. This approach minimizes land-use changes, which are a significant contributor to GHG emissions (Xu et al., 2022). By converting these residues into bioenergy, the ethanol production process can decrease its reliance on fossil fuels, therefore reducing overall GHG emissions. Utilizing these residues effectively closes the loop on waste, transforming what was once a byproduct into a valuable resource. Making bioenergy produced from biomass a renewable energy source that can replace fossil fuels in the energy sector. For example, biomass can generate heat and power for ethanol production processes, reducing dependence on fossil fuels and associated carbon emissions, especially during the early stages of production (Searle & Malins, 2016). One of the significant advantages of biomass is it is considered a carbon-neutral source of energy since the release of carbon dioxide during combustion is equivalent to the carbon dioxide absorbed by plants during their lifecycle (Shahbaz et al., 2021). This balance contrasts with fossil fuels, which release stored carbon into the atmosphere, contributing to continuously increasing carbon emissions. Achieving carbon neutrality with biomass supports global efforts to mitigate climate change.

All in all, incorporating bioenergy shows significant GHG reductions by replacing fossil-based inputs and energy with biomass which decreases the overall carbon footprint of ethanol production (Wang et al., 2015).

Precision Agriculture

Precision agriculture optimizes inputs–such as nitrogen and phosphorus–using GIS and employing technologies– like drones and GPS field mapping– which leads to more efficient and environmentally friendly farming practices. To begin with, precision agriculture technologies, such as GIS and remote sensing with drones, help farmers apply fertilizers more efficiently, in turn reducing excess application. For instance, drones equipped with sensors can monitor crop health and soil conditions in real time, ensuring nutrient application where needed (Gebbers & Adamchuk, 2010). This approach not only improves nutrient use efficiency but also reduces the environmental impact of fertilizer runoff and emissions.

Moreover, satellite field mapping and robotics automation enhance the efficiency of farming operations, providing detailed spatial data on soil properties, crop growth, and yield variability, enabling farmers to make informed decisions about fertilizer application and irrigation (Zhang et al., 2002). Robotics automation, including autonomous tractors and sprayers, ensures that inputs are applied with high precision, reducing fuel consumption and associated carbon dioxide emissions from farming machinery.

In addition to fertilizer optimization, precision agriculture plays a crucial role in crop monitoring and management. Remote sensing technologies, such as drones and satellites, provide valuable data on crop health, growth stages, and stress factors, allowing for timely interventions (Mulla, 2013). For example, early detection of pest infestations or nutrient deficiencies can prompt targeted treatments, reducing the need for broad-spectrum pesticide or fertilizer applications. This not only enhances crop yield and quality, but also minimizes the environmental footprint of agricultural practices.

The benefits of precision agriculture extend to harvesting corn for ethanol production. Harvesting machinery, powered by fossil fuels, is a significant source of carbon dioxide emissions. Precision agriculture technologies, such as GPS-guided harvesters and logistics planning tools, optimize harvest routes and schedules, reducing fuel consumption and emissions (Bongiovanni & Lowenberg-Deboer, 2004). Additionally, by improving crop yield and quality through optimized inputs and management, precision agriculture reduces the need for multiple harvests, further minimizing the carbon footprint.

Funding

Fortunately, there are numerous policy pathways for large-scale project funding using Renewable Energy Certificates (RECs), carbon credits, and direct funding from the Department of Energy’s (DOE) Bioenergy Technologies Office (BETO). RECs obtained from on-site generation can be sold or auctioned to utilities that want to develop their renewable energy portfolios for profit. In addition, measures taken to reduce GHGs can earn producers carbon credits that can be similarly sold. Lastly, BETO is an agency dedicated to funding research and development aimed toward sustainable biomass energy generation and biorefinery production, which include many of the technologies and solutions previously mentioned.

Cellulosic Ethanol

For example, starch ethanol production can be complemented by an emerging production tactic called cellulosic ethanol. Doing so may reduce waste, increase ethanol yields, and lower net emissions. Cellulosic ethanol relies on chemical pretreatments of crops and energy-intensive hydrolysis so that corn stover and other biomass can be further processed in the biorefineries to ferment (Maktabifard et al., 2023). It is generally considered more environmentally friendly compared to starch ethanol emissions; however, more research is needed to stabilize yields and GHG reductions after a study in China found such results to vary based on numerous environmental factors (Zhao et al., 2016; Aghaei et al., 2022). One such reason is that harvesting corn stover reduces available organic matter, thereby disturbing soil composition and its ability to sequester carbon. Agriculture BMPs, such as covering cropping and limited tillage, can offset soil disturbances–making cellulosic, corn-stover-sourced ethanol a more viable solution (Qin et al., 2018).

Finding a Policy Pathway to Fund Ethanol Solutions and Combat Externalities
Renewable energy and environmental justice are two priorities of the Biden-Harris Administration (The White House, n.d.). Signed in 2022–the Inflation Reduction Act (IRA) allocated $350 million to promote climate change resiliency and reduce GHG emissions in the US; this is the largest piece of US legislation for grants for climate change mitigation, technical assistance, renewable energy, sustainable infrastructure, and more (Inflation Reduction Act of 2022, 2022).

The 2024 Farm Bill, signed in 2023, creates several grant and loan programs to help implement solutions for climate-resilient agroecosystems. Bioenergy will benefit from the direct and guaranteed loan program, as well as the microloan program for equipment, reducing the high initial cost of biogas and ethanol production. Low-interest loans for women and minorities in agriculture can help improve energy independence and environmental justice in the sector. The outreach and assistance program for elderly farmers provides an opportunity to spread awareness about biogas technology and management practices, like cover cropping. The revenue protection for diversified farms can also be a way for ethanol producers to increase cover cropping. The most significant programs for biogas production are the Rural Energy for America Programs and the Biomass Crop Assistance Program. The rural energy program provides grants and loans for bioenergy producers, and the crop assistance program covers 50% of the cost of establishing the crop, and incentive money for producers (National Sustainable Agriculture Coalition, n.d.). Much of the financial support from these programs can help farmers implement practices that may not be profitable due to high fixed costs.

The EPA and USDA administers a program, AgSTAR, for livestock manure biogas production. AgSTAR purchases and implements anaerobic digesters based on the predicted benefits and risks of the project. These projects generally have a good capacity for generating profit (United States Environmental Protection Agency, 2023). However, according to the USDA, initial design, installation, limited capital, and low buy-back rates are the main roadblocks that farmers experience financially when operating a methane capture business. Indeed, whether or not the business is profitable or not highly depends on the farm. For example, the installation cost for a five-hundred dairy cow farm in California was $203,800, and the total costs over eight years from maintenance were $324,968. Meanwhile, the total income was $692,900. In order for biogas to be economically feasible, the dairy must have at least five hundred cows. Otherwise, smaller operations are unlikely to be profitable. Moreover, fixed costs are not the only significant cost that biogas producers face; biogas production requires staffing for the maintenance of the facility, and producers need an air and water pollution permit from the local water board and air district (Krich et al., 1994; Van Dyne et al., 1994).

Many pathways exist; among them is the practice of Cooperative Extension. Land-grant universities, established and funded through the Second Morrill Acts of 1862 and 1890, help communities through research and teaching. (Lawrence, 2022). Existing legislation regarding ethanol production exists through the recent Farm Bill, which subsidizes corn ethanol through resale and imposes a quota. There are several potential economic effects of this bill: the supply of ethanol will increase, which will cause the price to go down, and profit to increase for producers, assuming the resale price is competitive. However, the quota to be imposed by the USDA could increase the price of the relevant bioenergy. (Further Continuing Appropriations and Other Extensions Act, 2024).

Conclusion

Meeting emission reduction goals requires capitalizing on rapidly emerging technologies such as large-scale renewable energy, precision GIS tools, anaerobic digesters in biorefineries, feed production, manure management, and more. Over time, continued research will give rise to improvements that drive down costs and open accessible markets to producers. In addition, transitioning to renewable energy with agrivoltaics and renewable natural gas decreases fossil fuel dependency and promotes energy resilience. Agrivoltaics also allows for multiple land uses between food and energy generation, alongside notable benefits for plants and livestock. On the other hand, renewable natural gas from biomass and GHG emission capture systems can supplement fossil fuel consumption by ethanol biorefineries. To address emissions by enteric fermentation, incorporating certain feed like red seaweed and natural oils into their diet is a method for farmers to lower CH_4 emissions without compromising product quality and quantity.

To make these solutions practical within each industry, funding through the IRA and other organizations, like BETO, provides financial aid to producers. Producers may seek out RECs and carbon credits to profit from climate initiatives as further incentives for funding projects and shifting away from traditional farming practices; producers may seek out RECs and carbon credits in order to profit from climate initiatives. However, enacting these changes relies on public engagement and discussion within the scientific community to educate and help facilitate the process for producers. Others can get involved by reaching out to lawmakers and representatives, supporting nonprofits, and working alongside extension cooperatives. Climate change may not be solved within the next decade, but with these solutions, we can strive for a brighter future.

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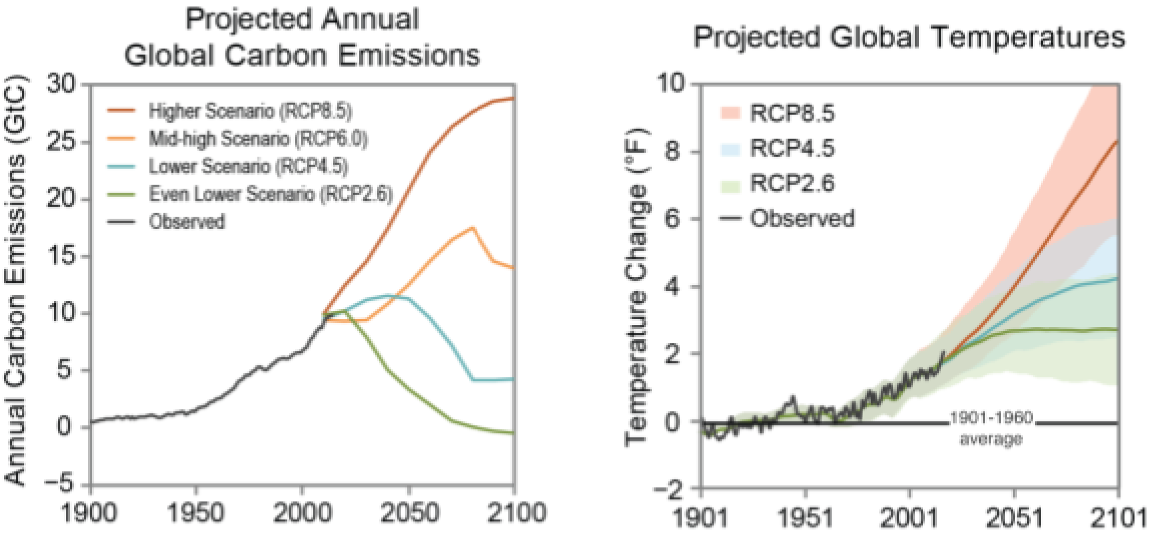
Appendix

Figure 1

Projected Annual Global Carbon Emissions and Average Global Temperatures

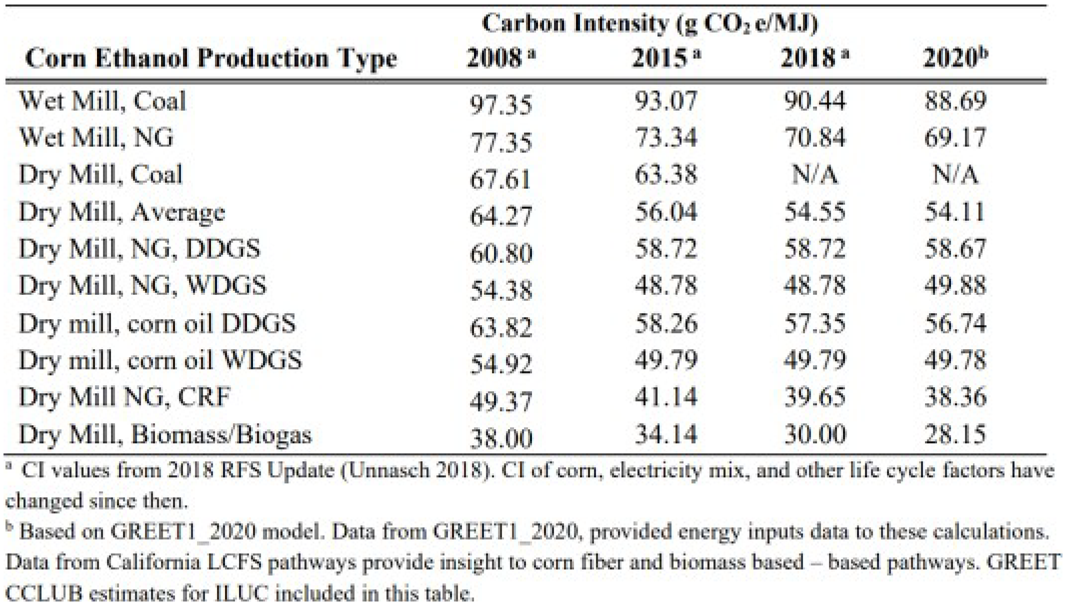


2017 Climate Science Special Report, Figure ES-3

(**left**) Historical and predicted trends for annual CO2 emissions (**right**) Projected ranges of temperature increase based on 1901-1960 average. Graphs by Katharine Hayhoe, from *2017 Climate Science Special Report* by the U.S. Global Change Research Program.

Table 2

Carbon Intensity by Corn Ethanol Production Type



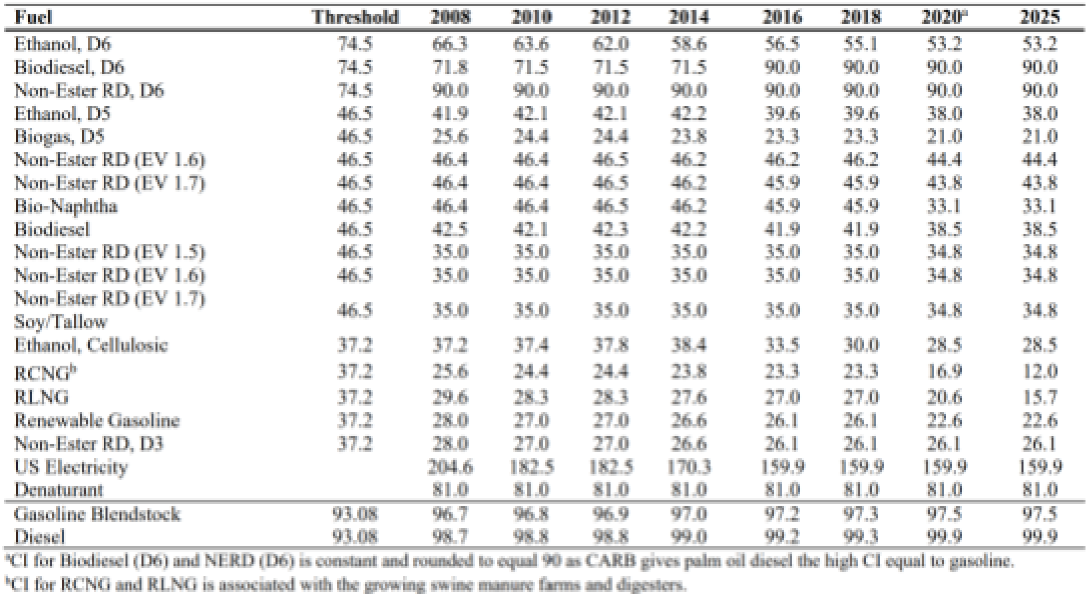
	Carbon Intensity (g CO_2 e/MJ)			
Corn Ethanol Production Type	**2008** [a]	**2015** [a]	**2018** [a]	**2020** [b]
Wet Mill, Coal	97.35	93.07	90.44	88.69
Wet Mill, NG	77.35	73.34	70.84	69.17
Dry Mill, Coal	67.61	63.38	N/A	N/A
Dry Mill, Average	64.27	56.04	54.55	54.11
Dry Mill, NG, DDGS	60.80	58.72	58.72	58.67
Dry Mill, NG, WDGS	54.38	48.78	48.78	49.88
Dry mill, corn oil DDGS	63.82	58.26	57.35	56.74
Dry mill, corn oil WDGS	54.92	49.79	49.79	49.78
Dry Mill NG, CRF	49.37	41.14	39.65	38.36
Dry Mill, Biomass/Biogas	38.00	34.14	30.00	28.15

[a] CI values from 2018 RFS Update (Unnasch 2018). CI of corn, electricity mix, and other life cycle factors have changed since then.

[b] Based on GREET1_2020 model. Data from GREET1_2020, provided energy inputs data to these calculations. Data from California LCFS pathways provide insight to corn fiber and biomass based – based pathways. GREET CCLUB estimates for ILUC included in this table.

Table 3

Carbon Intensity Estimates and GHG Reduction Thresholds by Fuel Type



Fuel	Threshold	2008	2010	2012	2014	2016	2018	2020[a]	2025
Ethanol, D6	74.5	66.3	63.6	62.0	58.6	56.5	55.1	53.2	53.2
Biodiesel, D6	74.5	71.8	71.5	71.5	71.5	90.0	90.0	90.0	90.0
Non-Ester RD, D6	74.5	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
Ethanol, D5	46.5	41.9	42.1	42.1	42.2	39.6	39.6	38.0	38.0
Biogas, D5	46.5	25.6	24.4	24.4	23.8	23.3	23.3	21.0	21.0
Non-Ester RD (EV 1.6)	46.5	46.4	46.4	46.5	46.2	46.2	46.2	44.4	44.4
Non-Ester RD (EV 1.7)	46.5	46.4	46.4	46.5	46.2	45.9	45.9	43.8	43.8
Bio-Naphtha	46.5	46.4	46.4	46.5	46.2	45.9	45.9	33.1	33.1
Biodiesel	46.5	42.5	42.1	42.3	42.2	41.9	41.9	38.5	38.5
Non-Ester RD (EV 1.5)	46.5	35.0	35.0	35.0	35.0	35.0	35.0	34.8	34.8
Non-Ester RD (EV 1.6)	46.5	35.0	35.0	35.0	35.0	35.0	35.0	34.8	34.8
Non-Ester RD (EV 1.7) Soy/Tallow	46.5	35.0	35.0	35.0	35.0	35.0	35.0	34.8	34.8
Ethanol, Cellulosic	37.2	37.2	37.4	37.8	38.4	33.5	30.0	28.5	28.5
RCNG[b]	37.2	25.6	24.4	24.4	23.8	23.3	23.3	16.9	12.0
RLNG	37.2	29.6	28.3	28.3	27.6	27.0	27.0	20.6	15.7
Renewable Gasoline	37.2	28.0	27.0	27.0	26.6	26.1	26.1	22.6	22.6
Non-Ester RD, D3	37.2	28.0	27.0	27.0	26.6	26.1	26.1	26.1	26.1
US Electricity		204.6	182.5	182.5	170.3	159.9	159.9	159.9	159.9
Denaturant		81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0
Gasoline Blendstock	93.08	96.7	96.8	96.9	97.0	97.2	97.3	97.5	97.5
Diesel	93.08	98.7	98.8	98.8	99.0	99.2	99.3	99.9	99.9

[a] CI for Biodiesel (D6) and NERD (D6) is constant and rounded to equal 90 as CARB gives palm oil diesel the high CI equal to gasoline.

[b] CI for RCNG and RLNG is associated with the growing swine manure farms and digesters.

(**Top**) Carbon intensity of corn ethanol (**Bottom**) Carbon intensity estimates of all biofuels and RFS GHG Reduction Thresholds (g CO2e/MJ). Tables from *GHG Emissions Reductions due to the RFS2-A 2020 Update* by Life Cycle Associates

Figure 4

GHG Balance Comparison of Gasoline and Corn Ethanol

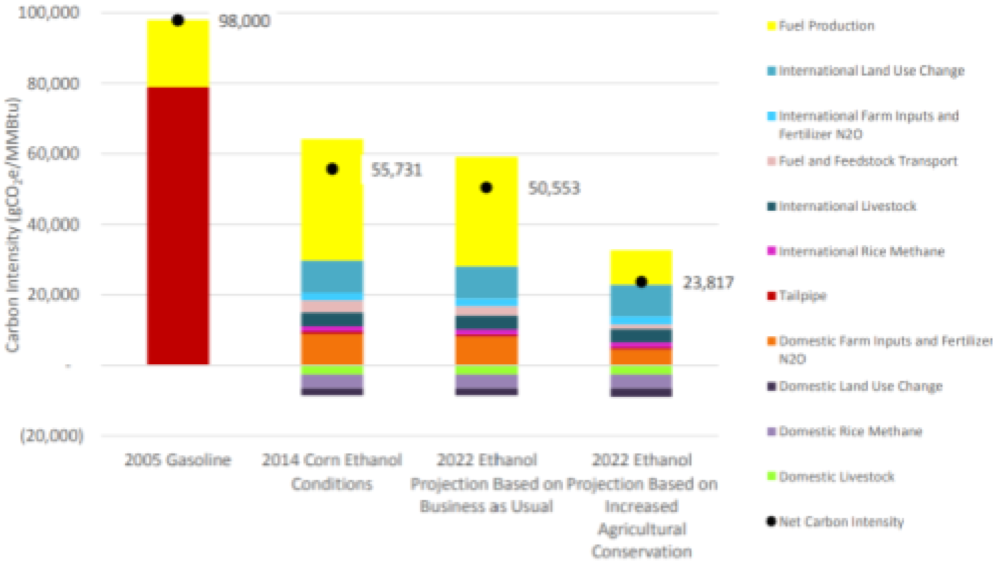
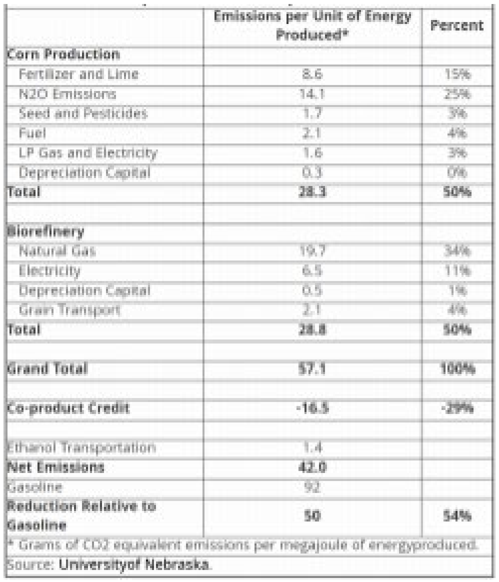


Chart of GHG balance of gasoline and corn ethanol. Graph from *USDA Factsheet: Lifecycle Greenhouse Gas Emissions of Corn-Based Ethanol*.

Table 5
GHG Emissions by Ethanol Production Sector



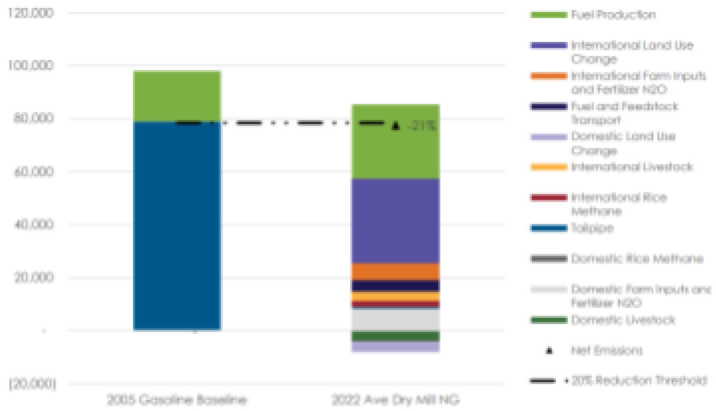
	Emissions per Unit of Energy Produced*	Percent
Corn Production		
Fertilizer and Lime	8.6	15%
N2O Emissions	14.1	25%
Seed and Pesticides	1.7	3%
Fuel	2.1	4%
LP Gas and Electricity	1.6	3%
Depreciation Capital	0.3	0%
Total	**28.3**	**50%**
Biorefinery		
Natural Gas	19.7	34%
Electricity	6.5	11%
Depreciation Capital	0.5	1%
Grain Transport	2.1	4%
Total	**28.8**	**50%**
Grand Total	**57.1**	**100%**
Co-product Credit	**-16.5**	**-29%**
Ethanol Transportation	1.4	
Net Emissions	**42.0**	
Gasoline	92	
Reduction Relative to Gasoline	**50**	**54%**

* Grams of CO2 equivalent emissions per megajoule of energyproduced.

Source: **Universityof Nebraska**.

Greenhouse Gas Emissions from Ethanol Production (Iowa natural gas biorefinery). Emissions expressed as CO2 equivalents. Table from *Greenhouse Gas Emissions of Corn Ethanol Production* by the University of Nebraska.

Figure 6
LCA of Ethanol Production Emissions



Life Cycle Analysis (LCA) emission factors relative contributions. from *A Life-Cycle Analysis of the Greenhouse Gas Emissions from Corn-Based Ethanol* by the IDF and USDA.