U.S. DEPARTMENT OF AGRICULTURE

Marginal Abatement Cost Curves for Greenhouse Gas Mitigation on U.S. Farms and Ranches

Marginal Abatement Cost Curves for Greenhouse Gas Mitigation on U.S. Farms and Ranches, Updated 2023

Executive Summary

This work provides estimates of the costs of greenhouse gas (GHG) mitigation that would occur on working U.S. farms and ranches for specific suites of technologies and practices. Understanding the costs and greenhouse gas benefits is important in helping U.S. farmers create new and expand existing market opportunities for agricultural commodities produced with "climate-smart" farming practices.

This report provides a valuable update to past studies the Office of the Chief Economist commissioned in 2013 and 2016. First, we have expanded the set of practices to include biochar amendments, alternate wetting-and-drying during rice production, cover crops, feed management strategies, enhanced efficiency fertilizers, and prescribed grazing. Second, we have updated cost and greenhouse gas reduction estimates for several practices included in past studies, like conservation tillage and manure management, based on more recent data.

The content is provided in a series of fact sheets. Each fact sheet describes the methodology and assumptions used by ICF International to develop the cost curves. Specifically, the fact sheets describe how they determined business-as-usual farming practices, the percentage of farms that would undertake mitigation practices, GHG mitigation estimates for climate-smart farming practices, cost functions for climate-smart practices, byproduct revenue if applicable (e.g., biogas sales from digesters), and, finally, the marginal abatement cost curves for that practice. Some of the fact sheets have several marginal abatement cost curves that reflect sensitivity analysis we performed with respect to certain parameters.

There are some limitations of these curves that readers should be cognizant of when interpreting them. First, the curves are static in the sense that they represent annual potential mitigation consistent with a given cost. However, the costs of "climate-smart practices" and the GHG mitigation from them can vary over time. Second, since we developed the curves on a practice-by-practice basis, they do not account for shifts in costs and GHG mitigation that would occur if a farm were to undertake multiple practices (i.e., cover crops and conservation tillage) at the same time.

Suggested Citations

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Chapter 1: Marginal Abatement Cost Curve Analysis–Biochar

Chapter 1 of 8.

Contents

Technology Overview

Biochar is a charcoal-like substance that is generated from the low-oxygen, high temperature combustion of biomass such as wood, nutshells, hulls, or manure (Spokas, 2020; Parikh et al., 2020). Biochar is primarily comprised of carbon in a range of black carbon chemical forms depending on how the feedstock is burned, cooled, and/or stored. The use of biochar goes back thousands of years as indigenous peoples of the Amazon basin produced biochar and mixed it into the soil to improve soil fertility and crop yields (Spokas, 2020). Today, biochar is used as a soil amendment to sequester carbon, improve soil health and moisture, raise soil pH, and remediate polluted soils (Neukrich, 2022). In 2018, the U.S. Biochar Industry estimated that approximately 45,000 tons of biochar are produced in the U.S. annually (Groot et al., 2018). This methodology document outlines the creation of a marginal abatement cost curve (MACC) that models the greenhouse gas mitigation potential and associated costs of large-scale biochar adoption in the U.S., and the results of that analysis.

To gain understanding of the current State of biochar application on U.S. cropland, the following elements were identified for in-depth research:

- State of the technology (e.g., U.S. research, development, deployment, and supply).
- Soil application impacts (e.g., biochar technology, cost, and impact on soil biochemistry).

Literature results were binned into the following three categories:

1. U.S. regional specific data
2. U.S. national level data
3. International data

It is also important to note that biochar application in soil has multiple beneficial impacts on the soil and local ecology. This MACC examines only the potential impacts on yield and greenhouse gas (GHG) emissions, but factors like environmental health should be considered as co-benefits when producers decide to apply biochar.

Greenhouse Gas Data

Data Collection and Analysis

Table 1. Data criteria for inclusion in MACC

Type of data	Included	Excluded
GHG emissions	• Quantitative • U.S.-specific estimates • Larger scale studies • Discussion of data limitations • Data limitation discussion	• Qualitative • International estimates • Small-scale/research project studies • Opaque or unscientific methods • More than 15 years old
Yield impacts	• Percent estimates based on U.S. national assumptions	• Qualitative discussions or theoretical ranges

- Performed a literature review of 24 scientific papers related to the impacts of biochar application on soils.
- Data in the papers were sorted for inclusion or exclusion based on the following characteristics (see table 1 for more details):
  - Qualitative or quantitative data
  - U.S. specificity
  - Discussion of data limitations
  - Research scale size (laboratory vs. regional or national scale)[1]
  - Measurement of biochar-specific GHG impacts
  - Quantitative or qualitative results of biochar application on yield
  - Publication date – reports more than 15 years old as of 2022 were excluded
  - Replicable analysis based on scientific data
- Papers that did not meet the inclusion criteria were used as background and comparative sources. Many also provided data for sections of the MACC other than GHG impacts, such as the impact of soil types, flooding systems in different parts of the U.S., and evidence to bolster the assumptions for this MACC analysis.
- Data from metanalyses were given extra weight as the limited availability for U.S. biochar application made individual studies less relevant to extrapolate conclusions into large scale conclusions. Whether the paper performed a meta-analysis of multiple papers or a specific experiment was for this reason an impactful criteria for consideration.

[1] Given the nascent State of this technology and its soil application, many studies were only focused on quantifying the process through which GHGs savings were happening, at a very small (often laboratory) scale. As the MACC project focuses on quantifying real life (i.e., large-scale) applications and resulting GHG savings, yield increase, and additional benefits from biochar application to soils, data from these small-scale studies were not included in the MACC.

- Economic, yield and carbon sequestration data were all obtained from Dokoohaki et al. (2019) a peer-reviewed meta-analysis of 40 biochar studies.
- Specifically, the following types of data were extracted:
  - Biochar application costs
  - Biochar yield impacts
  - Carbon sequestration rates of 0.24 MT CO_2e/acre
  - Biochar application rates of 15 mg per Ha.

Multiple peer-reviewed articles agreed on the high uncertainty that still surrounds the potential carbon sequestration resulting from biochar application in large scale operations, as the latter is still considered limited in the U.S., thus accurate and long-term observations and data are not at this time available to confirm the theoretical benefits of the technology, particularly with different soil properties and biochar sources (Dokoohaki et al., 2019).

The emissions reduction used in this analysis, 0.24 metric tons of CO_2e reduced per acre, focuses on the sequestration potential of the biochar itself. Future research may increase this reduction potential based on additive impacts of the biochar applications. Results from the literature search indicated that there are limited and conflicting impacts on both the large-scale application of biochar to soils and the long-term GHG impacts of biochar amendments to soil. For example, some studies found reduced N_2O emissions after biochar amendment (Amonette et al., 2021; Woolf et al., 2018) while other highlight the uncertainty and the potential increased emissions from biochar application (Dokoohaki et al., 2019). Meta-analysis of biochar studies indicates that overall, biochar application should lead to long-term decreases in N_2O emissions, but also note the difficulty in quantitating such estimates due to limited data and the complex, poorly understood interactions between biochar amendments and local environments, soil characteristics, and other factors.
This scope of this analysis is limited to the on-farm potential emissions reduction from biochar application, and therefore does not evaluate the emissions or costs from the biochar supply chain. The impact of carbon pricing mechanisms on biochar application are also only considered from the perspective of a producer who might apply biochar, but not a biochar producer or retailer. Due to logistical, processing, and feedstock considerations of large-scale adoption of biochar, such emissions should be considered in future research.

Cost Data

Data Collection and Analysis

- Costs and pricing data used was sourced from meta-analysis papers recording the price of biochar per ton for farmers to purchase and apply to their fields, then scaled by the amount of biochar needed to hit the threshold application value.[2]
- Pulled data from Dokoohaki et al. (2019) and Kauffman et al. (2014) for cost of biochar application per ton, converted the cost into 2020 dollars, and scaled up by the number of tons of biochar needed per acre.

Assumptions

- That biochar production costs will remain consistent as they scale up to meet demand
- That biochar production will not become limiting as demand increases

Table 2. Price of biochar application per acre

Average Price of Biochar	Rate of Biochar Application for GHG Impacts	Average Cost of Biochar Per Acre
$221.19/t	15 mg/ha	$1342.69/a

Note: t=metric ton, mg=milligram, a=acre, ha=hectare
Source: Dokoohaki et al. 2019.

Revenue Impacts From Increased Yield

A majority of studies have observed yield improvements across all crop types on degraded (i.e., low CEC/low pH) soils; on the other hand, lower to no statistically significant yield improvements have been observed from biochar application to already productive agriculture soils.[3] The key sources examined for this analysis did not differentiate yield increases across different crops, but rather presented increased yield as a function of climate and soil characteristics, such as the extent of soil degradation. Increased yields due to biochar application subsequently increases revenue per acre, which offsets some of the cost of biochar application.

[2] EQIP – the agricultural award pricing system used for many other technologies in this analysis – did include biochar awards. However, the awards were directed towards biochar producers, not the farmers purchasing and applying biochar. Therefore, those costs were not applicable to this model.
[3] The additional carbon sequestration potential of soil due to biochar application remains the same whether or not the soil is degraded.

To calculate these revenue impacts:

- This study used Dokoohaki to get average yield impacts per region (Dokoohaki et al., 2019).
    - First, we confirmed that the results were an average across all crops.
    - Dokoohaki et al. (2019) did not provide their background data or the results of their analysis but did provide a map of expected yield impacts.
    - Three experts independently reviewed this map visually and estimated the average expected yield increase in each USDA production region based on the color categories in the legend, then averaged the results. Regions were evaluated based on the average color in each region after excluding the dark area where biochar does not have an impact on yield (table 3).

Table 3. Average yield increases by region after visual inspection

Region	Reviewer 1	Reviewer 2	Reviewer 3	Average:
Appalachia	18%	20%	18%	18.67%
Corn Belt	11%	11%	13%	11.67%
Delta	12%	15%	15%	14.00%
Lake	12%	8%	12%	10.67%
Mountain	9%	9%	7%	8.33%
Northeast	15%	18%	15%	16.00%
Northern Plains	9%	8%	9%	8.67%
Pacific	6%	9%	10%	8.33%
Southeast	19%	20%	20%	19.67%
Southern Plains	8%	9%	10%	9.00%

- To get baseline average revenue per acre, we analyzed State-level total cash receipts for cropland and aggregated the cash receipts to total for a USDA production region. These totals were divided by the NASS total acres of cropland in each USDA production region, resulting in average revenue per acre (USDA ERS 2022).
- This value was multiplied by the yield impacts to get increased revenue per acre. See table 4.

Table 4. Revenue per acre for each region

Region	Crop Revenue Per Region ($1,000s)	Acres	Revenue Per Acre	Percent Increase in Yield From Biochar	Additional Revenue Per Acre From Biochar
Appalachia	9,877,842	20,272,666	$487.25	18.67%	$90.95
Corn Belt	45,645,304	95,712,567	$476.90	11.67%	$55.64
Delta	8,648,171	17,751,783	$487.17	14.00%	$68.20
Lake	17,279,352	38,628,104	$447.33	10.67%	$47.71
Mountain	11,837,030	155,689,803	$76.03	8.33%	$6.34
Northeast	8,691,084	9,819,782	$885.06	16.00%	$141.61
Northern Plains	29,434,450	166,394,602	$176.90	8.67%	$15.33
Pacific	48,115,300	37,133,526	$1,295.74	8.33%	$107.98
Southeast	11,640,839	13,224,958	$880.22	19.67%	$173.11
Southern Plains	7,611,896	102,909,555	$73.97	9.00%	$6.66

Additional notes about yield impacts:

- Dokoohaki et al. (2019) provided a national average yield increase that is much lower than the above regional yield increases—around 4 percent. The national average is lower because it includes the 100 percent of U.S. crop acreage, regions where biochar application has no or negative yield impacts.
- Dokoohaki et al.'s analysis on whether or not biochar would improve yield had to do with the soil characteristics and level of degradation in each region.

Acres and Applicability Data

Data Collection and Analysis

- As the rate or application of biochar is not crop-dependent or crop specific, all cropland is considered potentially available for biochar application
- Pulled information from USDA databases (NASS) on acreage.
    - NASS Census of Agriculture (2017) data was pulled for region-specific acres planted of "any type of cropland."[4]
- Regional Yield Increase Model:
    - Based on assumption from Dokoohaki et al. (2019) that 50 percent of all U.S. cropland could apply biochar.

[4] Dokoohaki et al. (2019) define crops that could benefit from biochar application to include all cropland, including row crops, horticultural crops, silviculture, etc.

            1. Estimated by dividing the region-specific number of cropland acres in half.

- National Application Model:
    - Based on results of Dokoohaki et al. (2019) that biochar could be applied to 100 percent of U.S. cropland to see positive emissions reduction potential, even when the biochar application has no or negative impact on crop yield.
    - Used the cropland acreage in each U.S. production region as applicable acres.

Assumptions

- **Assumption:**
    - Biochar application in the U.S. is currently negligible, therefore, applicable acres can be measured against all 100 percent of U.S. cropland acres.
    - Note: The accuracy of scaling the models GHG mitigation parameter estimates to such large-scale application of biochar may be limited by the following factors that require further research:
        1. **Feedstock Selection:**
            - Forest residues or wood-derived products are the main source of biochar current production and deployment.
            - Biochar production from other feedstocks would potentially affect the GHG emissions sequestration potential, as feedstock selection has an influence on macronutrient source (nitrate, phosphorus, and potassium), which may impact the Cation Exchange Capacity (CEC) rate (a soil/substrate's capacity to hold exchangeable positively charged ions and supply nutrients for plants uptake, improving soil fertility), and additional biochemistry processes. More research on the latter, especially applied to large-scale operations and variability in different soils and other biochar variables (temperature used, length and production vessel for the heating process), would be beneficial in understanding future potential of implementing this technology.
        2. **Large-scale Applications:**
            - Most current data on biochar application are based on small-scale or lab generated data.
            - Dependance on precipitation or seasonal flooding to provide water for irrigation could impact the effectiveness of biochar application to soils and crop yield when climatic events such as droughts or flooding change seasonal water availability.
        3. **Biochar Supply:**
            - Making enough biochar to cover 50 percent or 100 percent of U.S. cropland would require a large increase in biochar production beyond current supply.

- This report assumes increased demand for biochar would result in increased supply.
- It is not currently known how long it would take for U.S. production to meet this demand.

4. **Control Scenario Assumption:**
    - The data on biochar application in the United States used to create the MACC did not specify at a large scale how biochar application would impact fertilizer usage. Therefore, this model examines emissions from applying biochar on farm without changing any other farm practices like rates or type of fertilizer application.

MACC Modeling and Figures

- Prepared new MACC tabs in overall USDA MACC Excel file
- Entered data from summary table calculations into MACC model by region
    - Lifetime: 20 years. Most papers analyzed Stated that a single application of biochar has positive GHG, yield, and environmental impacts over 10–30 years.
    - Applicable Acres: 50 percent of cropland in each USDA production region (table 5); 100 percent of U.S. cropland in each USDA production region (table 6).
    - Capital Cost: $1,343 per acre for 15 mg per ha application (6 t per acre). This covers the cost of purchasing the biochar for application, and the labor to apply it. Biochar can be applied with existing machinery, such as machinery for fertilizer application.
    - Re-occurring Cost: NA. There is no cost that repeats every year for biochar.
    - Total Revenue: Regional Yield Increase × Regional Average Revenue per acre cropland
    - Emission Reduction: Total GHG emissions reductions in ton of carbon dioxide equivalent (CO_2) equivalents.
        i. This is constant at 15 mg/ha biochar application at 0.24 metric tons of CO_2e/acre.
    - Breakeven cost: Calculated using MACC formulas.

Table 5. MACC inputs and breakeven price – 50 percent of U.S. cropland

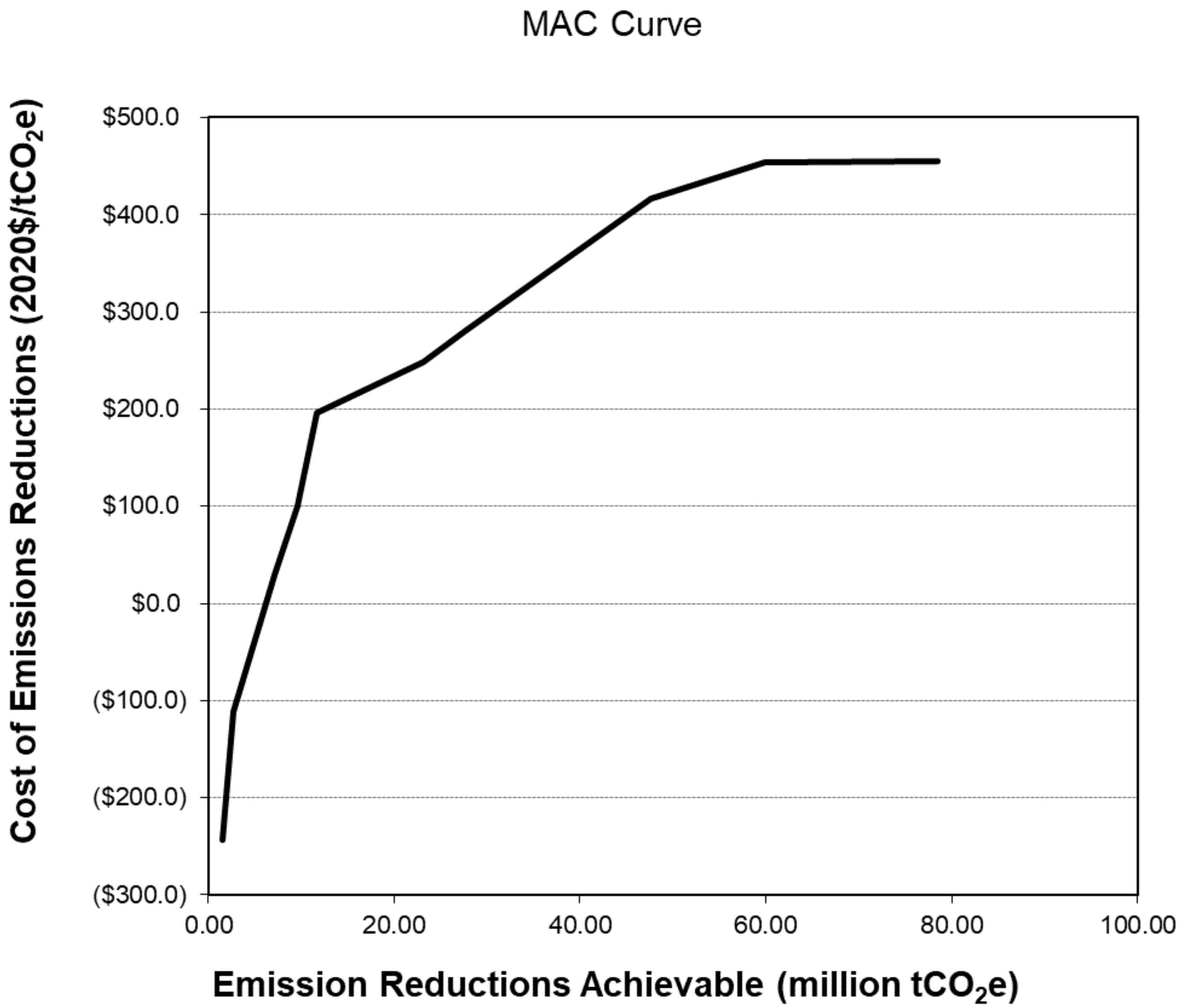
Region	Lifetime	Applicable Acres	Capital Cost ($/acre)	Total Revenue ($/acre)	Emissions Reduction (tCO_2e/acre)	Breakeven Cost
Appalachia	20	10,136,333	$1,343	$91	0.24	$100
Corn Belt	20	47,856,283	$1,343	$56	0.24	$248
Delta	20	8,875,892	$1,343	$68	0.24	$196
Lake States	20	19,314,052	$1,343	$48	0.24	$281
Mountain	20	77,844,902	$1,343	$6	0.24	$455
Northeast	20	4,909,891	$1,343	$142	0.24	$-112
Northern Plains	20	83,197,301	$1,343	$15	0.24	$417
Pacific	20	18,566,763	$1,343	$108	0.24	$29
Southeast	20	6,612,479	$1,343	$173	0.24	$-244
Southern Plains	20	51,454,777	$1,343	$7	0.24	$453

Table 6. MACC inputs and breakeven price – 100 percent of U.S. cropland

Region	Lifetime	Applicable Acres	Capital Cost ($/acre)	Total Revenue ($/acre)	Emissions Reduction (tCO_2e/acre)	Breakeven Cost
Appalachia	20	20,272,666	$1,343	$22.90	0.24	$385
Corn Belt	20	95,712,567	$1,343	$22.41	0.24	$387
Delta	20	17,751,783	$1,343	$22.90	0.24	$385
Lake States	20	38,628,104	$1,343	$21.02	0.24	$393
Mountain	20	155,689,803	$1,343	$3.57	0.24	$446
Northeast	20	9,819,782	$1,343	$41.60	0.24	$307
Northern Plains	20	166,394,602	$1,343	$8.31	0.24	$446
Pacific	20	37,133,526	$1,343	$60.90	0.24	$226
Southeast	20	13,224,958	$1,343	$41.37	0.24	$-12.85
Southern Plains	20	102,909,555	$1,343	$3.48	0.24	$467

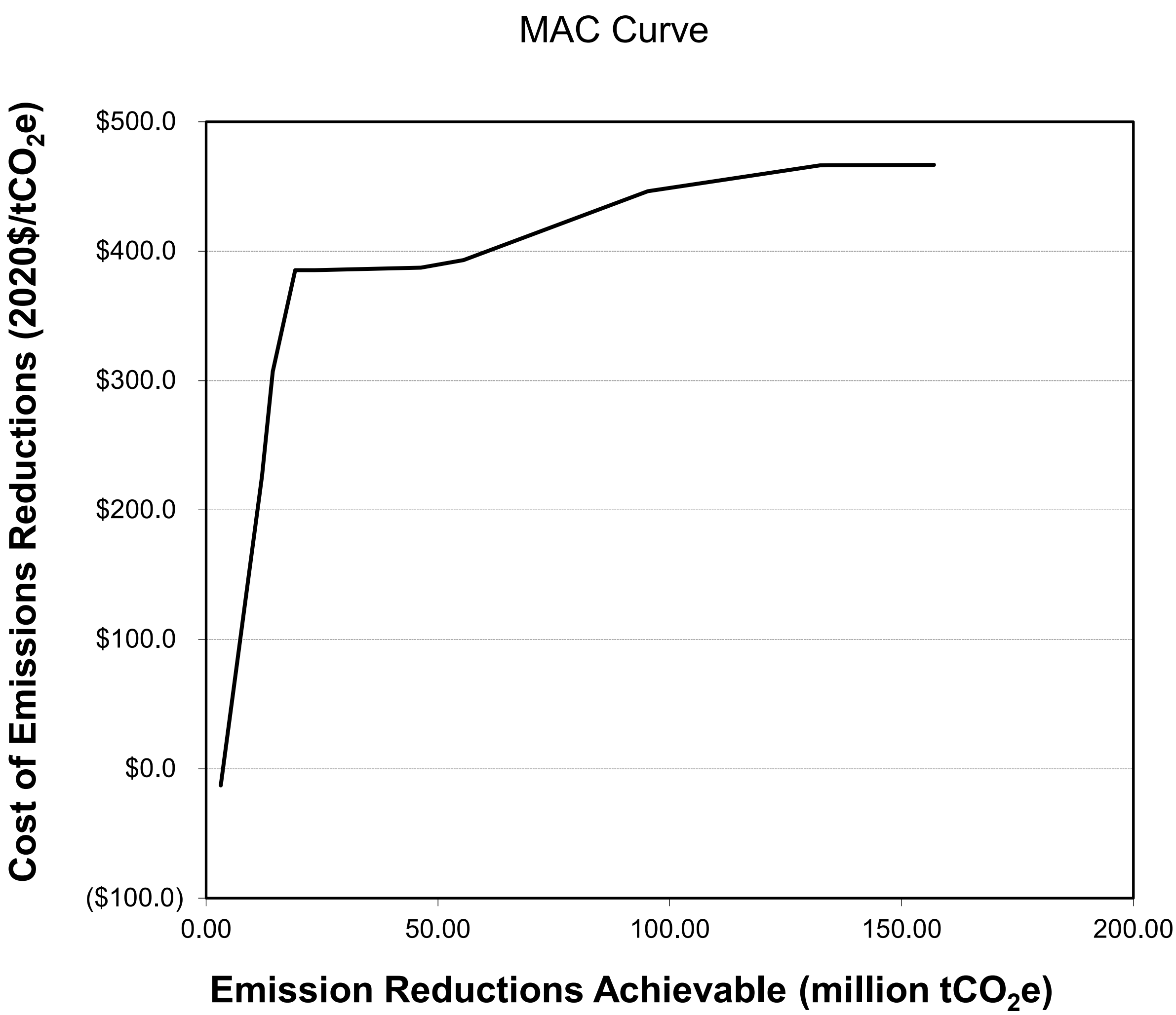
A note about yield impact: Uncertainty about how biochar impacts yield in each region is high and is influenced by some factors that were not reflected in the MACC at this time. These factors include the fact that in many regions higher value crops are planted on the highest quality land, which is also likely to benefit less from biochar since nutrients are not depleted. The MACC was therefore also run without the yield increase in the model, which resulted in a breakeven cost of $481 per metric ton carbon dioxide equivalent (CO_2e) and a maximum emissions reduction of 78.5 MMt CO_2e.

Figure 1. Fifteen milligrams per hectare application scenario and regional yield increases – 50 percent of U.S. cropland



Note: t=metric tons, CO_2e=carbon dioxide equivalent.

Figure 2. Fifteen milligrams per hectare application scenario and average national yield increase – 100 percent of U.S. cropland



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Chapter 2: Marginal Abatement Cost Curve Analysis – Cover Crops

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Technology Overview

Cover crops are defined by NRCS as “grasses, legumes and forbs planted for seasonal vegetative cover.” Usually planted in the late summer or fall around harvest and terminated in the spring, cover crops can increase soil organic matter and carbon sequestration, improve soil quality and soil moisture, reduce nitrogen leaching, erosion and soil compaction, suppress weeds and break pest cycles (Wallander et al., 2021; NRCS, 2014).

Climate change benefits from cover crop rotations include increased soil carbon accumulation, reduced N application on cash crops, and reduced nitrous oxide (N_2O) emissions from excess N in the soil (Wallander et al., 2021). Increased soil carbon accumulation from cover crop rotations is the result of increased biomass of the cover crops themselves (e.g., the cover crop roots, shoots, and leaves) which provide an additional food source for soil organisms that convert the plant biomass into soil carbon over time (Clark, 2015). Variables that impact soil carbon accumulation include the amount of biomass accumulated by cover crops, type of cover crop, soil type, moisture levels, number of years cover crops have been grown, and other factors (Blanco-Canqui, 2022; Wood & Bowman, 2021; Wallander et al., 2021). In terms of N impacts, growing legume cover crops—which increases available nitrogen in the soil—before cash crops that require high nitrogen levels (e.g., corn) can result in reduced N application during cash crop production. Also, growing grasses and small grains after crops with high N application works well to scavenge excess nitrogen in the soil, which reduces N_2O emissions (Wallander et al., 2021).

Farmer costs associated with cover crop rotations include buying seed, planting seed, and terminating cover crops at the end of the season (which may require additional herbicides or tillage), as well as additional costs for time for planning and labor for the aforementioned cover crop production practices (Wallander et al., 2021). Data indicate that cover crop rotations are generally not cost effective the first year of planting, and typically reach cost effectiveness after 3–5 years of continuous rotations (SARE, 2020).

Surveys indicate that rye is currently the most commonly planted cover crop in the US, both as a single species and as part of a mix of two or more species (Wallander et al., 2021; SARE, 2020). According to Sustainable Agriculture Research and Education (SARE) program surveys, approximately half of cover crop planted acres in 2019 were mixes (SARE, 2020). Given that cover crop species and cover crop mixes each have species-specific soil carbon accumulation and growth rates, as well as species-specific impacts on available N in the soil and N requirements for the following cash crop, accurate estimates of the GHG impacts of cover crop rotations need to take these differences into account.

This report describes how data were collected and processed for greenhouse gas impacts associated with cover crops, baseline cover crop adoption, applicable acreage for future cover crop adoption, and costs associated with cover crop rotations. The final section of the report, marginal abatement cost curve (MACC) Modeling, describes how these datapoints were used to generate the MACCs presented in Figure 1 and Figure 2.

Greenhouse Gas Data

GHG emissions and sequestration associated with cover crop rotations used in the MACC can be broken into three categories:

1. Soil carbon sequestration changes
2. N_2O emission changes (due to lower N fertilizer application to cash crops and/or reduced N_2O emissions from excess N in the soil)
3. CO_2 emissions from burning fossil fuels for cover crop management practices (e.g., cover crop seeding and termination).

Data Collection and Analysis

Soil Carbon Sequestration Changes

A brief literature search indicated that the emissions reductions factors in CarbOn Management & Emissions Tool (COMET)-Farm (USDA NRCS, 2022) were consistent with those found in the literature. COMET-Farm was therefore selected to estimate the difference in soil carbon sequestration and N_2O emissions between cash crop production rotations with and without cover crops (USDA NRCS, 2022). See table 1 for a comparison of increased metric tons of carbon dioxide equivalent ($MtCO_2e$) sequestration impacts from cover crop rotations from COMET-Farm compared to recent publications.

Table 1. Range of regional emissions reduction per acre ($MtCO_2e$)

Source	Value ($MtCO_2e$ per acre)
COMET, avg. Legume/Nonlegume	0.04–0.72
COMET, avg. Legume	0.05–0.92
COMET, avg. Nonlegume	0.04–0.66
Bolinder et al., 2020	0.12–0.19
Kaye & Quemada, 2017	0.40–0.60
Popelau and Dan, 2015	0.13

N_2O Emission Changes

To estimate the soil carbon and N_2O impacts of cover crop rotations, State-specific GHG values from COMET were averaged to USDA crop production regions. The region-specific COMET values for *nonirrigated cropland with a nonlegume cover crop* and *nonirrigated* *cropland with a legume cover crop* were used for each region (See table 2, column "Final" for more details). Of the four available cover crop values in COMET[5], the two nonirrigated values for legume and nonlegume cover crops were selected based on:

- The overall low-level of irrigated cropland in the US (approximately 6 percent) (USDA ERS, 2022).
- Recent survey data that show:
  - The majority of cover crop acres are planted with rye, either as a single species or in a mix (nonlegume) (Wallander et al., 2021; SARE, 2020).
  - Over 50 percent of cover crop acres are planted with cover crops mixes, and half of mixes contain a legume (SARE, 2020; Soil Health Partnership, 2020).
    - This indicates that legume cover crops are likely planted on around 25 percent of all cover crop acreage (50 percent mixes x 50 percent of mixes are legumes = 25 percent legume cover crops).
    - Note that Wallander et al. (2021) had different ratios on the types of cover crops planted and the percent of single species planted compared to cover crop mixes. Despite this difference, we decided to base our assumptions for cover crop type on the more recent SARE and Soil Health Partnership (SHP) surveys as they represent farmers currently growing cover crop rotations (SARE, 2020; Soil Health Partnership, 2020).

The final GHG factor represents a weighted average of nonlegume and legume COMET factors. Based on the survey results described above, the nonlegume factor was weighted at 75 percent and the legume factor was weighted at 25 percent. Table 2 shows the regional GHG reduction factors.

[5] COMET has four values for cover crops: (1) nonirrigated nonlegumes; (2) irrigated nonlegumes; (3) nonirrigated legumes; (4) irrigated legumes

Table 2. Regional COMET GHG impacts from soil carbon sequestration and N_2O impacts of cover crop reduction across types ($MtCO_2e$ per acre)

Region	Nonlegume	Legume	Final (75% nonlegume, 25% legume)
Appalachia	0.39	0.62	0.45
Corn Belt	0.39	0.55	0.43
Delta States	0.66	0.92	0.72
Lake States	0.12	0.15	0.13
Mid-Atlantic	0.22	0.45	0.28
New England	0.14	0.24	0.17
Northern Mountain	0.04	0.05	0.05
Northern Plains	0.16	0.23	0.18
Pacific	0.06	0.11	0.07
Southeast	0.37	0.53	0.41
Southern Mountain	0.07	0.06	0.07
Southern Plains	0.25	0.31	0.27

Note that the COMET values for cover crop rotations include large reductions in nitrogen fertilizer, 50 percent for legume cover crops and 25 percent for nonlegume cover crops. While recent literature indicates that use of cover crops can result in a reduction of N application and/or may result in reduced available N in the soil that could be turned into N_2O, COMET N reduction levels are higher than those reported in the literature (SARE, 2020). However, further examination of the N_2O values in COMET indicated that in some cases cover crops resulted in net N_2O emissions while others resulted in net N_2O removals. Given the complex interaction between N_2O emissions for different States, we did not remove the N_2O impacts from the overall GHG emissions. See table 3 for more details.

Table 3. Example of COMET Corn Belt values for CO_2 and N_2O impacts of nonirrigated nonlegume cover crops ($MtCO_2e$ per acre)*

State	Region	Total CO_2e ($MtCO_2e$ per acre)	CO_2 ($MtCO_2e$ per acre)	N_2O ($MtCO_2e$ per acre)
IA	Corn Belt	0.27	0.28	-0.01
IL	Corn Belt	0.50	0.49	0.01
IN	Corn Belt	0.43	0.42	0.01
MO	Corn Belt	0.51	0.49	0.02
OH	Corn Belt	0.26	0.26	0.00

*Negative N_2O values are italicized to illustrate the wide range of impacts cover crops have on N_2O emissions. Note that negative values in COMET indicate a release of emissions and positive values indicate an emissions reduction.

CO_2 Emissions from Burning Fossil Fuels

A literature search was also performed to determine average CO_2 emissions associated with diesel fuel use required for cover crop management practices (e.g., seeding and termination). Recent surveys indicate that the two most common cover crops are seeded by drilling or broadcast seeding, and the two most common ways cover crops are terminated are by using herbicides and winter kill[6] (Meyers & LaRose, 2022; SARE, 2020; Soil Health Partnership, 2020).

To estimate the GHG impacts of these two practices, a literature search of the amount of diesel used per acre for seeding and herbicide termination was conducted (table 4).

[6] Winter kill is the process where cover crops are terminated by being exposed to outdoor temperatures that are lower than the planted species can survive. As such, no additional management practices are required to terminate the cover crops.

Table 4. Diesel fuel use per acre for planting and cultivating

Type	Diesel Fuel Use (Gallons Per Acre)
Planting	
Strip rotary tilling and planting	0.95
Field cultivating and planting	0.90
Wheel-track planting	0.65
Conventional planting	0.50
Till planting, Nebraska type with sweeps	0.50
No-till planting, fluted coulter type	0.50
Grain drilling	0.35
Average of all planting:	*0.62*
Cultivating	
Cultivating, disk hillers	0.40
Cultivating, sweeps	0.35
Cultivating, rolling tines	0.35
Rotary hoeing	0.25
Spraying, trail type	0.15
Average of all cultivating:	*0.30*

For seeding, the average diesel fuel use for seven types of planting was used to account for the fact that cover crop seeding can be conducted using a variety of methods (Purdue University, 1980). Therefore, to simply the estimation of CO_2 impacts of the different cover crop management practices, fuel use was averaged across seeding types (0.62 gallons of diesel fuel use per acre) and further categorized into management scenarios:

1. Seeding and herbicide termination
2. Seeding and winter kill

For chemically terminating cover crops, the average value for controlling weeds (0.3 gallons of diesel/acre) was used. For winter kill, it was assumed that no additional fuel was required to terminate the cover crop. Both the seeding and termination estimates were consistent with other recently published diesel rates found for cover crop seeding and termination (Kaye & Quemada, 2017). Diesel use for seeding and termination were multiplied by EPA's emission factor for diesel fuel (0.04 $MtCO_2e$ per gallon) to determine CO_2 emissions associated with burning the fuel (EPA, 2022).

To estimate the percentage of cover crops that were terminated by herbicide use vs. winter kill, cover crop termination percentages based on SARE surveys were used. Surveys indicated that for row crops, herbicides were used to terminate crops by 60 percent of farmers and winter kill was used to terminate crops by approximately 25 percent of farmers (Myers and LaRose, 2022).[7] To approximate this ratio of termination methods, the different management scenario values were applied to the 12 USDA regions based on the feasibility of winter kill and non-winter kill each region. The Environmental Quality Incentives Program (EQIP) lists winter kill incentive payments in the Corn Belt, Lake States, Southern Mountain, and Northern Plains regions (NRCS, 2022). In regions where winter kill was possible, winter kill was assumed to be used 75 percent of the time and herbicide termination was assumed to be used 25 percent of the time (i.e., 75 percent of the acreage in a region was allocated to winter kill and 25 percent was allocated to herbicide termination). Herbicide termination was assumed to be used 100 percent of the time in warmer climates. Nationally, these percentages result in around 78 percent of all cover crop acres using herbicide termination and 22 percent using winter kill. Table 5 shows the termination strategies commonly deployed by each USDA production region.

Table 5. Termination scenarios used per USDA crop production region

Region	Termination Scenarios Available:
Appalachia	Herbicide Termination
Corn Belt	Winter Kill; Herbicide Termination
Delta States	Herbicide Termination
Lake States	Winter Kill; Herbicide Termination
Mid-Atlantic	Herbicide Termination
New England	Herbicide Termination
Northern Mountain	Herbicide Termination
Northern Plains	Winter Kill; Herbicide Termination
Pacific	Herbicide Termination
Southeast	Herbicide Termination
Southern Mountain	Winter Kill; Herbicide Termination
Southern Plains	Herbicide Termination

Assumptions Update

- Cover crops rotations will be planted with half of acres as a single species and half of acres as multispecies (SARE, 2020).
- Cover crop rotations will be planted at a ratio of 25 percent legume and 75 percent nonlegume to account for the fact that most cover crop rotations are planted with rye, and that over half of cover crop acres are planted with a mix, of which approximately half contain a legume (SARE, 2020).
- All cover crop rotations are planted on nonirrigated acres.

[7] Other termination methods that were included in the SARE survey, but are modeled in the MACC as herbicide termination for simplicity and their percentage of use include: tillage (10 percent), mowing (4 percent), and roller-crimpers (1 percent).

- That the GHG impacts of cover crops can be simplified to:
    - The region-specific average of the nonirrigated nonlegume and legume CO_2 and N_2O savings from COMET minus the CO_2 emissions from the average diesel fuel use for the planting and termination strategies used in each region (i.e., winter kill or herbicide termination).
        - Final GHG Emissions Reduction Factor = [COMET Emissions Reduction Factor – CO_2 emissions From Diesel Fuel Use]
- Chemical termination of cover crops can be effectively completed with a single tractor pass.

Cost Data

Two cost scenarios were developed for cover crop adoption and benefits:

1. Costs of cover crop adoption from Environmental Quality Incentives Program (EQIP) and average financial benefits from the first year of adoption from the Sustainable Agriculture Research and Education Program (SARE) survey
2. Average costs of cover crop adoption from the SARE survey and average financial benefits from the first year of adoption from the SARE survey.

EQIP's incentive payment rates were used to estimate costs associated with cover crop adoption. EQIP lists payment rates for basic and mixed species cover crop plantings, as well as for winter kill and non-winter kill terminations. To reflect that 50 percent of cover crop plantings are mixed species and 50 percent are basic (i.e., single species), 50 percent of the costs for the mixed species scenario and 50 percent of the cost of the basic scenario were used to calculate final costs for winter and non-winter kill terminations. Table 6–table 8 show the cost components for each scenario, while table 9 illustrates estimated costs to adopt per region based on EQIP data.

Table 6. Cost components in EQIP for basic cover crop, non-winter kill in the Corn Belt

Component Name	Cost Per Unit	Quantity	Component Unit	Component Cost	Component Justification	Quantity Justification
Chemical, ground application	$6.48	40	Acres	$259.24	Typical one herbicide application to terminate cover crop	One pass to terminate cover crop
Seeding Operation, No Till/Grass Drill	$23.06	40	Acres	$922.28	Typical seeding operation for cover crop	One pass per seeding
Herbicide, Glyphosate	$8.98	40	Acres	$359.10	Typical herbicide to terminate cover crop	Typical application rate of herbicide
Annual Grasses	$31.62	40	Acres	$1,264.80	Cover crop seed (typically single species grass)	Amount of seed needed for 40 acres.

Table 7. Cost components in EQIP for multispecies cover crop, non-winter kill in the Corn Belt

Component Name	Cost Per Unit	Quantity	Component Unit	Component Cost	Component Justification	Quantity Justification
Chemical, ground application	$6.48	40	Acres	$259.24	Typical one herbicide application to terminate cover crop	One pass to terminate cover crop
Seeding Operation, No Till/Grass Drill	$23.06	40	Acres	$922.28	Typical seeding operation for cover crop	One pass per seeding
Herbicide, Glyphosate	$8.98	40	Acres	$359.10	Typical herbicide to terminate cover crop	Typical application rate of herbicide
Annual Grasses, Legumes or Forbs	$47.16	40	Acres	$1,886.40	Lowest cost mix for multispecies	Amount of seed needed for 40 acres.

Table 8. Cost components in EQIP for winter kill in the Corn Belt

Component Name	Cost Per Unit	Quantity	Component Unit	Component Cost	Component Justification	Quantity Justification
Seeding Operation, Aerial	$14.16	100	Acres	$1,416.26	Component needed to seed cover crops	Entire area will be seeded
Annual Grasses	$31.62	100	Acres	$3,162.00	Component needed to establish cover crop seed	Amount of seed needed for 100 acres.

Table 9. EQIP incentive payments for non-winter kill and winter kill

Region	EQIP Non-Winter Kill ($ Per Acre)	EQIP Winter Kill ($ Per Acre)
Appalachia	$78.19	N/A
Corn Belt	$77.91	$45.78
Delta States	$76.80	N/A
Lake States	$77.95	$44.00
Mid-Atlantic	$82.81	N/A
New England	$77.70	N/A
Northern Mountain	$75.68	N/A
Northern Plains	$76.80	$69.45
Pacific	$77.01	N/A
Southeast	$76.80	N/A
Southern Mountain	$75.16	$56.35
Southern Plains	$72.57	N/A

It is important to note that EQIP's cost calculations do not appear to include co-benefits from cover crop adoption that can offer cost savings. To include these benefits, average SARE survey benefits from the first year of cover cropping were subtracted from EQIP payments. SARE administers a national annual cover crop survey that aims to understand farmer experiences with cover crops, particularly the costs, implementation characteristics, and benefits of adoption. Based on survey results, SARE estimated the range of the financial savings from the co-benefits of cover crop adoption, such as weed suppression, fertilizer reduction, and yield boosts over time (Myers et al., 2019). As shown in table 10, the financial returns from cover crop adoption increase over time from the first through the fifth year of cover crop adoption.

Table 10. SARE financial benefits of cover crop adoption over time

Budget Item	Years of Cover Cropping		
Input	**1**	**3**	**5**
Fertilizer	$0	$14.10	$21.90
Weed control	$0–$15	$10–$25	$10–$25
Erosion repair	$2–$4	$2–$4	$2–$4
Total savings on inputs (middle of range above):	$11	$34.60	$42.40
Income from extra yield in normal weather year:	$3.64	$12.32	$21
Total benefits in a normal weather year	$14.14	$46.92	$63.40
Converted to 2020 USD	**$14.49**	**$48.09**	**$64.40**

Our literature search results showed that EQIP's payment rates were higher than the SARE survey results. The SARE survey reported that the average cost of cover crop adoption was $37 per acre (Myers et al., 2019). A detailed comparison of cover crop adoption costs between EQIP and SARE showed that the majority of the difference in cost estimates between the two was due to seed costs. Planting costs are relatively similar across sources (See table 11).

Table 11. Cover crop planting costs reported by SARE, SHP, and EQIP

Source	Price	Price Year
SARE 2013–2014	$12	2014
SARE 2015–2016	$16	2016
Soil Health Partnership 2020 Survey	$12	2019
SARE 2019–2021	$9–$16	2020
Soil Health Partnership 2021 Survey	$10	2020
EQIP Planting, No-Till	$23	2021
EQIP Aerial Planting	$14	2021

Further research showed that the EQIP underlying costs for seeds are significantly higher than seed costs from multiple years of surveys (see table 6–table 8 and table 12). Compared to EQIP's seed costs of $31 per acre for single species and $47 per acre for mixed species, SARE surveys showed that seed costs for cover crops used in commodity crop rotations have steadily decreased since the first survey in 2012 and range from $16–$25 per acre. Table 12 summarizes cover crop seed costs for row crops reported by recent surveys.

Table 12. Cover crop seed costs reported by SARE, SHP, and EQIP

Source	Price	Price Year
SARE 2012–2013	$25	2013
SARE 2013–2014	$25	2014
SARE 2015–2016	$22	2016
Soil Health Partnership 2019 Survey	$15	2019
SARE 2019–2020	$16–$20	2020
Soil Health Partnership 2021 Survey	$15	2020
EQIP Single Species Grass	$31.62	2021
EQIP Annual Grasses & Legumes	$47.16	2021

Due to the large difference in seed costs between EQIP and recent cover crop surveys, a second MACC was generated using the same GHG data and average seed and planting costs from SARE cover crop surveys and net economic benefits estimated by SARE (i.e., cost savings per acre from cover cropping improving weed control, repairing erosion, and reducing fertilizer use) (Myers et al., 2019). For the regions with winter kill in the SARE MACC, the median cost of termination reported in the National Cover Crop Surveys ($5 per acre) was removed from the total cost estimate. Winter kill was estimated to cost $32 per acre.

Data Collection and Analysis

- Regional level data from EQIP on payment rates for NRCS Conservation Practice Standard 340, Cover Crop
    - i. Used costs from:
        1. Cover Crop – Basic,
        2. Cover Crop – Multiple Species,
        3. Winter Kill Cover Crop Species, and
        4. Cover Crop Multiple Species Frost Terminated
    - Selected EQIP payment rates that included costs associated with
        - i. Materials
        - ii. Equipment
        - iii. Education
        - iv. Labor
    - As EQIP payments are not crop specific, the management practice transition regional costs were applied to all five crop types.
- Cost data from SARE on:
    - Seed costs (basic and multispecies)
    - Planting
    - Termination
- First year of adoption benefit/cost savings data from SARE

    - Economic benefits of cover crop adoption (weed suppression, erosion repair, fertilizer reduction), represented in dollars (in 2020 USD) saved on inputs per acre.

Assumptions Update

- For simplicity and due to lack of data on farm size, assumed that farm size does not impact costs.
- Assumed that EQIP payments are a proxy for the costs for farmers to adopt cover crops for one set of MACCs
- Assumed that SARE adoption costs are a proxy for the costs for farmers to adopt cover crops for the second set of MACCs
- Assumed that the average benefits of the first year of adoption are a proxy for the benefits of cover crop adoption in both MACCs
- Assumed that the costs of adopting a practice were the same for the five crops of interest (i.e., there is no cost differentiation between crop types).

State-Level Financial Incentives

- In addition to the on-farm financial incentives for farmers to grow cover crops, some States give bonus payments for growing cover crops. Table 13 provides an overview of State programs that offer incentives for growing cover crops. While important, these programs are not included in the MACC analysis as the limited State budgets for incentive payments result in limited number of acres being eligible for cover crop adoption incentives.

Table 13. State cover crop incentive programs

State (Years Active)	Program/Implementing Agency	Program Scope (Acres)	Per-Acre Payment Range	Annual State Spending
Maryland (2009–present)	Maryland Agricultural Water Quality Cost-Share Program	639,710	$45–$95	$22.5 million
Maryland (2022–present)	Maryland Department of Agriculture Conservation Grants Program *Cover Crop+*	N/A	$115–$160	N/A
Iowa (2013–present)	Iowa Department of Agriculture and Land Stewardship (IDALS)	250,000	$15–$25	$5 million
Virginia (1998–present)	Virginia Department of Conservation and Recreation with funding from Water Quality Improvement Fund and real eState recordation fees	200,539	$15–$33	$5.1 million
Missouri (2015–present)	Department of Natural Resources	117,175	$30–$40	$3.8 million
Delaware (at least 2011–present)	County conservation districts	85,438	$30–$50	$2.9 million
Ohio (2012–present)	Various, including Muskingum Watershed Conservancy Project, Ohio Department of Natural Resources, and Ohio Department of Agriculture	~50,000	$12–$40	~$600,000
Indiana (2015–present)	Watersheds and county conservation districts with funding from Indiana State Department of Agriculture (ISDA) Clean Water Indiana Grants	18,278	Up to $20	$307,385
Illinois (2022–present)	Various, American Farmland Trust and Illinois Department of Agriculture	N/A	$5–$10	N/A
Kansas (2022–present)	Kansas Association of Conservation Districts	N/A	$10	N/A

Baseline Acreage

The MACCs estimate regional and crop specific total acres under production and acres currently using cover crop rotations from:

- USDA NASS (2022) for total acres under cropland production.
- USDA ERS ARMS (2022) for the percent of acres grown in rotation with cover crops by crop type and by crop production region.

Crop- and region-specific total acres of each crop are determined by multiplying the number of acres grown of each crop in each region by the percent of acres grown in rotation with cover crops.

Data Collection and Analysis

- Information from USDA databases (NASS) on acreage.
    - NASS (2022) data for 2021 was pulled for acres planted for corn, cotton, sorghum, soybean, and wheat planted in each State in the 12 regions across the United States.
- USDA (ARMS) on crops grown in rotation with cover crops.
    - Data from the most recent crop-specific ARMS surveys were pulled for crops grown in rotation with cover crops for each State in the survey.
    - Crop specific surveys were from the following years:
        - Corn, 2016
        - Cotton, 2015
        - Sorghum, 2019
        - Soybeans, 2018
        - Wheat, 2017
- To generate the crop-specific number of acres grown in rotation with cover crops for each region, the total acreage of the crop grown in each region was multiplied by the regional percent of acres in rotation with cover crops.

Assumptions

- Assumed that crop- and region-specific ARMS data on the percent grown in rotation with cover crops are a proxy for practice use in 2021 and can be applied to 2021 NASS acres.

Applicable Acres

The literature search did not result in any publications that estimated the potential number of acres where cover crop rotations could be used (e.g., the “applicable acres” or the total, regional specific number of acres that could be grown in rotation with cover crops).

Therefore, the MACCs estimate for number of applicable acres is based on personal discussions with Dr. Jennifer Moore and Dr. Daniel Manter (Moore and Manter, 2022). Using their recent research as the foundation for their expert opinions, Dr. Moore and Dr. Manter hypothesized cover crops could theoretically be grown on every acre in which cash crops are grown (Moore et al, 2022). However, they noted the caveat that rain-fed areas with low precipitation are not likely to have high rates of cover crop adoption as without enough moisture, the cover crops won't grow enough to result in farmer benefits to offset the costs of adoption.

Assumptions

- All cropland acres not currently growing cover crops could have cover crops grown in rotation with cash crops.
- For simplicity, it was assumed that all acres grown in rotation with cover crops will continue to be grown in rotation with cover crops, and that discontinuation does not occur.
    - Note that this assumption is not consistent with the literature:
        - Wallander et al (2021) shows that half of corn grain and soybean acres only have cover crops for 1 out of every 4 years (e.g., that cover crops are not planted on all corn grain and soybean acres 4/4 years)
        - Sawadgo & Plastina (2022) mapped cover crop acreage in specific counties in the Census of Agriculture in 2012 and 2017 and found that discontinuation or alternating adoption occurred in 863 counties, or 28.26 percent of all counties in the contiguous U.S. States, for a total of 930,506 acres.

MACC Modeling and Figures

Marginal Abatement Cost Curves (MACCs) provide a greater understanding of the regional costs of implementing cover crops by estimating what the price of carbon dioxide equivalent (CO_2e) would need to be for producers to adopt cover crops.

The steps to prepare the MACC were as follows:

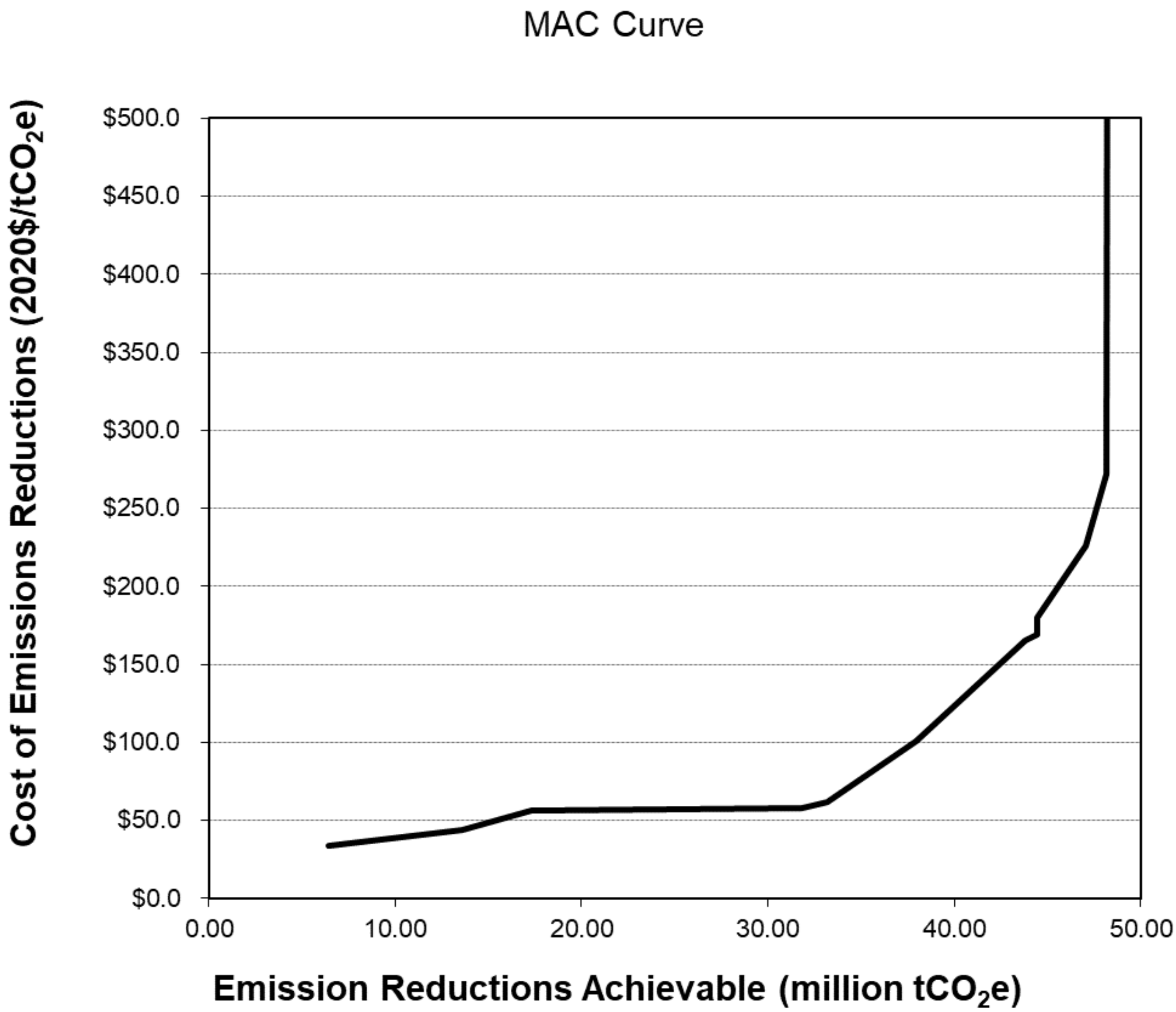
Background Data

- Performed literature review to gather background information on baseline adoption, applicable acres, emissions reductions per acre, and co-benefits (e.g., weed suppression, yield boosts, fertilizer reduction).
- Summarized background information in Excel spreadsheet
- Prepared new MACC tab in overall USDA MACC Excel file
- Entered in data from summary spreadsheet calculations into MACC model by region

MACC Component Calculations

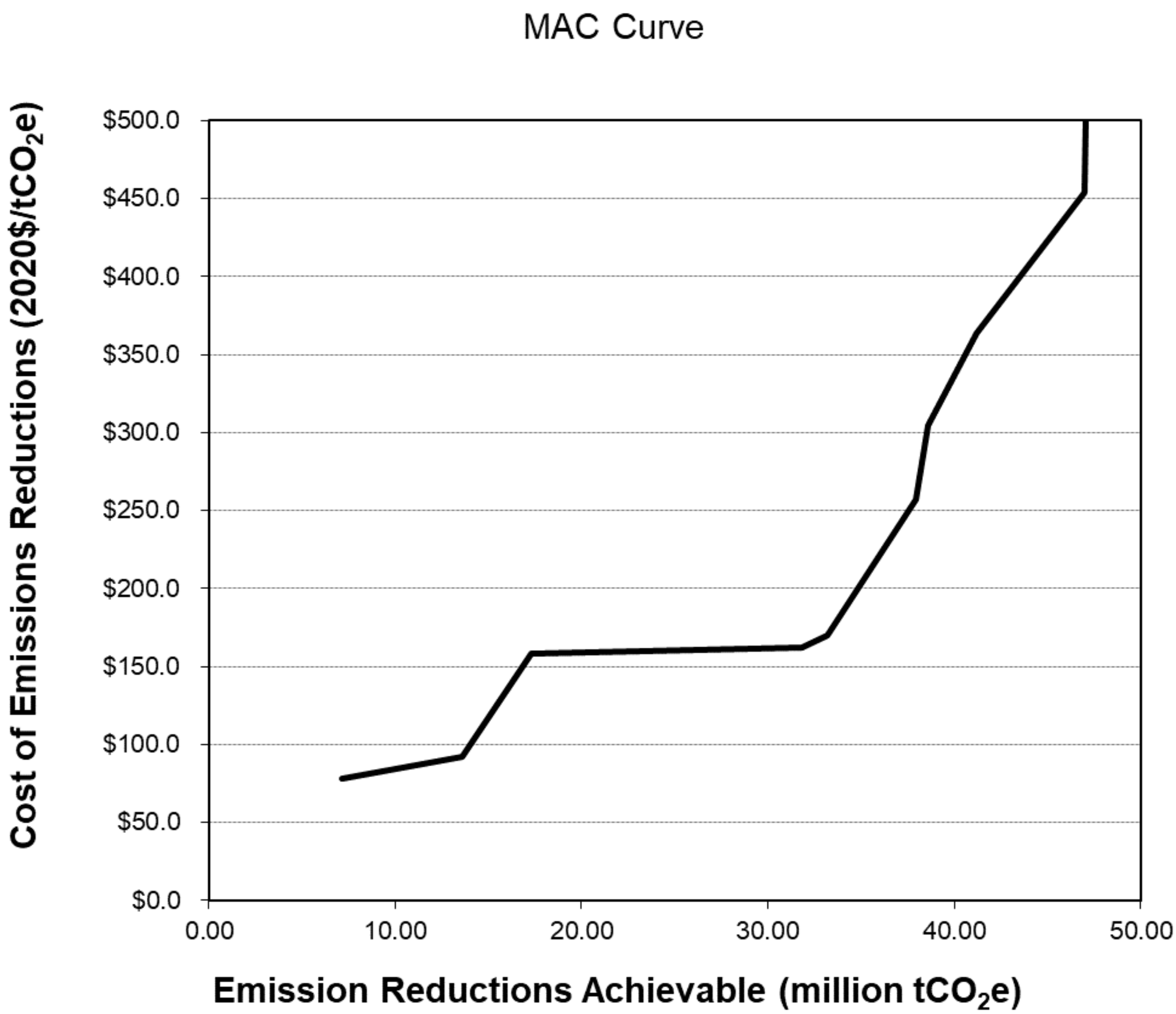
- **Lifetime:** 1 year. Payments in the EQIP contract were calculated over 1 year. The cost to purchase seed and implement cover cropping reoccurs annually.
- **Capital Cost:** None.
- **Recurring Cost:**
  - Two scenarios were created:
    - SARE = [SARE Adoption Cost – SARE Benefits]
    - EQIP = [EQIP Adoption Cost – SARE Benefits]
- **Total Revenue**: None. No impact is observed on revenue because the cost savings from co-benefits (i.e., yield improvements, weed suppression, fertilizer reduction) is already accounted for in the reoccurring cost to adopt SARE Benefits.
- **Emissions Reduction:** From COMET. CO_2 emissions from diesel combustion from Purdue University.
- **Regional Breakeven Cost:** in 2020 USD/tCO_2e; calculated using MACC formulas.
- For MAC curves see, figure 1–figure 2.
  - Note that the cost per MtCO_2e (i.e., the Y axis) for all the MACCs has been capped at $500 per ton, as most of the mitigation potential is achieved at $500 per Mt$CO_2$e and carbon prices above $500 per ton are likely not feasible at this time. Additionally, capping the MACC at a price of $500 per Mt$CO_2$e captures the majority of the mitigation potential.

Figure 1. SARE scenario



Note: t=metric tons, CO_2e=carbon dioxide equivalent.

Figure 2. EQIP scenario



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Chapter 3: Marginal Abatement Cost Curve Analysis – Digesters and Solid Separators

Chapter 3 of 8.

Contents

Technology Overview

The marginal abatement cost curve (MACC) methodology applied to digesters and solid separators assumed two farm types for which these technologies can be used: dairy farms and swine farms. For dairy farms, the digester and separator types considered are plug flow digesters, complete mix digesters, covered lagoons, and solid separators. For swine farms, plug flow digesters, complete mix digesters, and covered lagoons were considered.[8] The cost and emissions impact of transitioning to each of these digester and separator technologies was dependent on the baseline practice used by a given farm. The following baseline management practices were considered: anaerobic lagoons, liquid/slurry farms, and deep pits. For each of the management practices examined, we estimate alternative uses for the resulting methane gas including electricity generation (EG) potential across farm sizes, for covered lagoons we also examine biogas upgrading potential and the subsequent revenue streams from both of those generation practices, and revenue generated through the sale of generated compost from solid separation.

Baseline Practices

Dairy

There are three main baseline practices considered for adoption of the anaerobic digester and solid separator technologies: anaerobic lagoons, deep pits and liquid slurries. Figure 1 outlines the distribution of baseline practices across farm size in the United States based on EPA's Greenhouse Gas Inventory tables on Percentage of Dairy Farms Using Specific Types of Manure Storage Facilities, 2017 – 2019 (ERG, 2022a), provided by USDA. The other category in the figure is comprised of the following baseline practices: pasture, dry lot, daily spread, and solid storage.

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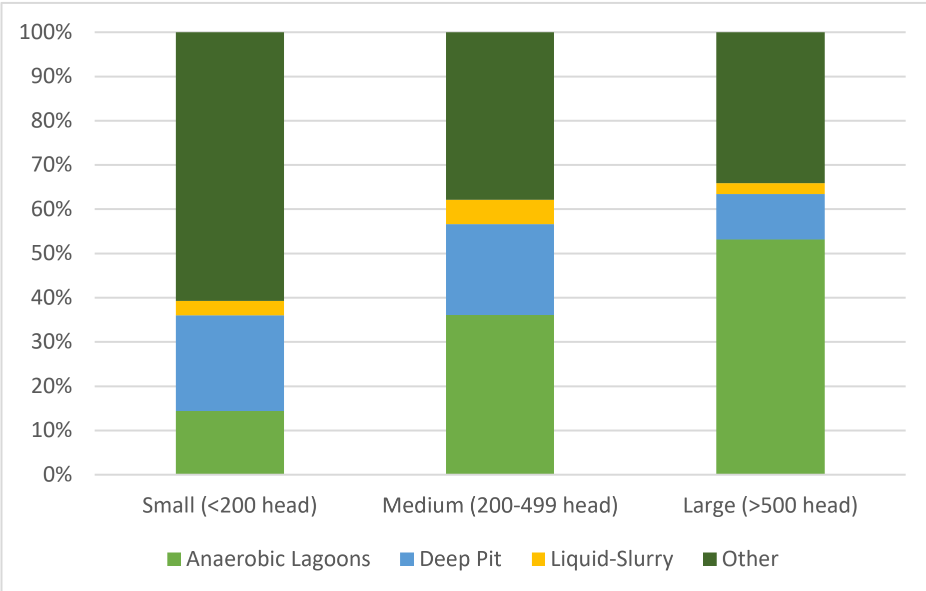
[8] Due to the reduced solid composition of swine waste when compared to dairy waste, solid separators were determined to have no applicability through expert consultation with Doug Williams.

Figure 1. Dairy business as usual practices by farm size



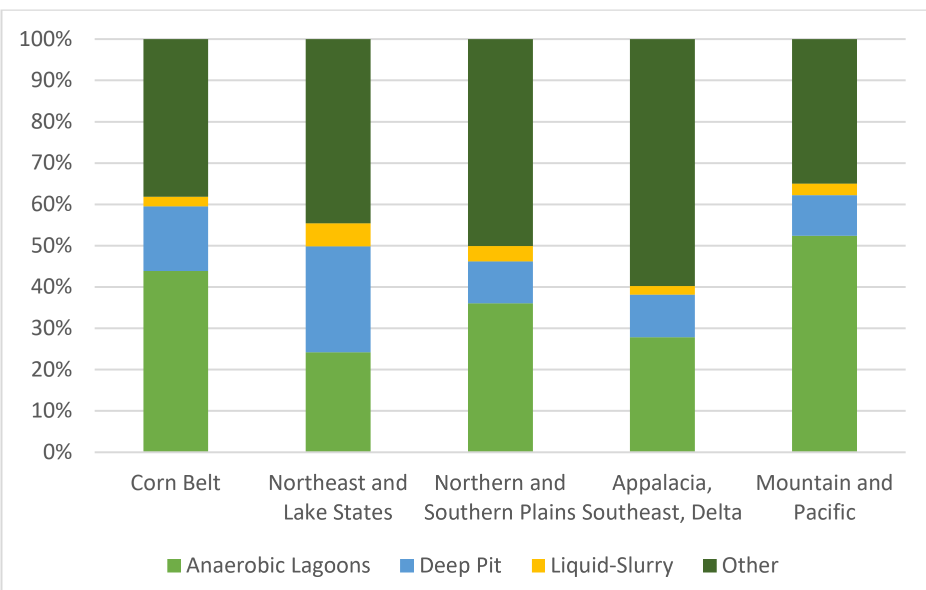
To create uniform regions across our primary data sources, sources that used alternative regional classifications were standardized against the US EPA GHG Inventory data classifications: West, Southwest, Corn Belt, Northeast, Upper Midwest and Southeast (ERG, 2022a). The distribution of States within each Inventory region were reallocated to the USDA regions used in our analysis based on the percentages outlined in table 1. Each region in the "USDA Region" column is comprised of data from the "Inventory Region" column based on the "Percent To" column ratios. The mapping is based on the State composition of the corresponding wrong and proper regions. In each "USDA Region" the sum of the comprising percentages sum to 100 percent to ensure complete mapping. For example, for the Mountain and Pacific region, 50 percent of those data stem from the West, and 50 percent from the Southwest. Another interpretation of this data is that all of the Northeast and Upper Midwest underlying States are combined to make the complete picture of the Northeast and Lake States data.

Table 1. USDA dairy business as usual region conversion

Inventory Region	Percent From	Percent To	USDA Region
West	100%	50%	Mountain and Pacific
Southwest	50%	50%	
Southwest	50%	50%	Northern and Southern Plains
Corn Belt	50%	50%	
Corn Belt	50%	100%	Corn Belt
Northeast	100%	50%	Northeast and Lake States
Upper Midwest	100%	50%	
Southeast	100%	100%	Appalachia, Southeast, and Delta

Figure 2 shows the distribution of baseline practices based on the region mapping done in table 1. Like the aggregate national baseline practices (figure 1), the other category comprises a large portion of each region's baseline practices. The largest of the three Business as Usual (BAU) practices is typically anaerobic lagoons, which varies by region, but represents roughly 25 percent in each region.

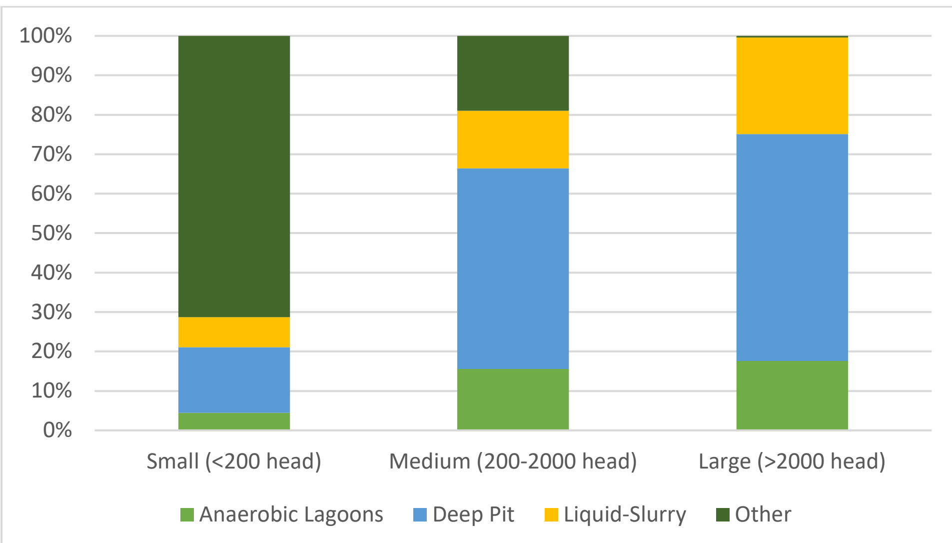
Figure 2. Dairy business as usual practices by USDA region



Swine

There are three main baseline practices exist with anaerobic digester and solid separator technologies: anaerobic lagoons, deep pits, and liquid slurries. Figure 3 outlines the distribution of baseline practices across farm size in the United States, data are based on EPA's Greenhouse Gas Inventory tables on Percentage of Swine Farms Using Specific Types of Manure Storage Facilities, 2017–2019 (ERG, 2022b), provided by USDA. The other category is comprised of the following baseline practices: pasture, dry lot, daily spread, and solid storage. For swine, most baseline practices consist of deep pit or other depending on the farm size.

Figure 3. Swine business as usual practices by farm size



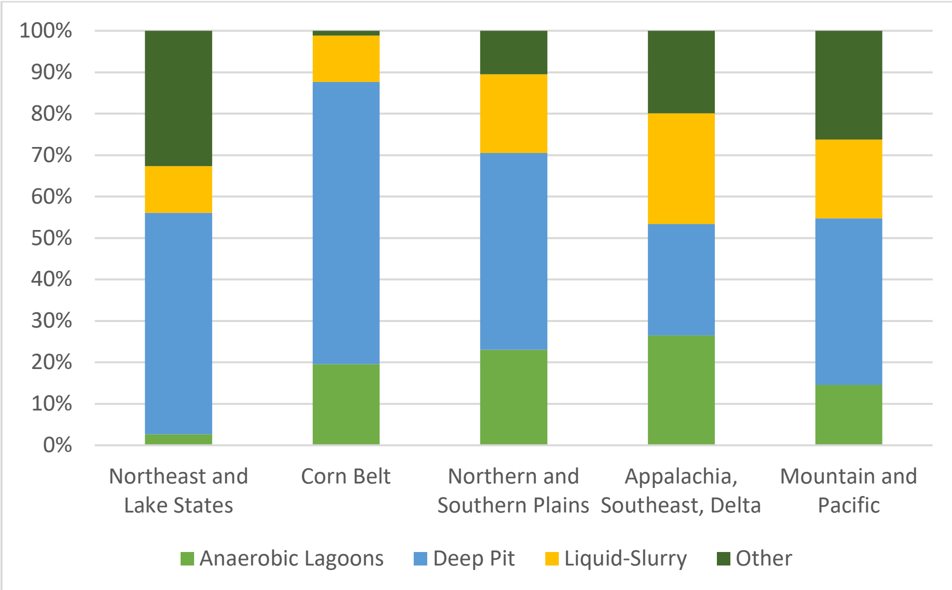
To unify regions across the data, region changes were made based on the EPA GHG inventory data classifications: Midwest, South, and North (ERG, 2022b). The States within each inventory region were reallocated to the USDA regions used in our analysis based on the percentages outlined in table 2. Each region in the "USDA Region" column is comprised of data from the "Inventory Region" column based on the "Percent To" column ratios. The mapping is based on the State composition of the corresponding wrong and proper regions. In each "USDA Region" the sum of the comprising percentages sum to 100 percent to ensure complete mapping. For example, for the Mountain and Pacific region, 50 percent of those data stem from the South, and 50 percent from the North. Another interpretation of this data is that all 50 percent of the underlying States from the Midwest and 33 percent of the underlying States from the South are combined to make the complete picture of the Northern and Southern Plains data.

Table 2. USDA swine business as usual region conversion

Inventory Region	Percent From	Percent To	USDA Region
Midwest	50%	100%	Corn Belt
Midwest	50%	50%	Northern and Southern Plains
South	33%	50%	
South	33%	100%	Appalachia, Southeast, and Delta
South	33%	50%	Mountain and Pacific
North	50%	50%	
North	50%	100%	Northeast and Lake States

Figure 4 shows the distribution of baseline practices based on the region mapping done in table 2. Similar to the aggregate national baseline practices (figure 3), the deep pit category comprises a large portion of each region's baseline practices. The largest of the three BAU practices is typically deep pit, which varies by region, but represents at least 25 percent in each region, and up to 65 percent in the Corn Belt.

Figure 4. Swine business as usual practices by USDA region



Applicability Updates

The applicability of each anaerobic digester and solid separator based on the baseline practices and farm size and livestock type. In Pape et al. (2016), these assumptions were based on expert judgement, however these values have been updated to also incorporate manure management practice data from EPA Agstar (EPA, 2022a). This data allowed for manure management practice adoption by farm size and livestock type to refine previous assumptions. The EPA Agstar database did not include what the BAU practice was, or include solid separators, thus this was obtained though expert opinion and based on Pape et al. (2016).

Dairy

For dairy farms, the applicability of each farm size and baseline practice combination are presented in table 3. The interpretation of this data yields that for small farms (1 – 199 milking cow places), for all baseline practices, 20 percent of those farms could utilize complete mix digesters with EG. Another example would be that for large farms (2,500+ milking cow places) that utilize Anaerobic Lagoons currently, 50 percent of those farms could transition to use Covered Lagoon Digester with Gas Conditioning. Blank cells refer to technologies that are not applicable for a given size or baseline, such as the transition from Anaerobic Lagoon to Plug Flow Digester.

Table 3. USDA dairy mitigation applicability assumptions based on baseline practice and farm size

Farm Size Category	BAU	Mitigation Options				
		Covered Lagoon Dig. EG	Covered Lagoon Dig. Gas Conditioning	Complete Mix Dig. EG	Plug Flow Dig. EG	Solids Separator
1–199	Anaerobic Lagoon	20%	50%	20%		10%
1–199	Deep Pit	20%	50%	20%	10%	
1–199	Liquid Slurry	10%	40%	20%	30%	
200–499	Anaerobic Lagoon	20%	50%	20%		10%
200–499	Deep Pit	20%	50%	20%	10%	
200–499	Liquid Slurry	10%	40%	20%	30%	
500–999	Anaerobic Lagoon	20%	50%	20%		10%
500–999	Deep Pit	20%	50%	20%	10%	
500–999	Liquid Slurry	10%	40%	20%	30%	
1,000–2,499	Anaerobic Lagoon	20%	50%	20%		10%
1,000–2,499	Deep Pit	20%	50%	20%	10%	
1,000–2,499	Liquid Slurry	10%	40%	20%	30%	
2,500+	Anaerobic Lagoon	20%	50%	20%		10%
2,500+	Deep Pit	20%	50%	20%	10%	
2,500+	Liquid Slurry	10%	40%	20%	30%	

Swine

For swine farms, the applicability of each farm size and baseline practice are presented in table 4. The interpretation of these data shows that for small farms (<999 head), who currently utilize liquid slurry, 30 percent of those farms could utilize complete mix digesters with electricity generation. Another example would be that for large farms (>5,000 head) that utilize Anaerobic Lagoons currently, 50 percent of those farms could transition to use Covered Lagoon Digester with Gas Conditioning. Blank cells refer to technologies that are not applicable for a given size or baseline, such as the transition from Anaerobic Lagoon to Plug Flow Digester.

Table 4. USDA swine mitigation applicability assumptions based on baseline practice and farm size

Farm Size Category	BAU	Mitigation Options			
		Covered Lagoon Digester with EG	Covered Lagoon Digester with Gas Conditioning	Complete Mix Digester with EG	Plug Flow Digester with EG
<999	Anaerobic Lagoon	20%	50%	30%	
<999	Deep Pit	20%	40%	40%	
<999	Liquid Slurry	10%	30%	30%	30%
1,000–2,499	Anaerobic Lagoon	20%	50%	30%	
1,000–2,499	Deep Pit	20%	40%	40%	
1,000–2,499	Liquid Slurry	10%	30%	30%	30%
2,500–4,999	Anaerobic Lagoon	20%	50%	30%	
2,500–4,999	Deep Pit	20%	40%	40%	
2,500–4,999	Liquid Slurry	10%	30%	30%	30%
>5,000	Anaerobic Lagoon	20%	50%	30%	
>5,000	Deep Pit	20%	40%	40%	
>5,000	Liquid Slurry	10%	30%	30%	30%

Greenhouse Gas Data

Baseline greenhouse gas (GHG) mitigation potential estimates were updated using the most recent Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020 data (EPA, 2022b). These estimates for methane, nitrous oxide, and volatile solids (VS) were used to calculate baseline emissions in each region for each technology and are used to estimate the potential emissions reductions from the adoption of specific management practices. These values were also used to update the per farm emission reduction potential through the estimation of regional emission factors generated by dividing regional methane emissions from the Inventory of U.S. Greenhouse Gas Emission and Sinks: 1990-2020 (EPA, 2022b) by the reported regional volatile solids production. These estimates were then applied consistently across farm sizes and types to develop baseline emissions for representative farms in each region. Other summary assumptions used to estimate the GHG impacts, and breakeven costs are presented in table 5. Estimates are based on expert opinion and in line with assumptions from Pape et al. (2016).

Table 5. Summary digester assumptions

Assumption	Value	Unit	Reference
Costs			
Equipment Lifetime	20	Years	Heinen and Petok (2022)
Annual Operations and Maintenance Cost[9]	4	Percentage of total costs	Estimate
Volatile Solid and Biogas Collection and Use			
Management system (MS) component efficiency	85	%	Climate Action Reserve 4.0 Protocol (Climate Action Reserve, 2013)
Operational hours of biogas system per year	8,000	Hour	Estimate
Electrical generation efficiency	14,000	BTU/kWh	EPA, AgStar Farmware 3.4 (2009)
Price of electricity	See table 7	$/kWh	EIA. Average Retail Price of Electricity to Ultimate Consumers by End-Use (EIA, 2022).
Solid Separation			
Solid Waste Extraction Efficiency	80	%	Assumption[10]
Animal Characteristics			
Manure production per milking cow place[11]	7.1	lb VS/head/day	Table 1.b of ASAE D384.2:Manure Production and Characteristics (2005)
Manure production per sow place[12]	5.2	lb VS/head/day	EPA AgSTAR Farmware 3.4 (2009)
Methane emitted from volatile solids, milking cow place	2.72	ft^3/lb VS	EPA Inventory of U.S. GHG Emissions and Sinks: 1990-2020 (2022)
Methane emitted from volatile solids, sow place[13]	7.7	ft^3/lb VS	EPA Inventory of U.S. GHG Emissions and Sinks: 1990-2020 (2022)
Methane Properties			
Global Warming Potential (GWP) of methane	24	Mt CO_2- eq/mt CH_4	IPCC Annex 2 Metrics & Methodology (2014)

[9] This operations and maintenance cost does not account for additional personnel that may be required for operating the digester system. The need for additional personnel will by operation and will result in an increase in the break-even prices presented in this report.
[10] Based on expert opinion, and Pape et. al (2016), the cause of efficiency ranges identified by Mukhtar, Sweeten, and Auvermann (2018) due to the flow rate, distribution, shape, size, and chemical nature of particles were refined and assumed to be 80 percent for the advanced separators examined.
[11] Milking cow place refers to the capacity of the dairy facility to hold cattle (milking cows) and includes both mature lactating cows and heifers.
[12] Sow place refers to the capacity of the swine facility to hold mature female swine (sows) and includes both the lactating sows and the gestating sows
[13] Farmware 3.4 estimates the ultimate methane yield for a farrow-to-finish operation as 0.3525 m^3/kg VS. If this ultimate methane yield is applied to the kinetic equation of Hashimoto used in calculating Farmware methane yields for a complete mix digester at 20-days HRT and 35 F temperature, the actual methane yield will be 0.29 m^3/kg VS, or 4.61 ft^3/lb VS.

Density of methane	0.0417	lb/ft^3	Density at normal temperature and pressure (20 C and 1 atm, respectively)
Energy content of methane	1,010	BTU/ft^3	EIA. Heat content of natural gas. Kopalek (2014)

Cost Data

Cost component data was identified for dairy and swine based on an in-depth literature review to reflect the experienced costs to farms and the variability of costs with farm size.

Dairy Lagoon

The base cost function revisions for dairy digesters with EG is based on data from 16 recent case studies of digesters on diaries ranging from 300 to 7,000 cows and summarized in table 6. The cost data from these studies were converted using the calculations in Appendix B. A best-fit curve was developed and shown below in figure 5. It was determined that for plug flow, complete mix, and covered lagoon digesters, the following equation fit this curve which expressed capital cost (Capex) per cow as a function of the number of cows per farm:

$$Capex\ per\ cow = -545.4 \text{ x } \ln(milking\ cows) + 6{,}068$$

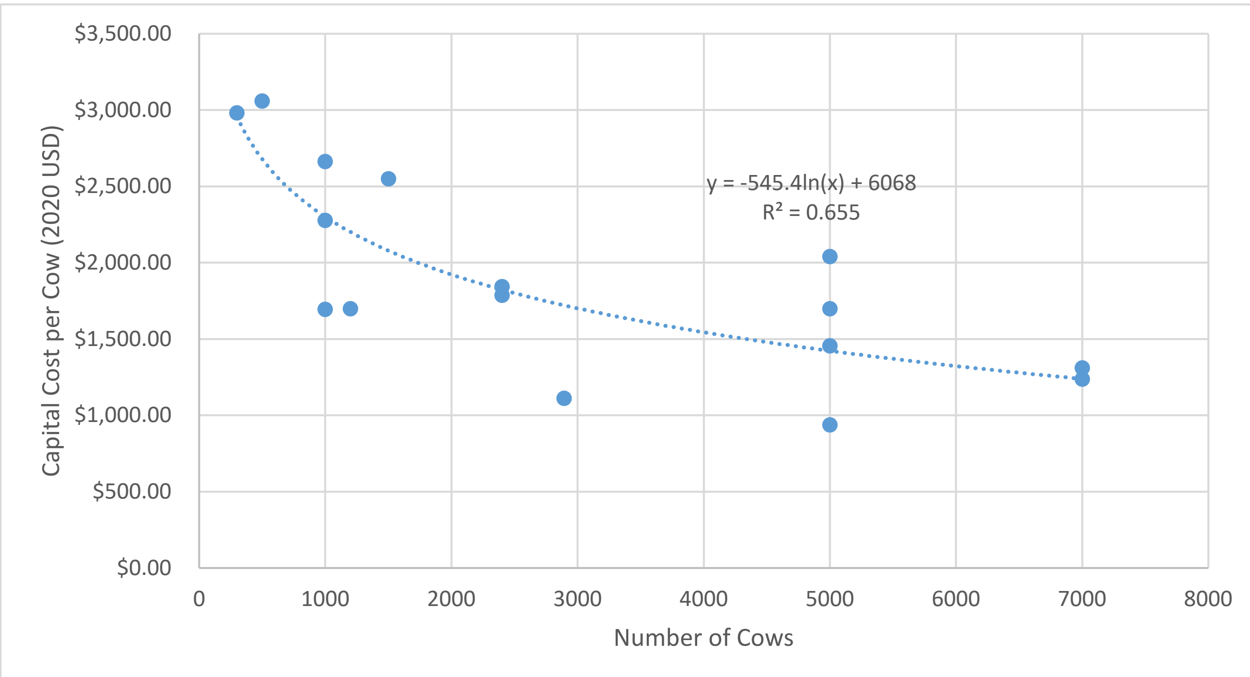
Also shown in table 6 are the annual operating costs (Opex) for the various sizes of digesters. This information was used to develop the Digester Cost Profile Spreadsheet, for which the summary cost profiles are shown in table 6. In this table the above equation was applied to all the digester types: complete mix, plug flow, and covered lagoon. In previous assumptions by Pape et al. (2016), the covered lagoon was found to be less expensive than complete mix or plug flow digesters. Over the past 10 years, covered lagoon technology has become more complex and expensive in part due to water and air quality regulations that require double lining, leak detection systems, and sophisticated methods for the lagoon cover with requirements varying by State. As a result, the per cow Capex for covered lagoon digesters is assumed like that of complete mix and plug flow. The annual per cow Opex is based on the assumptions from Pape et al. (2016) that those costs are equal to 4 percent of Capex, which yields a range of between $56 and $116 per cow.

Table 6. Literature cost estimates for dairy digesters in 2020 USD

Reference	Type	Number of Cows	Capital ($ per cow)	O&M ($ per cow)
Joshi and Wang (2018)	Complete Mix EG	2,892	$1,111.76	$38.48
Benevidez (2019)	Complete Mix EG	500	$3,060.00	
Benevidez (2019)	Complete Mix EG	1,500	$2,550.00	
Benevidez (2019)	Complete Mix EG	5,000	$2,040.00	
Cowley and Brorsen (2018)	Complete Mix EG	1,000	$1,695.20	$33.28
Cowley and Brorsen (2018)	Complete Mix EG	5,000	$938.08	$23.92
Williams, CalBio (2014)	Complete Mix EG	2,400	$1,787.50	$119.63
California Energy Comm (2014)	Complete Mix EG	2,400	$1,842.50	$63.61
Benevidez (2019)	Mixed Plug Flow EG	1,200	$1,699.32	
Benevidez (2019)	Mixed Plug Flow EG	5,000	$1,699.32	
Cowley and Brorsen (2018)	Mixed Plug Flow EG	1,000	$2,662.40	$52.00
Cowley and Brorsen (2018)	Mixed Plug Flow EG	5,000	$1,456.00	$37.44
Benevidez (2019)	Covered Lagoon EG	7,000	$1,238.28	$47.94
Benevidez (2019)	Covered Lagoon EG	7,000	$1,311.72	$60.18
SMUD (2015)	Covered Lagoon EG	1,000	$2,277.00	$183.70
California Energy Comm (2014)	Covered Lagoon EG	300	$2,981.00	$85.80
Covered Lagoon CalBio (2022)	Covered Lagoon RNG	5,000	$2,070.00	$118.68
Aaron Smith UC Davis (2021)	Covered Lagoon RNG	2,000	$2,376.00	$291.06
Aemetis (2022)	Covered Lagoon RNG	126,000	$2,189.60	
Duke University (2014)	Gas Upgrading Only	18,000	$550.00	$55.00

As shown in figure 5, the capital cost per cow (and resulting operating costs per cow) decrease as farm sizes increase, an expected economy of scale. This regression reads as: on average for a 1 percent increase in number of cows, you will see a decrease of $545 capex cost per cow. This trend is not linear, as clearly increases in farms size on smaller the end result in larger decreases in cost per cow, whereas large farms barely decrease capital costs per cow as the number continues to increase. This is exhibited in table 6, where among Covered Lagoon RNG operations, the number of cows ranged from 2,000 to 126,000 and capital costs per cow were almost identical.

Figure 5. Logistic regression of capital cost per cow on farm size



For the purpose of this analysis, specific thresholds for farm size and technology are necessary to generate representative farms which can have their breakeven costs calculated for. As a result, the estimates from figure 5 are used to calculate costs for specific farm size and technologies as seen in tables 7A and 7B. Using these values, input tables for the MACC curves can be generated. Base costs are computed by applying the equation from figure 5 to the specific farm size and technology. The hydrogen sulfide equipment cost is then estimated by multiplying the base cost by the hydrogen sulfide treatment percentage (in these cases 10.5 percent of base costs). The total Capital Costs are calculated by summing the Base, Hydrogen Sulfide, Flare, and Utility Charge costs. Recurring costs are generated based on the assumption that they are equal to 4 percent of the capital costs (Pape et al., 2016).

Table 7A. Calculated dairy digester costs for technology and farm size combinations - constants

Technology	$ per/animal	$ starting point	Electricity Generation (Y/N)	Farm Size	# of Cows	# of Heifers
Complete Mix Digester with EG			Y	200–499	300	300
Plug Flow Digester with EG			Y	500–999	600	600
Covered Lagoon Digester with Biomethane Upgrading(BMU)	$2,400	$0	N	1,000–2,499	1,000	1,000
Covered Lagoon Digester with EG			Y	2,500+	5,000	5,000

Table 7B. Calculated dairy digester costs for technology and farm size combinations

Farm Size	Mitigation Technology	Base Cost ($)	Hydrogen Sulfide Treatment ($)	Flare ($)	Utility Charges ($)	Capital Cost (2020 USD)	Recurring Cost (2020 USD)
2,500+	Complete Mix Digester with EG	$6,366,685	$197,367	$210,101	$337,434	$7,111,587	$284,463
2,500+	Plug Flow Digester with EG	$6,366,685	$197,367	$210,101	$337,434	$7,111,587	$284,463
2,500+	Covered Lagoon Digester with Biomethane Upgrading(BMU)	$12,000,000	$-	$-	$-	$12,000,000	$730,000
2,500+	Covered Lagoon Digester with EG	$6,366,685	$197,367	$210,101	$337,434	$7,111,587	$284,463
1,000–2,499	Complete Mix Digester with EG	$2,058,957	$63,828	$67,946	$109,125	$2,299,855	$91,994
1,000–2,499	Plug Flow Digester with EG	$2,058,957	$63,828	$67,946	$109,125	$2,299,855	$91,994
1,000–2,499	Covered Lagoon Digester with Biomethane Upgrading(BMU)	$2,400,000	$-	$-	$-	$2,400,000	$146,000
1,000–2,499	Covered Lagoon Digester with EG	$2,058,957	$63,828	$67,946	$109,125	$2,299,855	$91,994
500–999	Complete Mix Digester with EG	$1,384,985	$42,935	$45,704	$73,404	$1,547,028	$61,881
500–999	Plug Flow Digester with EG	$1,384,985	$42,935	$45,704	$73,404	$1,547,028	$61,881
500–999	Covered Lagoon Digester with EG	$1,384,985	$42,935	$45,704	$73,404	$1,547,028	$61,881
200–499	Complete Mix Digester with EG	$793,997	$24,614	$26,202	$42,082	$886,894	$35,476
200–499	Plug Flow Digester with EG	$793,997	$24,614	$26,202	$42,082	$886,894	$35,476
200–499	Covered Lagoon Digester with EG	$793,997	$24,614	$26,202	$42,082	$886,894	$35,476

Swine Lagoon

It was assumed, as in the original study, that swine farms with 150 sow places would be too small to justify the use of a digester. The base cost function revision for swine digesters with electric generation (EG) was derived from the dairy digester function and adjusted using a scaling factor based on the relative volatile solids produced by the swine to the volatile solids produced by dairy. This scaling factor is equal to the ratio of the volatile solids produced by one sow place to the volatile solids produced by a full-sized cow. The ratio is equal to 0.31. Based on the assumption in the Dairy digester rationale, it was determined that for plug flow, complete mix and covered lagoon digesters, the following equation fit this curve which expressed capital cost (Capex) per sow place as a function of the number of sow places per farm:

$$\textit{Capex/sow place} = -538.5 \ln(\# \textit{ of sow places} \times 0.31) + 6007.1$$

The annual operating costs (Opex) for the various sizes of digesters are then based on 4 percent of the Capex (Pape et al., 2016). This information was used to develop the Digester Cost Profile Spreadsheet, for which the summary cost profiles are shown in tables 8A and 8B. In this table the above equation was applied to all the digester types where electric generation (EG) was used: complete mix, plug flow, and covered lagoon. Originally the covered lagoon was found to be less expensive than complete mix and plug flow digesters. The covered lagoon technology has become more complex and expensive over the past 10 years due in part to water and air quality regulations that require double lining, leak detection systems and sophisticated methods for the lagoon cover. Therefore, the per sow place Capex for covered lagoon digesters is now similar to the Capex for complete mix and plug flow digesters. The operating costs, or Opex per sow place per year is based on the original assumption of 4 percent of the capital cost, resulting in an Opex ranging from $30 to $40/sow place per year.

As for digesters that are used to produce renewable natural gas (RNG) there was an example found while researching present day swine digesters. This example was the large producer, Smithfield (Kraig Westerbeek VP, Renewables 2822 Hwy 24 W, Warsaw, NC 28398 smithfieldfoods.com), who has a facility in Utah where there are 26 hog farms that each have 9,100 growing and fattening pigs (total 236,000 pigs). Each farm has covered lagoon digesters that are connected by pipelines to a central gas upgrading facility for injection into the utility natural gas distribution system, which purchases the renewable natural gas (RNG) at Low Carbon Fuel Standard (LCFS) prices. The overall cost of this system was reported to be $59 million for a Capex cost of $250 per pig. This facility would be the equivalent of 31,000 sow places. Therefore, the Capex cost function was assumed to be a simple $1,855 times the number of sow places.

As for the operating costs, Smithfield reported that the annual operating cost for digester with RNG would be approximately 10 percent of the capital cost. It is higher than the digesters with EG because of the higher power needs for compression and gas upgrading. When this is done with the parameters in tables 8A and 8B, the Opex is $185/sow place.

Table 8A. Calculated swine digester costs for applicable technology and farm size combinations – constants

Technology	$ per/animal	$ starting point	Electricity Generation (Y/N)	Farm Size	# of Sow Places
Complete Mix Digester with EG			Y	< 999	0
Plug Flow Digester with EG			Y	1,000–2,499	150
Covered Lagoon Digester with Biomethane Upgrading(BMU)	$1,855		N	2,500–4,999	500
Covered Lagoon Digester with EG			Y	> 5000	2500

Table 8B. Calculated swine digester costs for applicable technology and farm size combinations

Farm Size	Mitigation Technology	Base Cost ($)	Hydrogen Sulfide Treatment ($)	Flare ($)	Utility Charges ($)	Capital Cost (2010 USD)	Recurring Cost (2010 USD)
1,000–2,499	Complete Mix Digester with EG	$163,954	$5,083	$5,410.50	$8,690	$183,137	$7,325
2,500–4,999	Complete Mix Digester with EG	$456,574	$14,154	$15,067	$24,198	$509,993	$20,400
> 5000	Complete Mix Digester with EG	$1,681,717	$52,133	$55,497	$89,131	$1,878,478	$75,139
1,000–2,499	Plug Flow Digester with EG	$163,954	$5,083	$5,410	$8,690	$183,137	$7,325
2,500–4,999	Plug Flow Digester with EG	$456,574	$14,154	$15,067	$24,198	$509,993	$20,400
> 5000	Plug Flow Digester with EG	$1,681,717	$52,133	$55,497	$89,131	$1,878,478	$75,139
> 5000	Covered Lagoon Digester with Biomethane Upgrading(BMU)	$4,637,500	$-		$-	$4,637,500	$463,750
1,000–2,499	Covered Lagoon Digester with EG	$163,954	$5,083	$5,410	$8,690	$183,137	$7,325
2,500–4,999	Covered Lagoon Digester with EG	$456,574	$14,154	$15,067	$24,198	$509,993	$20,400
> 5000	Covered Lagoon Digester with EG	$1,681,717	$52,133	$55,497	$89,131	$1,878,478	$75,139

Solid Separators

The standard types of solid separators are classified as primary and advanced, which vary in capital costs, operating costs, and solids removal. Solid separator costs begin at around $10,000 and can range up to $50,000 (Iowa, 2022). Other additions can bring the total to around $123,000 (Illinois, 2022). Based on expert opinion, primary separators were assumed to consist of sloped screens, rotary screens, and screw presses, while advanced separators were assumed to consist of centrifuges, and flocculation systems. Based on those assumptions, a primary separator will remove about 50 percent of the solids in the mix, leading to 50 percent more capacity for treating waste in the covered lagoon (Worley, 2009). An advanced solid separator will attach to a current solid separator or be a step between the solid separator and the covered lagoon. Once the normal solid separator splits the liquids from the solids, the advanced solid separator can further break down the solids into more refined pieces. This will lead to more nutrient recovery in the refined solids (Frear et al., 2018).

These values are presented in table 9. Cost and efficiency estimates are based on estimates from Frear et al. (2018), Worley, J. (2009) and Swine Extension (2019).

Table 9. Solid separator costs (in 2020 USD) and efficiency estimates

Component	Cost	Unit
Primary Solid Separator		
Capital Costs	40	$/cow
Operating Costs	12	$/cow/year
Solid Removal Rate	20-50	%
Advanced Solid Separator		
Capital Costs	170	$/cow
Operating Costs	55	$/cow/year
Solid Removal Rate	80	%

The parameters for the advanced solids separation were used to revise the Solid Separator cost profile. Costs for advanced solid separators are significantly higher than the primary solid separators due to higher manufacturing and material costs. The resulting cost profile for solid separators are shown in tables 10A and 10B based on the applicable farms of 1,000 cows and larger.

Table 10A. Dairy solid separator cost profile - constants

Solids Separation Costs	Value	Compost Production Costs	Value	Farm Size	# of Cows	# of Heifers
Per cow Capital Cost for advanced solids separation	$170	Per-cow Operation Cost	8	1,000–2,499	1,000	1,000
Total Capital cost for advanced solids separation for 4,000 cows	$680,000	Percent of Capital Cost	0.04	2,500+	4,000	4,000
Total Capital cost for advanced solids separation for 1,000 cows	$170,000	Percent of VS in finished compost	0.5			
Per-cow Operation Cost	$55	Percent VS per finished compost	0.4			
Total operating cost for 4000 cows	$220,000	Value of finished compost ($/ton)	20			
Total operating cost for 1000 cows	$55,000	Composting (Y/N)	1			

Table 10B. Dairy solid separator cost profile

Farm Size	Capital Cost for Solids Separation	Annual Operating Cost for Solids Separation	Capital Cost for Windrow Composting Equipment	Annual Operating Cost for Composting Production	Capital Cost (2020 USD)	Recurring Cost (2020 USD)	VS (lb/day)	Finished Compost Quantity (tons/day)	Total Revenue (2020 USD)
2,500+	$680,000	$220,000	$350,000	$46,000	$1,030,000	$266,000	62,313	33.1	$241,659
1,000–2,499	$170,000	$55,000	$100,000	$12,000	$270,000	$67,000	15,578	8.28	$60,415

Revenue Update

Digester

There are two main types of revenue generation through digesters: EG and sale, and biogas generation and sale. For EG there are three technologies: solid separators, covered lagoons, and plug flow digesters. Each of these technologies generates electricity depending on the size and technology of the farm, which is used to either offset farm electricity costs and/or sold as excess. The electricity rates for these sales are a combination of industrial and commercial rates for the offset rates, and the utility generation rate for excess sales. For biogas revenue volatile solids are captured and sold via the interState gas pipelines to qualify for California's LCFS market (California Air Resources Board, 2022).

Electricity Generation

In order to generate electricity for digesters, volatile solids generated from both dairy and swine digesters are converted into electricity generation based on the digester specific conversion rates. EG is then divided into two categories: offset farm usage, and excess electricity generation. The reason for this is that the electricity rates vary based on how the electricity is consumed/refunded. Consumption of farms uses a 75 percent commercial, 25 percent industrial rate mix,[14] while rebate uses the industrial rate which is lower than commercial. As a result, offsetting farm energy use is more efficient than selling all generated electricity, and excess is used to generate surplus revenue.

The electricity generated by swine digesters is estimated using the number of hours of operation each year, the rate of volatile solid generation per sow place, and the conversion rate from volatile solids to electricity in kilowatts to create kilowatt hour averages for representative swine farms (tables 11A and 11B).

Table 11A. Electricity generation estimates for swine farms - constants

Operating hours per year for EG (hours/year)	Farm Size	# of Sow Places	Calculated # of Head Per Operation
8,000	< 999	0	
8,000	1,000–2,499	150	826
8,000	2,500–4,999	500	2,754
8,000	> 5,000	2,500	13,771

[14] This split is based on input from ICF energy market expert Craig Shultz, who also suggested that another split could be 90 percent commercial / 10 percent industrial if these offset rates were overestimating the revenue.

Table 11B. Estimates for complete mix digester with electricity generation on swine farms

Region	Electricity Region	Farm Size	Capacity of Conversion Equipment (kW)	Offset of On-site Electricity (kWh)	Electricity Required Per Operation (kWh)	Excess Electricity Sold Back to Grid (kWh)	Revenue from Offset (2010 USD)
Appalachia	South	1,000–2,499	10.7	85,413	214,822	-	$6,965
Appalachia	South	2,500–4,999	35.6	284,711	716,103	-	$23,218
Appalachia	South	> 5000	177.9	1,423,556	3,580,345	-	$116,088
Corn Belt	Midwest	1,000–2,499	10.7	85,413	125,588	-	$6,710
Corn Belt	Midwest	2,500–4,999	35.6	284,711	418,645	-	$22,368
Corn Belt	Midwest	> 5000	177.9	1,423,556	2,093,125	-	$111,842
Delta	South	1,000–2,499	10.7	85,413	214,822	-	$6,832
Delta	South	2,500–4,999	35.6	284,711	716,103	-	$22,774
Delta	South	> 5000	177.9	1,423,556	3,580,345	-	$113,870

Similarly, the electricity generated by dairy digesters is estimated using the number of hours of operation each year, the rate of volatile solid generation per milking cow place, and the conversion rate from volatile solids to electricity in kilowatts to create kilowatt hour averages for representative dairy farms (tables 12A and 12B).

Table 12A. Electricity generation parameters for dairy farms - constants

Farm Size	# of Cows	# of Heifers	Annual Hours of Operation
200–499	300	300	8,000
500–999	600	600	8,000
1,000–2,499	1,000	1,000	8,000
2,500+	5,000	5,000	8,000
Mitigation Technology	**Collection Efficiency for Cows**	**Collection Efficiency for Heifers**	**Annual Hours of Operation**
Complete Mix Digester with EG	0.90	0.50	8,000
Plug Flow Digester with EG	0.90	0.50	8,000
Covered Lagoon Digester with EG	0.75	0.45	8,000

Table 12B. Electricity generation estimates for dairy farms with complete mix digester with EG by size and region

Region	Farm Size	Capacity of Conversion Equipment (kW)	Offset of On-site Electricity (kWh)	Excess Electricity Sold Back to Grid (kWh)
Appalachia	200–499	60	237,300	239,523
Appalachia	500–999	119	474,600	479,046
Appalachia	1,000–2,499	199	791,000	798,410
Appalachia	2,500+	993	3,955,000	3,992,048
Corn Belt	200–499	60	330,600	146,223
Corn Belt	500–999	119	661,200	292,446
Corn Belt	1,000–2,499	199	1,102,000	487,410
Corn Belt	2,500+	993	5,510,000	2,437,048
Delta	200–499	60	237,300	239,523
Delta	500–999	119	474,600	479,046
Delta	1,000–2,499	199	791,000	798,410
Delta	2,500+	993	3,955,000	3,992,048

Electricity used to offset farm usage as well as kWh sold back to grid are multiplied by the corresponding rates to generate the estimated revenue for a given farm size/region combination. For the offset usage, the 75 percent commercial rate is used compared to the generate rate for excess energy sold back to the grid in order to account for the differences in how those energy offsets impact the offset costs or revenue generation incurred by the farm (table 13).

Table 13. Electricity rates in cents per kilowatt hour

Units are cents per kilowatt hour in 2020 dollars

Region	Weighted Average Price (based on Consumption)	90% Commercial Average	75% Commercial Average	Generation Rate for energy rebate	Flexible Average (on Commercial price)
Southeast	0.08	0.1	0.09	0.08	0.08
Pacific	0.14	0.15	0.14	0.07	0.13
Mountain	0.08	0.09	0.09	0.06	0.08
Delta	0.07	0.09	0.08	0.07	0.07
Northeast	0.11	0.12	0.11	0.08	0.1
Corn Belt	0.08	0.09	0.09	0.07	0.08
Northern Plains	0.08	0.09	0.09	0.04	0.08
Appalachia	0.08	0.09	0.08	0.06	0.08
Lake States	0.09	0.11	0.1	0.07	0.09
Southern Plains	0.06	0.07	0.07	0.08	0.06
Nation	0.09	0.1	0.1	0.07	0.09

U.S. Energy Information Administration, Form EIA-861, Annual Electric Power Industry Report.

Based on Craig Shultz's input, the 75% average could be used for larger farms, the 90% could be used for small/medium commercial farms. Other values are generated in the event that our assumptions want to be tested.

Biogas Upgrading

To generate the quantity of LCFS credits a representative farm in a given region, the following assumptions are used to estimate the quantity of biogas that is generated on an annual basis given the size and carbon intensity of the farm (table 8). For this analysis a standard carbon intensity of -250 gCO_2/MJ is used.[15] Over the past few years, the average weekly price of LCFS credits from California's system (linked with Oregon and Washington, but accessible to dairy and swine farms outside that region) has decreased significantly from over $200 in early 2020 to $115.62 during the week of May 16, 2022[16] (California Air Resources Board, 2022). For this analysis, $115.62 is used to estimate the revenue generated from biogas sales.

In addition, biogas generation qualifies for RIN credits, which currently are rated at $2.01 per credit (EPA, 2022c). Each credit represents 1 MJ of renewable energy, which can be estimated using the conversion from gallons of biogas using the energy content in joules of renewable

[15] We acknowledge that for swine farms a carbon intensity of -250 gCO_2/MJ is quite conservative. Based on the assumptions in this methodology, the breakeven price for all modeled swine farms using -250 gCO_2/MJ is negative and lowering the carbon intensity value would shift the curve lower. If a user has more farm specific information about the CI, the MACC model allows for the alteration of CI values in the Digester Background tab.

[16] This period was used because it was the most recent data available at the time of model creation.

biogas (See the calculated biogas gallons per RIN credit value below in table 14). In order to estimate the amount of biogas generated for a representative farm, the number of animals is multiplied by the pounds of volatile solids per day, the methane volume per pound of volatile solids, and subsequently either the conversion from cubic feet of methane to gallons of biogas or transformed to into megajoules in order to account for the revenue from RIN credits.

Table 14. Biogas upgrading assumptions

Assumptions	Units	Value
VS per day (dairy)	Lbs	7.1
VS per day (swine)	Lbs	5.2
Methane per lb of VS (dairy)	Ft^3	2.72
Methane per lb of VS (swine)	Ft^3	7.7
BTU per ft^3 of Methane	BTU/ft^3	1000
BTU per Megajoule	BTU/MJ	947.82
Cubic meter per cubic foot	M^3/ft^3	0.0283168
Days per year	Days	365
Value of LCFS Credit	$	115.62
Biogas carbon intensity	gCO_2/MJ	-250
Energy content of biogas	MJ/ft^3	1.055053
Gallons per ft^3	Ft^3/gal	0.012
Biogas gallons per RIN credit	Gal/credit	11.67

Compost Revenue Generation

In order to estimate the potential revenue generated from the conversion of solids into marketable compost, pounds of volatile solids per day are multiplied by the solid separation rate to estimate the percent of volatile solids that end up as finished compost. That total compost per day is converted from pounds per day to tons of compost per year. For this analysis the value of compost is estimated to be a net return of $20 per ton across all regions.[17] Revenue per ton of compost is an estimate generated from expert opinion and assumptions from Frear et al. (2018) and Pape et al. (2016). The contribution of compost revenue may be reevaluated in the future once more studies are published establishing estimates on regional heterogeneity in prices, and regional shipping costs.

MACC Modeling and Figures

MACCs provide a greater understanding of the regional costs of implementing anaerobic digesters by estimating what the price of carbon dioxide equivalent (CO_2e) would need to be for producers to adopt various technologies of anaerobic digesters.

The steps to prepare the MACC were as follows:

- **Background Data**
  - Performed literature review to gather background information on baseline GHG emissions, emissions reductions per digester implemented, number of head per region, labor costs, cost to install/operate various digesters, electricity/biogas rates for generated energy, and efficiency improvements.
  - Summarized background information in Excel spreadsheet
  - Prepared new MACC tab in overall USDA MACC Excel file
  - Entered in data from summary spreadsheet calculations into MACC model by region
- **MACC Component Calculations:**
  - **Abatement Options:** By farm size in terms of number of head (i.e., 1-199 head, 200-499 head, etc.)
  - **Lifetime:** 20 years. Capital and Recurring costs are adjusted by lifetime in the final calculation.
  - **Capital Cost:** Estimated from literature, as the dollar value to install a specific digester.
  - **Recurring Cost:**
    - Total Recurring Cost by Region = 4 percent of Capital Costs based on expert opinion and existing assumptions.
    - Set for values inputted into the MACC.
  - **Total Revenue:** Revenue was generated by estimating kWh generated for the electricity generation, or the number of LCFS credits based on farm size and efficiency of the digester. Those values are then applied to the current offset

[17] Since compost prices and input costs vary from region to region, and if retail prices varied by enough, it could be economically efficient to ship compost to a different region for sale. Due to the lack of sufficient data, we were unable to model the drying, packing, and shipping costs for farmers and as a result estimate net revenue per ton for comparison to sale within region and as a result a uniform net revenue per ton was used.

electricity/excess electricity rates, the current LCFS price, and any revenue from applicable regional renewable energy program.

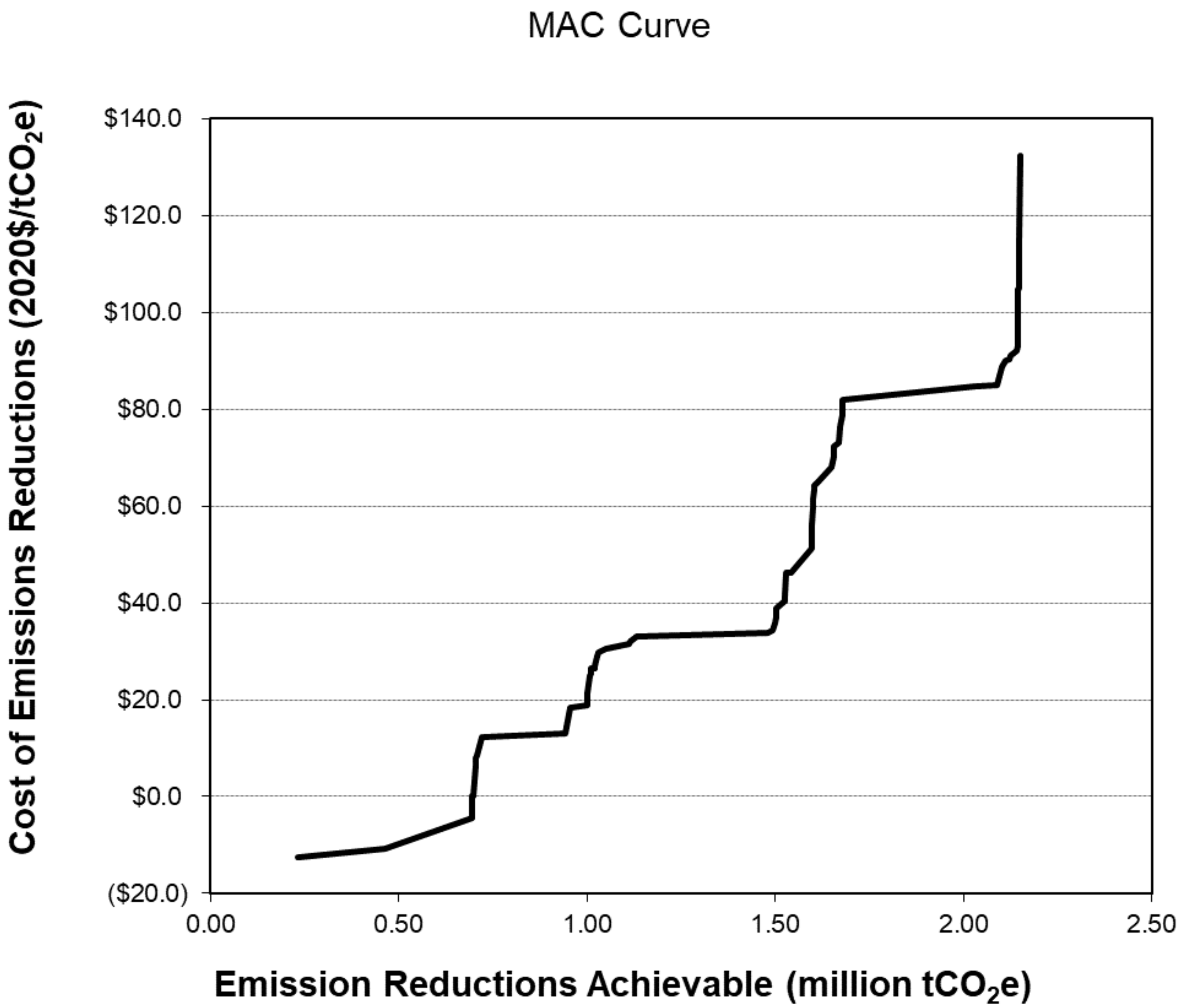
- **Emissions Reduction:** Total GHG Emissions Reductions Per Region in tons of CO_2e
  - tCO_2e Reduction Per Region = [(Baseline GHG Emissions Per Head x % Reduction in CH_4) x GWP CH_4 x Number of Head Per Region]
- **Regional Breakeven Cost:** In 2020 USD/tCO_2e; calculated using MACC formulas.

For MACC curves see Appendix A. The following table represents the technologies in each Appendix A figure.

Appendix figure	Technology Represented
Appendix A–1	**Dairy Covered Lagoon – Electricity Generation**
Appendix A – 2	**Dairy Complete Mix Digester**
Appendix A – 3	**Dairy Plug Flow Digester**
Appendix A – 4	**Dairy Covered Lagoon – Biogas Upgrading**
Appendix A – 5	**Swine Covered Lagoon – Electricity Generation**
Appendix A – 6	**Swine Complete Mix Digester**
Appendix A – 7	**Swine Plug Flow Digester**
Appendix A – 8	**Swine Covered Lagoon – Biogas Upgrading**
Appendix A – 9	**Dairy Solid Separator**

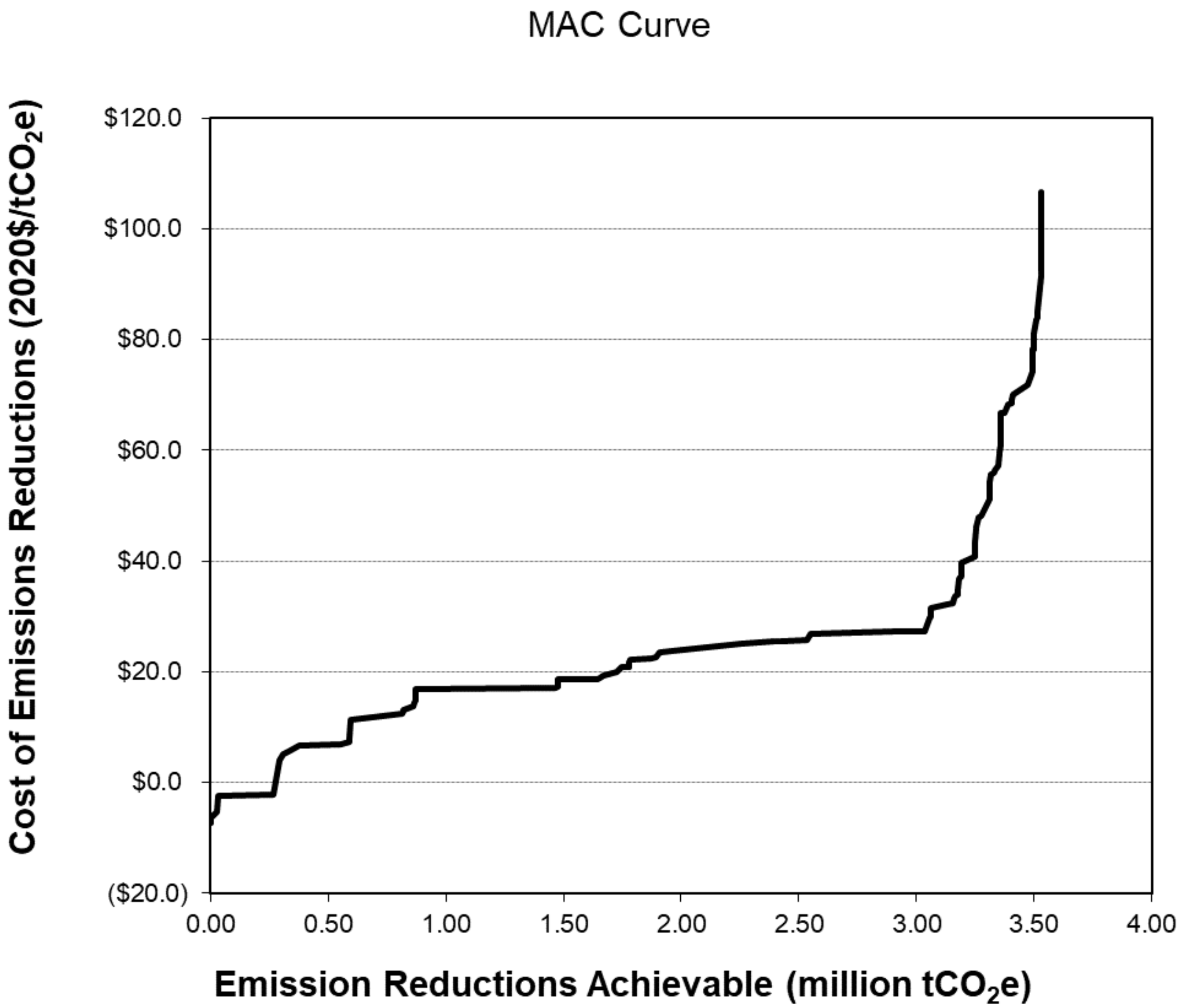
Appendix A

Appendix A-1. Dairy covered lagoon – electricity generation

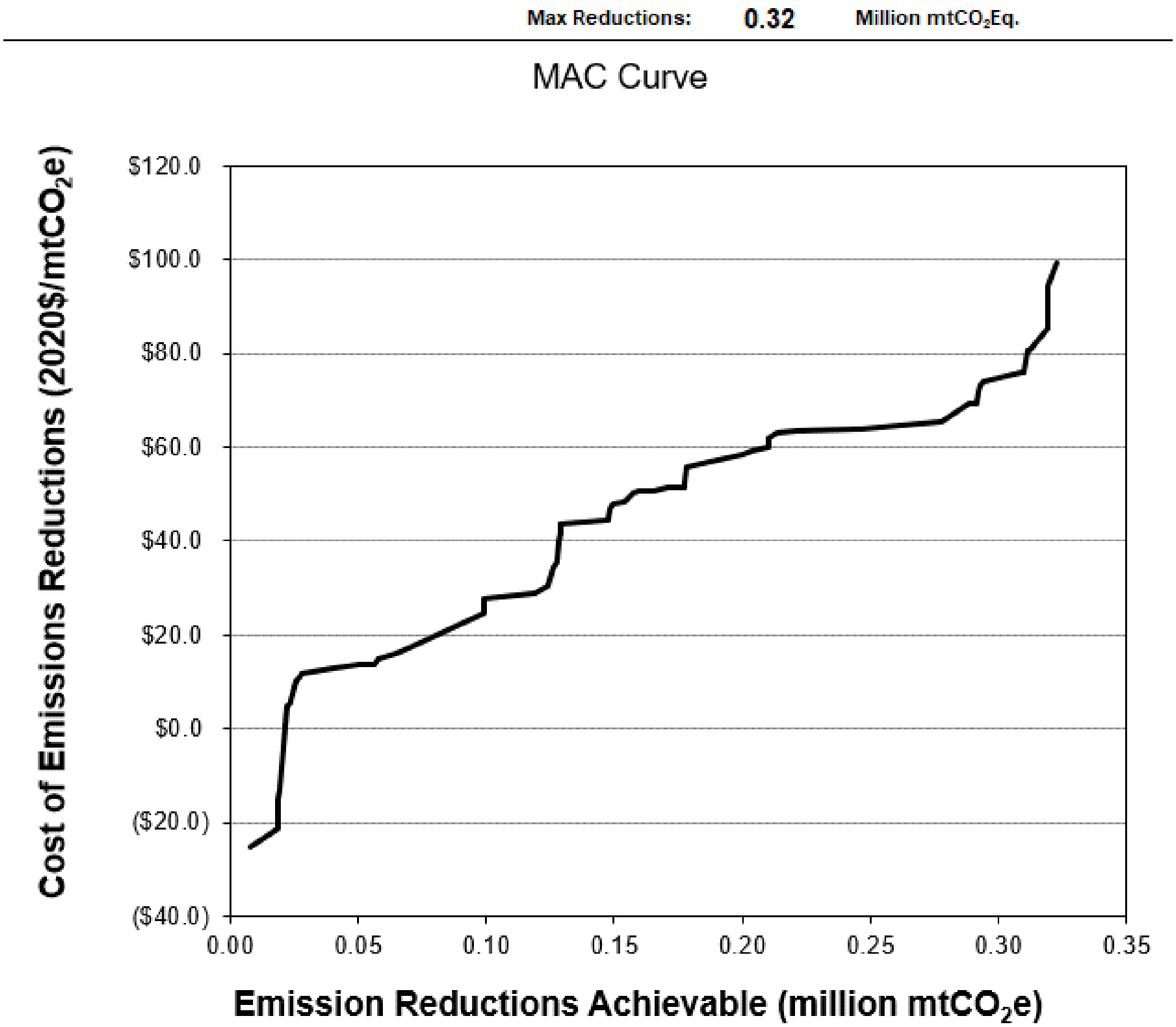


Note: t=metric tons, CO_2e=carbon dioxide equivalent.

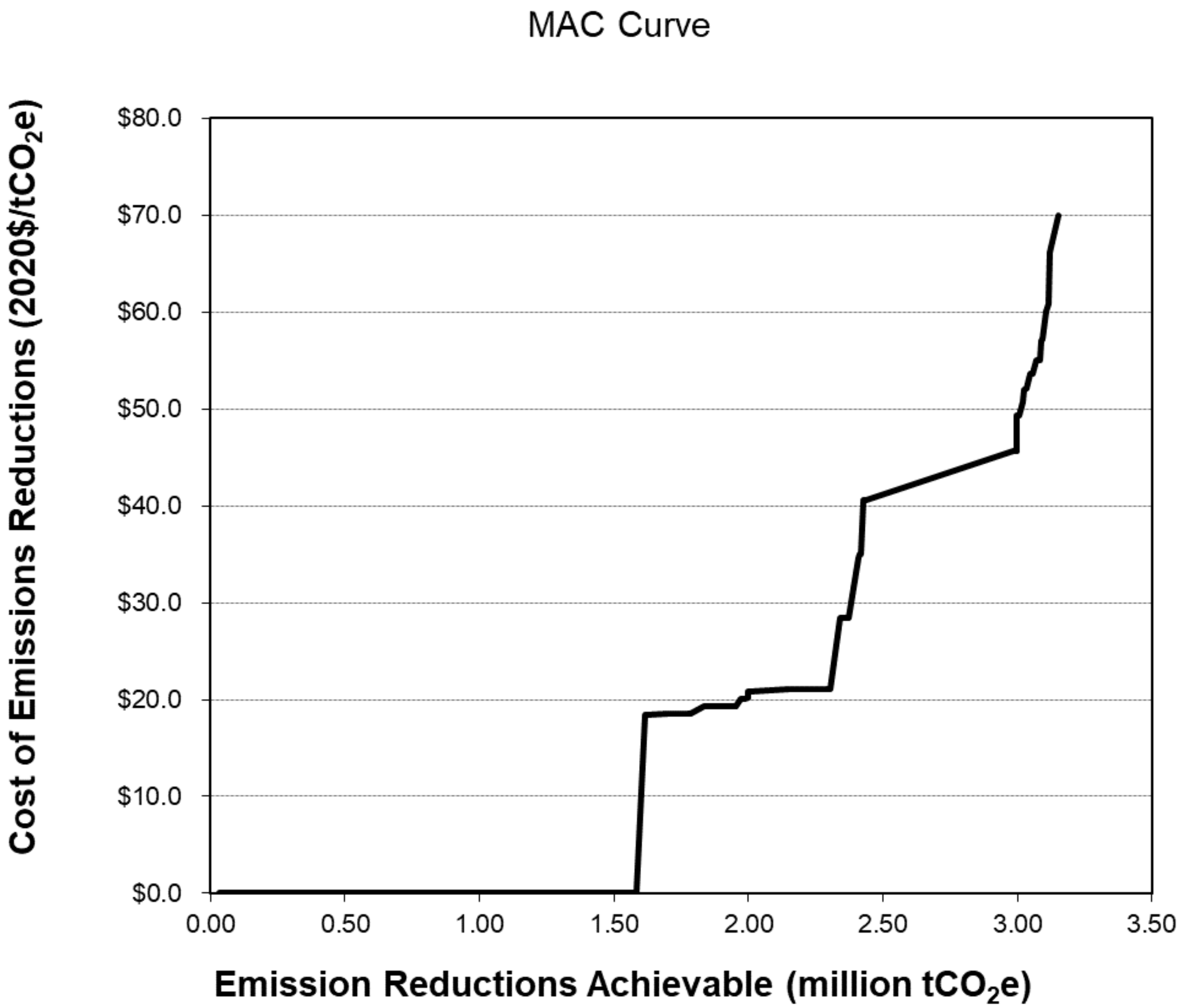
Appendix A-2. Dairy complete mix digester



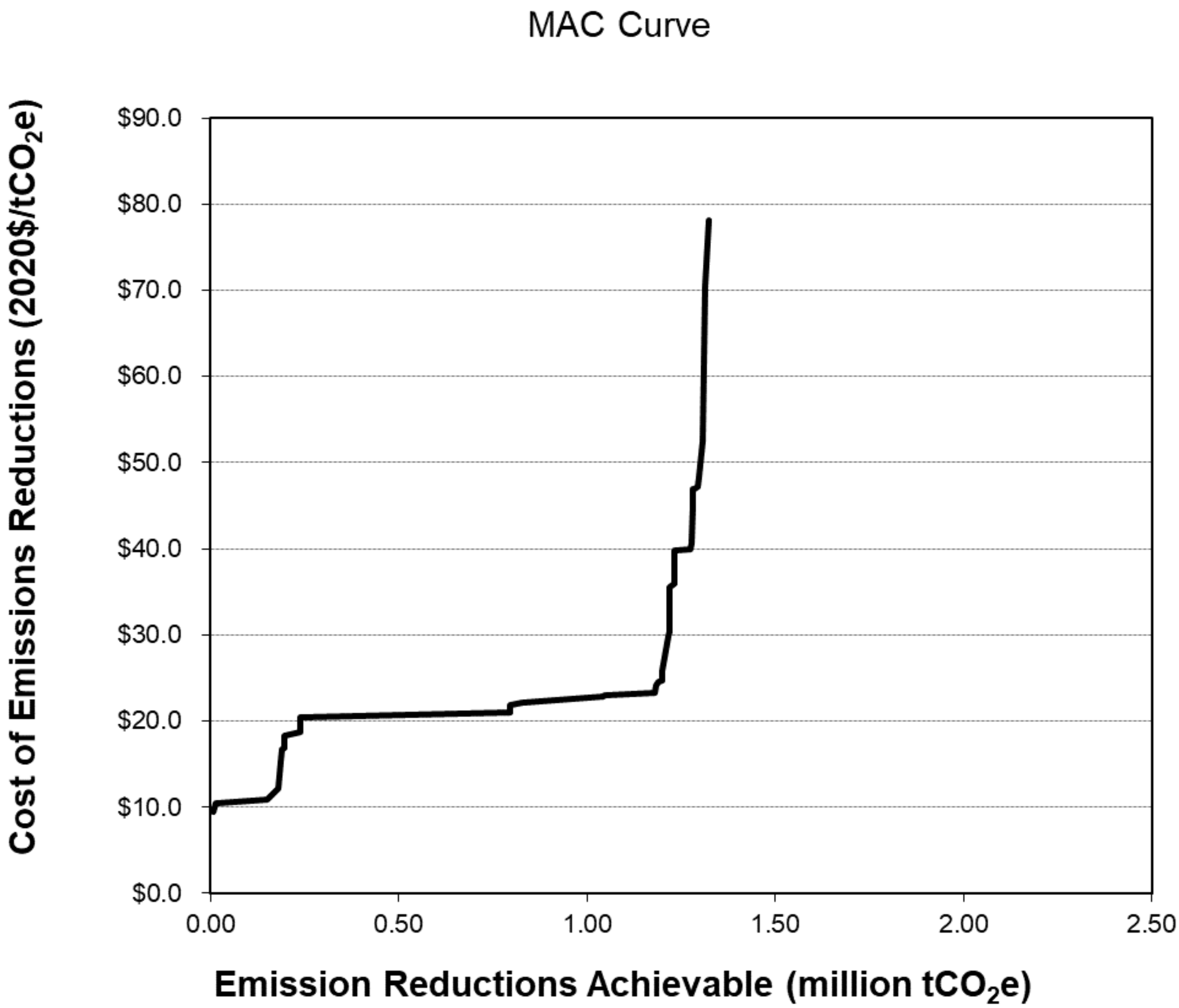
Appendix A-3. Dairy plug flow digester



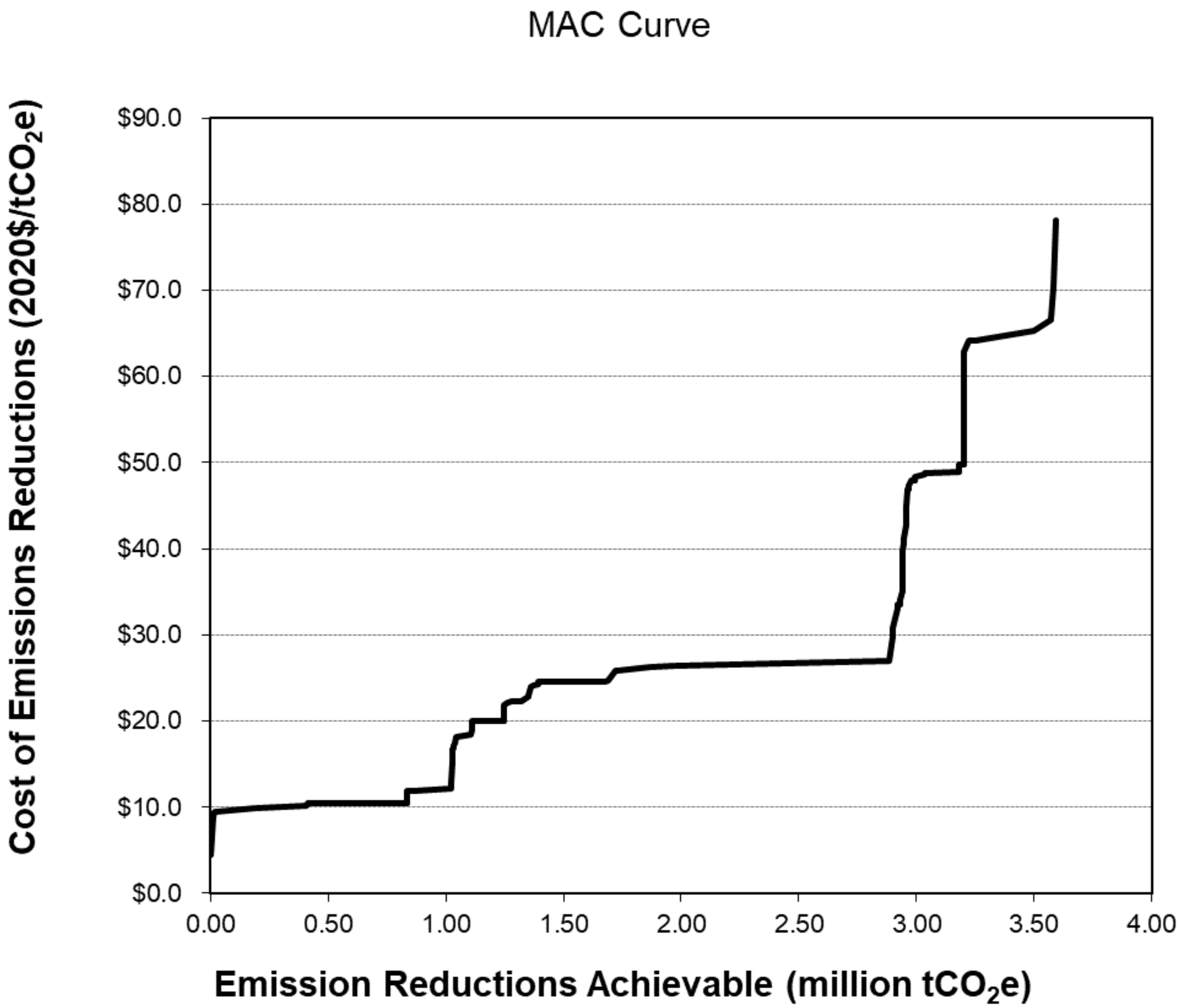
Appendix A-4. Dairy covered lagoon – biogas upgrading



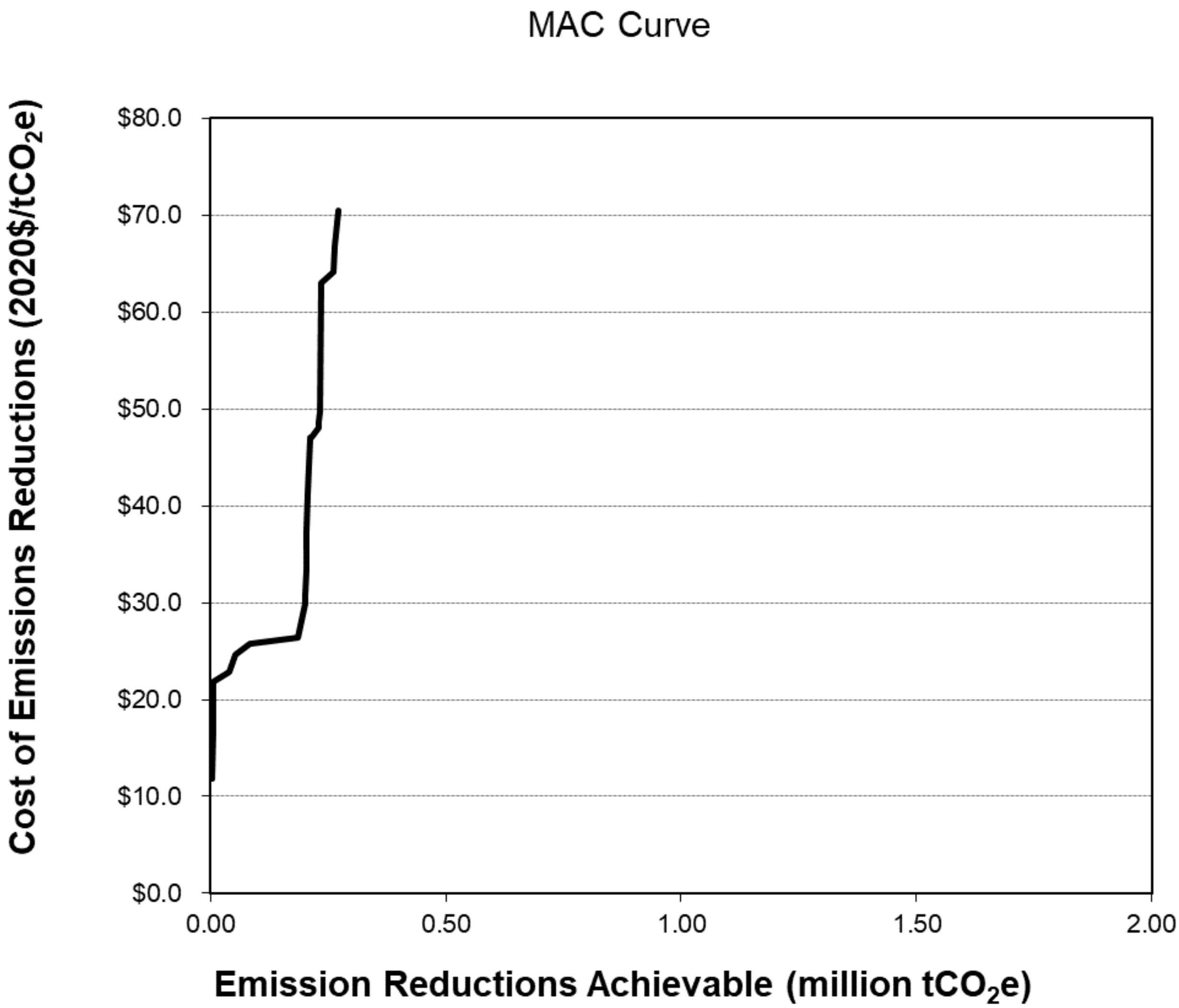
Appendix A-5. Swine covered lagoon – electricity generation



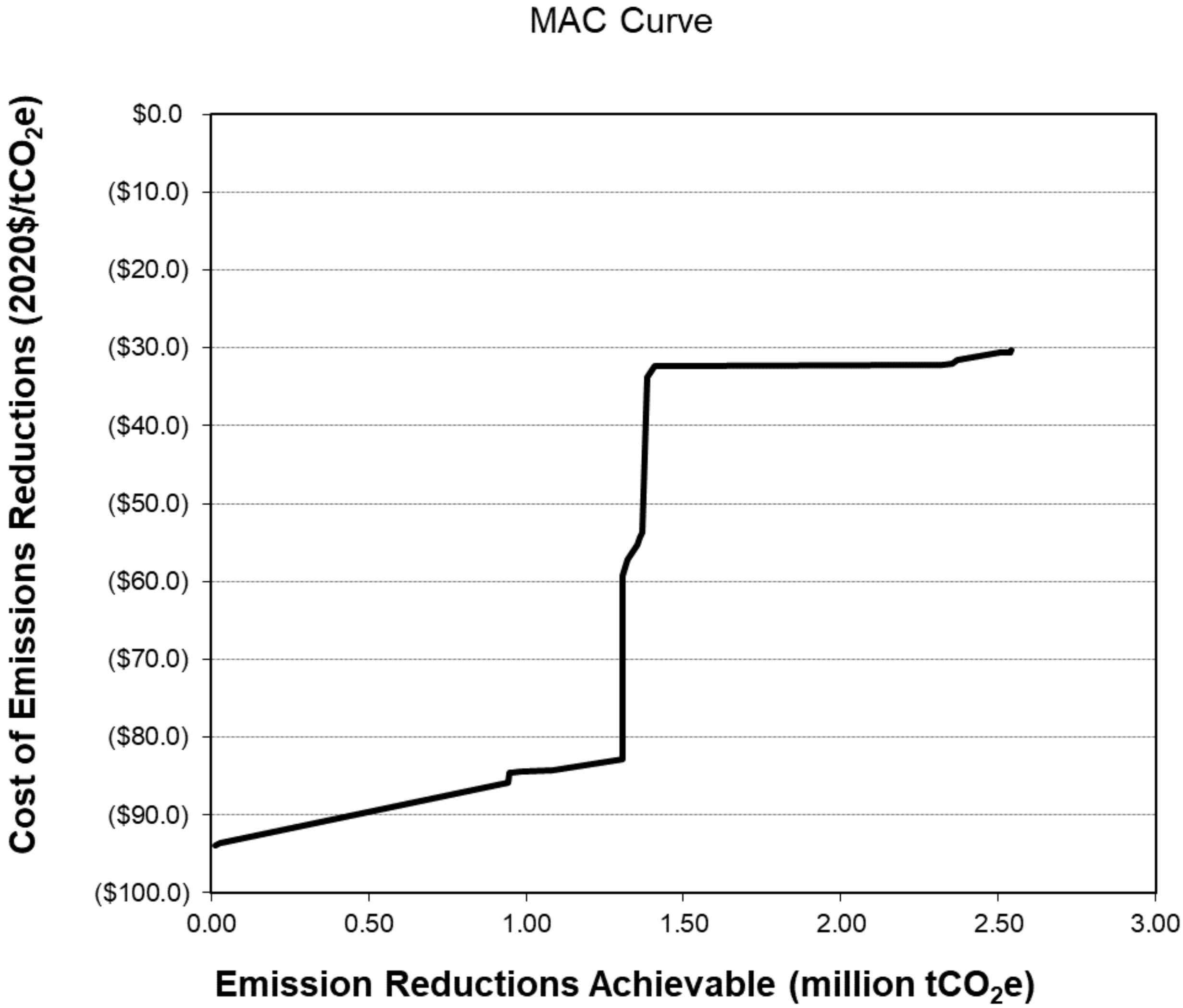
Appendix A-6. Swine complete mix digester



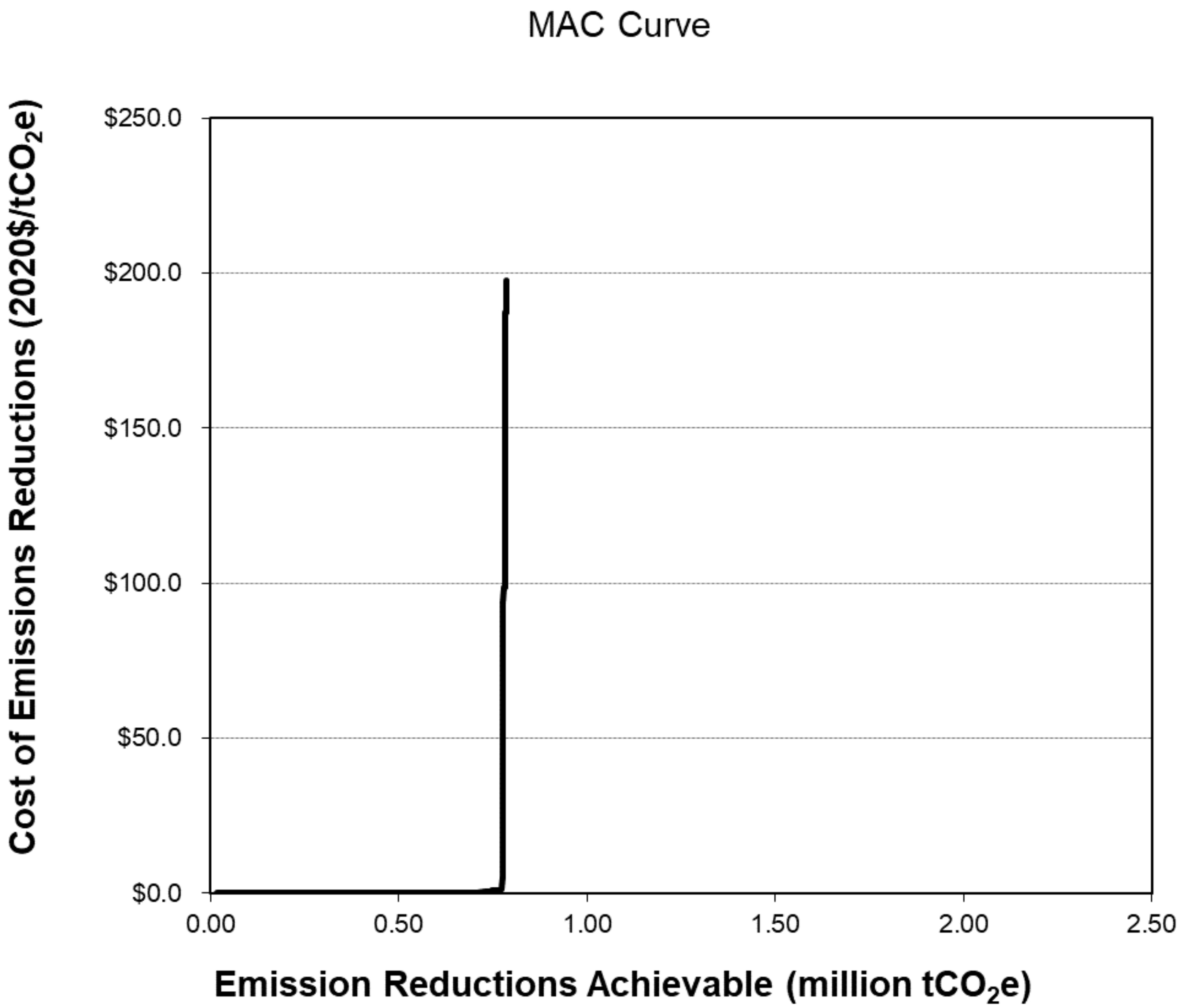
Appendix A-7. Swine plug flow digester



Appendix A-8. Swine covered lagoon – biogas upgrading



Appendix A-9. Dairy solid separator[18]



[18] Due to the current construction of the MACC tool, emission reductions less than 0.01 million $mtCO_2e$ are not able to be displayed.

Appendix B

Fact sheet re: covered lagoon dairy digester with EG costs:

1. 2013 USDA report costs (2010): 5,000 cow dairy and 5,000 heifers
    a. Digester Cost: $2,961,790/4689 full-sized cow equivalents (FCE)= $631.55/FCE
    b. Recurring annual costs: $118,472/4689 FCE= $25.27/FCE
    c. Net Methane production: 87,288,000 cubic feet/4,689 FCE = 18,615 cu ft/FCE/yr
    d. Electrical Production: 837 KW X 8,000 hrs/yr = 6,7000,000 kwhrs/4,689 = 1,429 kwhrs/FCE
2. Benavidez (2019): 7,000 FCE's
    e. Digester Cost: $8,500,000/7,000 FCE = $1214/FCE
    f. Recurring annual costs: $330,000/7,000 FCE= $47 FCE
    g. Net Methane production: 83,271,100 cubic feet/7,000 FCE = 12,000 cu ft/FCE/yr
    h. Electrical Production: 942 KW × 7368 hrs/yr = 6,940,000 kwhrs/7,000 FCE = 991 kwhrs/FCE
3. 2019 Calif Energy commission report costs: 7,000 FCE's
    i. Digester Cost: $9,000,000/7,000 FCE = $1286/FCE
    j. Recurring annual costs: $414,000/7,000 FCE= $59/FCE
    k. Net Methane production: 128 million cubic feet/7,000 FCE = 18,000 cu ft/FCE/yr
    l. Electrical Production: 995 KW × 8,388 hrs/yr = 8,346,000 kwhrs/7,000 FCE = 1,192 kwhrs/FCE
4. 2014 Calif Energy commission report costs: 300 FCE's
    m. Digester Cost: $625,000/300 FCE = $2,083/FCE (add 30% for inflation $2,710 /FCE)
    n. Recurring annual costs: $16,553/300 FCE= $55/FCE (add 30% for inflation $78/FCE)
    o. Net Methane production: 8 million cubic feet/300 FCE = 26,667 cu ft/FCE/yr
    p. Electrical Production: 51 KW × 8,431 hrs = 430,000kwhrs/365 FCE = 1,178 kwhrs/FCE
5. 2015 SMUD report (Sison-Lebrilla, Elaine, Tiangco, Valentino, Lemes, Marco, and Ave, Kathleen. SMUD Community Renewable Energy Deployment Final Report. United States: N. p., 2015. Web. doi:10.2172/1185122).: 1000 FCE's
    q. Digester Cost: $1,800,000/1000 FCE = $1800/FCE (add 15% for inflation- $2070/FCE)
    r. Recurring annual costs: $166,794/1000 FCE= $167/FCE (add 15% for inflation: $192/FCE)
    s. Net Methane production: 30 million cubic feet/1000 FCE = 30,000 cu ft/FCE/yr
    t. Electrical Production: 564 KW X 3285 hrs = 1,852,740 kwhrs/1000 FCE = 1853 kwhrs/FCE

Fact sheet re: covered lagoon dairy digester with RNG (renewable natural gas) costs:

6. UC Davis report by Aaron Smith 2021: 2,000 FCE's
    a. Digester Cost: $480,000/2,000 FCE = $2,400/FCE
    b. Recurring annual costs: $588,000/2,000 FCE= $294/FCE
    c. Net Methane production: 45 million cubic feet/2000 FCE = 22,500 cu ft/FCE/yr
    d. RNG produced per year: 45,000 MMBTU/yr/2,000= 22.5 MMBTU/FCE
7. Aemetis : 126,000 FCE's and RNG upgrading
    a. Digester Cost: $300,000,000/126,000 FCE = $2,380/FCE
    b. Recurring annual costs: N/A
    c. Net Methane production: 1500 million cubic feet/126,000 FCE = 12,000 cu ft/FCE/yr
    d. RNG produced per year: 1,500,000 MMBTU/yr/126,000= 12 MMBTU/FCE
8. Duke University: RNG upgrading only , 18,000 FCE
    a. D: $9,000,000/18,000 FCE = $500/FCE
    b. Recurring annual costs: $900,000/18,000 FCE = $50/FCE
    c. Net Methane production: 72 million cubic feet/4,589 FCE = 15.6 cu ft/FCE/yr
    d. RNG produced per year: 72,000 MMBTU/yr/4,589= 15.6 MMBTU/FCE

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Chapter 4: Marginal Abatement Cost Curve Analysis – Feed Management

Chapter 4 of 8.

Contents

Technology Overview

Feed additives have the potential to mitigate methane emissions from enteric fermentation. Feed additives work by altering the chemical processes associated with enteric fermentation in the cattle rumen, which in turn suppresses methane production. This report examines the efficacy of monensin and lipid feed additives in reducing methane emissions, as these feed additives are already commonly used by cattle producers to manage a variety of concerns, including disease incidence, feed efficiency, bloat reduction, and meat and milk quality (Appuhamy et al., 2013) (Hegarty et al., 2021).This report does not examine other feed additives that have shown high methane mitigation potential, such as seaweed or 3-Nitrooxypropanol (3-NOP), due to lack of market readiness and FDA approval (Searchinger et al., 2021).

Monensin feed additives can reduce methane emissions by 3–8 percent in beef cattle operations. Monensin feed additives suppress methane production by changing the composition of bacteria in the rumen bacteria and inhibiting the growth of Gram-positive bacteria, which produce the substrates used in methane production (Appuhamy et al., 2013). Monensin can be mixed directly into feed rations for cattle raised in confinement or incorporated into medicated blocks and fed as a free choice supplement in forage systems (Elanco, 2022). Monensin is typically fed at a rate of 7-22 mg per pound of dry matter intake (Hegarty et al., 2021).

Lipid feed additives (i.e., supplemental fat) have also been widely shown to inhibit methane production (Honan et al., 2021). Lipid supplements replace a portion of the calories sourced from typical feed rations, thus reducing the intake of fibrous material, which in turn suppresses methane production. The type of lipid used is less important than increasing overall dietary fat intake (Beauchemin et al., 2008). Lipid supplementation reduces methane emissions by approximately 4-5 percent for every 1 percent increase in dietary fat, (Beauchemin et al., 2008); (Rasmussen & Harrison, 2011). Total lipid supplementation, however, should not exceed 6-7 percent of total dry matter intake, as supplementation beyond this level can harm rumen health (Honan et al., 2021).

Greenhouse Gas Data

The Feed Additives MACC relies on the U.S. Inventory of Greenhouse Gas Emissions and Sinks for baseline emissions factor for different cattle types in 2020. The U.S. Inventory estimates cattle emissions using the Cattle Enteric Fermentation Model (CEFM), which uses cattle dietary characteristics to develop annually variable emissions factors for each cattle type (e.g., dairy, forage, feedlot, etc.) (U.S. EPA, 2022). Please see the Inventory of U.S. Greenhouse Gas Emissions and Sinks, Appendix 3, Part B for further information on the underlying assumptions in the CEFM. The emissions factors used in the MACC are presented in table 1.

Table 1. Emissions factors per animal type

Production System	Animal Type in U.S. Inventory	2020 Emissions Factor–Kg CH_4 Per Head Per Year	CH_4 Emissions tCO2e Per Head Per Year
Beef, Forage*	Bulls/Cows	96.5	2.41
Beef, Feedlot	Feedlot Cattle	43	1.08
Dairy	Cows	150	3.75

*Beef, Forage emissions factor is the average of the emissions factors for beef bulls and beef cows.

A literature review was performed to determine the methane emissions reductions achieved by supplementation with feed additives. The degree of reduction in methane emissions depends both on the type of feed additive and the production system, i.e., beef or dairy. Table 2 shows the percent reduction in methane emissions per animal type and production system.

Table 2. Percent reductions in CH_4 emissions per feed additive and production system (inputted into MACC)

Feed Additive	Production System	Baseline CH_4 (tCO_2e Per Head Per Year)	Reported Percent Reduction in CH_4 Emissions from Enteric Fermentation	Net Reduction in CH_4 Emissions (tCO_2e per head per year)	Source
Monensin	Beef, Forage	2.41	8.0%	0.19	(McGinn et al., 2004); (Appuhamy et al., 2013); (Vyas et al., 2018); (Hemphill et al., 2018)
Monensin	Beef, Feedlot	1.08	20.0%	0.22	(Appuhamy et al., 2013); (Guan et al., 2006); (Vyas et al., 2018); (Thornton & Owens, 1981)
Lipids	Beef, Forage	2.41	9.4%*	0.23	(Beauchemin et al., 2008); (Hales & Cole, 2017)
Lipids	Beef, Feedlot	1.08	8.2%*	0.09	(Beauchemin et al., 2008); (Winders et al., 2020); (Hales et al., 2017)
Lipids	Dairy	3.75	9.0%	0.34	(Eugène et al., 2008)

*Assumes a 2 percent total increase in supplemental fat.
**Note that the monensin dairy scenario was not estimated due to limited effectiveness of monensin on dairy cattle.

Data Collection and Analysis

To determine the emissions reductions achieved by supplementation with feed additives, the percent reductions in methane emissions were multiplied by the baseline emissions estimates per cattle type.

- **Formula:** CH_4 Reduction Per Head Per Year = (Baseline GHG Emissions Per Head Per Year x % Reduction in CH_4 Per Head Per Year)
- **Formula:** Net Reduction in CO_2e Emissions = CH_4 Reduction x GWP CH_4
    - **Example:** Lactating dairy cows emit 150 kg CH_4 per head per year (U.S. EPA, 2022). Supplementation with lipid feed additives has been shown to reduce methane emissions by around 9 percent, resulting in a 13.5 kg (0.34 tCO_2e) reduction in methane emissions per head per year.

Assumptions Update

- The Feed Additives MACC only accounts for direct reductions in methane emissions from enteric fermentation and does not consider indirect reductions in greenhouse gas emissions, such as any emissions reductions that may occur from reducing demand for animal feed. Indirect emissions reductions fall outside the scope of this MACC.

Cost Data

The Environmental Quality Incentives Program (EQIP) was used to determine labor costs to adopt feed additives. EQIP pays for feed additives under the Feed Additives Scenario in CPS 592 Feed Management. EQIP costs include cost of the feed additive and labor to unload shipments of feed additive and load the feed additive into the mixer. EQIP specifically pays for the cost to purchase zeolite, a feed additive used to control ammonia emissions in animal manure. Zeolite is not used to reduce methane emissions from enteric fermentation. Because the focus of this MACC is monensin and lipid feed additives that reduce methane emissions, the cost of the zeolite feed additive listed in the EQIP costs components ($40.54 per head) was subtracted from all regions to isolate only the costs associated with labor. Labor costs to adopt zeolite feed additives were assumed to be the same as the labor costs to adopt monensin and lipid feed additives. Table 3 shows the EQIP costs for labor and purchased zeolite feed additives, while table 4 shows the final EQIP labor costs per head.

Table 3. EQIP cost components for feed additives

Region	Component Cost ($ per head)	Component Justification	Quantity Justification
Appalachia	$23.20	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Appalachia	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
Corn Belt	$31.50	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Corn Belt	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
Delta States	$23.18	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Delta States	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect

Lake States	$24.68	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Lake States	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
Mid-Atlantic	$24.51	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Mid-Atlantic	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
New England	$29.90	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
New England	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
Northern Plains	$23.74	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Northern Plains	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
Pacific	$31.03	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Pacific	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
Southeast	$21.88	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Southeast	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
Southern Mountain	$26.10	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Southern Mountain	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect
Southern Plains	$23.83	General labor to unload shipments of zeolite, handle zeolite on farm, and load zeolite into feed mixer	1 hour of labor per animal unit per year.
Southern Plains	$40.54	Each animal unit will be fed 0.1 tons of zeolite per year to decrease ammonia emissions.	Each animal unit will need 0.1 tons of product to achieve desired effect

Table 4. EQIP labor costs per region

Region	EQIP Labor Cost Per Head
Appalachia	$23.20
Corn Belt	$31.50
Delta	$23.18
Lake States	$24.67
Mid-Atlantic	$24.50
Northeast	$29.90
Northern Mountain	$26.09
Northern Plains	$23.74
Pacific	$31.03
Southeast	$21.88
Southern Mountain	$25.08
Southern Plains	$23.83

Costs to purchase the monensin and lipid feed additives were calculated from outside EQIP. Feed additive costs were estimated based on a literature review since supplementation costs are primarily based on the additive type and the dosage. Monensin is estimated to cost around $0.02 cents per head per day for beef cattle, based on recommended rates of supplementation per cattle type (Elanco, 2022) (Hutjens, 2019) (Woolam, 2016). Costs for lipid feed additives are dictated primarily by the type of fat used. Since reductions in methane emissions are observed regardless of the type of the specific type of fat used, it was assumed that producers would use the cheapest fat supplement available, which was sunflower meal as of spring 2022 when this MACC was completed (Beauchemin et al., 2008); (USDA Market News Service, 2022). Additionally, lipids are often already included in cattle diets, typically at a baseline rate of 3 percent of total dry matter intake (Beauchemin et al., 2008). Supplemental fat, however, generally should not exceed 6-7 percent of total dry matter intake (Honan et al., 2021). To avoid exceeding this threshold, dosages were set at 2 lbs. for dairy cattle and 0.5 lbs. for beef cattle. Dosages for dairy cattle are greater than beef cattle since dairy cattle consume greater amounts of feed. Table 5 shows the cost of purchasing each type of feed additive supplement.

Table 5. Feed additives, supplement cost per year

Feed Additive	Dosage	Cost Per Head Per Year (2020 USD)	Source
Monensin, Beef	200 mg of monensin	$10.95	(Elanco, 2022); (Woolam, 2016)
Lipids, Beef	0.5 lbs. of sunflower meal	$27.83	(USDA Market News Service, 2022)
Lipids, Dairy	2 lbs. of sunflower meal	$111.33	(USDA Market News Service, 2022)

Supplementation with feed additives can reduce feed costs for producers by improving feed efficiency. Feed efficiency is the measure of how much feed it takes to produce a unit of product, i.e., a pound of weight gain or a pound of milk. Improving feed efficiency thus reduces the amount of feed needed to produce a pound of weight gain or milk. The MACC assumes that any percentage increase in feed efficiency translates to a direct reduction in feed costs, i.e., a 6.4 percent improvement in feed efficiency would reduce feed costs by 6.4 percent. Table 6 shows the feed efficiency gains achieved by each feed additive.

Table 6. Improvements in feed efficiency from feed additives

Feed Additive	% Improvement in Feed Efficiency	Source
Monensin, Beef	6.4%	(Duffield et al., 2012); (Marques & Cooke, 2021); (Hegarty et al., 2021)
Lipids, Beef	7-10%*	(Winders et al., 2020); (Boadi et al., 2004); (Buttrey et al., 2013)
Lipids, Dairy	6.4%	(Eugène et al., 2008)

*A 7 percent reduction was used in the model to conservatively estimate improvements in feed efficiency for beef cattle.

Baseline regional feed costs are needed to calculate savings as a result of improved feed efficiency. Baseline costs were determined using ERS Commodity Costs and Return estimates for beef cattle raised on forage and dairy cattle (USDA ERS, 2022). The Cow-Calf spreadsheet was used to estimate the feed costs for beef cattle on forage, while the Milk spreadsheet was used for dairy cattle feed costs. Milk costs were not given for the Mississippi Portal ERS region, so costs for the Mississippi Portal region were proxied to the Southern Seaboard ERS region. The ERS regions were converted to USDA regions by weighting feed costs by the proportion of each ERS region contained in each USDA region. Feed costs for beef cattle raised in feedlots were estimated using costs from State extension budgets and were averaged at the regional level, as shown in table 7. Regions without State-level costs were proxied to the average of the costs in regions with available data. Table 8 shows the annual feed costs for dairy and forage and feedlot beef cattle.

Table 7. Feedlot enterprise budgets

State	Feedlot Feed Cost ($ per head per year; 2020 dollars)	Name	Link
WI	$485.36	Feedlot Enterprise Budget UW	https://livestock.extension.wisc.edu/articles/look-at-all-costs-not-just-daily-feed-cost-when-evaluating-feedlot-rations/
IA	$598.00	Iowa Feedlot Estimated Livestock Returns	http://www2.econ.iaState.edu/estimated-returns/
ND	$433.00	A Cow-Calf Producer's Guide to Custom Feeding	https://www.ndsu.edu/agriculture/ag-hub/publications/cow-calf-producers-guide-custom-feeding
MO	$351.00	2021 Enterprise Budgets for Missouri Crops and Livestock	https://extension.missouri.edu/media/wysiwyg/Extensiondata/Pro/AgBusinessPolicyExtension/Docs/2021-budgets.pdf
SD	$370.00	Beef Cattle Budgets	https://extension.sdState.edu/beef-cattle-budgetscalculators/algebra
KS	$388.00	Beef Farm Management Guide Spreadsheet Budget	https://www.asi.k-State.edu/extension/beef/focusareas/costofproduction.html
TX	$601.00	Beef Cattle Decision Aids	https://agecoext.tamu.edu/resources/decisionaids/beef/
OH	$506.00	Market Beef Budget	https://farmoffice.osu.edu/farm-management/enterprise-budgets
MT	$648.00	Feedlot Enterprise Budget Tool	https://www.canr.msu.edu/news/enterprise-budget-tool-available-for-feedlot-producers
PA	$329.00	Sample Slaughter Steer Budget	https://extension.psu.edu/feeding-beef-cattle
GA	$352.00	Beef Cattle Budgets	https://agecon.uga.edu/extension/budgets.html

Table 8. Annual feed costs per head

Region	Dairy	Beef, Forage	Beef, Feedlot
Appalachia	$1,921.92	$353.25	$440.25
Corn Belt	$2,046.77	$395.18	$492.51
Delta States	$1,932.98	$342.40	$426.73
Lake States	$2,143.16	$394.63	$491.82
Mid-Atlantic	$2,109.05	$367.75	$458.32
New England	$2,104.56	$371.78	$463.35
Northern Mountain	$2,096.62	$386.59	$481.80
Northern Plains	$2,166.85	$426.95	$532.10
Pacific	$2,291.74	$326.53	$406.95
Southeast	$2,090.64	$294.83	$367.44
Southern Mountain	$2,118.28	$380.71	$474.48
Southern Plains	$2,209.68	$355.93	$443.59

Table 9. Feed savings per head per feed additive type

Region	Monensin, Beef Forage	Lipids, Beef Forage	Monensin, Beef Feedlot	Lipids, Beef Feedlot	Lipids, Dairy
Appalachia	$22.61	$24.73	$29.45	$32.21	$123.00
Corn Belt	$25.29	$25.29	$31.04	$33.95	$130.99
Delta States	$21.91	$21.91	$29.45	$32.21	$123.71
Lake States	$25.26	$25.26	$31.06	$33.98	$137.16
Mid-Atlantic	$23.54	$23.54	$21.06	$23.03	$134.98
New England	$23.79	$23.79	$29.45	$32.21	$134.69
Northern Mountain	$24.74	$24.74	$41.47	$45.36	$134.18
Northern Plains	$27.32	$27.32	$25.41	$27.79	$138.68
Pacific	$20.90	$20.90	$29.45	$32.21	$146.67
Southeast	$18.87	$18.87	$22.53	$24.64	$133.80
Southern Mountain	$24.37	$24.37	$29.45	$32.21	$135.57
Southern Plains	$22.78	$22.78	$38.46	$42.07	$141.42

Costs to feed dairy cattle are much greater than beef, as they consume much greater amounts of feed per day than beef cattle. Dairy cattle consume 50-55 lbs. of dry matter intake per day, while beef cattle consume around 18-26 lbs. of dry matter intake, depending on their growth stage (Fischer & Hutjens, 2019); (New et al., 2020).

Assumptions Update

The reduction in feed costs as a result of feed additives supplementation was calculated by multiplying the total feed cost by the percentage improvement in feed efficiency.

- **Formula:** Feed Savings Per Region = (Feed Cost Per Region x percent Improvement in Feed Efficiency Associated with Feed Additive Supplementation)
    - Assumes that any increase in feed efficiency translates to an equal percentage reduction in feed costs.

Total reoccurring costs were calculated by subtracting the feed savings from the EQIP labor costs and the cost to purchase the feed additives.

- **Formula:** Total Reoccurring Cost Per Head Per Year = [(EQIP Labor Costs + Feed Additive Cost) – Feed Savings]
    - EQIP labor costs are assumed to be the same for monensin and lipid feed additives and assumed to be equal to labor costs required to adopt zeolite feed additives, which as the feed additive NRCS used in the EQIP cost calculations.

The EQIP labor costs and the cost to purchase the supplement are assumed to reoccur annually.

- Some recurring costs are negative, meaning that the feed cost savings as a result of improved feed efficiency outweighed the cost to adopt feed additives.

Table 10. Total recurring cost to adopt feed additives (inputted into MACC)

Region	Monensin, Beef Forage	Lipids, Beef Forage	Monensin, Beef Feedlot	Lipids, Beef Feedlot	Lipids, Dairy
Appalachia	$11.54	$26.30	$4.70	$18.82	$11.52
Corn Belt	$17.16	$34.04	$11.41	$25.38	$11.83
Delta States	$12.22	$29.10	$4.68	$18.80	$58.44
Lake States	$10.36	$27.25	$4.56	$18.53	-$1.17
Mid-Atlantic	$11.91	$28.80	$1.08	$14.63	$0.85
New England	$17.06	$33.94	$15.60	$30.11	$6.53
Northern Mountain	$12.30	$29.18	$9.28	$23.78	$3.23
Northern Plains	$7.37	$24.25	$12.53	$26.65	-$3.61
Pacific	$21.08	$37.96	$10.30	$25.07	-$4.32
Southeast	$13.96	$30.84	-$3.68	$9.59	-$0.60
Southern Mountain	$11.66	$28.55	$6.80	$20.88	$0.83
Southern Plains	$12.00	$28.88	$4.70	$18.82	-$6.26

Applicability

The prevalence of feed additive supplementation varies by production system. Table 11 presents an overview of the current baseline adoption of feed additives in the United States. Baseline adoption levels will be used in the projection phase of the MACC report to estimate growth in feed additive use over time.

Table 11. Baseline adoption of feed additives

Feed Additive	Production System	Baseline Feed Additives Adoption Rate	Source
Monensin	Beef, Forage	6.0%	(USDA APHIS, 2019)
Monensin	Beef, Feedlot	29.0%	(USDA APHIS, 2019)
Lipids	Beef, Forage	11.3%	(USDA APHIS, 2019)
Lipids	Beef, Feedlot	54.2%	(USDA APHIS, 2019)
Lipids	Dairy	50%	Assumption based on literature reporting common supplementation of lipids (Searchinger et al., 2021)

Data on dairy and beef cattle populations were pulled from USDA's National Agricultural Statistics Service. The MACC uses beef and dairy cattle populations reported in the 2017 Census of Agriculture, which lists the number of head per farm size per State. The Census's Inventory of Milk Cows was used to estimate dairy cow populations, the Inventory of Cattle on Feed was used to estimate the number of cattle in feedlots, and the Inventory of Beef Cows was used to estimate forage beef cattle populations. The population estimates for each State were then summed by USDA region to estimate the number of head in each farm size category in each region. Table 12 shows beef and dairy populations per USDA region.

Table 12. Beef and dairy cattle populations per region

Production System	Type	# of Head	Appalachia	Corn Belt	Delta States	Lake States	Mid-Atlantic	New England	Northern Mountain	Northern Plains	Pacific	Southeast	Southern Mountain	Southern Plains
Forage	Beef	1–199	2,758,001	3,278,257	1,471,756	675,137	373,825	42,299	787,822	2,697,791	571,537	1,455,916	854,363	4,649,786
Forage	Beef	200–499	315,167	536,474	305,340	57,848	960	-	931,142	2,113,688	345,588	369,429	554,823	1,050,678
Forage	Beef	500–999	58,658	117,094	66,987	-	-	-	524,118	864,630	215,984	182,663	315,279	502,729
Forage	Beef	1,000–2,499	11,764	-	41,329	-	-	-	330,371	313,798	164,597	115,177	206,978	317,473
Forage	Beef	2,500+	-	-	-	-	-	-	192,873	196,244	187,346	178,123	141,804	285,302
Dairy	Dairy	1–199	127,092	367,237	17,291	738,362	601,443	74,973	20,498	48,647	34,743	26,211	16,868	26,114
Dairy	Dairy	200–499	54,918	148,098	8,452	445,556	169,873	47,300	28,334	33,026	133,234	26,014	20,295	26,150
Dairy	Dairy	500–999	12,698	73,282	-	292,819	143,712	26,723	44,784	24,844	261,498	33,610	43,913	33,178
Dairy	Dairy	1,000–2,499	16,331	86,016	-	329,677	210,381	38,368	100,994	65,599	747,588	64,670	156,667	95,176
Dairy	Dairy	2,500+	-	177,192	-	580,211	98,935	-	516,441	239,230	1,593,495	114,351	916,106	558,029
Feedlot	Beef	1–199	23,123	436,138	–	343,930	89,845	298	15,246	168,280	8,381	–	17,998	18,956
Feedlot	Beef	200–499	13,219	419,560	–	237,224	33,597	–	21,321	264,414	8,526	–	20,498	11,160
Feedlot	Beef	500–999	–	585,793	–	232,950	16,772	–	12,075	371,496	5,376	–	15,092	3,269
Feedlot	Beef	1,000–2,499	–	352,136	–	86,597	–	–	12,083	379,355	13,757	–	48,483	6,690
Feedlot	Beef	2,500+	–	420,689	–	121,669	–	–	315,571	4,770,453	783,110	–	977,938	2,942,807

MACC Modeling and Figures

Marginal Abatement Cost Curves (MACCs) provide a greater understanding of the regional costs of implementing feed additives by estimating what the price of carbon dioxide equivalent (CO_2e) would need to be for producers to adopt feed additives.

The steps to prepare the MACC were as follows:

- Performed literature review to gather background information on baseline GHG emissions, emissions reductions per feed additive, number of head per region, labor costs, cost to purchase feed additives, feed costs, and feed efficiency improvements.
- Summarized background information in Excel spreadsheet
- Prepared new MACC tab in overall USDA MACC Excel file
- Entered in data from summary spreadsheet calculations into MACC model by region

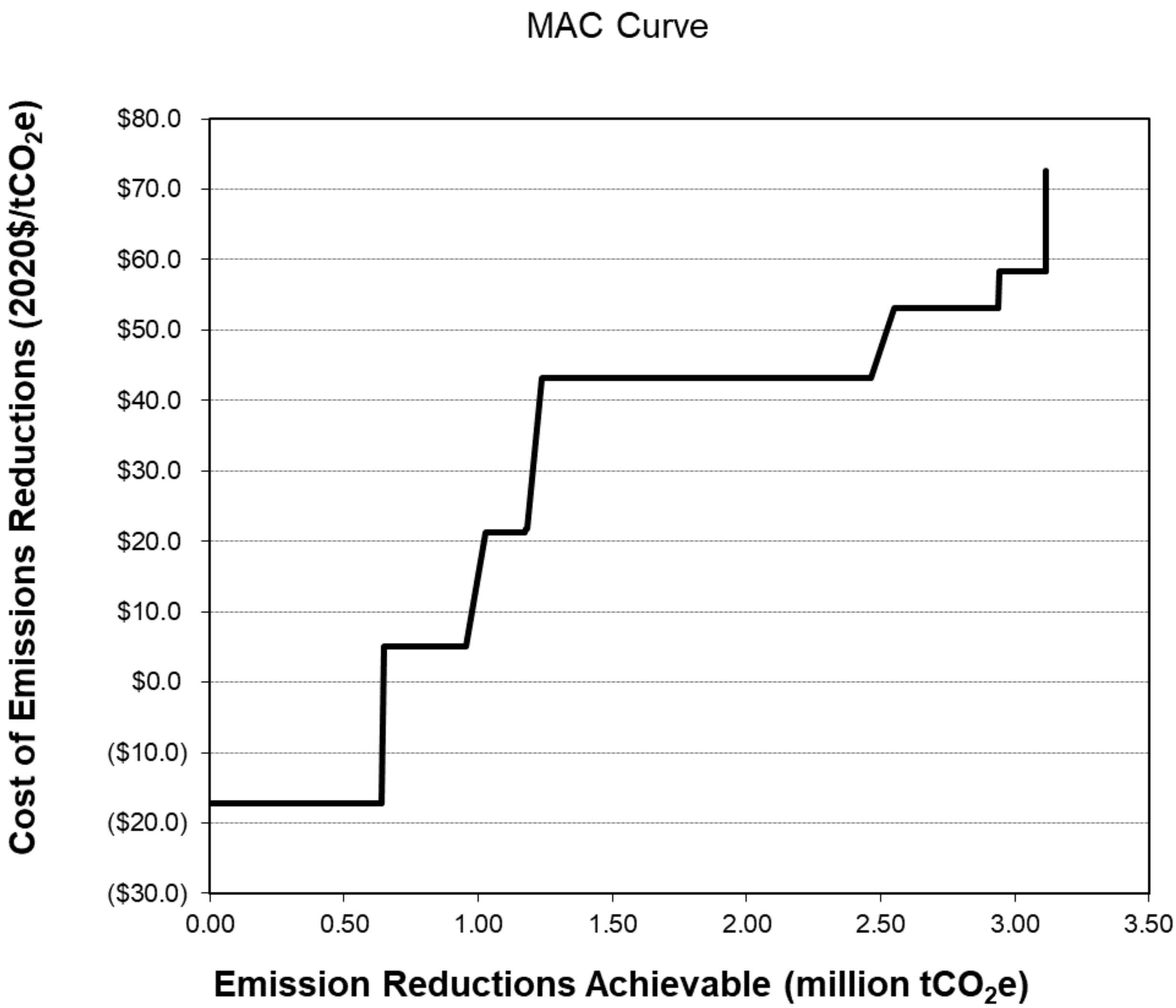
MACC Component Calculations

- **Abatement Options:** By farm size in terms of number of head (i.e., 1-199 head, 200-499 head, etc.)
- **Lifetime:** 1 year. Labor costs in the EQIP contract were calculated over 1 year. The cost to purchase the feed additive supplement reoccurs annually.
- **Capital Cost:** None.
- **Recurring Cost:**
    - Total Recurring Cost by Region = [(EQIP Labor Costs Per Head + Feed Additive Cost Per Head) – Feed Savings Per Head] x Number of Head Per Region, where
        - Feed Savings Per Region Per Head = (Feed Cost Per Region Per Head x % Improvement in Feed Efficiency Per Feed Additive)
    - Table 10 shows the values inputted into the MACC.
- **Total Revenue:** None. No impact is observed on revenue because the increased impact on yield (i.e., boosted milk production or boosted weight gain) is already accounted for in the savings on feed costs.
- **Emissions Reduction:** Total GHG Emissions Reductions Per Region in tons of CO_2e
    - tCO_2e Reduction Per Region = [(Baseline GHG Emissions Per Head x % Reduction in CH_4) x GWP CH_4 x Number of Head Per Region]
    - See table 1 for values per head inputted into MACC.
- **Regional Breakeven Cost:** in 2020 USD/tCO_2e; calculated using MACC formulas.
- For MACC curves see figures 1–5.

Table 13. Total recurring cost to adopt feed additives (inputted into MACC)

Region	Monensin, Beef Forage	Lipids, Beef Forage	Monensin, Beef Feedlot	Lipids, Beef Feedlot	Lipids, Dairy
Appalachia	$11.54	$26.30	$4.70	$18.82	$11.52
Corn Belt	$17.16	$34.04	$11.41	$25.38	$11.83
Delta States	$12.22	$29.10	$4.68	$18.80	$58.44
Lake States	$10.36	$27.25	$4.56	$18.53	-$1.17
Mid-Atlantic	$11.91	$28.80	$1.08	$14.63	$0.85
New England	$17.06	$33.94	$15.60	$30.11	$6.53
Northern Mountain	$12.30	$29.18	$9.28	$23.78	$3.23
Northern Plains	$7.37	$24.25	$12.53	$26.65	-$3.61
Pacific	$21.08	$37.96	$10.30	$25.07	-$4.32
Southeast	$13.96	$30.84	-$3.68	$9.59	-$0.60
Southern Mountain	$11.66	$28.55	$6.80	$20.88	$0.83
Southern Plains	$12.00	$28.88	$4.70	$18.82	-$6.26

Figure 1. Beef, feedlot monensin



Note: t=metric tons, CO_2e=carbon dioxide equivalent.

Figure 2. Beef, forage monensin

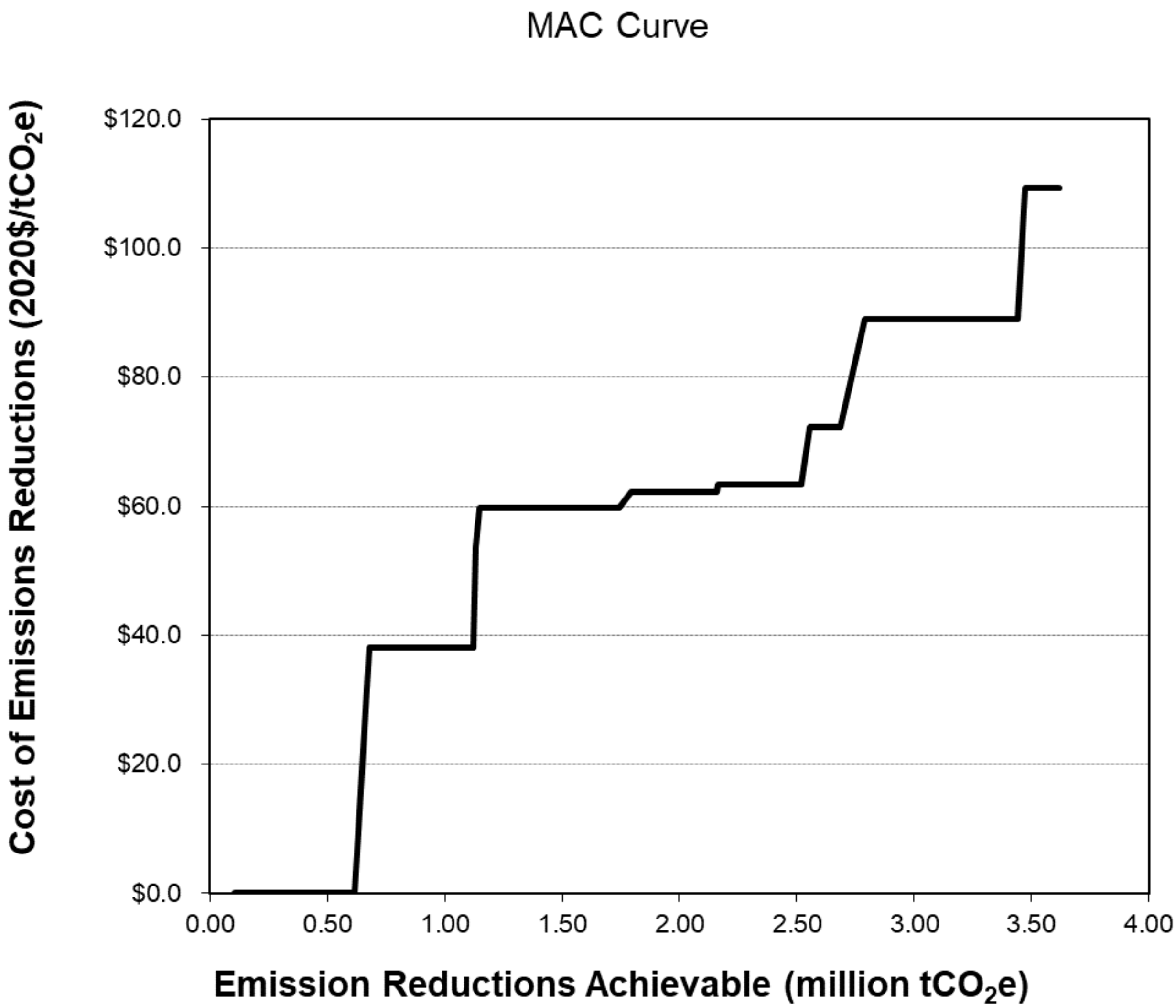


Figure 3. Beef, feedlot lipids

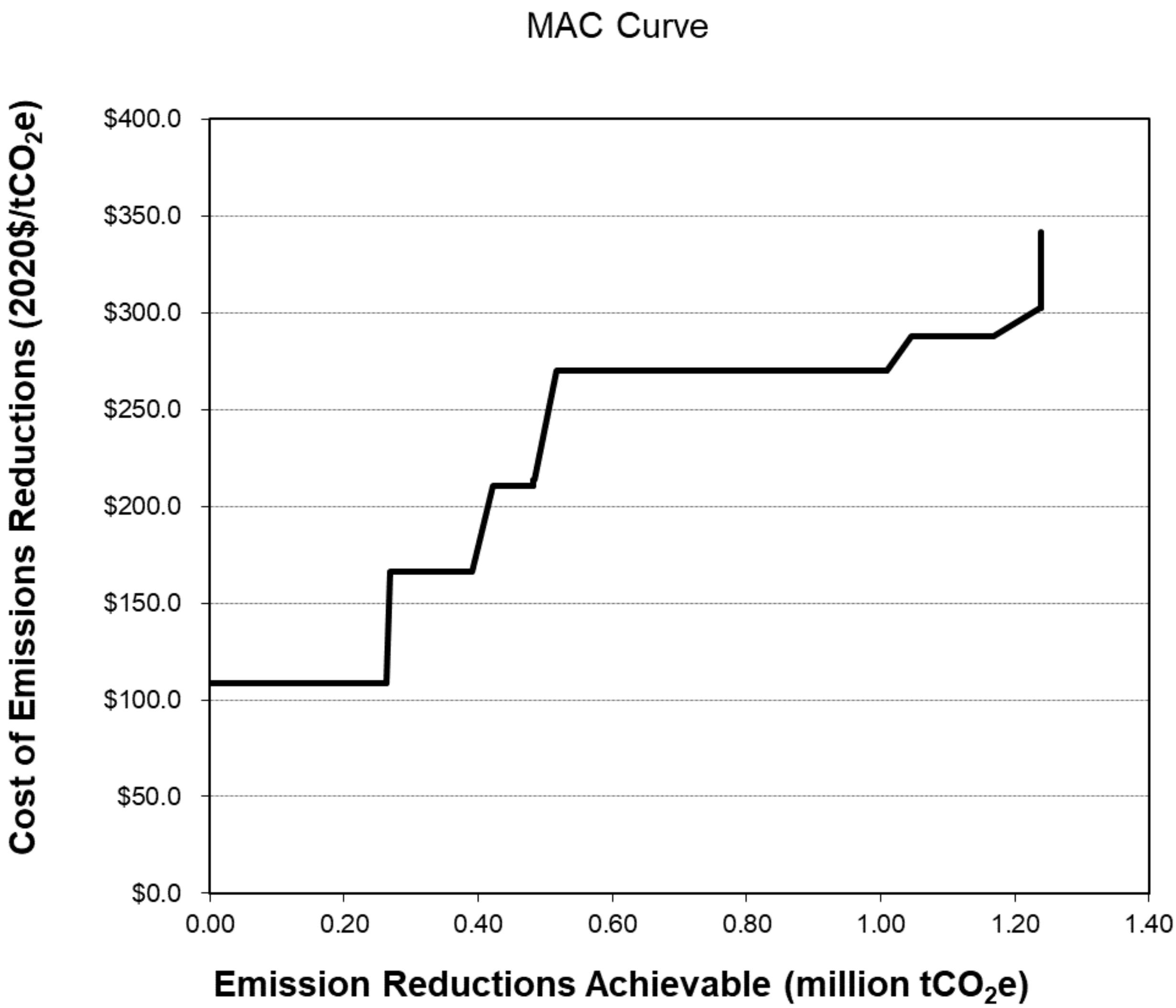


Figure 4. Dairy, lipids

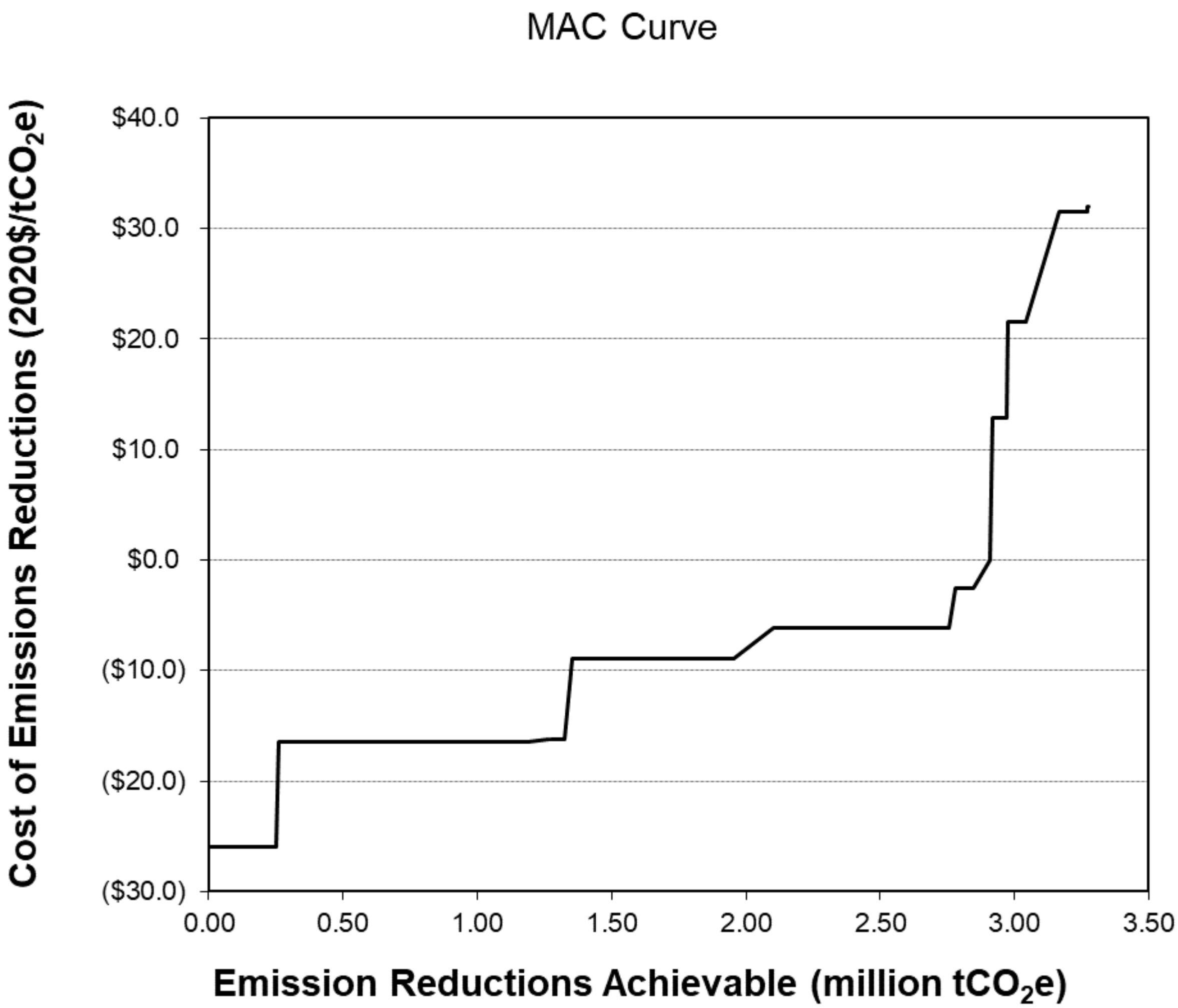
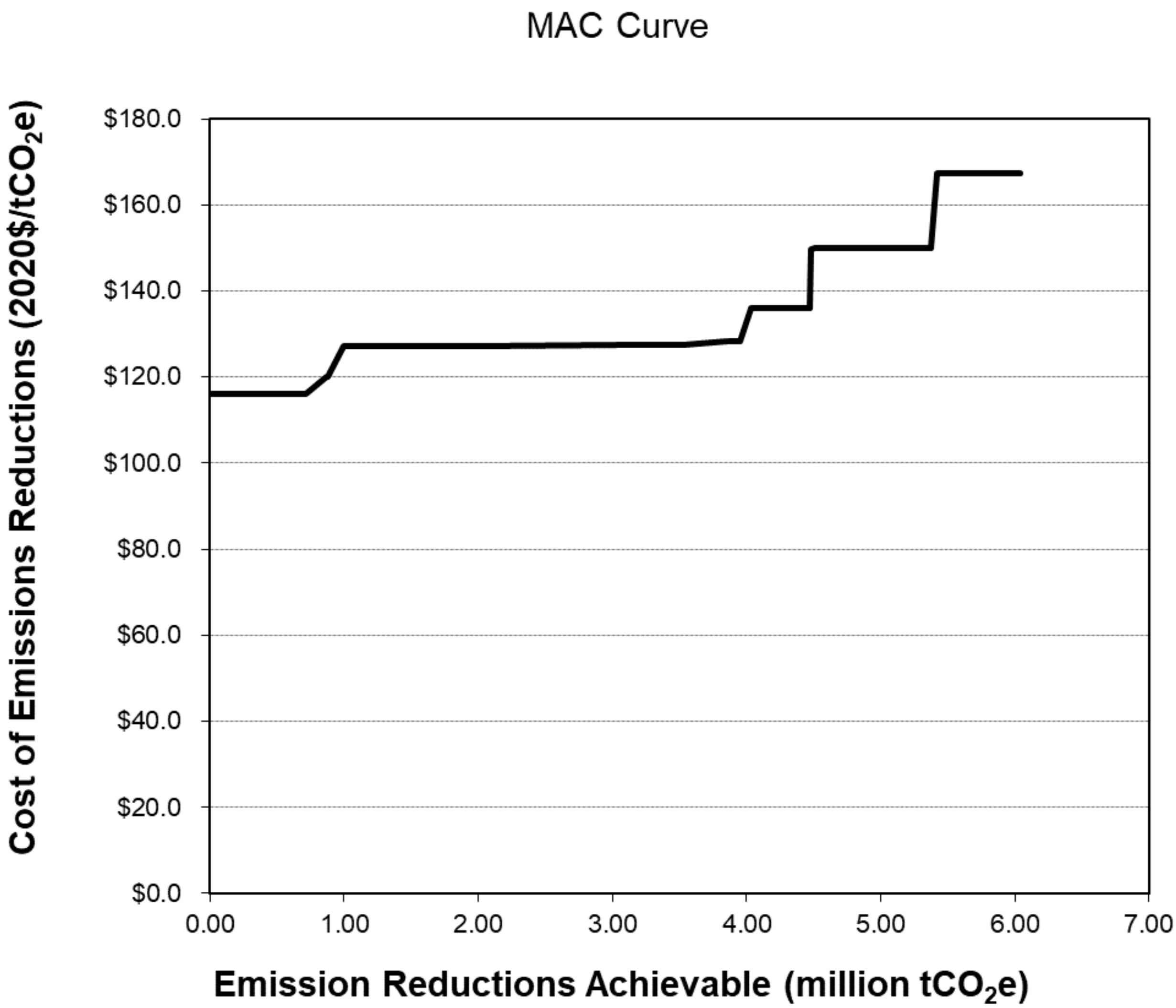


Figure 5. Beef, forage lipids



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Chapter 5: Marginal Abatement Cost Curve Analysis – Grazing Land

Chapter 5 of 8.

Contents

Technology Overview

Prescribed grazing refers to "managing the harvest of vegetation with grazing and/or browsing animals with the intent to achieve specific ecological, economic, and management objectives" (NRCS, 2017). Under prescribed grazing, the intensity, frequency, and duration of grazing periods are managed to improve pasture, soil, and animal health. The intensity of each grazing period is determined by the pasture's location and baseline productivity, and objectives.

Rotational grazing is a subset of prescribed grazing. As opposed to continuous grazing where animals are let to graze the same area for a long period of time, rotational grazing occurs when the producer rotates livestock through two or more pastures based on the number of animals, time grazed, or on remaining plant matter. Intensive grazing can be measured several ways, such as the amount of vegetation removed or the frequency of rotation. For the purposes of this document, "intensive" rotational grazing refers to rotations that let livestock graze each paddock for 0-14 days, while "basic" rotational grazing allows livestock to graze each paddock for fourteen days or longer with adequate rest provided for the forage (Wallander et al., 2022).

Greenhouse Gas Data

The updated Marginal Abatement Cost Curves (MACCs) use COMET (USDA, 2022; Conservation Practice Standard (CPS) 528) data to estimate the greenhouse gas (GHG) reductions in carbon dioxide equivalent (CO_2e) resulting from the implementation of both intensive and basic rotational grazing on land that had previously been continuously grazed. The same GHG reduction potential was used for intensive and basic rotational grazing, since COMET uses the NRCS definition of prescribed grazing that does not break the practice down into intensive and basic. However, given the implementation cost difference between intensive and basic intensity grazing, both are represented in the MACC (for more information on grazing implementation costs see Cost Data section). Note that COMET does not have separate practice codes for the use of prescribed grazing on pasture or rangeland, so GHG reduction as represented in COMET CPS 528 reflects the reduction on pasture and rangeland through regional differences.

Note: These MACCs examine the mitigation potential on all livestock grazing land and are not specific to a particular species of livestock.

Data Collection and Analysis

County-level data from USDA's COMET model was used to estimate the annual GHG impacts of transitioning from continuously grazed land to land managed with prescribed grazing, then maintaining the prescribed grazing regime.

- COMET provided county-level GHG impacts for irrigated and non-irrigated prescribed grazing implementation. In order to synthesize average GHG emissions reduction for prescribed grazing per USDA production region:
    - First, we averaged county-level parameters for each State, resulting in Statewide average irrigated and non-irrigated parameters.
    - Then, we applied the ratio of irrigated to non-irrigated grazing land in each State from NASS survey reports (table 1) to the irrigated and non-irrigated average GHG results to get a weighted average of overall State-level GHG impacts.
    - Finally, we took a weighted average of States in each USDA production region based on acreage of grazing land in each State to get a weighted average of overall region-level GHG impacts (table 2).

Table 1. Percent of irrigated grazing land by USDA region

Region	All Acres	Irrigated Acres	Ratio of Irrigated to All
Northern Mountain	6,533,022	1,412,241	21.6170%
Pacific	20,471,015	1,182,926	5.7785%
So. Mountain	81,990,791	927,807	1.1316%
Southern Plains	17,718,825	293,475	1.6563%
Northern Plains	16,445,705	91,564	0.5568%
Appalachia	95,831,433	5,848	0.0061%
Lake States	33,659,521	6,177	0.0184%
Mid-Atlantic	8,573,072	1,269	0.0148%
Southeast	26,227,628	46,389	0.1769%
Corn Belt	73,906,488	16,823	0.0228%
New England	1,197,156	473	0.0395%
Delta States	13,237,220	15,891	0.1200%

Table 2. Average GHG reduction from prescribed grazing implementation by region

Region	Weighted Average GHG Reduction (metric tons of CO_2e/acre)
Northern Mountain	0.006894
Pacific	0.015397
Southern Mountain	0.053845
Southern Plains	0.036157
Northern Plains	0.014096
Appalachia	0.063314
Lake States	0.027300
Mid-Atlantic	0.038944
Southeast	0.059433
Corn Belt	0.037269
New England	0.023014
Delta States	0.070393

Cost Data

Payment schedules from Environmental Quality Incentives Program (EQIP) were used as a proxy for the labor, fencing, and cattle hydration costs to adopt prescribed grazing on existing grazing land. EQIP provides financial incentives to producers to adopt rotational grazing under Conservation Practice Standard (CPS)[19] 528–Prescribed Grazing. Although most producers who adopt prescribed grazing will likely apply the practice on existing grazing land, we also included costs for fencing and cattle hydration pipelines as transitioning from continuous grazing to divided paddocks for prescribed grazing requires additional fencing and water sources (Briske et at. 2011).

Examination of the CPS 528 Prescribed Grazing indicated that the incentive only includes labor costs, such as the additional time required to move livestock and fences, haul supplies, attend training workshops, and receive help from specialists. As prescribed grazing requires the creation of multiple paddocks in which to rotate cattle, farmers that receive assistance under CPS 528 are often awarded additional funding under CPS 382–Fence and CPS 516–Livestock Pipeline, which cover the associated additional fencing (average of all fence types) and cattle hydration costs (USDA, ERS "ARMS", 2022). However, unlike CPS 528, these payments are defined using different units (such as feet) instead of per acre.

[19] Conservation practice standards describe why, where, and how a practice is applied. They also set minimum quality criteria that must be met during the application of that practice in order for it to achieve its intended purpose (NRCS, 2022). Conservation practice standards are published in the National Handbook of Conversation Practices.

To develop a per acre proxy that could be added to the CPS 528 payments, ICF used ARMS data from USDA ERS, who analyzed EQIP funding for practices related to prescribed grazing from 2005 to 2018 (S. Wallander and C. Whitt, personal communication, 2022). Total obligation in millions dedicated to each practice (fence and livestock pipeline) was divided by the practice count (i.e., the number of farms who received funding) to develop a per farm cost. The per farm cost was then divided by the typical acreage listed for pasture and range under CPS 528 Prescribed Grazing to develop a cost per acre estimate. Labor costs were repeated annually in the model, while fencing and water costs were repeated every 5 years according to the project lifecycle specifications under CPS 528.

The EQIP payment schedules define two characteristics of rotationally grazed land that can influence what payments a producer can receive. The land can either be pasture or range and either basic or high intensity. NRCS and EQIP provided the following definitions:

- **Pasture:** Land with primarily introduced forage for livestock grazing (NRCS, 1997).
- **Range:** Land with primarily native species, such as grasses, grass-like plants, forbs, and shrubs. Rangeland operations are generally larger than 500 acres (NRCS, 1997).
- **Basic Intensity:** Livestock graze each pasture for 14 or more days in rotation and adequate rest is provided for the forage.
- **High intensity:** Livestock graze each pasture or paddock for less than 14 days in rotation. Rotation is based on monitoring livestock demand and supply.

Because rangeland is primarily found in the west of the 100th meridian and pasture is concentrated east of the 100th meridian, USDA regions were classified as east or west. Eastern regions (Appalachia, Lake States, Mid-Atlantic, Southeast, Corn Belt, New England, and Delta States) were assigned pasture costs, while western regions (Northern Mountain, Southern Mountain, Pacific, Southern Plains, and Northern Plains), were assigned range costs.

Lastly, three cost scenarios were developed to include the overall annual costs per acre of the basic and intensive rotational grazing systems per year:

- **Scenario 1:** Includes labor, fencing, and water costs, covering situations where the land was not at all previously equipped for the smaller paddocks needed for rotational grazing.
- **Scenario 2:** Includes labor and fencing costs for situations where there are sufficient water supplies, but not enough additional fencing to convert the land from continuous grazing to prescribed grazing.
- **Scenario 3:** Includes only labor costs from EQIP under the assumption that adoption of prescribed grazing land did not require any new fencing or livestock pipelines.

The potential mitigation from prescribed grazing is therefore modeled under six scenarios, Cost Scenario 1 with Intensive Grazing or Basic Grazing, Cost Scenario 2 with High Intensity

Grazing or Basic Intensity Grazing, and Cost Scenario 3 with High Intensity Grazing or Basic Intensity Grazing.

Data Collection and Analysis

- Obtained prescribed grazing annual labor payments as a proxy for costs from USDA EQIP CPS 528.
- Analyzed equipment costs for fencing (CPS 382) and cattle hydration (CPS 516) from EQIP contracts.
    - EQIP per unit payment rates for CPS 382 Fence and CPS 516 Livestock Pipeline cannot be directly combined with EQIP payment rates for CPS 528 Prescribed Grazing, as they used different units of measurement. Specifically, the payment rate for CPS 528 Prescribed Grazing is reported in units of $ per acre, while the payment rates for CPS 516 Livestock Pipeline and CPS 382 Fence are reported in $ per foot.
    - The cost per farm for fencing and pipeline varies depending on farm size, as well as the type of fencing and pipeline installed. To streamline the cost per farm calculations, we calculated the average per farm contract payment for CPS 382 and CPS 516 using ERS end of year ProTracts data for obligated (signed) EQIP contracts.
    - To calculate per farm cost, we divided total obligation in millions of dollars by EQIP-reported count of producers receiving EQIP payments for that practice.
        - Example for CPS 382 Fence: $357 million obligated in 2018 / 71,956 contracts awarded in 2018 = average per farm payment of $4,961.37
    - Then, we converted per farm cost into cost per acre by dividing per farm cost by typical acreage as reported by the typical acreage for each scenario listed in EQIP CPS 528 Prescribed Grazing.
        - Example for CPS 382 Fence: $4,961.37 average per farm cost for fencing / 80 acres typical farm size in the Corn Belt = $62.02 per acre to install fencing.
        - Note that average farm size varies by region and by farm type (e.g., pasture or range)

Price per acre for each region, intensity, and scenario is shown in table 3.

Table 3. Cost per acre for each scenario and region

Region	Pasture or Rangeland	Basic Cost Per Acre	Intensive Cost Per Acre	Basic + Fence Cost Per Acre	Intensive + Fence Cost Per Acre	Basic + Fence + Water Cost Per Acre	Intensive + Fence + Water Cost Per Acre
Appalachia	Pasture	$13.46	$23.71	$96.15	$106.40	$159.30	$169.55
Lake States	Pasture	$57.78	$79.41	$181.81	$203.44	$276.54	$298.17
Mid-Atlantic	Pasture	$57.78	$67.15	$181.81	$191.18	$276.54	$285.91
Southeast	Pasture	$57.78	$38.03	$181.81	$162.06	$276.54	$256.79
Corn Belt	Pasture	$55.98	$61.07	$118.00	$123.09	$165.36	$170.45
New England	Pasture	$12.57	$145.72	$154.32	$287.47	$262.58	$395.73
Delta States	Pasture	$48.81	$80.79	$119.69	$151.67	$173.82	$205.80
Northern Mountain	Rangeland	$4.53	$23.45	$11.15	$30.07	$16.20	$35.12
Pacific	Rangeland	$8.94	$6.22	$18.86	$16.14	$26.44	$23.72
Southern Mountain	Rangeland	$5.62	$10.09	$12.24	$16.71	$17.29	$21.76
So. Plains	Rangeland	$5.62	$16.67	$12.24	$23.29	$17.29	$28.34
No. Plains	Rangeland	$8.94	$21.03	$18.86	$30.95	$26.44	$38.53

Acres and Applicability Data

"Applicable acres" are acres that could sustain a prescribed grazing regime in the United States. Because prescribed grazing can be applied to any grazing land, this analysis assumed that 100 percent of grazed acres not already being used for prescribed grazing could be converted to a prescribed grazing regime (NRCS, 2017). Further, land already using basic intensity prescribed grazing was assumed to be capable of conversion to high intensity grazing. The analysis also assumed that no land currently using high intensity prescribed grazing would revert back to basic intensity, or conventional grazing.

Data Collection and Analysis

Total grazing acres were obtained from the 2018 USDA, ARMS Cattle and Calves survey and were allocated to each grazing type using data from Wallander et al. (2022). Baseline acreage was estimated for:

- Continuously grazed acres
- Basic prescribed grazing acres
- Intensive prescribed grazing acres (USDA, ARMS Cattle and Calves, 2018).

First, grazing acres in each State were aggregated into USDA production regions. Then, we used the percentages of basic and intensive rotational grazing in the graph below from ARMS to get the acres of that practice in each region. Regions with low levels of prescribed grazing incidence that were not reported in figure 1 were analyzed using a weighted average of basic vs. intensive prescribed grazing in other regions based on the acreage of each region.

Figure 1. Adoption rate of farms practicing rotational grazing by region. From USDA, ERS 2018 Agricultural Resource Management Survey Cattle and Calf Special Tabulation for OCE (February 16, 2022) [Personal communication with Christine Whitt].

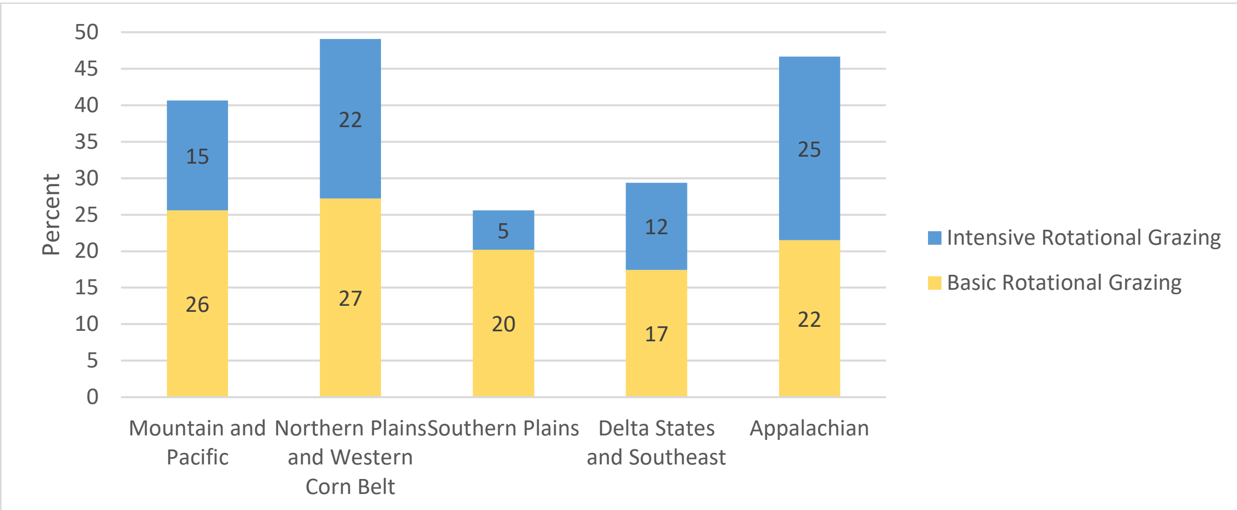


Table 4. Acres of prescribed grazing practice types as of 2018.

Region	Basic	Intensive	Total Rotational	Acres	Basic	Intensive
Appalachia	22%	25%	47%	95,831,433	21,082,915	23,957,858
Lake States	24%	20%	45%	33,659,521	8,184,619	6,868,078
Mid-Atlantic	24%	20%	45%	8,573,072	2,084,621	1,749,298
Southeast	17%	12%	29%	26,227,628	4,458,697	3,147,315
Western Corn Belt	27%	22%	49%	73,906,488	19,954,752	16,259,427
New England	24%	20%	45%	1,197,156	291,099	244,274
Delta	17%	12%	29%	13,237,220	2,250,327	1,588,466
Mountain	26%	15%	41%	88,523,813	23,016,191	13,278,572
Pacific	26%	15%	41%	20,471,015	5,322,464	3,070,652
Southern Plains	20%	5%	25%	17,718,825	3,543,765	885,941
Northern Plains	27%	22%	49%	16,445,705	4,440,340	3,618,055

Table 5. Applicable acres by prescribed grazing implementation by type.

Grazing Type	Region	Applicable Acres for Basic Prescribed Grazing	Applicable Acres for Intensive Prescribed Grazing
Pasture	Appalachia	50,790,659	71,873,575
	Lake States	18,606,824	26,791,443
	Mid-Atlantic	4,739,154	6,823,774
	Southeast	18,621,616	23,080,313
	Corn Belt	37,692,309	57,647,061
	New England	661,782	952,882
	Delta States	9,398,426	11,648,754
	Northeast	5,400,936	7,776,656
Range	Northern Mountain	3,854,483	5,553,069
	Pacific	12,077,899	17,400,363
	Southern Mountain	48,374,567	69,692,172
	Southern Plains	13,289,119	16,832,884
	Northern Plains	8,387,310	12,827,650
	Mountain (Combined)*	52,229,050	75,245,241

* The graphic from ARMS separates the Mountain production region into Northern Mountain and Southern Mountain by State. The above methodology was carried out for the Northern Mountain and Southern Mountain regions separately, then combined at the last step to get a total acreage.

MACC Modeling and Figures

MACCs provide a greater understanding of the regional costs of implementing prescribed grazing by estimating what the price of carbon dioxide equivalent (CO_2e) would need to be for enough producers to adopt prescribed grazing to achieve a given amount of emission reductions. The steps to prepare the MACC were as follows:

Background Data

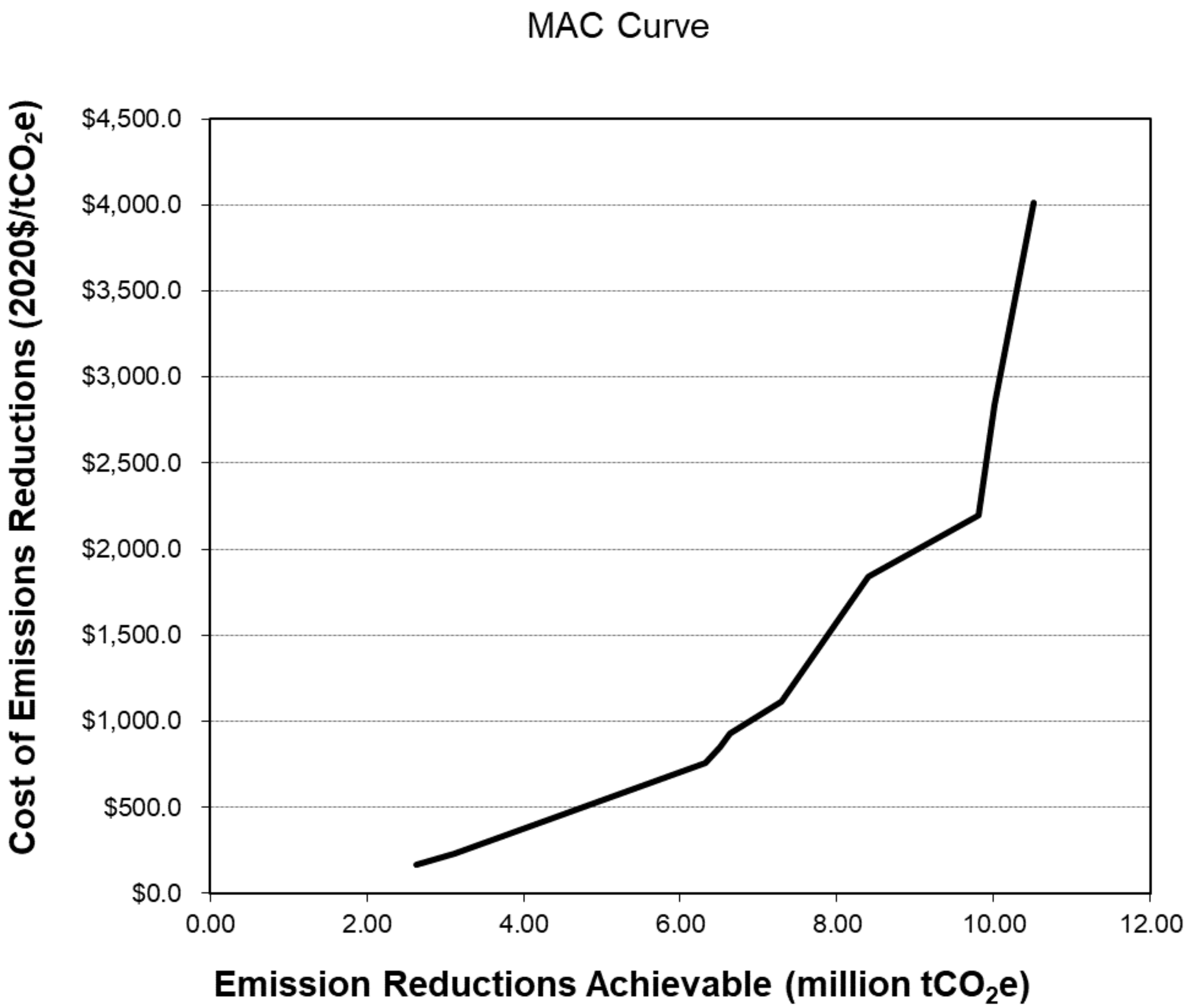
- Performed literature review to gather background information on baseline GHG emissions, emissions reductions per prescribed grazing regime, grazing acres per region, labor costs through EQIP, and additional fencing and water pipeline cost. Data was obtained from EQIP, COMET, and NASS and analyzed.
- Summarized background information in Excel spreadsheet
- Prepared new MACC tab in overall USDA MACC Excel file
- Entered in data from summary spreadsheet calculations into MACC model by region and cost scenario

MACC Component Calculations:

- **Abatement Options:** No distinction by farm size
- **Lifetime:** 5 years. Labor costs in the EQIP contract were calculated over 1 year, but fencing and water pipe costs have a longer lifespan.
- **Capital Cost:** Fencing and water pipe cost per acre, for scenarios that include one or both of those costs. Note that the formulas in the MACC discount this cost over 5 years.
- **Recurring Cost**: EQIP Labor Costs per acre. Note that in the MACC these costs are assumed to reoccur annually.
- **Total Revenue:** None. No impact is observed on revenue because the correlation between prescribed grazing and faster finishing rates or higher quality product is not confirmed by a plurality of studies.
- **Emissions Reduction:** Total GHG Emissions Reductions Per Acre per region per year in tons CO_2e
- **Regional Breakeven Cost:** in 2020 USD/tCO_2e; calculated using MACC formulas.

For MACC curves see figures 2–7.

Figure 2. Basic intensity, scenario 1 (labor, fencing, and water)



Note: t=metric tons, CO_2e=carbon dioxide equivalent.

Figure 3. Basic intensity, scenario 2 (labor and fencing)

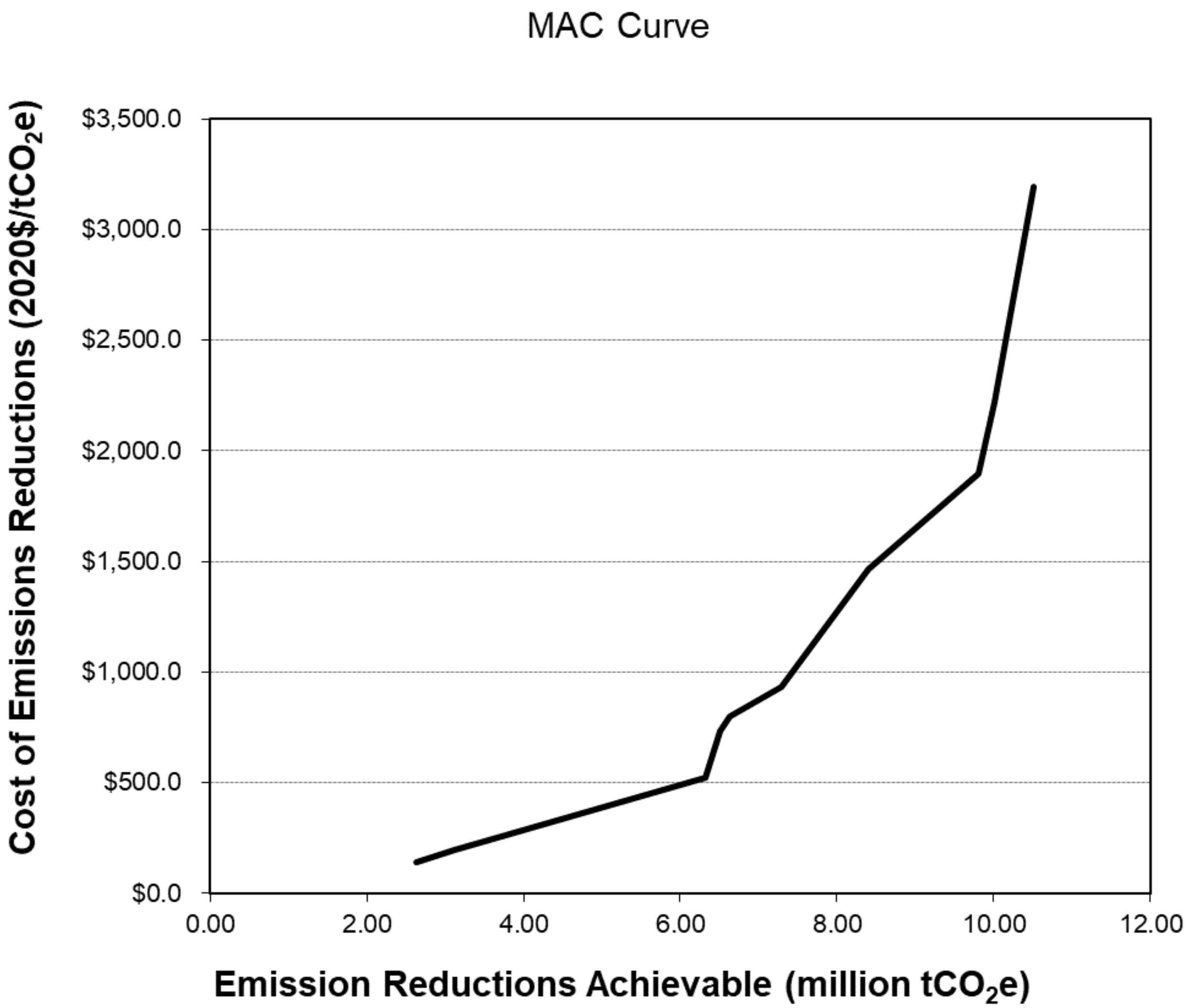


Figure 4. Basic intensity, scenario 3 (labor only)

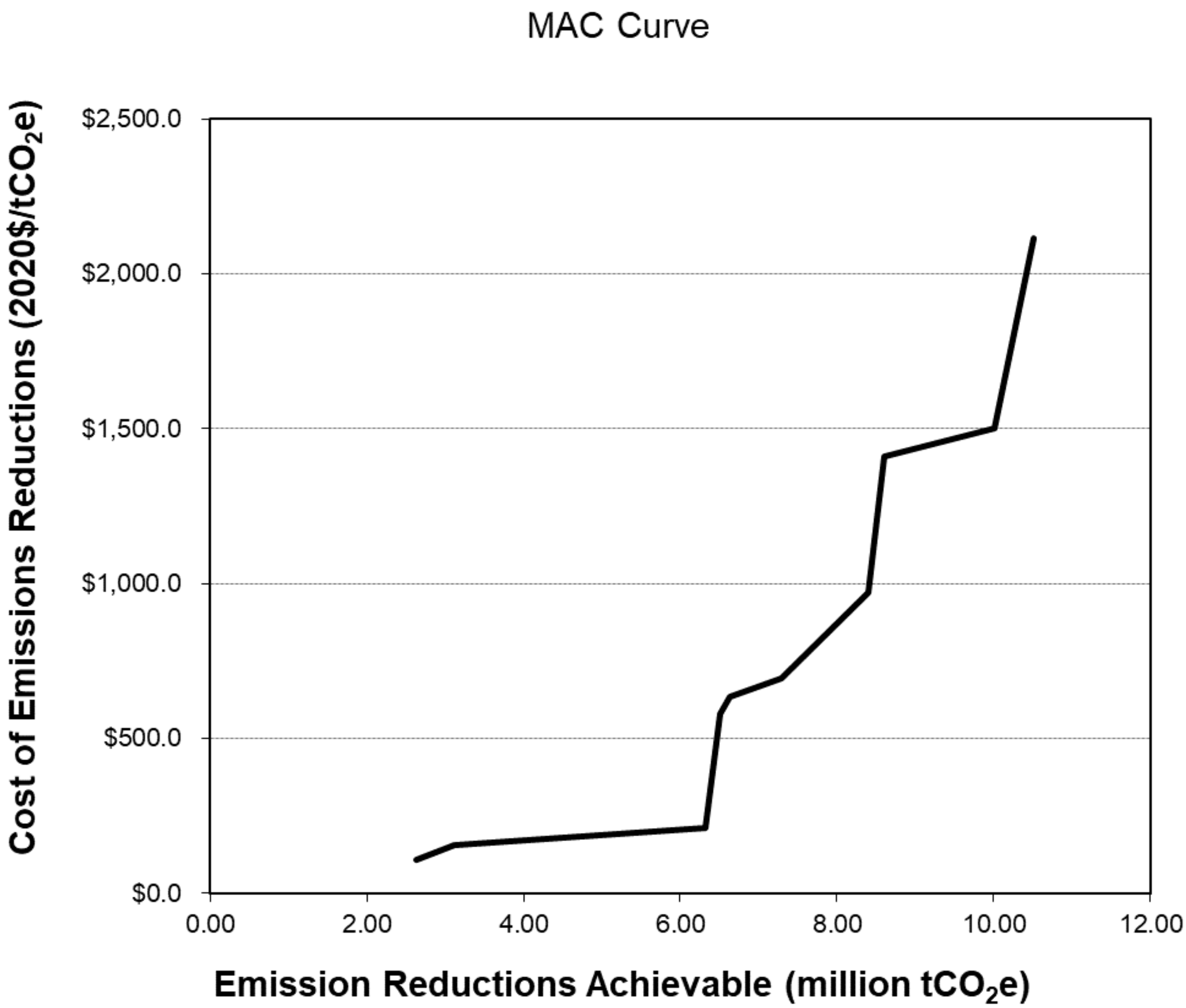


Figure 5. High intensity, scenario 1 (labor, fencing, and water)

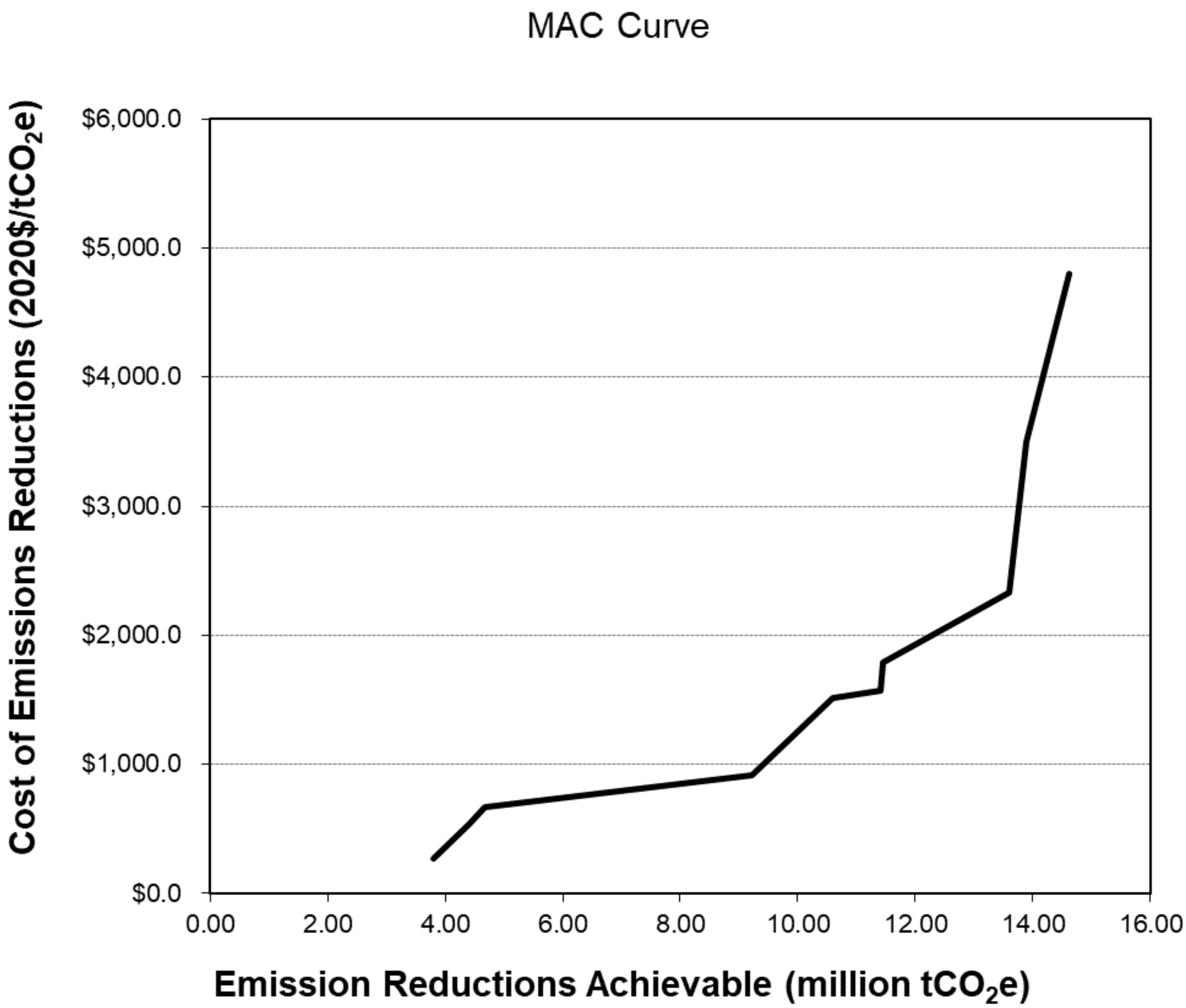


Figure 6. High intensity, scenario 2 (labor and fencing)

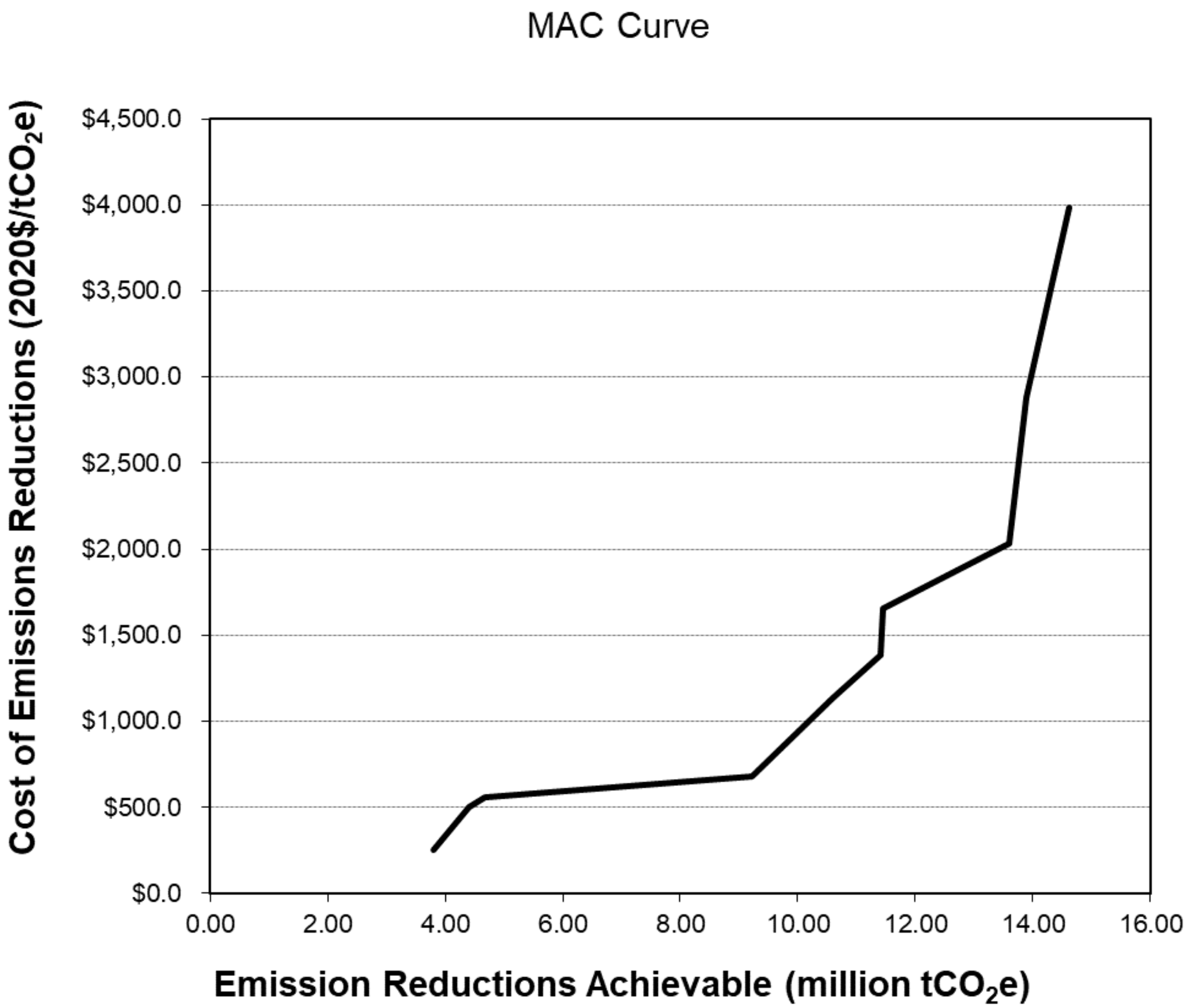
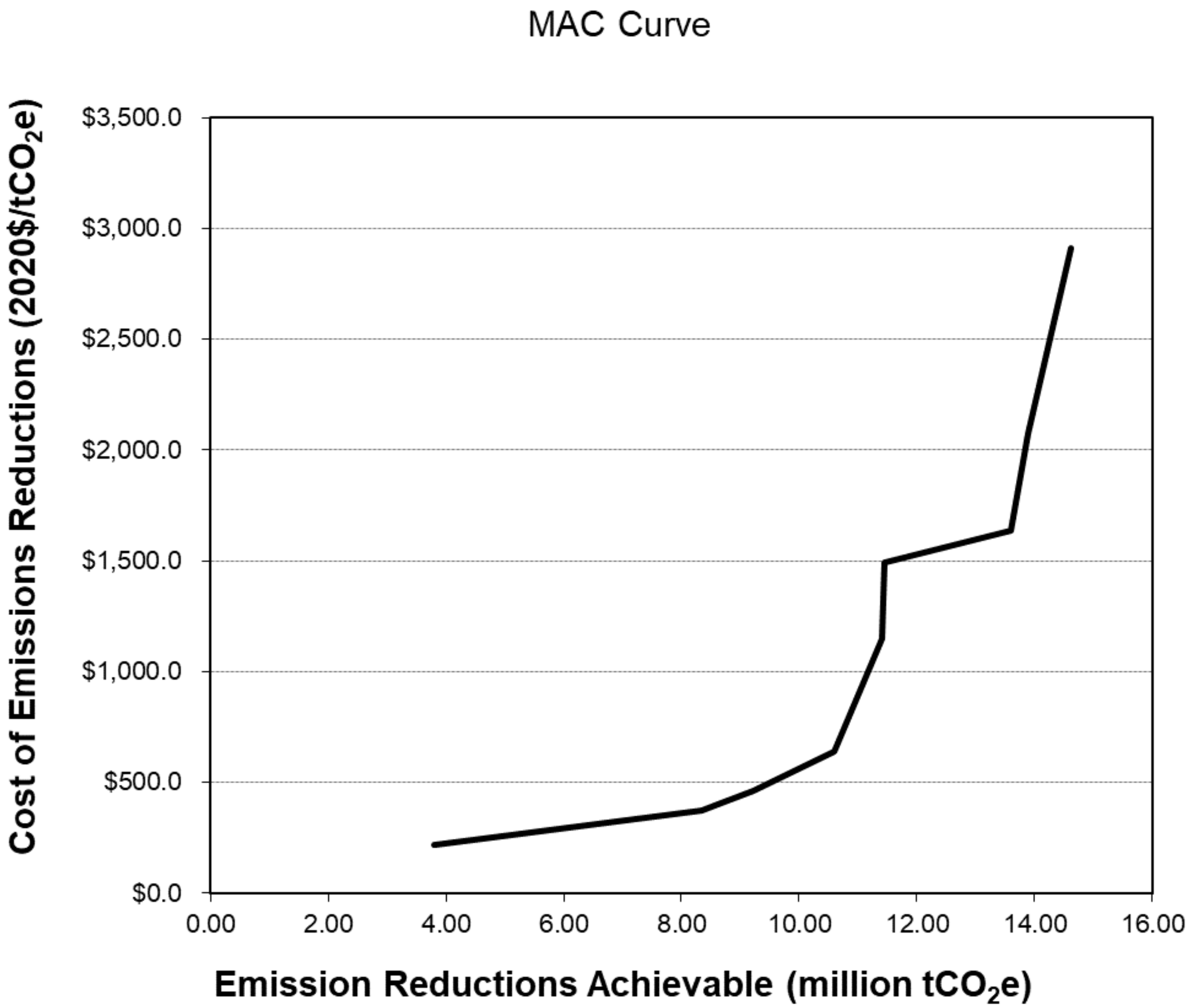


Figure 7. High intensity, scenario 3 (labor only)



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Chapter 6: Marginal Abatement Cost Curve Analysis–Rice

Chapter 6 of 8.

Contents

Technology Overview

Alternate Wetting and Drying (AWD) in rice production is an irrigation practice wherein rice paddies are allowed to dry out to a certain level of soil water saturation before being reflooded. Conventional rice production keeps the rice paddies entirely flooded throughout the entire growing season, from early leaf stage until 2-3 weeks before harvest, and therefore emits large amounts of methane (CH_4) due to anaerobic microbial processes in the soil. By allowing the soil to dry out for portions of the growing season, aerobic processes proceed instead, inhibiting production of methane, but some additional nitrous oxide (N_2O), which is a more potent greenhouse gas than carbon dioxide. AWD uses existing irrigation infrastructure in rice paddies to periodically flood the paddies and requires little extra labor cost.

AWD 60 is the process of reflooding a paddy once the soil reaches 60 percent volumetric soil moisture. This process has been found to have no impact on rice yield, and to be the most commonly used form of AWD in the U.S. AWD 60 tends to reduce the amount of irrigation water, which accordingly reduces water and pump costs by an average of 23 percent.

The team initially met with Michele Reba, Ph.D., at USDA to discuss different rice mitigation practices. We then reviewed and extracted data from the key sources identified by Dr. Reba, as well as additional sources, in a literature review. Through the literature review and discussion with rice production specialists, two initial assumptions were defined: (1) AWD 60 has no impact on rice yield, and (2) AWD 60 is the most common form of AWD in the United States. Data pulled from the literature review was organized by data type, region, and specific value:

- Recorded data as available for the California region, the Mid-South (in this context, Arkansas, Louisiana, Mississippi, Missouri, Texas), and national.
- All sources used grouped non-Californian rice-producing States into a larger "Mid-South" region.
- Papers that looked at a particular State within the Mid-South were applied to the entire Mid-South region and scaled by production.

Greenhouse Gas Data

- Performed a literature review of over 80 scientific papers related to the impacts of alternate wetting and drying.
  - Results were narrowed down by:
    1. Whether their results applied to the U.S. (California or the Mid-South)
    2. Whether they specifically measured the impact of AWD on GHG emissions

iii. Whether the paper examined AWD 60 or an analogous practice, defined as AWD that refloods before there is any impact on rice yield.
   1. Not every paper defined AWD water threshold for reflooding by the percent soil moisture. Some classified levels of AWD by grain yield impacts, timing of drying and reflooding, number of drying and reflooding cycles, etc.

iv. Sources were also evaluated separately for:
   1. Whether the paper discussed the impact of AWD 60 or its analogue on water, fuel, and labor usage.
   2. Whether the results of this analysis could be applied to U.S. rice production (e.g., a meta-analysis of dozens of AWD papers world-wide and including the U.S. could be reasonably applied to U.S. production, but papers analyzing production features specific to East Asia could not).
   3. Whether the cost and pricing data used in these sources was either:
      a. Recent enough to be applicable to the analysis in the Marginal Abatement Cost Curve (MACC), or
      b. Transparent enough in its discussion of the data sources used in its analysis that the sources could be individually updated to more recent data if trying to replicate and update the analysis.

  - Papers that did not meet these criteria were used as background and comparative sources. Many also provided data for sections of the MACC other than GHG impacts, such as the impact of soil types, flooding systems in different parts of the US, and evidence to bolster our assumptions for the MACC analysis.

- Averaged paper results for CH_4 and N_2O impacts in each region and nationally.
  - CH_4 emission reductions in the Mid-South and California were similar (3,646 kg CO_2e reduced per acre vs 3,726 kg CO_2e per acre)
  - N_2O emission increases were significantly larger in the Mid-South (125 kg CO_2e per acre) than for California (4 kg CO_2e per acre).
  - Note that CH_4 emissions reductions vastly outweigh additional N_2O emissions as a result of AWD 60, leading to a large net-benefit for mitigative potential.
- Took the weighted average of impacts on CH_4 and N_2O from each region based on the proportion of rice grown in that region across all component States to get a revised national average that could be compared to papers that looked at national results to ensure that the component papers were in line with what was expected nationally (table 1).

Table 1. Average GHG impacts in the Pacific and Mid-South regions

Region	GHG Results from Literature	Acres	Weighted Average by Acres	Flat Average of GHG Results
Pacific*	1,506 kg CO_2e	436,710	-	-
Mid-South	1,425 kg CO_2e	1,916,008	-	-
National		2,352,718	1,440 kg CO_2e (1506 x (436,710/ 2,352,718) +1,425 x (1,916,008/ 2,352,718))	1466 kg CO_2e

*The Pacific USDA production region includes California, Oregon, and Washington; however, rice production is only notable in California out of these States.

Note: kg=kilograms, CO_2e=carbon dioxide equivalent

Cost Data

Data Collection and Analysis

- Pulled information from USDA databases (EQIP) on cost.
    - EQIP averaged costs of AWD over all the States, so there is only one cost to apply to every region.
    - EQIP costs currently included additional labor costs and soil testing requirements for AWD.

Irrigation Costs

- Pulled information and data on the impact of water use from papers found in literature review.
- Performed an additional literature review on irrigation strategies in rice producing States to provide background.
- Found and analyzed the most recent State extension sample budgets for rice production for each rice producing State.
    - Pulled the average cost of water per acre-inch, the cost of the diesel to pump that water, and the ratio of diesel to water per acre, performing unit conversions as necessary.
    - Compared line items of State budgets to find costs where there is higher regional variation to ensure that costs with higher variability were being included in the regionalization of the breakeven analysis.
    - Results from the State budgets were then converted back into 2020 dollars from 2022 or 2021 dollars.
    - For quality control, pulled the cost of diesel in each region from the Energy Information Administration (EIA) data for the year covered by the State budgets to make sure they were reasonable.

- Determined which percent reduction in water use should be used for the MACC
    - Reviewed 20 separate studies on the impact of AWD on water and fuel use
    - Narrowed down search by same factors listed above
    - Checked methodology of studies to make sure they examined AWD 60 or its analogue specifically.
    - Carrijo et al. (2017) is a meta-analysis of 56 studies that contained 528 comparisons of conventional rice production and AWD, including AWD's impacts on water use worldwide. This meta-analysis includes all studies that we reviewed separately as potential percent reductions to use in the MACC. The literature review showed water use reductions are relatively stable across the globe. Therefore, the 23.4 percent reduction in water use due to "mild" AWD (AWD 60) was applied within the MACC.

Table 2. Water use reduction

Paper:	Region	% Reduction in Water Use
Carrijo et al. (2016). Rice yields and water use under alternate wetting and drying irrigation: a meta-analysis. Field Crops Research. 203(1):172-180.	National	25.70%
Carrijo et al. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. Field Crops Research 203 173–180	Global	23.40%
Linquist et al. (2014). Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. Global Change Biology, doi: 10.1111/gcb.12701	Arkansas	47.08%
Nalley et al. (2015). The Economic Viability of Alternative Wetting and Drying Irrigation in Arkansas Rice Production. Agron. J. 107:579–587.	Arkansas	31.33%

- The 23.4 percent reduction was applied to the cost of water and diesel fuel directly on each State budget. The resulting reduction in cost of rice production was subtracted from the EQIP practice cost to get the final cost per acre of AWD 60.
    - The cost reduction for Louisiana, Arkansas, and Mississippi were averaged using an unweighted average to get the cost reduction for the Delta production region.
- California (Pacific USDA Production Region) and Texas (Southern Plains Region) have the highest cost of water for irrigation out of the rice producing States, therefore, the resulting reduced cost of rice production was much higher. Missouri (Corn Belt Region) and Louisiana, Arkansas, and Mississippi (Delta Region) have higher proportions of farmers who do not have to pay for off-farm water, so the reduction in water usage did not have as large an impact on the cost of implementing AWD.

Assumptions Update

- Assumed that the EQIP average cost across States can be applied to each region without modification.

Acres and Applicability Data

Data Collection and Analysis

- Pulled information from USDA databases (NASS) on area.
    - NASS Census of Agriculture (2017) data was pulled for acres planted of any type of rice in the six States that produce almost all the rice in the US.
- Assuming 100 percent of the acres that currently grow rice could implement AWD 60.
    - Confirmed as a good assumption by Dr. Michele Reba.
    - Three potential limitations that require further research:
        - Zero-Grading:
            1. AWD works best on zero-grade paddies (i.e., totally level paddies) so that water is not likely to pool and dry unevenly. EQIP does not cover the costs of converting a paddy to zero-grade.
            2. Zero-grade paddies are already relatively common in the U.S., so these additional costs would not be ubiquitous.
            3. Having a slight grade in your paddy impacts all outcomes of AWD, such as GHG emissions reductions, water use reductions, and pumping costs. However, these differences would already be present when comparing paddies that do not apply AWD.
        - Flooding type and irrigation water source
            1. Rice farms in the mid-south, especially near the Mississippi River, sometimes use surface water to irrigate their paddies instead of ground water. Dependance on less predictable natural processes to provide water for flooding could impact how readily a farm could switch to AWD. The shift to surface water is also driven by expanding and deepening cones of depression of the Mississippi River Valley Alluvial Aquifer. This topic requires further study before it can be incorporated into any breakeven analysis.
        - Nitrogen Fertilization
            1. AWD has the potential to increase N losses due to increased nitrification and subsequent denitrification. Soil N losses must be low prior to implementing AWD in order to limit additional N_2O emissions. This in turn may create a need for additional or alternate varieties of N fertilizer. However, the additional N_2O

emissions still have a lower global warming potential than the avoided emissions from reduced CH_4 (methane) emissions.

- Assuming 1 percent of acres that currently grow rice are already using AWD 60.
    - This is based on a variety of factors, such as the acreage of AWD test plots in the U.S., the reported number of AWD farms with California's Air Resources Board, the current use of EQIP payments for AWD, and discussions with Dr. Reba.

MACC Modeling and Figures

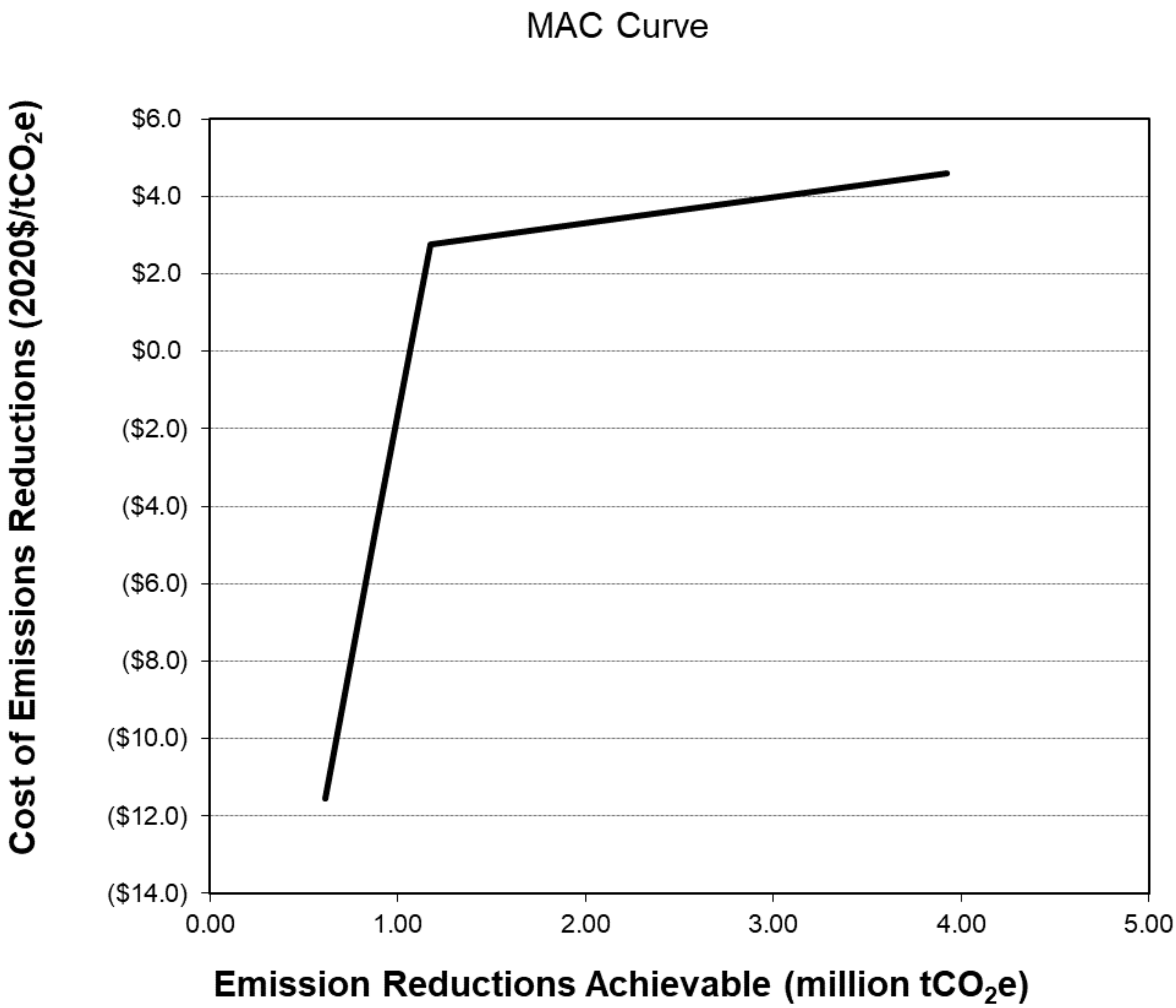
- Prepared new MACC tab in overall USDA MACC Excel file
    - Removed regions that had no rice production from estimates
- Entered in data from summary table calculations into MACC model by region
    - **Lifetime:** 1 year since farmers can choose each year whether they want to leave the field flooded or not.
    - **Applicable Acres:** Total acres growing rice in 2017 in each USDA region multiplied by 99 percent to represent the 1 percent already using AWD.
    - **Capital Cost:** None. Farms use existing irrigation practices to flood the paddies.
    - **Recurring Cost:** Additional cost of AWD according to EQIP.
    - **Total Revenue:** NA, AWD 60 doesn't impact yield.
    - **Emission Reduction:** Total GHG emissions reductions in ton of CO_2 equivalents (CH_4 reduction minus additional N_2O emissions).
        i. Rice production emits minimal CO_2, and AWD has no impact on those emissions.
    - **Breakeven cost:** Calculated using MACC formulas.

Table 3. MACC results

Region	Lifetime (Years)	Applicable Acres	Capital Cost (2020 USD)	Recurring Cost (2020 USD)	Total Revenue (2020 USD)	Emission Reduction / Option (tCO_2e)	Breakeven Cost (2020 USD / tCO_2e)
Corn Belt	1	165,897.27	$-	$4.80	$-	1.74	$2.75
Delta	1	1,576,744.29	$-	$8.01	$-	1.74	$4.59
Pacific	1	432,342.90	$-	$-16.46	$-	1.43	$-11.54
Southern Plains	1	154,206.36	$-	$-7.79	$-	1.74	$-4.47

(1) Region
   (a) Corn Belt: Missouri
   (b) Delta: Louisiana, Mississippi, Arkansas
   (c) Pacific: California
   (d) Southern Plains: Texas
(2) Lifetime
   (a) Assumed that since the practice depends on actions throughout the season, a farmer would be able to decide each year if they wanted to flood continuously or not.
(3) Applicable Acres
   (a) Equal to the combined acreage of rice in each State in a region minus the 1 percent of acres already assumed to be under AWD regimes.
(4) Capital Cost
   (a) Assumed to be zero, as farmers' current irrigation systems are already sufficient to support AWD without prerequisite changes.
(5) Recurring Cost
   (a) Assumed to be the EQIP practice cost (same for each region) minus the regional reduction in costs of irrigation and diesel for water pumps resulting from AWD implementation.
   (b) Water is much more expensive in California and Texas so the reduction in cost of water and diesel resulting from AWD result in a negative recurring cost. This is possible because this model only looks at costs that are impacted by AWD, not the entire cost of production of rice.
(6) Total Revenue
   (a) This value is not impacted because rice yield is not reduced due to AWD 60 implementation.
(7) Emission Reduction
   (a) Average emissions reduction in metric tons of CO_2e per acre.
   (b) Value obtained for the Mid-South and California by calculating the total GHG emissions reduction (CH_4 emissions reduction minus the increase in N_2O emissions) in CO_2e for each relevant paper and averaging the results.
   (c) The resulting Mid-South value was used for all non-Californian rice producing States.
(8) Breakeven Cost
   (a) The resulting breakeven cost for carbon payments to farmers to offset the cost of AWD implementation. This value is negative for areas where the cost savings from water and diesel reduction is already higher than the cost of implementing AWD 60.

Figure 1. Rice AWD MACC



Note: t=metric tons, CO_2e=carbon dioxide equivalent.

Appendix 1: Calculation Reference

Final Results Calculation Component Sources:

- California:
  - CH_4: Average of Linquist 2018 and Balaine 2019
  - N_2O: Average of Balaine 2019 and LaHue 2016
  - Final result: Average CH_4 reduction minus increased average N_2O emissions, in CO_2e.
- Mid-South:
  - CH_4: Average of Linquist 2018 and Nalley 2015
  - N_2O: Average of Linquist 2015 and Nalley 2015
  - Final result: Average CH_4 reduction minus increased average N_2O emissions, in CO_2e.

Example data transformation prior to inclusion in calculations:

Linquist et al. (2018) Calculation Process:	**California**	**Mid-South**
Average CH_4 Emissions in Source (kg CH_4/ ha per growing season)	218	194
Percent reduction for multiple dry downs	83%	83%
Average CH_4 emissions reduction due to AWD (kg CH_4/ha per growing season)	181	161
GWP of CH_4 to CO_2e	25	25
Average CH_4 emissions reduction with AWD (kg CO_2e/ha per growing season)	4025.5	4523.5
Average CH_4 emissions reduction with AWD (metric tons CO_2e/acre per growing season)	1.831	1.629

Appendix 2: Key References and Use

Source	Use in Analysis	Value
NASS 2017 Data	Harvested Acres by State	Arkansas 1,103,733 California 436,710 Louisiana 397,653 Mississippi 91,285 Missouri 167,573 Texas 155,764
EQIP	Cost data by region [Note: EQIP averaged labor costs from each State to get a nationwide average cost]	$33.35 per acre
Irrigation and Diesel Costs	Cost data by State, aggregated into region. Cost after 23.4% reduction in water and diesel use. (Obtained from State budgets)	**Region** **Cost ($)** **AWD Cost** Delta 108.30 82.96 Pacific 212.84 163.04 Corn Belt 122.00 93.45 So. Plains 175.81 134.67
Total Costs (EQIP – Irrigation and Diesel Costs)	EQIP minus irrigation and diesel cost reduction	**Region** **Cost ($)** Delta 8.01 Pacific -16.46 Corn Belt 4.80 Southern Plains -7.79
Greenhouse Gases From Irrigated Rice Systems Under Varying Severity of Alternate-Wetting and Drying Irrigation. (Balaine et al. 2019)	CH_4, N_2O (California only)	CH_4: 2,929 kg CO_2e saved per hectare per year (1.185 tons per acre) N_2O: 4 kg CO_2e emitted per hectare per year (0.002 tons per acre)

Greenhouse Gas Emissions and Management Practices That Affect Emissions in U.S. Rice Systems. (Linquist et al. 2018)	CH_4 (California and Mid-South)	CH_4 California: 4,523.5 kg CO_2e saved per hectare per year (1.831 tons per acre) CH_4 Mid-South: 4,025.5 kg CO_2e saved per hectare per year (1.629 tons per acre)
Reducing Greenhouse Gas Emissions, Water Use, and Grain Arsenic Levels in Rice Systems. (Linquist et al. 2015)	N_2O (Mid-South)	N_2O: 134.7 kg CO_2e emitted per hectare per year (0.055 tons per acre)
Alternate Wetting and Drying in High Yielding Direct-Seeded Rice Systems Accomplishes Multiple Environmental and Agronomic Objectives. (LaHue et al. 2016)	N_2O (California)	N_2O: 4.47 kg CO_2e emitted per hectare per year (0.002 tons per acre)
Reducing Greenhouse Gas Emissions, Water Use, and Grain Arsenic Levels in Rice Systems. (Linquist et al. 2014)	CH_4, N_2O (National); Yield impacts	CH_4: 4,406.7 kg CO_2e saved per hectare per year (1.783 tons per acre) N_2O: 96.5 kg CO_2e emitted per hectare per year (0.039 tons per acre)
The Economic Viability of Alternative Wetting and Drying Irrigation in Arkansas Rice Production. (Nalley et al. 2015)	CH_4, N_2O (Mid-South)	CH_4: 3,270.7 kg CO_2e saved per hectare per year (1.324 tons per acre) N_2O: 117.1 kg CO_2e emitted per hectare per year (0.047 tons per acre)

Calculation – Average of Literature Review Results	Total GHG Emissions, California and Mid-South	California: 1.506 tCO_2e saved per acre per year Mid-South: 1.425 tCO_2e saved per acre per year
A Farmer Using the Alternate Wetting and Drying Technique that Reduce Methane Emissions by 30%-70%. (UN Environment Programme 2021).	Image in introduction of report.	N/A

Chapter 7: Marginal Abatement Cost Curve Analysis–Tillage

Chapter 7 of 8.

Contents

Technology Overview

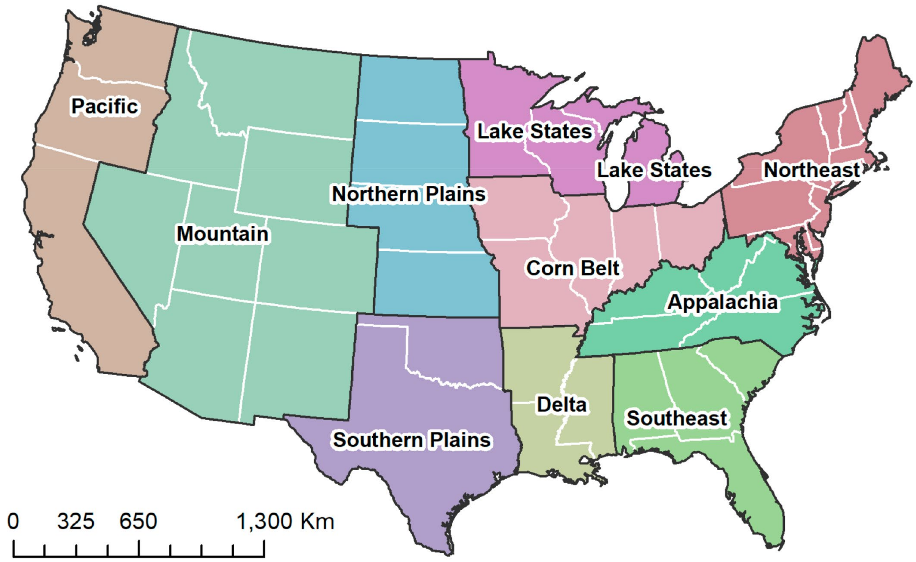
Tillage is a field management practice used to prepare land for planting, incorporate crop residue or fertilizers, and control weeds (Claassen et al., 2018). Conventional Till (CT)—the most intensive form of tillage—results in less than 15 percent of crop residue remaining on the field after tillage is conducted (Claassen et al., 2018). Mulch Till (MT) is less intensive than CT and is defined as "managing the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round while limiting soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting" (USDA NRCS, 2016a). MT leaves between 15 and 30 percent of crop residue on the field (USDA NRCS, 2006). No Till (NT), defined as "limiting soil disturbance to manage the amount, orientation and distribution of crop and plant residue on the soil surface year-round" has an absence of tillage operations and results in more than 30 percent of crop residue remaining on the field (USDA NRCS, 2006). Tillage practice can also be classified based on their soil tillage intensity rating (STIR), which are values are based on a combination of the soil disturbance and the severity of the disturbance. Components of the STIR value include operational speed of tillage equipment, tillage type, depth of tillage operation and percent of the soil surface area disturbed. For the MACCs, STIR values of less than 10 correspond to NT, 10 to 80 to MT, and greater than 80 to CT (USDA NCRS, 2017).

MACC Overview

Marginal Abatement Cost Curves (MACCs) estimate the price of carbon dioxide equivalent (CO_2e) would need to be paid to farmers to adopt conservation tillage practices based on on-farm changes in GHG emissions associated with practice adoption.[20] The 2022 MACCs estimate what the cost of a metric ton of carbon dioxide equivalent (MTCO_2e) would have to be based on the greenhouse gas (GHG) impacts (including soil carbon and CO_2 emissions from on-farm fossil fuel use) of transitioning tillage management practices from CT-MT, CT-NT, and MT-NT on corn, cotton, sorghum, soybean, and wheat in the 10 USDA regions across the United States as shown in figure 1.

[20] The MACCs are based strictly on changes in on-farm greenhouse gas emissions associated with practice adoption. They do not include any upstream or downstream emissions that might also be affected by practice adoption.

Figure 1. USDA production regions used in MACC



Data Updates

To update the 2016 MACCs, more recent data were collected, and, where applicable, new assumptions were made. Table 1 shows a comparison of the 2016 and the 2022 data sources and assumptions that were updated in the 2022 MACCs. Sources and further information on each of the data sources for 2022 are provided in the respective sections below.

Table 1. Comparison of 2016 and 2022 data sources and assumptions

Scenario	2013/2016 MACC	2022 MACC
GHG Sources	Soil Carbon – DAYCENT[1] On-Farm GHG–N/A	Soil Carbon – COMET[2] On-Farm GHG–CEAP-1[3]
Cost Sources	Bottom-up farm budget based[1]	Top-down EQIP payment based[4]
Acreage Source	Total Acreage – NASS[1] Percent of each tillage type–ERS/ARMS[1]	Total Acreage – NASS[5] Percent of each tillage type–ERS/ARMS[6]
Applicability Source	Assumptions not based on prior studies[1]	Moore et al., (2022) tillage adoption projection-based assumptions[7]

Note: COMET=CarbOn Management Evaluation Tool, GHG=greenhouse gas, N/A=not applicable.
[1] ICF (2013) and Pape et al, (2016)
[2] USDA CarbOn Management Evaluation Tool (2022)
[3] USDA NRCS (2016b)
[4] USDA Environmental Quality Incentives Program (2022)
[5] USDA NASS (2022)
[6] USDA ERS (2022)
[7] Moore et al, (2022)

The following sections give:

1. Overview of the update
2. Detailed descriptions of the updated data sources, including any data manipulation
3. Descriptions of changes to assumptions

Greenhouse Gas Data

The updated MACCs estimate for the GHG reductions that result from transitioning to conservation tillage come from:

- COMET (USDA, 2022) as total CO_2e differences from transitioning from the starting tillage practice (CT or MT) to the ending tillage practice (MT or NT).
- CEAP-1 (USDA NRCS, 2016b) data as the total fuel use related CO_2e differences from transitioning from the starting tillage practice (CT or MT) to the ending tillage practice (MT or NT).
- The total CO_2e values from COMET and CEAP-1 were combined to generate the GHG benefits of transitioning tillage practices.
- The scope of GHG impacts was limited to changes in on-farm GHG emissions and soil carbon sequestration. Upstream and downstream changes in emissions that that occur as the result of practice adoption are not included (i.e., emissions from herbicide production, equipment manufacturing, post-harvest processes etc.).

Data Collection and Analysis

- Pulled county-level data from USDA databases (COMET) on GHG impacts of transitioning from:
    - CT-MT
    - CT-NT
    - MT-NT
- Note that COMET values are not crop specific.
- Took simple averages of county-level results to get Statewide average GHG impacts for each practice.
- Regional values per acre were generated using a weighted average of greenhouse gas reductions by total acres in each State.
- For fuel use related CO_2e differences we used the values from the CEAP-1 surveys as estimated in Table 2 of USDA NRCS (2016).
    - Specifically, the greenhouse gas impacts measured in CO_2e estimated by NRCS (2016) were subtracted from the baseline management case to generate management practice specific estimate and then added to COMET greenhouse gas reductions for each of the three management practices (CT-MT, CT-NT, MT-NT).
    - For example: For CT-MT, the mulch till value (0.03987 tons CO_2e per acre) is subtracted from the CT value (0.06776 tons CO_2e per acre) to generate the reduction value per acre of 0.02789 tons CO_2e per acre.

- Total GHG impacts each of the three management practice transitions were then estimated by combining the COMET values with the management specific fuel use value. For more details see table 2.

Table 2. COMET and CEAP-1 adjusted regional greenhouse gas reductions by management practice (MT CO_2e acre)

Scenario	Southeast	Mountain	Delta	Pacific	Northeast	Corn Belt	Northern Plains	Appalachia	Lake States	Southern Plains
CT–MT	0.18	0.09	0.21	0.09	0.18	0.23	0.18	0.2	0.2	0.16
CT–NT	0.49	0.24	0.61	0.24	0.51	0.73	0.52	0.59	0.58	0.48
MT–NT	0.36	0.17	0.46	0.17	0.38	0.56	0.39	0.44	0.44	0.36

Assumptions Update

- Assumed that COMET values are a proxy for soil-related GHG impacts of farmers switching practices from CT-MT, CT-NT, and MT-NT.
- Assumed that the CEAP-1 estimates of fuel use for CT, MT, and NT are applicable to all crop types in all regions as an estimate of the CO_2e fuel use impacts of the three tillage practices.
- Assumed that the combination of COMET GHG emissions and CEAP-1 fuel emissions are a proxy for the total on-farm GHG emissions associated with transitioning tillage practices from CT-MT, CT-NT, and MT-NT.

Cost Data

The updated MACCs cost estimates for transitioning tillage practices to conservation tillage are based on EQIP payment rates. EQIP payment rates were used as a proxy for the minimum payment required to encourage landowners to adopt conservation till practices. EQIP has been used as a proxy for the costs of adopting conservation tillage in two previously published MACCs, Biardeau et al., (2016) and Sperow, (2020).

Assumptions Update

- Assumed that COMET values are a proxy for soil-related GHG impacts of farmers switching practices from CT-MT, CT-NT, and MT-NT.
- Assumed that the CEAP-1 estimates of fuel use for CT, MT, and NT are applicable to all crop types in all regions as an estimate of the C fuel use impacts of the three tillage practices.
- Assumed that the combination of COMET GHG emissions and CEAP-1 fuel emissions are a proxy for the total on-farm GHG emissions associated with transitioning tillage practices from CT-MT, CT-NT, and MT-NT.

Data Collection and Analysis

- Pulled regional level payment rate data from USDA databases (EQIP).
- NRCS CPS 345, Reduced and Tillage Management, Reduced Till.

    - Scenario name Residue and Tillage Management, Reduced Till.
    - Captures payment rates from adoption costs associated with transitioning from CT-MT.
    - Assumes typical farm size of 100 acres.
- NRCS CPS 329 Residue and Tillage Management, No-Till.
    - Scenario name No-Till/Strip-Till.
    - Captures payment rates from startup costs associated with transitioning from CT-NT.
    - Assumes typical farm size of 100 acres.
- As there are no EQIP payment rates for transitioning from MT-NT, we used CT-NT payment rates as a proxy value. The higher payment rate of CT-NT was selected over the CT-MT rate to ensure that the costs of transitioning from MT-NT were not underestimated.
- Selected EQIP payment rates that included costs associated with:
    - Materials.
    - Equipment.
    - Labor.
- As EQIP payments are not crop specific, the three management practice transitions regional costs were applied to all five crop types.
- For more details:
    - Tables 3 and 4 show examples of the cost components used in total tillage pricing by NRCS for EQIP.
    - Table 5 shows the payment rates used in the MACC.

Table 3. EQIP component payment rates for CSP 345–residue and tillage management, reduced till in the Corn Belt

Component Name	Quantity & Unit	Total Component Cost	Rate Per Unit ($ per unit)	Component Justification
Seeding Operation, No Till/Strip Till Planter	100 acres	$2,155.44	$21.55 per acre	Equipment to seed and establish the crop using no-till, strip till, or direct seed. All of the acres are planted with a planter.

Table 4. EQIP component payment rates for CSP 329–residue and tillage management, no-till in the Corn Belt

Component Name	Quantity & Unit	Total Component Cost	Rate Per Unit ($ per unit)	Component Justification
Seeding Operation, No Till/Grass Drill	100 acres	$2,305,70	$23.06 per acre	Equipment to seed and establish the crop using no-till, strip till, or direct seed. All of the acres are planted with a drill.

Table 5. EQIP MT and NT payment rates by region

Region	Rates Per Acre, CPS 329 No-Till	Rates Per Acre, CPS 345 Reduced Till
Northern Plains	$22.18	$20.35
Delta States	$22.18	$20.35
Appalachia	$23.44	$21.91
Corn Belt	$23.06	$21.55
Lake States	$23.08	$21.58
Mid-Atlantic	$26.91	$25.15
New England	$22.81	$21.32
Northern Mountain	$21.25	$19.86
Pacific	$22.29	$20.83
Southeast	$22.72	$21.24
Southern Mountain	$21.00	$19.63
Southern Plains	$18.89	$17.66

Assumptions Update

- Assumed that farm size does not impact costs.
- Assumed that EQIP payment rates are a proxy for what carbon payments would have to be for farmers to adopt practices.
- Assumed that the costs of adopting a practice were the same for the five crops of interest (i.e., there is no cost differentiation between crop types).
- As there are no EQIP payment rates for transitioning from MT-NT, assumed that the costs for transitioning from MT-NT are equivalent to those of transitioning from CT-NT.

Acres Under Current Tillage Practices

The updated MACCs estimate for regional and crop specific total acres under production and acres currently grown using specific tillage practices comes from:

- USDA NASS for total acres under production.
- USDA ERS ARMS for the percent of acres grown using each tillage practice by crop and by region.
- Crop and regional specific total acres of each crop are determined by multiplying the number of acres grown of each crop in each region by the percent of acres grown using each tillage type.

Data Collection and Analysis

- Pulled information from USDA databases (NASS) on acreage.
  - NASS (2022) data for 2021 was pulled for acres planted for corn, cotton, sorghum, soybean, and wheat planted in each State in the 10 regions across the U.S.
- Received ARMS data from USDA ERS on tillage utilization.
  - Data from the most recent crop specific ARMS surveys were pulled for CT, MT and NT utilization for each State in the survey.
  - Crop specific ARMS data were from the following years:
    - Corn, 2016.
    - Cotton, 2015.
    - Sorghum, 2019.
    - Soybeans, 2018.
    - Wheat, 2017.
- As not all States which reported crop acres in NASS (2021) were surveyed in the 2015–2019 ARMS surveys for each given crop, State management practice rates were generated using the following rules:
  - For State/crop combinations for which tillage percentages were available from ARMS:
    - We multiplied the tillage rate by that crop's acreage.
  - For State/crop combinations that did not have a specific tillage rate available from ARMS, but for which ARMS had tillage rates for neighboring States in their region:
    - We multiplied a regional value for tillage rates for that crop (which they derived as a weighted average of tillage rates of neighboring States weighted by their crop acreage) by that crop's acreage.
  - For State/crop combinations that had neither a specific tillage rate nor tillage rates from neighboring States in their region available from ARMS:
    - We multiplied a national value for tillage rates for that crop (which they derived as the weighted average of States in the ARMS survey weighted by their crop acreage) by that crop's acreage.
- To generate the crop-specific number of acres grown under each production practice for each region, the total acres of the crop grown in each region was multiplied by the regional percent of acres grown under each practice type.
- For more details see table 6.

Assumptions Update

- Assumed that all acres under a given tillage practice are permanent (e.g. long-term NT, long-term MT, long-term CT) and that acres do not transition between tillage practices.
- Assumed that crop and regional specific ARMS data on the percent of acres under each practice type (e.g., CT, MT and NT) are a proxy for practice use in 2021 and can be applied to 2021 acres.

Table 6. Total acres by current management practice, crop, and region

Total Acres by Crop and Region	Appalachia	Corn Belt	Delta States	Lake States	Northeast	Mountain	Northern Plains	Pacific	Southeast	Southern Plains	Total
Corn-CT	564,040	11,713,706	12,968	8,057,782	1,094,635	925,181	6,302,517	2,989	387,967	1,854,006	30,915,788
Corn-MT	1,248,223	16,752,697	12,968	5,641,977	675,958	273,701	7,225,819	2,989	634,868	364,876	32,834,076
Corn-NT	2,288,737	7,983,597	2,134,065	1,050,241	1,500,407	1,076,119	12,321,665	674,023	307,165	271,118	29,607,136
Wheat-CT	1,227	245,440	1,831	1,215,069	2,855	1,684,710	4,787,702	1,478,189	760	4,392,454	13,810,238
Wheat-MT	1,227	967,128	1,831	548,085	2,855	2,230,242	2,807,046	663,526	760	3,066,068	10,288,769
Wheat-NT	1,562,546	1,017,431	301,338	346,847	847,291	5,680,048	8,615,251	1,273,284	518,479	2,441,478	22,603,993
Sorghum-CT	-	-	-	-	-	23,376	224,385	-	-	1,308,706	1,556,467
Sorghum-MT	-	-	-	-	-	14,905	1,704,699	-	-	1,284,382	3,003,986
Sorghum-NT	-	-	-	-	-	456,719	2,300,916	-	-	-13,088	2,744,547
Soybeans-CT	280,606	7,592,073	3,485,441	6,002,710	5,589	-	4,419,885	-	1,236	3,808	21,791,347
Soybeans-CT	759,551	15,628,708	1,988,457	4,338,303	5,589	-	6,611,540	-	1,236	3,808	29,337,192
Soybeans-CT	4,609,843	13,729,219	866,102	1,558,987	1,658,823	-	12,118,575	-	842,529	682,383	36,066,461
Cotton-CT	71,285	182,755	676,996	-	-	170,439	246	114,000	248,659	4,248,089	5,712,469
Cotton-MT	168,693	47,553	286,062	-	-	295	246	-	641,410	1,427,269	2,571,528
Cotton-NT	485,022	84,692	76,942	-	-	6,766	109,508	-	985,932	1,186,642	2,935,503

Applicable Acres

The updated MACCs estimate for number of applicable acres or the total, regional specific number of acres that could be converted conservation tillage come from Moore et al., (2022). To estimate the number of acres that could be converted from CT to conservation till (with a focus on converting to NT over MT) we used the final 10-year accelerated adoption estimates and MT-to-NT ratios of Moore et al., (2022) as a proxy for total applicable acres of each conservation tillage type in each region. Specifically, we used the Moore et al, (2022) ratio of NT:MT acres to model the percent of acres transitioned out of CT and the ratio of CT:MT acres to model where new NT acres originated from (e.g., from CT or MT). These ratios were then applied to ERS data on tillage baseline adoption. Given the focus on converting to NT over MT, 100 percent of applicable CT acreage (i.e., the acreage remaining after the maximum adoption rate has been applied) was converted to NT in every region except the Lake States.

Data Collection and Analysis

- For acres remaining in CT, used Moore et al., (2022) 10-year accelerated conservation till adoption rate percentages to estimate total number of acres that did not adopt conservation tillage.
  - Baseline acreage available for tillage was calculated by multiplying NASS (2022) data for 2021 planted crop acreage by ERS data on tillage adoption by practice (e.g., CT, MT and NT) and crop type.
  - Multiplied CT acres by Moore et al., (2022) regional conservation tillage adoption rate percentages to determine maximum number of acres that transition to MT or NT.
    - For example, the Corn Belt achieved a CT adoption rate of 95.6 percent under Moore et al., (2022)'s accelerated scenario, meaning that 4.4 percent of total acres remained in CT.
    - See figure 2, step A.
- For the percent of acres transitioning from CT-MT, CT-NT, and MT-NT, we used CT, MT, and NT acreage from the Moore et al., (2022) accelerated adoption scenario as the acreage after conservation tillage adoption and back-calculated the percent of acres that transitioned from each starting tillage category.
  - Used the same baseline acreage values for tillage as described above.
  - Moore et al., (2022) determined how acres transitioned out of CT to NT and MT using the 2017 ratio of NT:MT. At the end of the accelerated adoption period, most of the acres previously under CT are converted to NT. This occurs because the 95th percentile ratio between NT:MT is already quite high for most regions. This high baseline adoption ratio of NT, coupled with high overall conservation tillage adoption rates set by using the 95th percentile, means that most CT acres transition to NT under an aggressive adoption scenario, rather than being evenly split between NT and MT. Because of this, it is assumed that 100 percent of CT acres transition to NT for most regions. However, the 95th percentile ratio

for the Lake States is lower at 0.622, which is why the transition from CT to NT is not 100 percent for this region.

- Moore et al., (2022) modeled the source of new NT acres using the 2017 ratio between CT:MT and calculated how many acres transitioned by source type, i.e., conversion from CT to NT and MT to NT.
    - In all regions except the Lake States, Moore et al., (2022) projections showed a dramatic increase in NT and a net loss of MT (e.g., CT and MT acres were transitioned to NT, resulting in fewer ending MT acres).
    - To model this, in all regions except for the Lake States, 100 percent of CT acres were transitioned to NT.
    - In the Lake States, 44 percent of CT goes to MT and 56 percent of CT goes to NT.
        1. See figure 2 step A.[21]
- To model transition from MT:NT, we compared the baseline acreage of MT with the new acres of NT that Moore et al., (2022) estimated originated from the conversion of MT:NT, which Moore et al., (2022) predicted using the 2017 ratio of CT:MT.
    - In the Corn Belt, for example, Moore et al., (2022) calculated that 14,833,914 acres of new NT would originate from converting MT:NT. The Corn Belt had 30,246,106 acres of MT tillage in 2017, meaning that 49 percent of the existing MT acres transitioned to NT at the end of the accelerated adoption scenario. Conversely, this would mean 51 percent of the original MT acreage remained in MT.
    - On average, around 50 percent of the MT acreage per region transitioned from MT to NT. (See figure 2 step B.)

For more details see figure 2 and table 8.

[21] Note that figure 1 shows only Corn Belt transitions and does not include Lake States transitions, so the values match with the Corn Belt acreages and not the Lake States acreages.

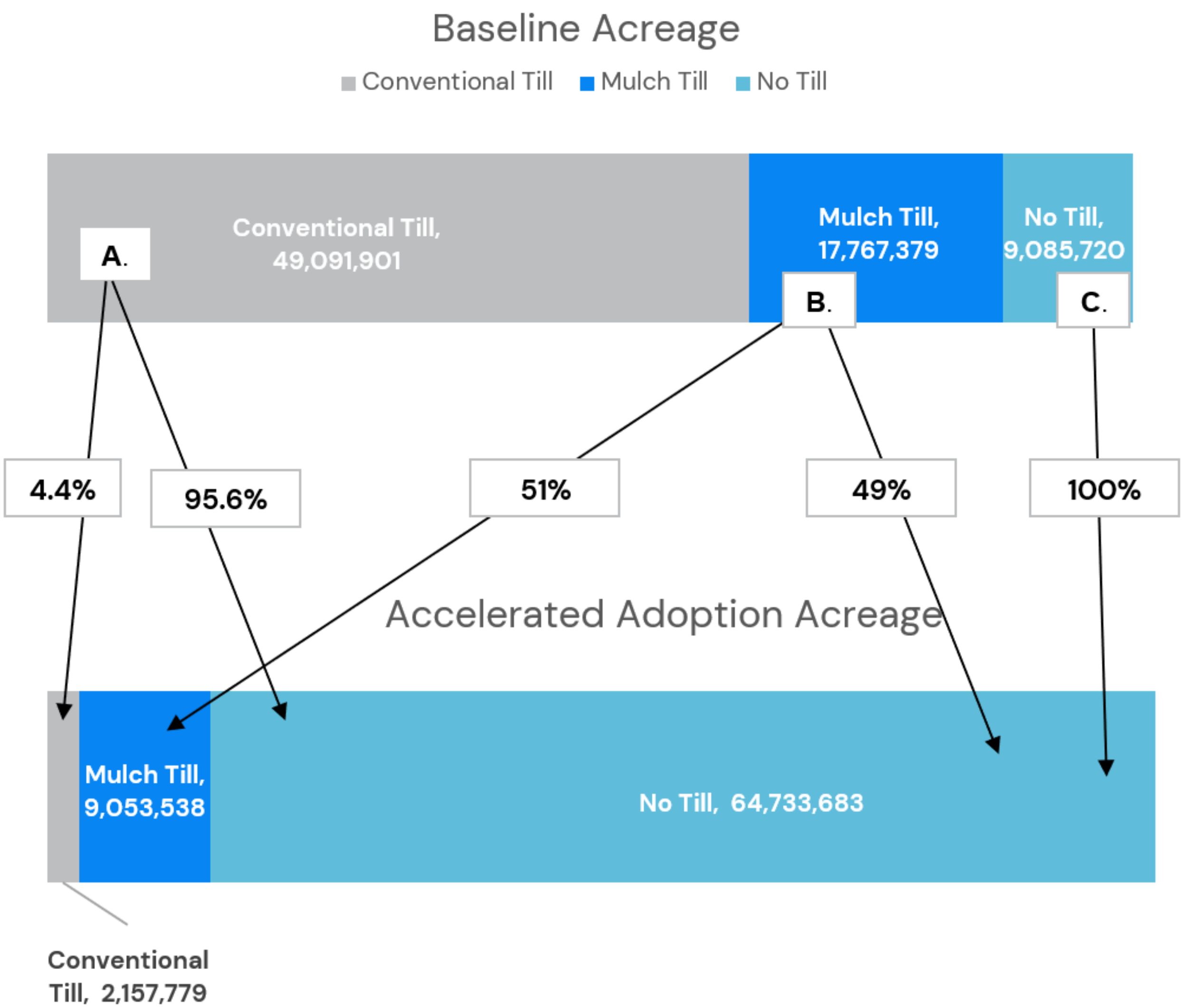
Table 7. Tillage transition projections

Region	Conservation Tillage (NT + MT) Adoption Rate	% of Acres Remaining Conventional	CT to MT	CT to NT	MT to NT
Appalachia	100%	0%	0%	100%	62%
Delta States	94%	6%	0%	100%	69%
Southeast	97%	3%	0%	100%	70%
Southern Plains	89%	11%	0%	100%	41%
Pacific	95%	5%	0%	100%	29%
Mountain	98%	2%	0%	100%	36%
Northern Plains	99%	1%	0%	100%	58%
Northeast	97%	3%	0%	100%	51%
Corn Belt	96%	4%	0%	100%	49%
Lake States	87%	13%	44%	56%	26%

Table 8. Tillage transition in the Corn Belt

Tillage Type	Baseline Acreage	New Acreage at End of Growth Period	Change
Conventional Till	49,091,901	2,157,778.9	-46,934,122
No Till	9,085,720	64,733,683.4	+55,647,963
Mulch Till	17,767,379	9,053,537.7	-8,713,841

Figure 1. Tillage transition assumptions



Corn Belt Transition Examples:

Steps:

A. The Corn Belt achieved a CT adoption rate of 95.6 percent under the Moore et al., (2022) accelerated scenario, meaning that 4.4 percent of total acres remained in CT.

- 95.6% x 49,091,901 = 46,934,122 acres of CT available for conversion and 2,157,778 acres that remain in CT. Of the 46,934,122 acres of CT available for conversion, it is assumed that 100 percent of the CT acres will transition to NT (figure 2 step A).

B. Moore et al., (2022) data indicated that in the Corn Belt, 51 percent of the original MT acreage remains in MT and that 49 percent of the original MT acreage transitions to NT.

- 17,767,379 x 49 percent = 8,713,841 MT acres transition to NT (Figure 2 Step B).

C. It is assumed that NT cannot revert to CT or MT. Therefore 100 percent of the existing NT acres will remain in NT.

- 46,934,122 CT to NT + 9,085,720 baseline NT + 8,713,841 MT to NT = 64,733,683 total NT acres (Figure 2 Step C).

Assumptions Update

- Assumed that all transitions to MT or NT are permanent and that no acres transition “back” to more intensive tillage (i.e., NT-MT, MT-CT or NT-CT does not occur).
- Assumed that the regional conservation tillage adoption rate achieved under the 10-year accelerated adoption scenario (i.e., percent of acres transitioning from CT-MT and CT-NT) is a proxy for the maximum possible adoption level for conservation tillage in each region.
- Assumed that the regional NT:MT ratios of adoption under the 10-year accelerated adoption scenario (e.g., percent of acres transitioning from CT-MT and CT-NT) is a proxy for the regional percent of acres that will transition from CT-MT and CT-NT.
- Assumed that the regional CT:NT ratio of adoption under the 10-year accelerated adoption scenario (e.g., percent of acres transitioning from CT-MT and CT-NT) is a proxy for how many NT acres were transitioned from CT-NT and how many were transitioned from MT-NT regionally.
- Assumed that the regional transition ratios were the same for all five crop types.
- Based on the above, assumed that in every region except the Lake States, 100 percent of applicable CT acreage (i.e., the acreage remaining after the maximum adoption rate has been applied) was converted to NT. The only region with MT remaining at the end of the 10-year accelerated adoption scenario is the Lake States region.

MACC Modeling and Figures

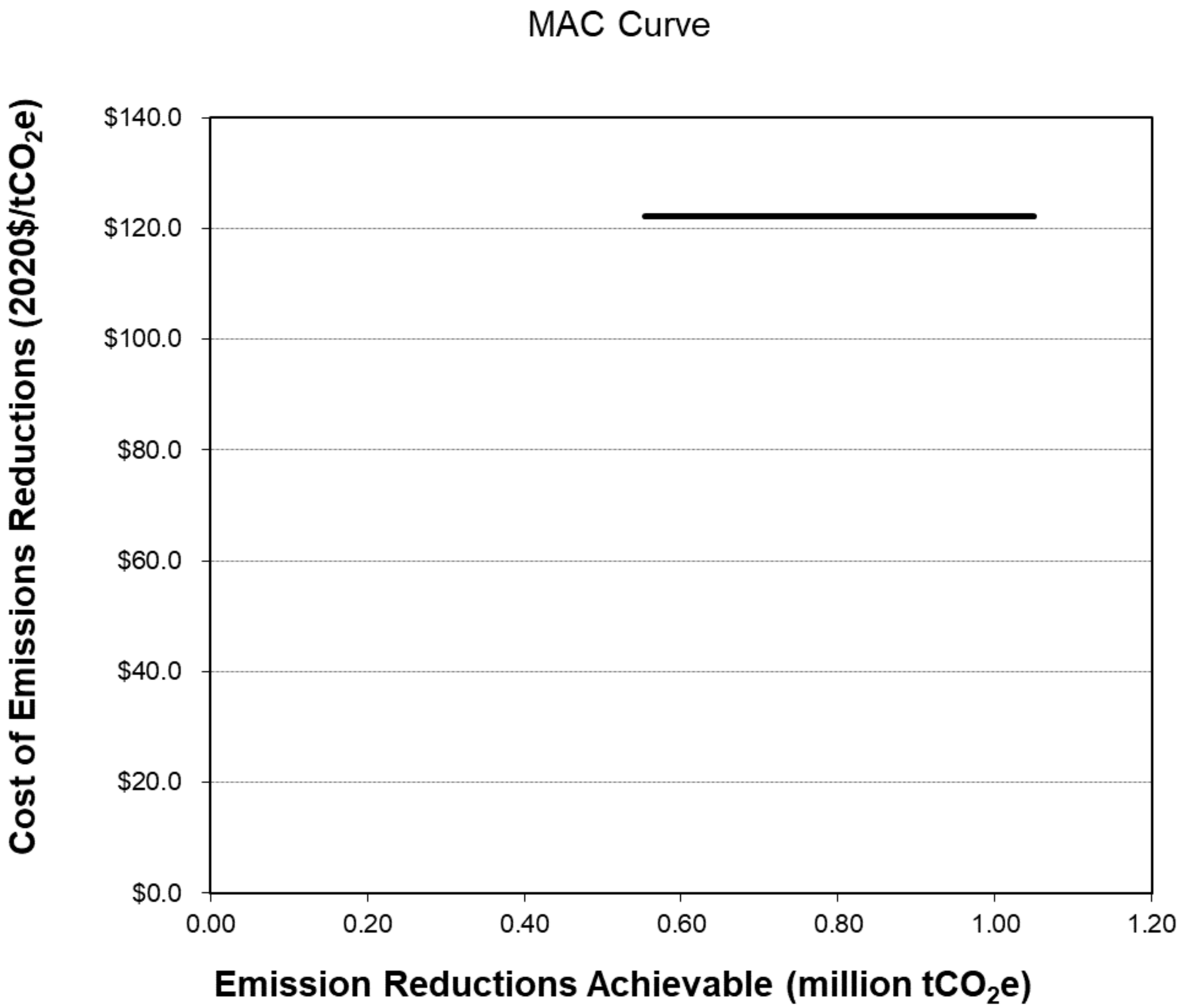
Due to the simplification of GHG savings, and the cost data compared to the previous versions of the MACCs, there is less regional and crop variation between management practice breakeven costs in this updated MACC for conservation tillage when compared to previous versions. As a result, the MACC results for tillage practices are likely to have fewer inflection points.

- Prepared new MACC tab in overall USDA MACC Excel file.
- Entered in data from summary table calculations into MACC model by region.
    - **Lifetime:** 1 year as farmers can choose their tillage practice annually.

- No diminishing returns to soil carbon storage from continued use of a specific tillage management practice.
- **Applicable Acres:** Total applicable acres were estimated using 2016 and 2013 report methodologies as well as employing the new Moore et al., (2022) applicable acre estimates.
- **Capital Cost:** None.
- **Recurring Cost:** Additional costs were entered according to EQIP payment rates.
- **Total Revenue:** None, EQIP is assumed to encompass all costs associated with transitioning management practices.
- **Emission Reduction:** Total GHG emissions reductions in tons of CO_2e from COMET and reductions in CO_2e from fuel use from CEAP-1.
- **Breakeven cost:** Calculated using MACC formulas.

For MACC curves see figures 3–6.

Figure 2. CT – MT



Note: t=metric tons, CO_2e=carbon dioxide equivalent.

Figure 3. CT–NT

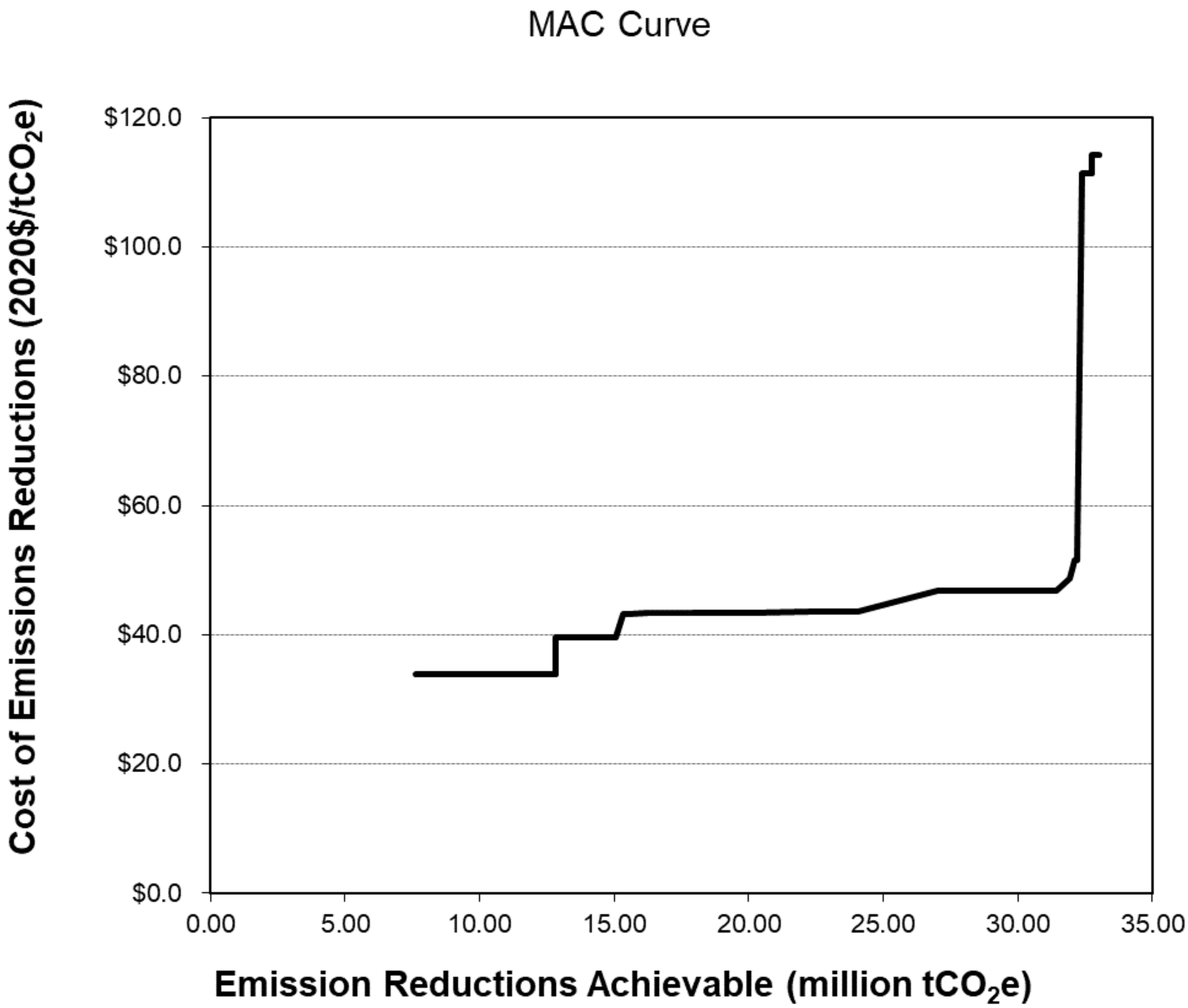


Figure 4. MT–NT

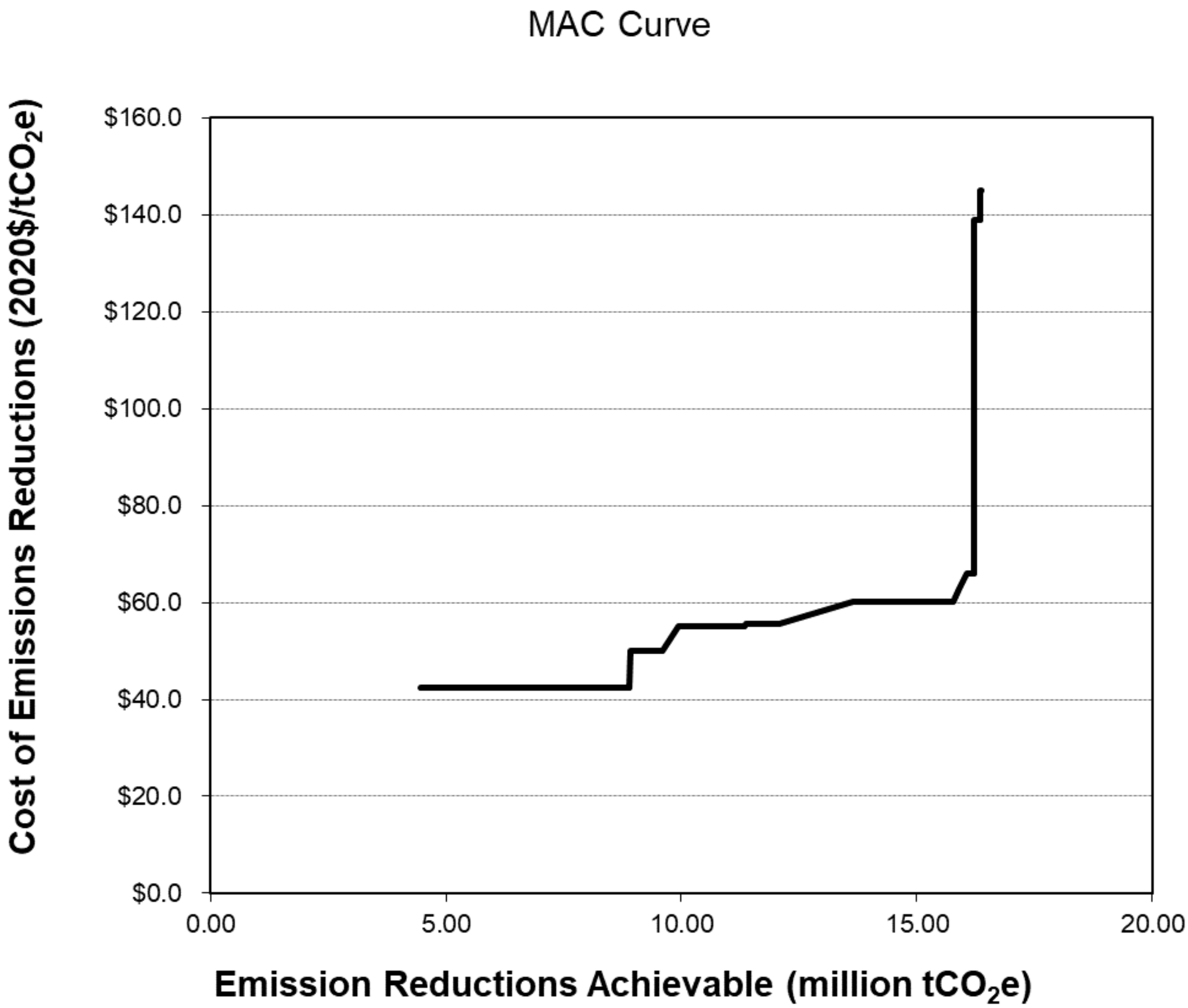
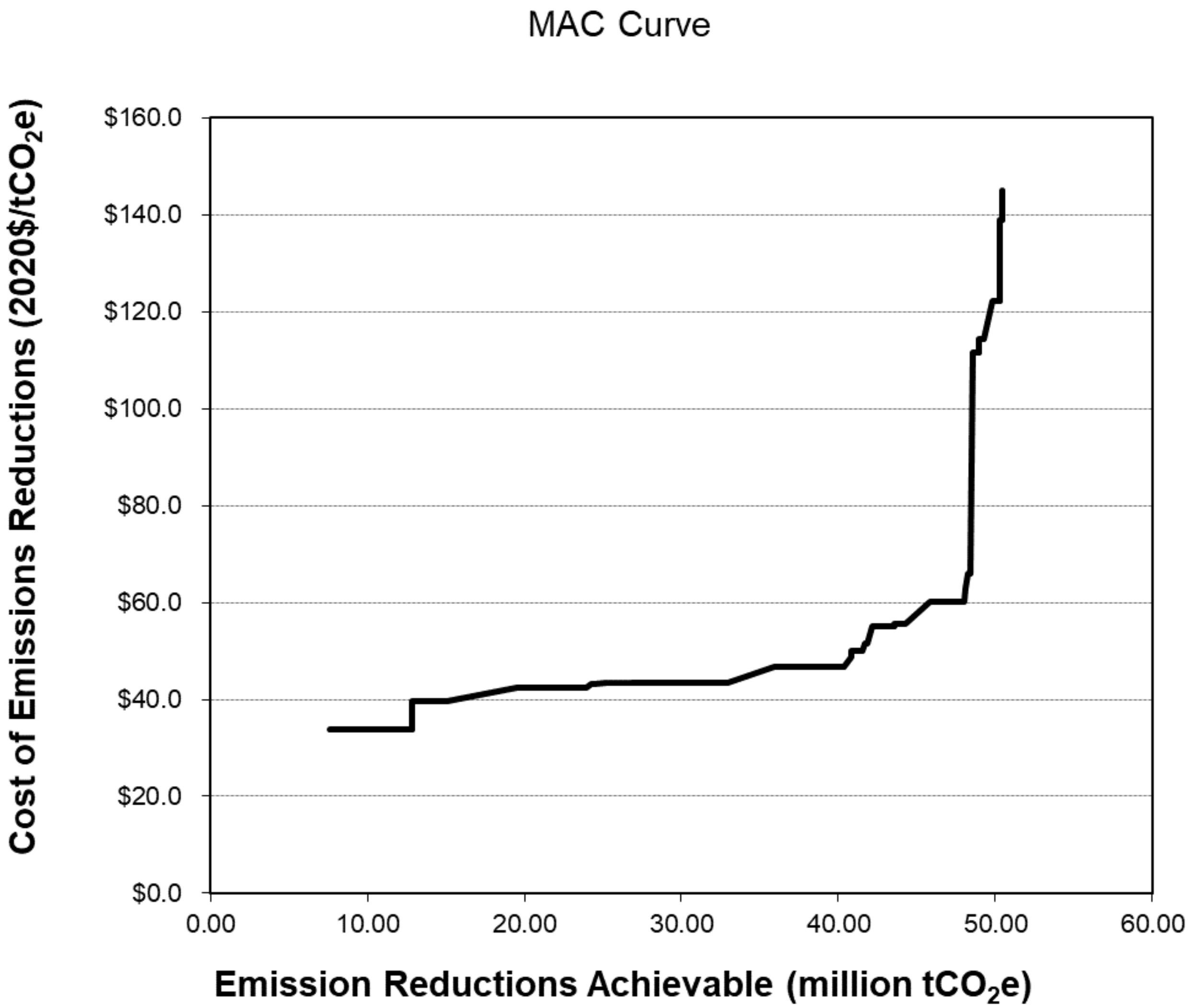


Figure 5. All tillage (CT-MT, CT-NT, MT-NT)



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Chapter 8: Marginal Abatement Cost Curve Analysis – Enhanced Efficiency Fertilizers and Variable Rate Technology

Chapter 8 of 8.

Contents

Technology Overview

This document explains the methodology used to develop independent marginal abatement cost curves (MACCs) for enhanced efficiency fertilizers (EEFs) and variable rate fertilizer application (referred to as VRT throughout). It is important to note that the MACCs were built assuming that both technologies could be implemented on the same acreage (e.g., that both EEFs and VRT could be applied to the same acreage). However, while the EEF and VRT MACCs are designed with the assumption that applicable acres are overlapping, the greenhouse gas (GHG) impacts of each technology are estimated individually. Due to a lack of available data, the MACCs do not estimate the combined GHG impacts of using both EEFs and VRT. As such, it is not known if using both technologies would result in additive impacts (e.g., the GHG savings of using EEFs + the GHG savings of using VRT) or if the overall GHG savings would be less than adding the two together but more than either of the practices individually, or another value.

Additionally, given that the GHG and financial benefits of each technology varies based on a wide range of factors (e.g., soil type, production method, local ecosystem, temperature) it is challenging to select one set of conditions to represent their impacts for all crops under all conditions for the entire United States. As such, both technologies were modeled with two sets of assumptions: (1) that using the technology resulted in no yield impacts and (2) that using the technology resulted in minor yield benefits as supported by the literature.

Enhanced Efficiency Fertilizers

Nitrogen fertilizer is an important agricultural input added to approximately 65 percent of major field crops in the United States. (Ribaudo, 2017). Nitrogen (N) management is complex, and when N is applied at rates higher than is taken up by crops, excess N can be "lost" through multiple pathways, such as ammonia (NH_3) volatilization; emissions of nitrous oxide (N_2O), N oxides (NO and NO_2), and dinitrogen (N_2) gases; nitrate leaching (NO_3); off-site transport of N (via wind or water erosion) in organic matter, and loss of NO_3 and ammonium (NH_4) in inorganic matter (Delgado, 2002). Ammonia volatilization, nitrate leaching, runoff, and N_2O emissions all have negative atmospheric and water quality impacts. In 2020, synthetic N application resulted in emissions of 63.8 million metric tons of carbon dioxide equivalent (CO_2e), around 23 percent of direct N_2O emissions from agricultural soils (U.S. EPA, 2022).

Efforts to reduce leaching, atmospheric losses, and runoff from excess nitrogen fertilization include application of nitrogen using the "4Rs" (right source, right rate, right time, right place), implementing conservation practices (i.e., use of cover crops and riparian buffers, etc.) and the use of Enhanced Efficiency Fertilizers (EEFs) (Akiyama et al., 2010; Drury et al., 2017; Reetz et al., 2015; Smith et al., 2007; USDA NRCS, 2019; Wade et al., 2015; Delgado et al., 2018). EEFs are fertilizer products with characteristics that allow increased plant nitrogen uptake and reduce the potential of nutrient losses to the environment (e.g., gaseous losses, leaching, or runoff) when compared to an appropriate reference product (AAPFCO, 2013). These products include nitrification inhibitors (NIs), urease inhibitors (UIs), double inhibitors and chemical-coated fertilizers (coated) (USDA ERS, 2016). EEFs function by slowing the process through which fertilizers are broken down into byproducts that can be volatilized, leached, and/or are utilized by the plant. See table 1 below for a description of each of these EEF types.

Table 1. EEF types and descriptions

EEF type	Description
Slow- or controlled-release or coated-fertilizer	A fertilizer containing a plant nutrient in a form which delays its availability for plant uptake and use after application, or which extends its availability to the plant significantly longer than a reference "rapidly available nutrient fertilizer." Products that have been amended with an additive that reduces the rate of transformation of fertilizer compounds, resulting in extended time of availability in the soil.
Nitrification inhibitor	A substance that inhibits the biological oxidation of ammoniacal-N to nitrate-N.
Urease inhibitor	A substance that inhibits hydrolytic action on urea by the enzyme urease.
Double inhibitor	A combination of both a nitrification inhibitor and a urease inhibitor.

(Definitions based on AAPFCO, 2013)

EEFs are more expensive to purchase than traditional fertilizers, meaning that producers must decide that using EEFs will be cost effective (Li et al., 2018; Zhou et al., 2018). To make such decisions, producers need to determine whether use of EEFs will result in additional nitrogen use efficiency (NUE), yield benefits, and/or will reduce N_2O and NH_4 emissions and NO_3 leaching.

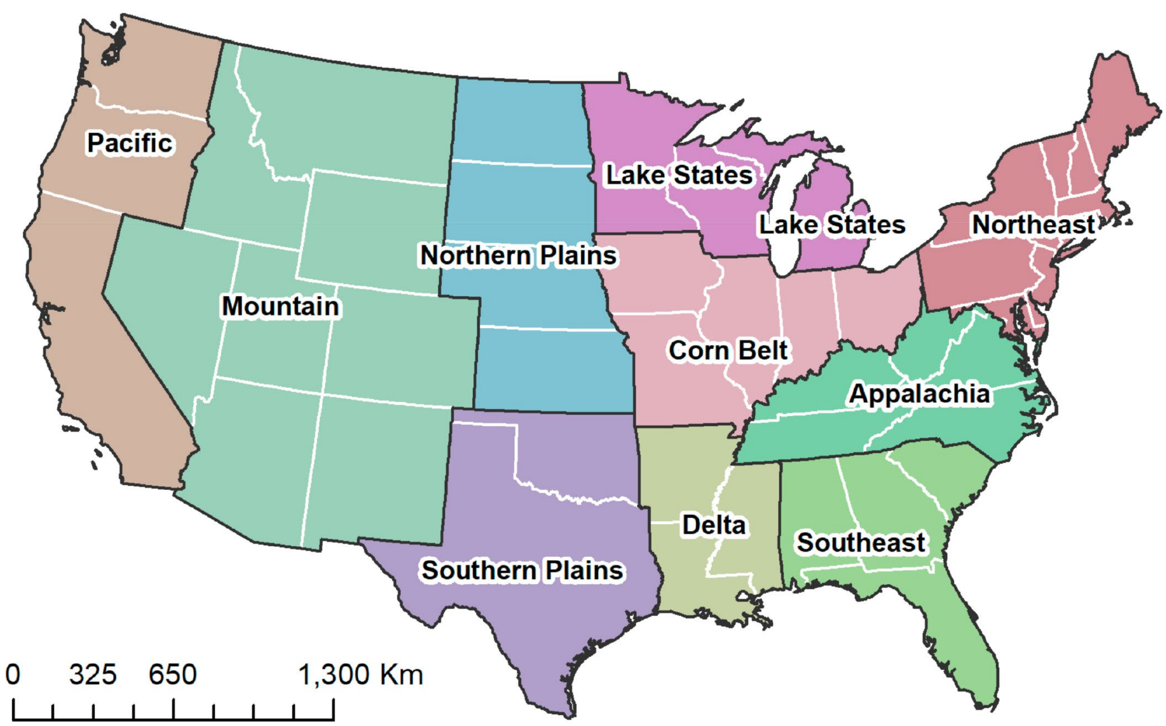
Variable Rate Technology

The highly variable nature of soil types within an individual field result in correspondingly variable rates of N application required to support crop production. Given such soil variability, a uniform N application rate across a field can result in both underapplication and overapplication of N to different portions of a field, resulting in reduced yield potential for underfertilized areas and increased N costs, volatilization, leaching and runoff in overfertilized areas. Variable rate fertilization technology (referred to as VRT throughout this document) is a technology designed to vary fertilizer rates according to the needs of each area within a field thereby improving fertilizer use efficiency and reducing leaching. VRT is implemented by varying the application rate of fertilizers on uniquely different soil areas within a field according to a pre-set field map that is developed through soil testing.

MACC Overview

Marginal Abatement Cost Curves (MACCs) estimate what price of carbon dioxide equivalent (CO_2e) would need to be paid to farmers to adopt use of NIs, UIs, and/or coated urea[22] or VRT for N application based on on-farm changes in GHG emissions associated with practice adoption.[23] The 2022 MACCs provide a greater understanding of the costs of implementing EEFs and adopting VRT across the 10 USDA production regions (figure 1).

Figure 1. USDA regions used in MACCs



[22] For simplicity, the MACC estimates the impacts of applying one type of EEF (e.g., NI, UI, or coated) per acre of land. While double inhibitors exist (e.g., inhibitor with NI and UI combined) the MACC does not assess the impact of using multiple inhibitors on the same parcel of land.
[23] The MACCs are based strictly on changes in on-farm GHG emissions associated with practice adoption. They do not include any upstream or downstream emissions that might also be affected by practice adoption.

Data Updates

To update the 2016 MACCs, more recent data were collected, and, where applicable, new assumptions were made. Table 2 shows a comparison of the 2016 and the 2022 data sources and assumptions that were updated in the 2022 MACCs. References and further information on each of the data sources for 2022 are provided in the respective sections below.

Table 2. Comparison of 2016 and 2022 data sources and assumptions

Component	2013/2016 MACC	2022 MACC
GHG Sources-EEF	N_2O low emission reductions – DAYCENT. N_2O high emission reductions- estimate baseline emissions using Ogle et al. (2010) N_2O emission factor × total N applied using USDA Economic Research Service (ERS)/Agriculture Resource Management Survey (ARMS) and National Agriculture Statistics Service (NASS) data and EEF emission reductions from Akiyama et al. (2010) for NI and Hoeft et al. (2000) for UI.[1]	One emission reduction scenario. Estimate baseline N_2O emissions by multiplying amount of N applied[2] by direct and indirect N_2O emission factors.[3] Emissions reductions from EEF application estimated using crop and EEF specific emissions reductions from the literature.[4]
GHG Assumptions-EEF	Assume corn, cotton, soybeans and wheat only apply anhydrous ammonia and can use NI, while cotton only uses urea and applies UI. No change in N application rate[1].	Assume all crops in all regions apply national ratio of synthetic N types[5], and corresponding EEFs used (e.g., NI, UI or Coated) based on the national ratio (see table 10 for more details). Assume 10 percent reduction in N application rate for all crops in all regions.
GHG Sources-VRT	Estimate baseline emissions using Ogle et al. (2010) N_2O emission factor × Total N applied using ERS/ARMS and NASS data.[1]	One emission reduction scenario. Estimate baseline N_2O emissions by multiplying amount of N applied[5] by direct and indirect N_2O emission factors.[3] Emission reductions from reduced N application estimated using a 10 percent reduction in N application rate.
GHG Assumptions-VRT	Assume 15 percent reduction in emissions from low emissions scenario and 34 percent reduction in emissions from high emission scenario.	Assume all crops in all regions apply national ratio of synthetic N types.[5] Assume 10 percent reduction in N application rate for all crops in all regions.
Cost Sources-EEF	Per acre costs of NI and UI inhibitors.[1] Assume no change in N application rate, labor costs, or crop yield.	Top-down EQIP payment based including labor and soil testing.[6] Cost impacts of a 1 percent reduction in N application rate and EEF specific yield increases from USDA estimates.[6]
Cost Sources-VRT	Assume one-time capital cost for GreenSeeker technology divided by number of acres per farm. Assume 10	Top-down EQIP payment based including labor and soil testing.[6] Assume no capital cost as farmers can

	percent reduction in N application to wheat and 21 percent reduction in N application for corn and no change in labor costs or crop yield.	use service providers/subscription services.[10] Assume 10 percent reduction in N application rate and crop specific yield increases.
Baseline Acreage Source- EEF	Total Acreage – NASS. Percent acres where N as applied, pounds of N applied per acre and percent of acres where EEFs are used ERS/ARMS.[1]	Total Acreage – NASS[8] Percent acres where N as applied, pounds of N applied per acre and percent of acres where EEFs are used ERS/ARMS.[9]
Baseline Acreage Source- VRT	Total Acreage – NASS. Percent acres where N as applied, pounds of N applied per acre and percent of acres where VRT is used ERS/ARMS.[1]	Total Acreage – NASS[8] Percent acres where N as applied, pounds of N applied per acre and percent of acres where VRT is used ERS/ARMS.[9]
Applicability Source- EEF	Assume EEFs will only be applied on acres where N is applied at correct timing and rate and where EEFs are not currently used. Assume EEFs are applied on all farms meeting those criteria between 100 and 250 acres and on 50 percent of farms > 250 acres. Assume that EEFs and VRTs will not be applied on the same acres.[1]	Assume all acres where N is applied and not already using EEFs could use EEFs. Not limited by N use practices (e.g., meeting timing and/or rate criteria) farm size and/or use of VRT.
Applicability Source- VRT	Assume VRT will only be used on acres where N is applied at correct timing and rate where VRT is not currently used. Assume VRT will be used on half of farms meeting those criteria > 250 acres and that VRT and EEFs will not be applied on the same acres.[1]	Assume all acres where N is applied and not already using VRT could use VRT. Not limited by N use practices (e.g., meeting timing and/or rate criteria) farm size and/or use of EEFs.

[1] ICF (2013) and Pape et al., (2016); [2] USDA ERS Special Tabulation (2022); [3] Hansen et al. (2023 forthcoming)
[4] Hansen et al. (2023–forthcoming), Tian et al. (2015), Khan et al. (2017); [5] USDA ERS (2019); [6] USDA Environmental Quality Incentives Program (2022); [7] Li et al. (2018); [8] USDA NASS (2022); [9] USDA ERS Special Tabulation (2022); [10] Keating (2020), Schimmelpfennig (2016), Bedord (2022), Griffin & Traywick (2020).

Greenhouse Gas Data

GHG emissions associated with EEFs and VRT used in the MACC are based on changes in N_2O emissions associated with use of EEFs compared to traditional fertilizers and the use of VRT compared to uniform fertilizer application.

Crop specific EEF reduction rates were estimated by averaging changes in GHG emissions for each specific EEF (e.g., UI, NI, and coated urea) for each crop type from papers cited in Li et al. (2018) and other publications:[24]

- Determined N_2O emissions for corn and wheat for coated urea, NIs, and UIs from Li et al. (2018).
    - Proxied sorghum to corn data for coated urea, NIs, and UIs
- Determined N_2O changes for cotton and soybean from USDA Chapter 3 and other literature sources
    - Cotton: general (not crop specific values) Hansen et al. (2023 – forthcoming) for coated urea and NIs; Tian et al. (2015), and Khan et al. (2017) for UIs
    - Soybean: general (not crop specific values) Hansen et al. (2023 – forthcoming) for coated urea and NIs; Khan et al. (2017) for UIs

Values from the above sources were averaged to determine an average GHG reduction value for each type of EEF for each the different crops (see table 3). Note that while these values are known to vary by a variety of factors including local environment, soil type, temperature, moisture, crop production system, irrigation and other factors, due to lack of data, average, crop specific national level EEF impacts were used when available (Li et al., 2018). As crop specific values were not found for soybeans and cotton, general NI and Coated values were sourced from Hansen et al. (2023 forthcoming) which included specific factors for wet and dry climates.

[24] To estimate crop and EEF specific emission factor reductions, the spreadsheet containing individual data points from each paper that was used to develop the Li et al. (2018) estimates was mined for crop and EEF specific data points from US studies and global studies. When available, these values were combined with crop and EEF specific reduction factors from more recent values to generate average reduction factors.

Table 3. Percent emission reduction factor by crop and EEF type (expressed as percent reduction in N_2O emissions)

Crop Type*	Coated Urea	Nitrification Inhibitor	Urease Inhibitor
Corn	24%	41%	33%
Wheat	32%	23%	2%
Soybean Wet	20%	33%	2%
Soybean Dry	38%	46%	2%
Sorghum	24%	41%	33%
Cotton Wet	20%	33%	52%
Cotton Dry	38%	46%	52%

*Soybean and cotton emission factors are based on general NI and Coated emission factors sourced from Hansen et al. (2023 – forthcoming). Emissions reduction varied by wet and dry region, as described above figure 2.

Baseline N_2O emissions and N_2O emission reduction calculations

The first step to estimating the reduction in N_2O emissions from applying EEFs or using VRT is to determine baseline N_2O emissions from N application to those acres not already using the technologies (e.g., the applicable acres). The MACCs estimated three types of baseline N_2O emissions from N application:

1. Direct N_2O emissions
2. Indirect N_2O emissions from runoff and leaching
3. Indirect N_2O emissions from volatilization

The crop and regional specific N application rates were determined by multiplying:

Applicable acres for VRT or EEFs × crop and region-specific N application rate per acre = crop and regional specific amount of N applied on applicable acres

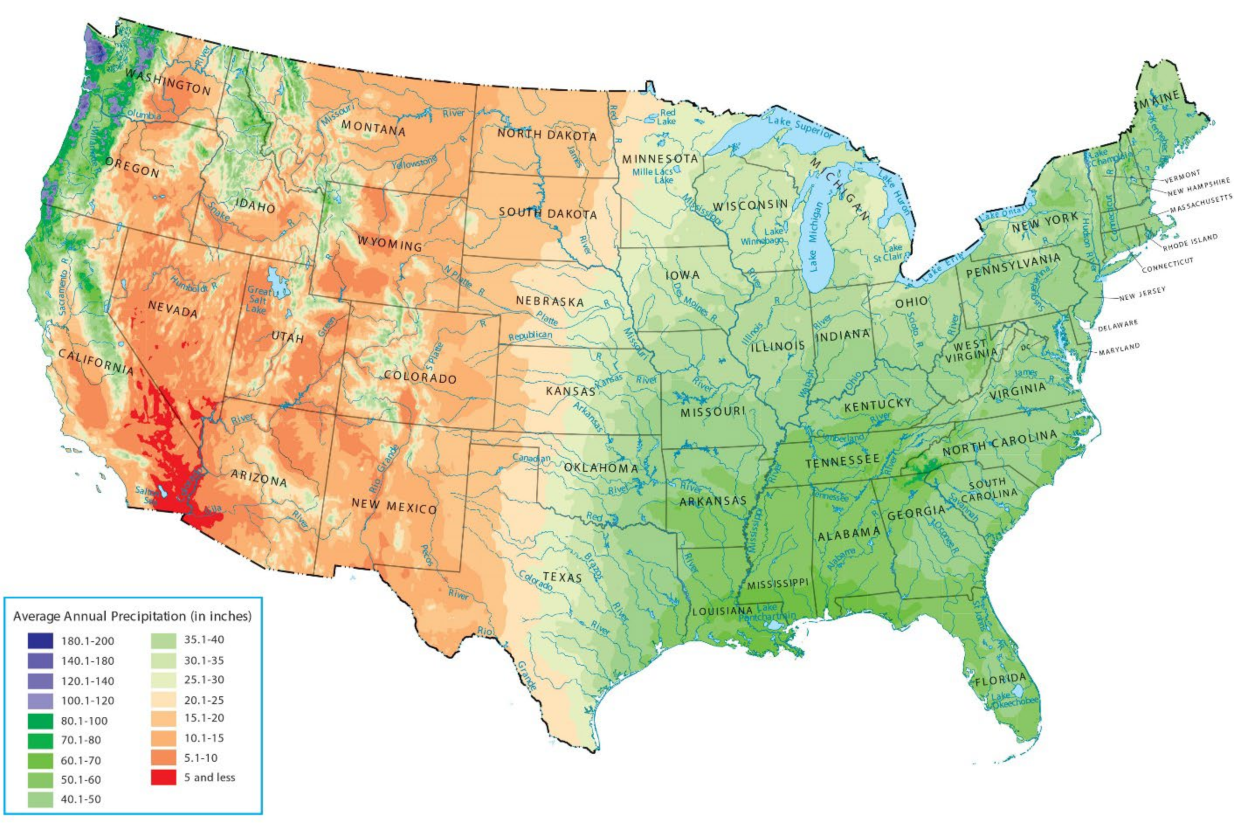
Example for corn in the Corn Belt: 31,593,949 × 165.66 lbs. N applied per acre ÷ 2205 lbs. to metric tons = 2.3 million metric tons of N applied to corn in the Corn Belt

The value generated for the crop and regional specific amount of total N applied on applicable acres was the basis for generating direct and indirect N_2O emissions.

Emission factors for direct and indirect N_2O emissions were taken from Hansen et al. (2023 – forthcoming) as were the estimates for the loss pathways of N applied (e.g., the percent of N applied that was emitted as direct N_2O emissions, the percent that was emitted as indirect in the form of nitrate through runoff and leaching, and the precent that was emitted through volatilization as NH_3).

As both direct and indirect N_2O emissions from runoff and leaching and vary in magnitude depending on if the climate is wet or dry, the 10 USDA regions were divided into “wet” and “dry” regions based on annual rainfall patterns (Hansen et al., 2023 – forthcoming; Wang et al., 2021). Wet/mesic climates occur where the mean annual precipitation is greater than 1,000 mm (~40 inches) and other climates are considered dry/semi-arid (Hansen et al., 2023 – forthcoming). Regions west of the Rockies were determined to be dry, and regions east of the Rockies were determined to be wet. See figure 2 for a precipitation map of the U.S.

Figure 2. Map of average annual precipitation in the United States (GISGeography, 2022).



Once regions were divided into wet and dry, baseline direct (e.g., N_2O emitted directly to the atmosphere from applied N) and indirect N_2O emissions (e.g., emissions from volatilization and leaching/run-off of applied N) were estimated using both the emissions and volatilization factors shown in table 4 and the equations in table 5.

Table 4. Emission factors and conversions used in calculating N_2O emissions (taken directly from Hansen et al., 2023 – Forthcoming)

Description	Value	Units
Wet direct N_2O emission factor	0.016	Metric ton N_2O-N per metric ton N applied
Wet indirect N_2O from volatilization emission factor	0.014	Metric ton N_2O-N per metric ton N volatized
Dry direct and indirect N_2O emission factor	0.005	Metric ton N_2O-N per metric ton N applied
Indirect N_2O from leaching and runoff emission factor	0.011	Metric ton N_2O-N per metric ton of N leached
Fraction of synthetic nitrogen (NSN) that remains unvolatilized	.9	Metric tons N unvolatilized per metric ton N applied
Fraction of synthetic nitrogen (NSN) that volatilizes	.1	Metric tons N volatilized per metric ton N applied
Fraction of synthetic N that leaches	0.24	Metric tons N leached per metric ton of unvolatilized N
Molecular weight conversion N to N_2O	44/28	Dimensionless
GWP N_2O	298	Dimensionless
Emission reduction factor per EEF	Varies by crop and EEF type; see table 3.	Dimensionless

Table 5. Methodology for estimating baseline N_2O emissions

Step	Equation
Step 1: Total N applied	= acres per crop per region where N is applied × metric tons of N applied per crop per acre
Step 2a: Wet region baseline N_2O emissions	= **[**Total N applied × (.9 unvolatilized) × (0.016 wet emission factor) + Total N applied × (.1 volatilized) × (0.014 wet emission factor) + Total N applied × (.9 unvolatilized) × (.24 leach) × (0.011 leach emission factor)**]** × 44/28 × 298
Step 2b: Dry region baseline N_2O emissions	= **[**Total N applied × (.9 unvolatilized) × (0.005 dry emission factor) + Total N applied × (.1 volatilized) × (0.005 dry emission factor) + Total N applied × (.9 unvolatilized) × (.24 leach) × (0.011 leach emission factor)**]** × 44/28 × 298

After determining baseline emissions, the emissions reductions associated with EEF application (e.g., a 10 percent reduction in N application and reduced emissions per metric ton of N applied) were calculated using the equations in table 6. As shown in table 8, note that emissions reductions from using EEFs come from two sources:

1. A 10 percent reduction in N application
2. Reduced emissions per metric ton of N applied

Table 6. N_2O emissions reduction from 10 percent reduction in N application and EEF application

Step	Equation
Step 1: Total N applied after fertilizer reduction	= acres per crop per region × metric tons of N applied per crop per acre × .85 x total N application is reduced by 10 percent
Step 2a: Wet region N_2O emissions after fertilizer reduction	= **[**Total N applied after fertilizer reduction × (.9 unvolatilized) × (0.016 wet emission factor) + Total N applied × (.1 volatilized) × (0.014 wet emission factor) + Total N applied × (.9 unvolatilized) × (.24 leach) × (0.011 leach emission factor)**]** × 44/28 × 298

Step 2b: Dry region N_2O emissions after fertilizer reduction	= **[**Total N applied after fertilizer reduction × 9 unvolatilized) × (0.005 dry emission factor) + Total N applied × (.1 volatilized) × (0.005 dry emission factor) + Total N applied × (.9 unvolatilized) × (.24 leach) × (0.011 leach emission factor)**]** × 44/28 × 298
Step 3: N_2O emissions after EEF application and fertilizer reduction	= N_2O emissions after fertilizer reduction – (N_2O emissions after fertilizer reduction × EEF subtype specific emissions reduction factor)
Step 4: Total N_2O emissions reduction from EEF application	= N_2O baseline emissions from Table 5–N_2O emissions after EEF application and fertilizer reduction from Step 3

Similar to the process used to estimate N_2O reductions for EEF use, emissions reductions associated with VRT use were calculation by subtracting the emissions associated with the reduction in N application from VRT use (10 percent) from baseline N application emissions. Unlike EEF emissions reductions, there are only 3 steps to estimating emissions associated with VRT use as VRT use, unlike EEF use, does not reduce N_2O emissions per metric ton of N applied. Table 9 shows the formula used to estimate N_2O emissions reductions associated with VRT use.

Table 7. N_2O emissions reduction from 10 percent reduction in N application from VRT adoption

Step	Equation
Step 1: Total N applied after fertilizer reduction	= acres per crop per region × metric tons of N applied per crop per acre × .90 x total N application is reduced by 10 percent
Step 2a: Wet region N_2O emissions after fertilizer reduction	= **[**Total N applied after fertilizer reduction × (.9 unvolatilized) × (0.016 wet emission factor) + Total N applied × (.1 volatilized) × (0.014 wet emission factor) + Total N applied × (.9 unvolatilized) × (.24 leach) × (0.011 leach emission factor)**]** × 44/28 × 298
Step 2b: Dry region N_2O emissions after fertilizer reduction	= **[**Total N applied after fertilizer reduction × 9 unvolatilized) × (0.005 dry emission factor) + Total N applied × (.1 volatilized) × (0.005 dry emission factor) + Total N applied × (.9 unvolatilized) × (.24 leach) × (0.011 leach emission factor)**]** × 44/28 × 298
Step 3: Total N_2O emissions reduction from VRT adoption	= N_2O baseline emissions from Table 5–N_2O emissions after fertilizer reduction from Step 2a or 2b

EEF Assumptions

- Assumed that use of EEFs is not impacted by farm size and that both EEF and VRT technologies can be used on any acres where N fertilizer is applied that the technology is not already in use (e.g., both technologies can be used on the same acres).
- The national fertilizer application percentages by N type are representative of N-type application ratios for all crops in all regions
    - Table 10 shows the short tons of nitrogen applied by type in 2015
    - Note that values in table 10 have been adjusted to reflect the N content of each fertilizer type.
- That EEF specific and crop-specific GHG emission reduction factors represent reductions in both indirect and direct emissions and are representative across all regions. Note that while these values are known to vary by a variety of factors (e.g., local environment, soil type, temperature, moisture, crop production system, and other factors), due to lack of data, average, crop-specific national level EEF impacts must be used.

- That EEFs are used in consistent, specific ratios with each type of fertilizer applied for all crop types in all regions. (See table 10 for the usage assumptions associated with each fertilizer type).
- That EEF application allowing for a 10 percent reduction in N application for all crops in all regions does not affect negatively impact crop yields.
    - While the literature does not support a yield boost associated with a universal 10 percent reduction in N application for all crops in all regions associated with EEF use, this reduction represents the average reduction in N application associated with EEF use in the literature and field trials, which ranged from 0 percent to 30 percent without yield losses (Abalos et al., 2014; USDA & EPA, 2022).
    - This value is also consistent with the fertilizer reduction rate estimated for EEFs COMET-planner (Swan et al., 2020).
- That EEF use could result in crop and EEF specific yield boosts for all crops and all regions.
    - While the literature does not support a consistent yield boost for all crops in all regions associated with EEF use, multiple meta-analyses found average crop-specific yield boosts associated with EEF application (Lindquist et al., 2013; Abalos et al., 2014).
    - To conservatively model the impacts of EEF use on yield, MACCs were modeled with and without yield impacts. Figure 3 shows the impact of not including yield boosts on the cost of emissions reductions as a result of EEF use, and figure 4 shows the impact of including a yield increase on the cost of emissions reductions as a result of EEF use.

VRT Assumptions

- Assumed that use of VRT is not impacted by farm size and that both EEF and VRT technologies can be used on any acres where N fertilizer is applied to where the technology is not already in use (e.g., both technologies can be used on the same acres).
- That VRT results in a 10 percent reduction in fertilizer application for all crops in all regions.
    - While the literature does not support a yield boost associated with a universal 10 percent reduction in N application for all crops in all regions where VRT is adopted, this reduction represents a conservative average reduction found in the literature, which ranged from 0 percent to 25 percent without yield losses (McNunn et al., 2018; Kazlauskas et al., 2021; Balafoutis et al., 2017; Griffin & Traywick, 2020; Späti et al., 2021).
- That VRT results in a 1 percent increase in yield for all crop types in each region.
    - While the literature does not support a consistent yield boost for all crops in all regions associated with VRT use, a small yield increase was used in the MACC

as small to mixed impacts on yield are reported in the literature (Balafoutis et al., 2017; Basso et al., 2019; Li et al., 2016).

- To conservatively model the impacts of VRT use on yield, MACCs were modeled with and without yield impacts. Figure 5 shows the impact of not including yield boosts on the cost of emissions reductions associated with VRT, and figure 6 shows the impact of including a yield increase on the cost of emissions reductions associated with VRT use.

Cost Data

EQIP payment rates from USDA NRCS (2022) were used as a proxy for adoption costs for EEF (EQIP CPS E590A) and VRT (EQIP CPS E590B). For EEFs, costs include the combination of increased labor for planning, soil testing and the additional cost of purchasing EEFs compared to conventional fertilizer. For VRT, costs include the combination of increased labor for planning, soil testing, and the surcharge for precision fertilizer application compared to uniform application. See table 8 below and tables 15 and 16 in Appendix A which list component costs for each practice.

Fertilizer prices per acre, average yields per acre, and prices per product (i.e., bushel of corn or pound of cotton) come from USDA ERS (2022)'s Commodity Costs and Returns files for each of the five crops (see table 14 in Appendix A). Note that fertilizer prices per acre, average yields per acre, and prices per product vary by crop and by region.

Table 8. EEF and VRT adoption cost per acre

Region	EEF Adoption Cost ($ per acre)	VRT Adoption Cost ($ per acre)
Appalachia	$32.35	$14.44
Corn Belt	$35.29	$15.76
Delta States	$34.06	$15.21
Lake States	$34.77	$15.53
Mid-Atlantic	$33.99	$15.18
New England	$35.73	$15.95
Northern Mountain	$35.67	$15.93
Northern Plains	$34.06	$15.21
Pacific	$36.80	$16.43
Southeast	$32.87	$14.68
Southern Mountain	$34.11	$15.23
Southern Plains	$33.63	$15.02

Data Collection and Analysis

As shown in the formula below, the net cost of adopting EEFs or VRT was calculated by subtracting any "costs savings" (e.g., cost savings from applying less fertilizer per acre) and increased profits (e.g., increase in money earned from increased yield per acre) from baseline adoption costs.

Net Adoption Cost = [Adoption cost – fertilizer savings – income from increased yield]

For both EEF and VRT use, the net adoption cost was estimated using crop and region-specific adoption costs, fertilizer prices, baseline yields and payment prices. For EEFs, yield impacts were estimated for each crop using EEF specific yield impacts (e.g., crop specific yield impacts for NI, UI, and coated) based on the national ratio of N types applied (see tables 3 and 4 for more details). Since yield impacts can vary depending on a multitude of factors and may not always be observed in every region/every crop, MACC scenarios were ran with and without savings from yield boost to conservatively estimate adoption costs associated with EEFs and VRT.

Table 9 shows example data for coated urea application on corn acreage. Not all crop and EEF types are shown due to space constraints. The fertilizer savings and increased income from yield are represented as negative costs since they offset total adoption costs.

Table 9. EEF net adoption for coated urea applied to corn

Region	EEF Adoption Cost ($ per acre)	Fertilizer Savings ($ per acre)	Increased Income from Yield ($ per acre)	Net cost to adopt ($ per acre)*
Appalachia	$32.35	-$26.06	-$13.38	-$7.09
Corn Belt	$35.29	-$18.19	-$14.38	$2.72
Delta States	$34.06	-$18.19	-$14.38	$1.49
Lake States	$34.77	-$18.94	-$13.33	$2.50
Mid-Atlantic	$33.99	-$18.94	-$13.33	$1.72
New England	$35.73	-$18.94	-$13.33	$3.46
Northern Mountain	$35.67	-$18.94	-$13.33	$3.41
Northern Plains	$34.06	-$14.65	-$11.98	$7.44
Pacific	$36.80	-$14.65	-$11.98	$10.18
Southeast	$32.87	-$26.06	-$13.38	-$6.56
Southern Mountain	$34.11	-$26.06	-$13.38	-$5.32
Southern Plains	$33.63	-$14.65	-$11.98	$7.01

*A negative number indicates that adoption of EEFs results in profit; a positive number indicates an increased cost associated with EEF use.

EEF Assumptions

- There are no capital costs associated with EEF adoption.
- EQIP payment rates for Conservation Practice Standard E590A are a proxy for the costs associated with adopting EEFs.
- A 10 percent decrease in fertilizer application results in a 10 percent decrease in fertilizer costs.
- When yield increases are included, each percent increase in yield (crop and region specific) results in a corresponding percent increase in yield income.

VRT Assumptions

- There are no capital costs associated with VRT adoption.
    - Variable rate fertilizer application is increasingly being outsourced by farmers to third party service providers who offer custom application at a small surcharge (Virk & Harris, 2022; Iowa State University, 2022; Griffin & Traywick, 2020; Späti et al., 2021).
- EQIP payment rates for Conservation Practice Standard E590B are a proxy for the costs associated with adopting VRT.
- A 10 percent decrease in fertilizer application results in a 10 percent decrease in fertilizer costs.
- When yield increases are included in the analysis, a 1 percent increase in yield can be uniformly applied to all crops and regions.

Acres Currently Using EEFs and VRT Technologies and Applicable Acres

Baseline EEF and VRT Adoption

Baseline acres for EEFs and VRTs were estimated using the same methodology, but with adoption-specific data for each practice (e.g., EEF specific data was used to estimate current acreage grown using EEFs and applicable acres where EEFs could be used, and VRT specific data was used to estimate current acreage grown using VRT and applicable acres where VRT could be used). Applicable acres for each technology were estimated independently, meaning that it is assumed that both technologies could be applied on the same acres and that the pool of available acres for each technology overlaps.

The MACCs estimate regional and crop specific total acres under production and acres currently using EEFs or VRT from:

- USDA NASS (2022) for total acres under cropland production.
- USDA ERS Special Tabulation (2022) for the percent of acres grown using N fertilizer by crop type and by crop production region.

- USDA ERS Special Tabulation (2022) for the percent of acres grown using “N inhibitor” or “VRT used for any fertilizing” by crop type and by crop production region.
- USDA ERS (2019) for fertilizer use data on N material usage to determine how to apportion acreage to each EEF subtype (see table 10 and table 11).
    - Type of N material applied (e.g., ammonia derivatives, nitrogen solutions, and urea) determines what EEF can used (see table 10).

Crop- and region-specific total acres of each crop are determined by multiplying the number of acres each crop grown in each region by the regional and crop specific percent of acres where N is applied by the percent of acres where EEF are applied or VRT is used.

Data Collection and Analysis

- Pulled information from USDA databases (NASS) on acreage.
    - NASS (2022) data for 2021 was pulled for acres planted for corn, cotton, sorghum, soybean, and wheat planted in each State in the 10 regions across the United States.
- Received data from USDA (ARMS) on percent of total crop acres where N fertilizer was applied and percent of total crop acres using EEFs or VRT
    - Data from the most recent crop-specific ARMS surveys were pulled for crops including the percent of acres where N is applied, and the percent of acres grown using EEFs or VRT for each State in the survey.
    - Crop specific surveys were from the following years:
        - Corn, 2016
        - Cotton, 2015
        - Sorghum, 2019
        - Soybeans, 2018
        - Wheat, 2017
- For States where no ARMS data were available for that crop, the national average was used.
- To generate the crop-specific number of acres grown using EEFs or VRT, the total acreage of the crop grown in each region was multiplied by the crop and regional specific percent of acres where N fertilizer is applied, then multiplied by the crop and regional percent of acres grown using EEFs or VRT.
    - For EEFs, a portion of the total applicable acreage within each region was also allocated to each EEF subtype to simplify the application.
    - For VRT, all acres where N is applied not currently using VRT are considered applicable acres.

Table 10. U.S. national fertilizer application apportioned to each EEF type

Fertilizer Type	Short tons of N Applied in 2015 from USDA ERS (2019)*	% of Total N Applied	Mapped to EEF	% of Total N Apportioned to Each EEF Type
Urea	1,970,655	20%	Coated urea	20%
UAN – Urea Ammonium Nitrate (Nitrogen Solutions)	3,568,998	35%	50% UI and 50% NI	17.6% UI and 17.6% NI
Ammonia Types + Sodium Nitrate	3,834,556	38%	NI	38% NI
Other N	728,410	7%	50% NI and 50% UI	3.5% NI and 3.5% UI
Total	**10,102,619**	**100%**	**N/A**	**100%**

*Adjusted for N content from table 4. U.S. consumption of selected nitrogen materials, sourced from USDA ERS (2019). See table 12 in Appendix A for raw data.

Table 11. Acreage apportioned to each EEF type

EEF Type	Percent of Applicable Acres Apportioned to Each EEF Subtype
Coated urea	20%
UI	21%
NI	59%

The formulas for estimating current number of acres grown using either EEFs or VRT are show below. To estimate total baseline acres where N is applied for a given crop in a given region, the following formula was used:

> **Step 1:** [NASS total acres for a given crop in a given region] x [percent acres where N is applied for a given crop in a given region] = crop and region-specific baseline acres

To estimate the number of acres where EEFs are already being applied or VRT is being used, the following formula was used:

Step 2: [crop and region-specific baseline acres] x [percent acres where EEFs or VRT are already being used for a given crop in a given region] = current acres in use

To estimate the number of acres on which EEFs or VRT could be used (e.g., the applicable acres), the crop and regional specific value for current acres in use for EEF or VRT was subtracted from the crop and region-specific baseline acres. The remaining acres (e.g., acres in which N is applied but EEFs or VRT are not currently used) were considered applicable acres for EEFs or VRT in the MACC.

Step 3: crop and region-specific baseline acres]- [current acres in use] = applicable acres

Applicable Acres for VRT

Only Steps 1-3 are required for VRT.

Example for corn in the Corn Belt region for VRT applicable acres:

Step 1: 36,450,000 x 99.06 percent = 36,107,370 crop and region-specific baseline acres

Step 2: 36,107,370 x 37.6 percent = 13,590,814 current acres in use

Step 3: 36,107,370 − 13,590,814 = 22,516,556 applicable acres

Applicable Acres for EEFs

For applicable acres for EEFs, one additional step was required. Applicable acres within each region need to be apportioned to each EEF subtype. The percentage use of each EEF subtype was determined based on fertilizer use data from USDA ERS, and the EEF types typically use with each fertilizer type (table 10).

Step 4: applicable acres x percent acres allocated to each EEF subtype = applicable acres per subtype

Example for corn in the Corn Belt region for EEF applicable acres:

Step 1: 36,450,000 x 99.06 percent = 36,107,370 crop and region-specific baseline acres

Step 2: 36,107,370 x 12.5 percent = 4,513,421 current acres in use

Step 3: 36,107,370 – 4,513,421 = 31,593,949 applicable acres

Step 4: 31,593,949 x 59 percent = 18,711,465 acres for nitrification inhibitors

31,593,949 x 21 percent = 6,719,648 acres for urease inhibitors

31,593,949 x 20 percent = 6,162,836 for coated urea

Assumptions

- USDA ERS ARMS (2022) percentages by crop type and by crop production region for the percent of acres grown using “N inhibitor” were considered to be a proxy for the percent of acres on which any type of EEF was applied (e.g., NI, UI or coated).
    - This assumption is consistent with EEF application percentages reported in CEAP II surveys (USDA NRCS, 2022)
- USDA ERS Special Tabulation (2022) percentages for “VRT used for any fertilizing” by crop type and by crop production region are a conservative proxy for VRT use for N application.
    - This assumption is consistent with previous USDA ERS Special Tabulation survey data which collected data on both “VRT Used for Any Purpose” and “VRT Used for Nitrogen Application” allowing for comparison of the two. For crops surveyed, VRT use for N application ranged from 50 percent to 100 percent of VRT use for any fertilizing (USDA ERS, 2015).
- For simplicity, it was assumed that all acres grown using EEFs or VRT will continue to be grown using those technologies and will not revert back to baseline practices (e.g., using conventional N fertilizer or uniform N application rates)
- Assumed that crop- and region-specific ARMS data on the percent of acres grown using EEFs or VRT are a proxy for practice use in 2021 and can be applied to 2021 NASS acres.
- Assumed that use of EEFs or VRT is not impacted by farm size and that both technologies can be used on any acres where N fertilizer is applied (e.g., both technologies can be used on the same acres).

MACC Modeling and Figures

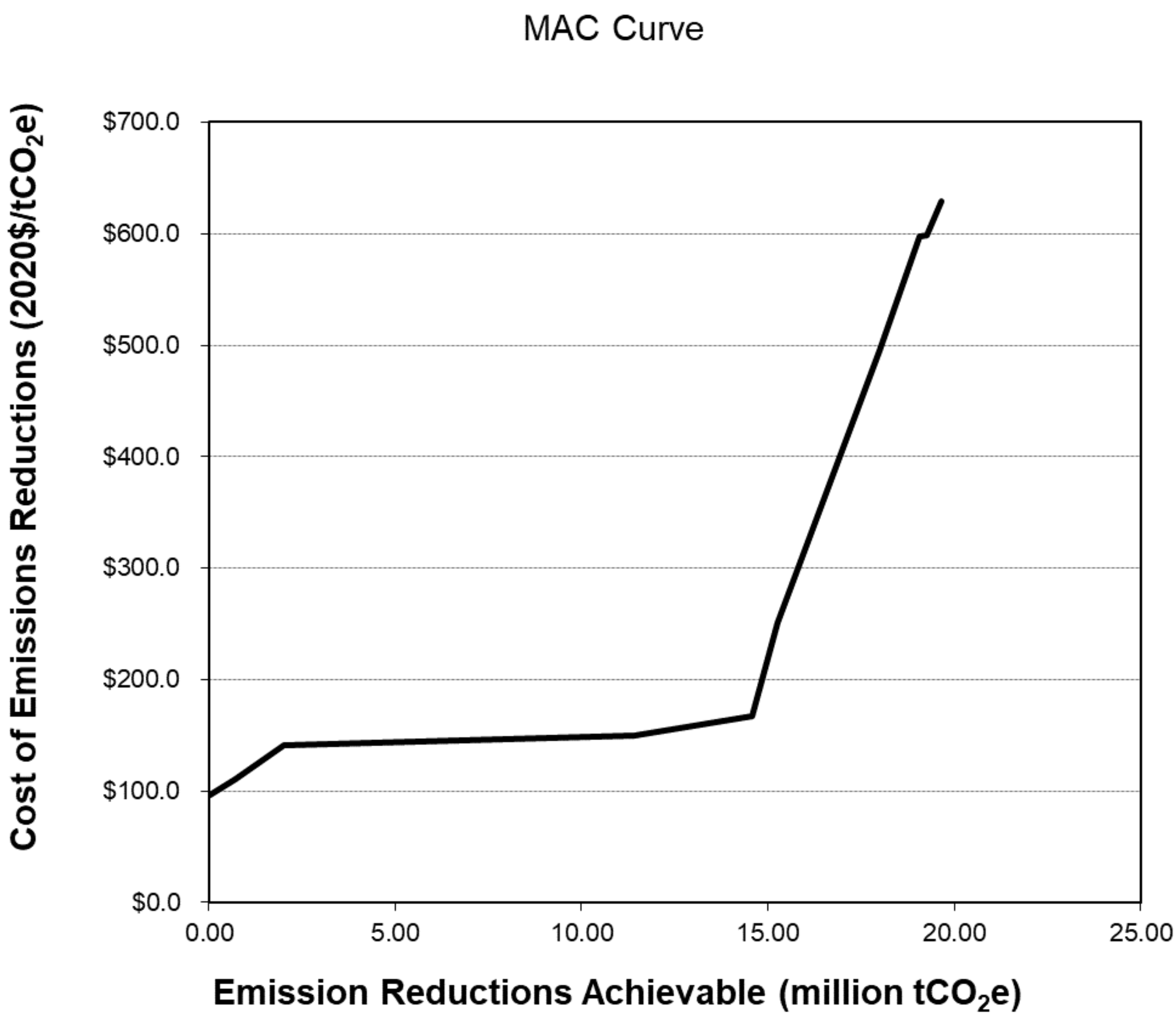
Marginal Abatement Cost Curves (MACCs) provide a greater understanding of the regional costs of implementing EEF application and VRT adoption by estimating what the price of carbon dioxide equivalent (CO_2e) would need to be for producers to adopt cover crops.

The steps to prepare the MACC were as follows:

- **Background Data**
    - Performed literature review to gather background information on baseline adoption, applicable acres, emissions reductions per acre, and co-benefits (e.g., yield boosts and fertilizer reduction).
    - Summarized background information in Excel spreadsheet
    - Prepared new MACC tab in overall USDA MACC Excel file

- Entered in data from summary spreadsheet calculations into MACC model by region
- **MACC Component Calculations:**
  - **Lifetime:** 1 year. Payments in the EQIP contract were calculated over 1 year. The cost to apply fertilizers recurs annually.
  - **Capital Cost:** None.
  - **Recurring Cost:** Net adoption cost = [Adoption cost – Savings on fertilizers – Increase income from yield boost]
  - **Total Revenue:** None. No impact is observed on revenue because the cost savings from co-benefits (i.e., yield improvement and fertilizer reduction) already accounted for in the reoccurring cost to adopt.
  - **Emissions Reduction:** Crop, region, and technology specific emission impacts calculated as described in table 6 and table 7.
  - **Regional Breakeven Cost:** in 2020 USD/tCO_2e; calculated using MACC formulas.
- For MACC curves see figures 3–6.

Figure 3. EEF MACC scenario A (10 percent fertilizer reduction without yield boost)



Note: t=metric tons, CO_2e=carbon dioxide equivalent.

Figure 4. EEF MACC scenario B (10 percent fertilizer reduction with yield boost)

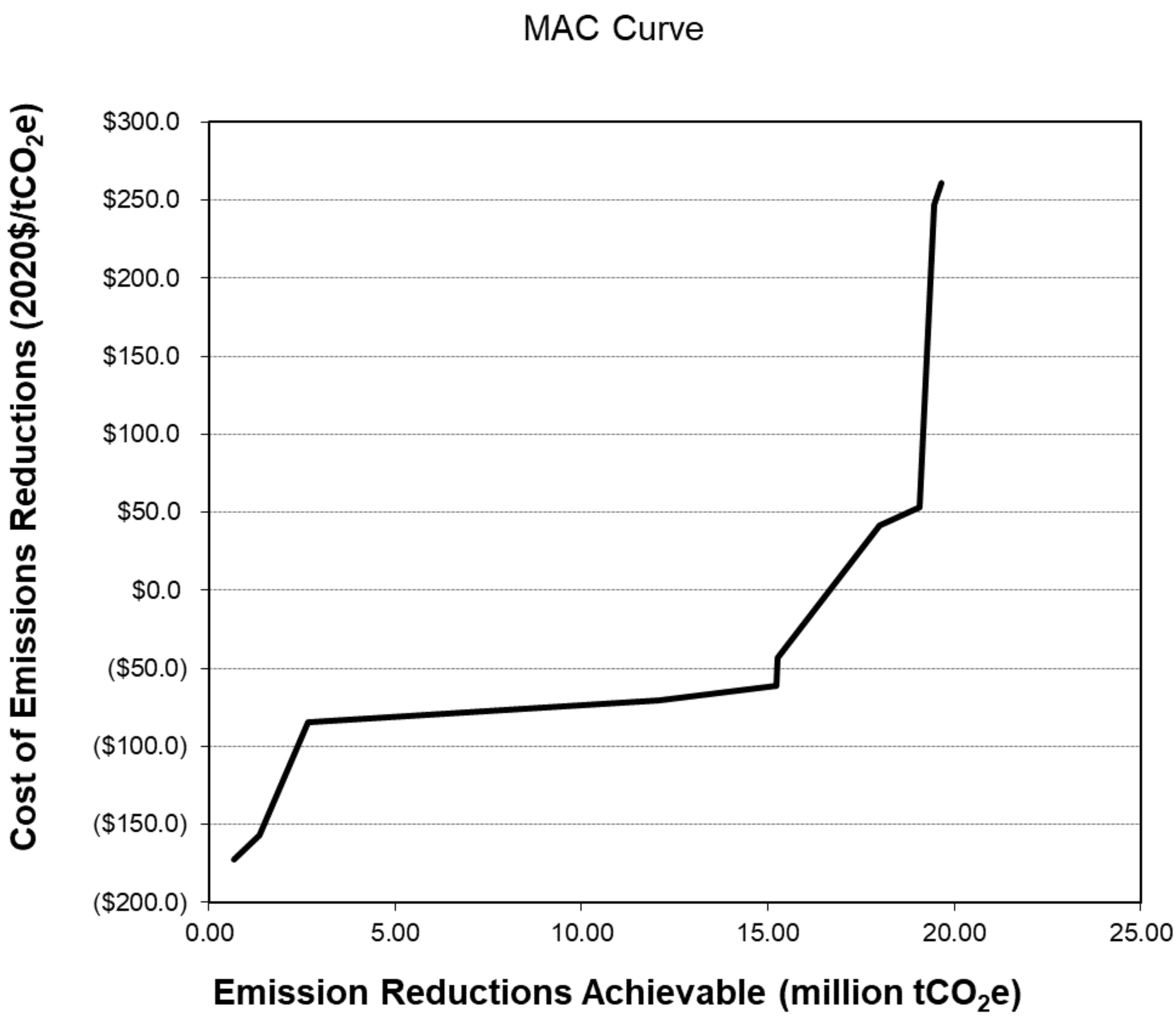


Figure 5. VRT MACC scenario A (10 percent fertilizer reduction without yield boost)

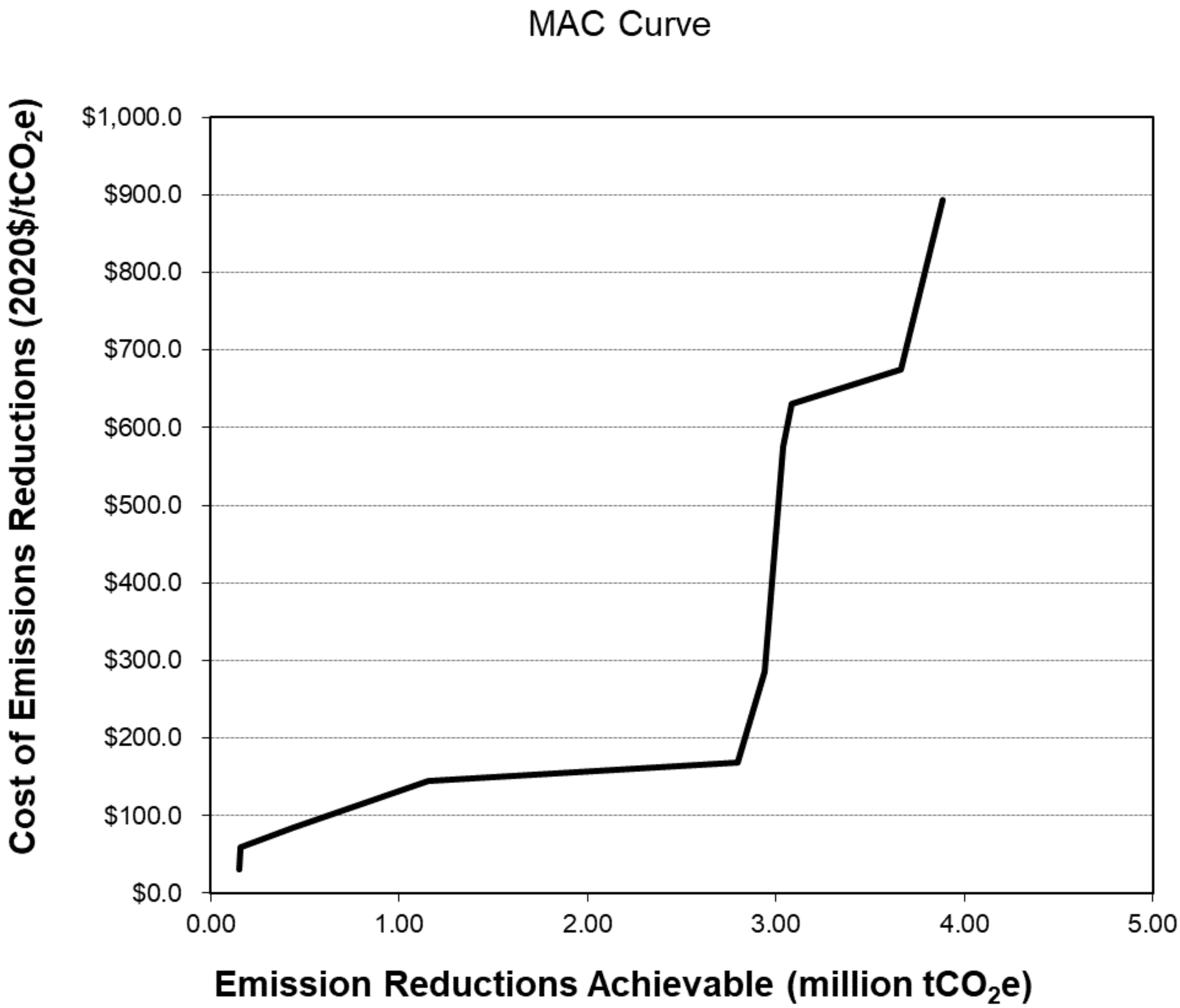
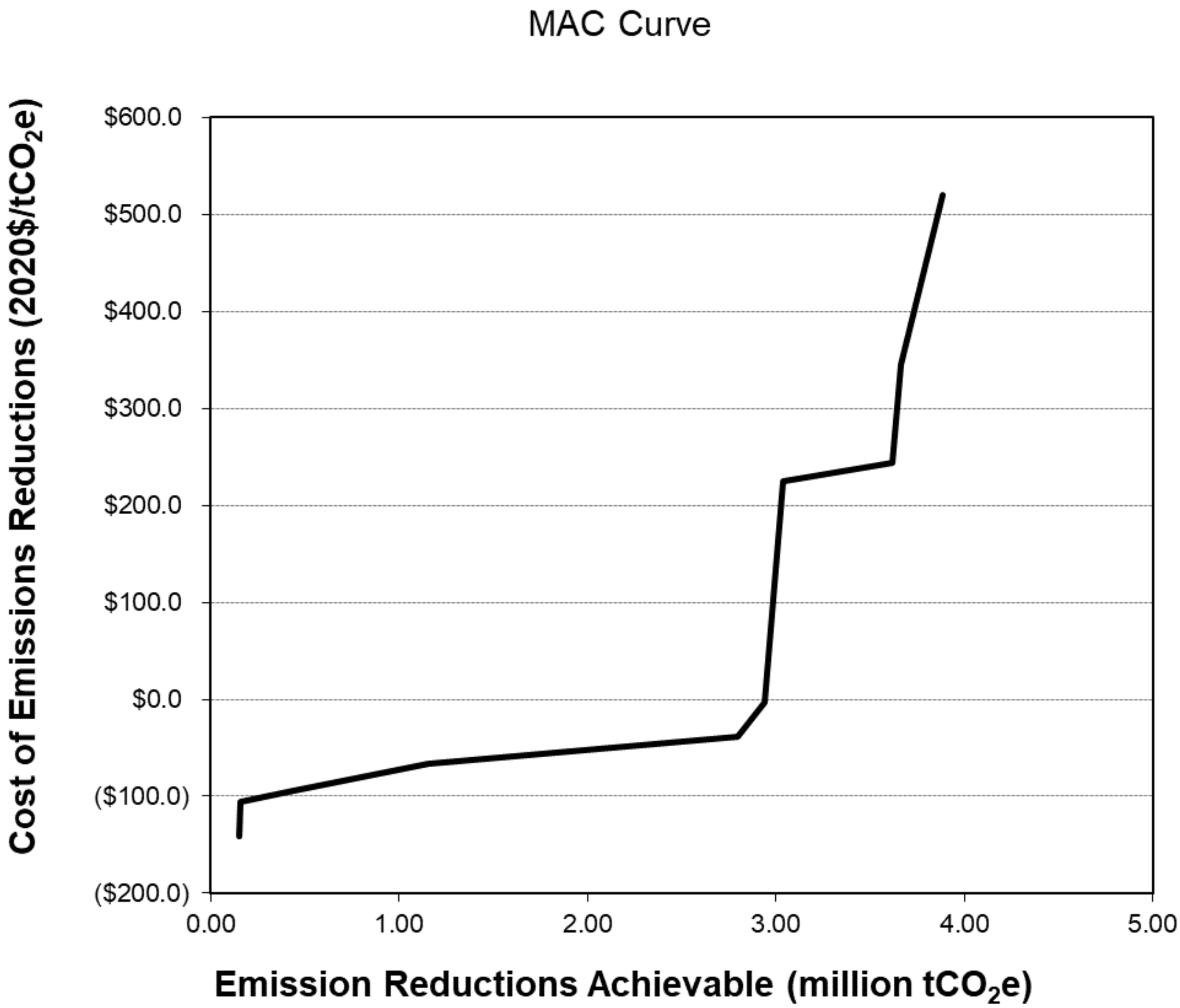


Figure 6. VRT MACC scenario B (10 percent fertilizer reduction with yield boost)



Appendix A

Table 12. U.S. consumption of selected nitrogen materials (short tons) from USDA ERS (2019)

Year	Ammonia Anhydrous	Ammonia (Aqua)	Ammonium (Nitrate)	Ammonium (Sulfate)	Nitrogen Solutions	Sodium Nitrate	Urea	Other
2015	3,854,515	286,703	608,268	1,935,361	11,896,660	13,694	7,038,055	2,193,063

Table 13. N content per fertilizer type

Fertilizer Type	N Content (% N)
Anhydrous Ammonia	82%
Aqua Ammonia	23%
Ammonium Nitrate	33%
Ammonium Sulfate	21%
UAN	30%
Sodium Nitrate	16%
Urea	28%
Other*	33%

* "Other" is average of all other fertilizer types.

From USDA NRCS (n.d.)

Table 14. Fertilizer costs per acre, yield per acre, and price per product for each USDA region from USDA ERS (2022)

Crop	ERS Name	Appalachia	Corn Belt	Delta States	Lake States	Mid-Atlantic	New England	Northern Mountain	Northern Plains	Pacific	Southeast	Southern Mountain	Southern Plains
Corn	Price (dollars per bushel at harvest)	$5.79	$5.01	$5.01	$5.02	$5.02	$5.02	$5.02	$5.12	$5.12	$5.79	$5.79	$5.12
Corn	Fertilizer (dollars per planted acre)	$173.70	$121.28	$121.28	$126.25	$126.25	$126.25	$126.25	$97.64	$97.64	$173.70	$173.70	$97.64
Corn	Yield (bushels per planted acre)	161	200	200	185	185	185	185	163	163	161	161	163
Cotton	Price (dollars per pound)	$0.88	$0.76	$0.72	$0.72	$0.72	$0.72	$0.72	$0.90	$0.91	$0.88	$0.88	$0.90
Cotton	Fertilizer (dollars per planted acre)	$137.30	$117.74	$98.70	$98.70	$98.70	$98.70	$98.70	$30.60	$62.87	$137.30	$137.30	$30.60
Cotton	Yield (pounds per planted acre)	1041	1389	1176	1176	1176	1176	1176	724	1455	1041	1041	724
Soybean	Price (dollars per bushel at harvest)	$12.50	$11.97	$12.16	$12.04	$12.04	$12.04	$12.04	$11.77	$11.77	$12.50	$12.50	$11.77
Soybean	Fertilizer (dollars per planted acre)	$67.05	$30.68	$35.92	$37.79	$37.79	$37.79	$37.79	$21.45	$21.45	$67.05	$67.05	$21.45
Soybean	Yield (bushels per planted acre)	47	61	55	55	55	55	55	49	49	47	47	49
Wheat	Price (dollars per bushel at harvest)	$6.67	$6.52	$6.52	$6.05	$6.05	$6.05	$7.26	$5.97	$6.96	$6.96	$7.26	$5.97
Wheat	Fertilizer (dollars per planted acre)	$43.63	$86.97	$86.97	$82.59	$82.59	$82.59	$57.94	$30.17	$54.17	$54.17	$57.94	$30.17
Wheat	Yield (bushels per planted acre)	42	74	74	87	87	87	39	41	50	50	39	41
Sorghum	Price (dollars per bushel at harvest)	$5.49	$5.49	$5.49	$5.49	$5.49	$5.49	$5.49	$5.48	$5.50	$5.50	$5.50	$5.48
Sorghum	Fertilizer (dollars per planted acre	$39.97	$39.97	$39.97	$39.97	$39.97	$39.97	$39.97	$40.67	$35.02	$35.02	$35.02	$40.67
Sorghum	Yield (bushels per planted acre)	72	72	72	72	72	72	72	74	74	74	74	74

Table 15. Example component costs in EQIP CPS E590A payment rate for EEFs in the Corn Belt

Component Name	Unit	Unit Cost	Quantity	Total Cost (Typical farm size of 100 acres)	Component Justification
Specialist labor	Hours	$110.41	2 hours	$220.83	Additional time to plan and improve timing of nutrient application
Nitrogen or urease inhibitor	Acres	$31.37	100 acres (typical farm size)	$3,136.50	Use of inhibitors to increase nutrient use efficiency; produce will be used on all acres
Soil nitrogen testing	Each test	$9.97	5 soil tests	$48.34	Additional soil testing needed to improve nutrient application and efficiency

Table 16. Example component costs in EQIP CPS E590B payment rate for VRT in the Corn Belt

Component Name	Unit	Unit Cost	Quantity	Total Cost (Typical farm size of 100 acres)	Component Justification
Fertilizer, precision application	Acres	$8.56	100 acres (typical farm size)	$885.76	Variable rate application
Specialist labor	Hours	$110.41	2 hours	$220.83	Additional time to plan VRT application of fertilizers
Standard soil test	Each test	$12.70	35 soil tests	$444.44	Soil samples collected for grid or zone management system

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