GHG Mitigation Report
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Greenhouse Gas Emissions from Odell Brewing Company's Malting-Quality Barley Production and Opportunities for Mitigation (2017-2039)

Executive Summary

Understanding upstream agricultural emissions is essential for breweries seeking to reduce their climate impact. New Belgium Brewing provides a compelling example of how climate accountability can be integrated into brewing operations at scale. The company has implemented a broad range of sustainable strategies, from conducting full life cycle assessments and hotspot analyses to installing solar arrays, generating biogas from wastewater, and advocating for renewable energy at the municipal level. Its Fort Collins, Colorado and Asheville, North Carolina facilities are positioned to lead clean energy transitions, including a company-wide shift toward non-carbon electricity by 2030. These efforts reduced emissions and built consumer trust and brand value in a saturated craft beer market.

Odell Brewing Company (Odell) is another brewery in Fort Collins, also intending to be more sustainable in the production of beer. They are uniquely positioned as an established operation with deep roots throughout the community in which they sit, but have not taken full advantage of the opportunity to harness consumer preferences toward sustainable operations. Therefore, my objective was to compile a greenhouse gas inventory and analyze related mitigation strategies for processes associated with Odell's annual barley use, including some of the most potent categories for emissions and emission reduction: nitrogen fertilizer application and on-farm energy use from tillage. Specific mitigation strategies include decreasing fertilizer application rates and adding an amendment of PSI-362 to improve nitrogen uptake and utilization efficiencies.

Total greenhouse gas emissions are expressed in CO_2 equivalence, with uncertainty reported as 95 percent confidence intervals. In 2017, total emissions from barley production

were estimated at 6.496 Gg, with a confidence interval ranging from 3.233 to 9.760 Gg. Emissions increased to 6.790 Gg in 2018, ranging from 3.391 to 10.188 Gg, and rose again in 2019 to 7.132 Gg, with a range of 3.537 to 10.805 Gg. These values reflect trends in emissions from direct and indirect soil N_2O and from diesel used in tillage. Over the 2020–2039 projection period, mitigation through reduced nitrogen fertilizer application could avoid an estimated 42.209 Gg of emissions, with a 95 percent confidence interval ranging from 15.295 to 69.123 Gg. Applying a 17 percent buffer pool to account for high uncertainty would reserve 7.176 Gg, ranging from 2.600 to 11.751 Gg, resulting in a net climate benefit of 35.034 Gg, with a confidence interval of 7.734 to 62.334 Gg.

The current inventory provides Odell with a quantitative foundation to support future sustainability strategies and differentiate itself through credible environmental action, growing its commitment to sustainability along with its beer sales. Additionally, this inventory focuses on agricultural emissions; these data are especially influential due to the magnitude of grain production for breweries and are necessary for operational emissions inventories within supply chains. While such calculations are not yet required for companies with revenue under one billion dollars annually, future policy may necessitate emissions inventories, favoring those breweries who have already begun quantifying their environmental impacts (Colorado General Assembly, 2025).

This report also assists in an analysis of possible strategies for mitigation, to be used for both marketing plans and possible future policy compliance. The results suggest that reducing nitrogen fertilizer application offers a promising path to meaningful climate benefits. While uncertainty, particularly around N_2O emissions and long-term fertilizer trends, is a limiting factor for immediate carbon crediting, the mitigation strategy shows strong potential in terms of additionality, permanence, and minimal risk of leakage. These findings position Odell to lead with credible climate action while further refining its sustainability commitments through targeted agricultural interventions and partnerships.

Introduction

Agricultural systems contribute significantly to global greenhouse gas emissions, accounting for 9.3 billion tonnes of CO_2 equivalence in 2018 (United Nations Food and Agriculture Organization, 2018). As Scope 3 emissions, upstream agricultural emissions represent a substantial portion of breweries' overall carbon footprints and have become a growing area of focus in the beverage industry's climate strategies (Olajire, 2020). Accurate estimation and reduction of these emissions is critical for sustainability in beer production, driven by both ethical responsibility and competitive business advantage. New Belgium Brewing represents an example of a widely successful implementation of mitigation strategies, both in terms of emission reduction and retail value gains resulting from more sustainable operations (New Belgium Brewing, n.d.). Odell Brewing Company (Odell), a regional brewery located in Fort Collins, Colorado, has the chance to follow a similar path, but first needs to quantify its emissions and explore possible opportunities for mitigation. Therefore, my objective was to compile a greenhouse gas emissions inventory to help identify critical emission sources, such as mineral fertilizer application and field energy use associated with tillage, and support future mitigation planning regarding agricultural grain production within the brewery's supply chain. Specifically, mitigation activities analyzed include a reduction in nitrogen fertilizer application rates and an amendment of PSI-362 for the crop's uptake and utilization efficiencies of such nitrogen (Goñi et al., 2021).

Barley is Odell's primary grain input, used in 132,396 barrels of beer in 2019 prior to the COVID-19 pandemic (pre-pandemic values are used to demonstrate the brewery's growth without the impact of extraneous variables). This volume corresponds to approximately 23,855 acres, or 9,654 hectares, of annual barley production, based on an estimate of 20 bushels of barley required per barrel of beer and 111 bushels of barley produced per acre in Colorado (Bower, 2018; Licata, 2022; USDA National Agricultural Statistics Service, 2022). In earlier years, production was slightly lower, with 120,810 barrels brewed in 2017 (equivalent to about

21,768 acres or 8,809 hectares) and 126,375 barrels in 2018, requiring roughly 22,770 acres or 9,215 hectares of agricultural fields (Kendall, 2019). Based on these historical values, new datapoints were extrapolated linearly for 20 years after data availability ends (2020 to 2039).

This inventory includes emissions from mineral fertilizer applications and field energy use associated with tillage on grain production fields in supply relationships with Odell. Mineral fertilizer application is a significant source of agricultural greenhouse gas emissions due to the release of N_2O, a potent greenhouse gas with a global warming potential approximately 265 times that of CO_2 over 100 years. N_2O emissions occur via two primary pathways: direct emissions, which result from microbial nitrification and denitrification processes in soils, and indirect emissions, which are produced after nitrogen is lost through leaching or volatilization and then re-emitted as N_2O elsewhere in the environment (Intergovernmental Panel on Climate Change, 2006, Volume 4, Chapter 11). The rate of these emissions depends on nitrogen application amounts, soil properties (such as texture and organic matter content), irrigation levels, and precipitation patterns, all of which influence nitrogen availability and transformation in the soil. Nitrogen application amounts tend to be decided based on expected yield, soil nitrate levels, and soil organic matter levels, though other factors can play a role as well, such as the nitrogen uptake and utilization efficiencies of the given crop (i.e., the higher the efficiency, the less fertilizer is necessary, because more nitrogen is effectively put to use by the plant).

In addition to fertilizer-related emissions, this inventory includes emissions from diesel combustion during tillage operations, which contribute to atmospheric CO_2, CH_4, and N_2O. These emissions are primarily driven by the amount of diesel fuel consumed, which depends on tillage intensity, equipment type, soil conditions, and field size. Fuel use tends to be higher under conventional or intensive tillage systems compared to reduced or no tillage, making such management decisions a key driver of emissions (Auzins et al., 2021). Each variable listed above must be considered when modeling greenhouse gas outputs associated with upstream agricultural production and should be paid special attention when considering possible emission reduction strategies

By quantifying emissions associated with its primary agricultural input, Odell is better equipped to assess its climate impact, identify mitigation strategies, and meet rising expectations from consumers, investors, and policymakers. As the craft beer market becomes increasingly value-driven and competitive, the brewery can leverage these findings to strengthen its environmental credibility and distinguish itself. This inventory also establishes a baseline against which modeled mitigation strategies and their projected impacts can be assessed over time, supporting more informed decision-making as sustainability efforts evolve.

Methods

This inventory follows the Intergovernmental Panel on Climate Change (IPCC) Tier 1 methods to estimate annual greenhouse gas emissions from Odell's barley use for the years 2017 through 2039. This section provides details on the equations, activity data, emission factors, uncertainty assumptions, and supporting references used. Furthermore, it outlines the proposed mitigation strategies and describes the methods used to assess leakage, permanence, and required discounting, based on additionality quantified by comparing mitigation scenarios to business-as-usual baselines. These assessments are based on American Carbon Registry (ACR) standards. Because 80 to 85 percent of Colorado's barley production occurs in the San Luis Valley, and Odell does not publicly disclose specific sourcing regions, methods in this inventory assume that all the barley used by Odell is produced in that region. Assumptions for typical crop management practices follow the same logic, using information from the National Integrated Pest Management Database when more recent or specific information was unavailable (McDonald et al., 2002).

Direct and indirect soil N_2O emissions from mineral N fertilizer application were estimated based on Tier 1 equations from IPCC Volume 4, Chapter 11, included here (2006):

$$N_2O_{Direct} = F_{SN} \times EF_1$$

$$N_2O_{Indirect} = (F_{SN} \times Frac_{LEACH} \times EF_5) + (F_{SN} \times Frac_{GASF} \times EF_4)$$

F_{SN} is the amount of synthetic N applied, EF_1 is the emission factor for N_2O emissions from N inputs, EF_4 is the emission factor for N_2O emissions from volatilized N, EF_5 is the emission factor for N_2O emissions from leached N, $Frac_{GASF}$ is the fraction of fertilizer lost to volatilization, and $Frac_{LEACH}$ is the fraction of fertilizer lost to leaching. Assuming an expected yield of 111 bushels per acre, medium NO_3-N levels (7 to 12 parts per million), and a soil organic matter content of 1.1 to 2.0 percent, recommended fertilizer input (F_{SN}) is 65 pounds of N per acre per year, or approximately 72.86 kilograms per hectare per year. Conservatively, 30 percent uncertainty was applied to a normal probability distribution for this value to account for spatial and management variability (Davis & Westfall, 2022; IPCC, 2006, Volume 4, Chapter 2; USDA National Agricultural Statistics Service, 2022).

Baseline scenarios applied a simple linear extrapolation method to predict future growth in fertilizer application rates based on Odell's growth between 2017 and 2019, and mitigation scenarios applied a 25% reduction in applications to baseline values. This reduction is supported by scientific literature indicating that such a decrease results in minimal impacts on yield. Specifically, a study by De Gryze et al. found that cutting nitrogen application by 25% led to less than a 5% reduction in crop yields under typical field conditions, suggesting that modest nitrogen reductions are agronomically viable (2011). To further safeguard yield while pursuing reductions in emissions, the mitigation scenario includes the application of PSI-362, a plant growth-promoting rhizobacterium. Recent research has shown that PSI-362 can maintain or even improve yield performance under reduced fertilizer regimes by enhancing nitrogen use efficiency and promoting root development; empirical results indicate that combining PSI-362 with a 25% fertilizer reduction preserves yield levels comparable to conventional nitrogen inputs without microbial supplementation (Goñi et al., 2021).

The default emission factors from the IPCC were used, and provided triangular distributions were implemented. For direct emissions, the emission factor (EF_1) is 0.01 kilograms of N_2O-N per kilogram of mineral N fertilizer, ranging from 0.003 to 0.03; for indirect emissions via leaching, the emission factor (EF_5) is 0.0075 kilograms of N_2O-N per kilogram of mineral N fertilizer, ranging from 0.0005 to 0.025; for emissions via volatilization, the emission factor (EF_4) is 0.010 kilograms of N_2O-N per kilogram of mineral N fertilizer, ranging from 0.002 to 0.05; indirect emissions were estimated on a fixed percentage basis, assuming values of 0.3 and 0.1 for leaching ($Frac_{LEACH}$) and volatilization ($Frac_{GASF}$), respectively (IPCC, 2006, Volume 4, Chapter 11). Both are default values, but the value for leaching assumes that fields are usually wet, either due to rainfall or irrigation; irrigation is extremely common in the San Luis Valley (McDonald, 2002).

Leakage is assessed to be minimal in this context. The mitigation strategy involves on-farm fertilizer management rather than land-use shifts or activity displacement that could lead to emissions increases elsewhere. Additionally, the use of PSI-362 does not appear to create significant market ripple effects or input substitution that would drive up demand or prices for fertilizer, microbial products, or barley outputs at scale. In fact, farmers might save money by applying less fertilizer and reaping similar or greater yields, so market leakage is not a concern (Goñi et al., 2021). This localized, input-based intervention is also considered unlikely to cause activity-shifting leakage, so no carbon credit discount for leakage is applied.

Permanence, while often more relevant for carbon stock-based mitigation, is still a meaningful consideration for N_2O emission reductions. Because N_2O is an annually recurring emission tied to seasonal fertilizer application, reductions are not stored in the system long-term but instead avoided each year. Therefore, permanence is not an issue. Given that yield is maintained, farmer adoption is likely durable. A buffer pool is still included to conservatively account for implementation risks and interannual variability, following standard ACR practice.

On-farm energy use from tillage was estimated by applying emission factors to activity data based on Tier 1 equations from IPCC Volume 2, Chapter 3, included here (2006):

$$Emissions_{GHG} \;\; = \sum(Fuel_{Diesel} \times EF_{GHG})$$

$Fuel_{Diesel}$ is the amount of diesel fuel used, and EF_{GHG} represents a variable that is replaced by emission factors for diesel use specific to CO_2, CH_4, and N_2O emissions as the equation is iterated and summed. Tillage is assumed to be mulch tillage, a type of reduced tillage common in Colorado, especially where crop residue is retained (as is assumed in this case) (McDonald, 2002). Annual diesel energy use was estimated using the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS) Energy Estimator with 20 percent uncertainty based on energy modeling precedents, applied to a normal probability distribution. Since barley specifically is not an option for crop selection in this estimation tool, winter wheat was used as a proxy (USDA NRCS, n.d.-b). The diesel fuel amounts ($Fuel_{Diesel}$) were as follows: 109,928 gallons (14.48 terajoules) in 2017, 114,988 gallons (15.15 terajoules) in 2018, and 120,467 gallons (15.87 terajoules) in 2019 to produce the amounts of barley required for the level of beer production in Fort Collins.

Baseline diesel emissions were estimated using a simple linear extrapolation of diesel use from 2017 to 2019, reflecting Odell's observed growth in production activity during that period. This approach assumes that fuel demand will continue to scale proportionally with cultivated area in the absence of specific mitigation measures. Because no diesel-related mitigation scenario was implemented in this analysis, the baseline projection serves solely as a business-as-usual reference for future emissions.

The default emission factors from the IPCC were used, and provided triangular distributions were implemented. For CO_2 emissions from diesel combustion, the emission factor is is 74,100 kilograms per terajoule, ranging from 72,600 to 74,800; for CH_4, the emission factor is 4.15 kilograms per terajoule, ranging from 1.67 to 10.4; finally, for N_2O, the emission factor is 28.6 kilograms per terajoule, ranging from 14.3 to 85.8 (IPCC, 2006, Volume 2, Chapter 3).

The additionality of the project was quantified by comparing cumulative emissions over the 20-year projection period between baseline and mitigation scenarios using Monte Carlo simulations, completed before estimation of emissions from diesel use but applied after aggregation. The difference in cumulative emissions represented the total avoided emissions attributable to the mitigation activity. Given that there are no widespread regulations in effect requiring reductions in common fertilizer application rates or the use of nitrogen uptake or utilization efficiency amendments, reduced rates are not common practice (nor is the application of PSI-362), and most farmers are untrained in the use of PSI-362 and skeptical of fertilizer reductions, the project passes ACR's three-pronged additionality test (ACR, 2023).

To quantify and address management, governance, and natural disaster risks associated with this mitigation project, I applied default 4% deductions in additionality for both financial and project management risks, a default 2% deduction for social/policy risk (given the project's location in the United States), a 1% deduction for fire risk since the project is agricultural, a 4% deduction for diseases and pest risks in the area (none are known within the project area), and a 2% deduction for other natural disaster risks (ACR, 2023). In total, this resulted in a 17% deduction of carbon credits from the total additionality value that was instead placed in the buffer pool to safeguard against such risks.

An uncertainty analysis was conducted as consistently as possible across emission categories. I derived 95 percent confidence intervals from Monte Carlo simulations and reported in CO_2 equivalence, combining across all sources at the end using simple error propagation and root sum of squares (i.e., Approach 1 from the IPCC Guidelines) (2006, Volume 1, Chapter 3). Since uncertainty was greater than the recommended values based on the ACR Standard, a 100% discount had to be applied, invalidating carbon credits from this mitigation project (ACR, 2023). However, results from analyses, including total hypothetical carbon credits, after subtraction of the buffer pool, are still noted below. All analyses were conducted in R version 4.4.2.

Results and Discussion

The total historical greenhouse gas emissions from barley production in 2017, including direct and indirect soil N_2O emissions and diesel use for tillage, were estimated at 6.496 Gg of CO_2 equivalence, with a 95 percent confidence interval ranging from 3.233 to 9.760 Gg. In 2018, emissions increased to 6.790 Gg, ranging from 3.391 to 10.188 Gg, with additional increases in 2019 estimated at 7.132 Gg, ranging from 3.537 to 10.805 Gg (Figure 1). Over the projection period from 2020 to 2039, mitigation of direct and indirect N_2O emissions through reduced fertilizer application could result in an estimated 42.209 Gg of avoided emissions, with a 95 percent confidence interval ranging from 15.295 to 69.123 Gg. Applying a 17 percent buffer pool for non-permanence and uncertainty would reserve approximately 7.176 Gg, with a 95 percent confidence interval ranging from 2.600 to 11.751 Gg, leaving a net climate benefit of 35.034 Gg, ranging from 7.734 to 62.334 Gg. Though not supported by ACR discounting procedures, these reductions represent a significant opportunity for climate benefits in barley production under relatively straightforward management interventions.

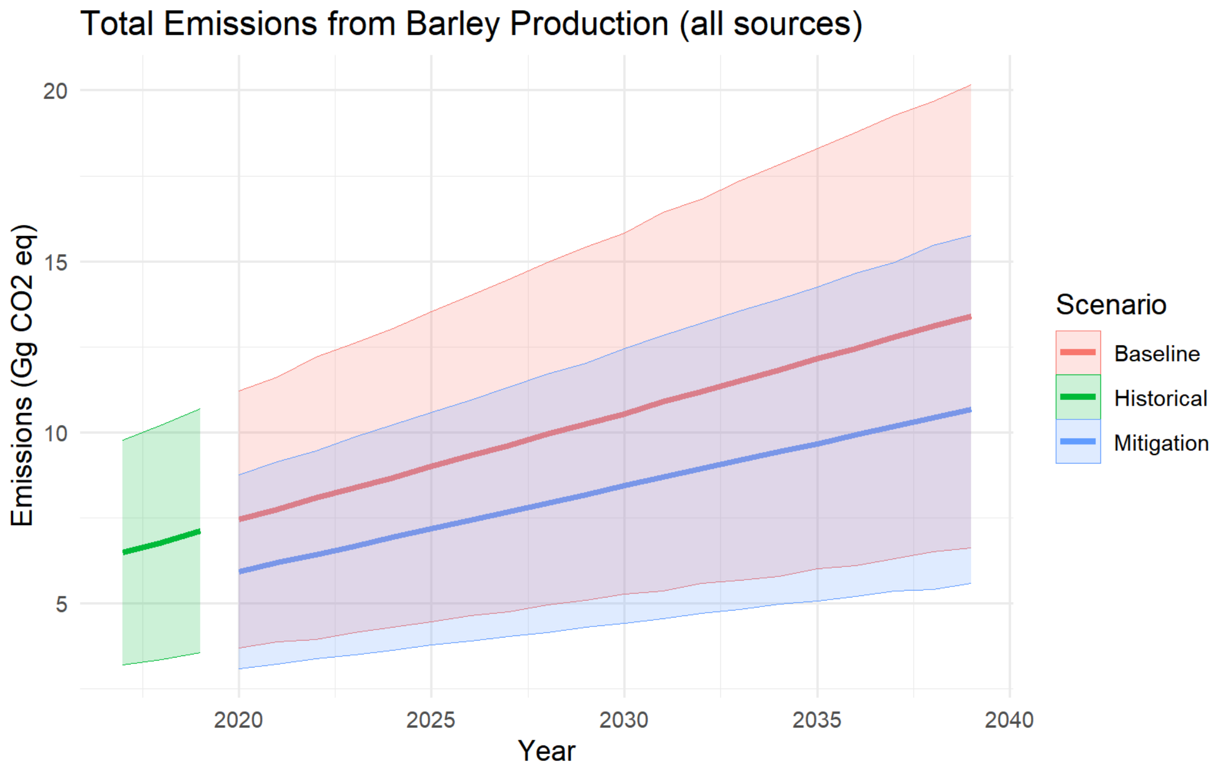

Figure 1

Total Emissions from Barley Production (all sources; shaded areas represent 95% confidence intervals derived from Monte Carlo simulations)

Direct soil N_2O emissions from synthetic nitrogen fertilizer application rose steadily across the three-year inventory period, estimated at 3.831 Gg of CO_2 equivalence in 2017, 4.004 Gg in 2018, and 4.205 Gg in 2019. Confidence intervals ranged from 1.327 to 7.520 Gg in 2017, 1.370 to 7.836 Gg in 2018, and 1.425 to 8.145 Gg in 2019, widening slightly in later years due to the increased fertilizer application associated with expanding production (Figure 2). These emissions accounted for the largest share of total emissions in each year.

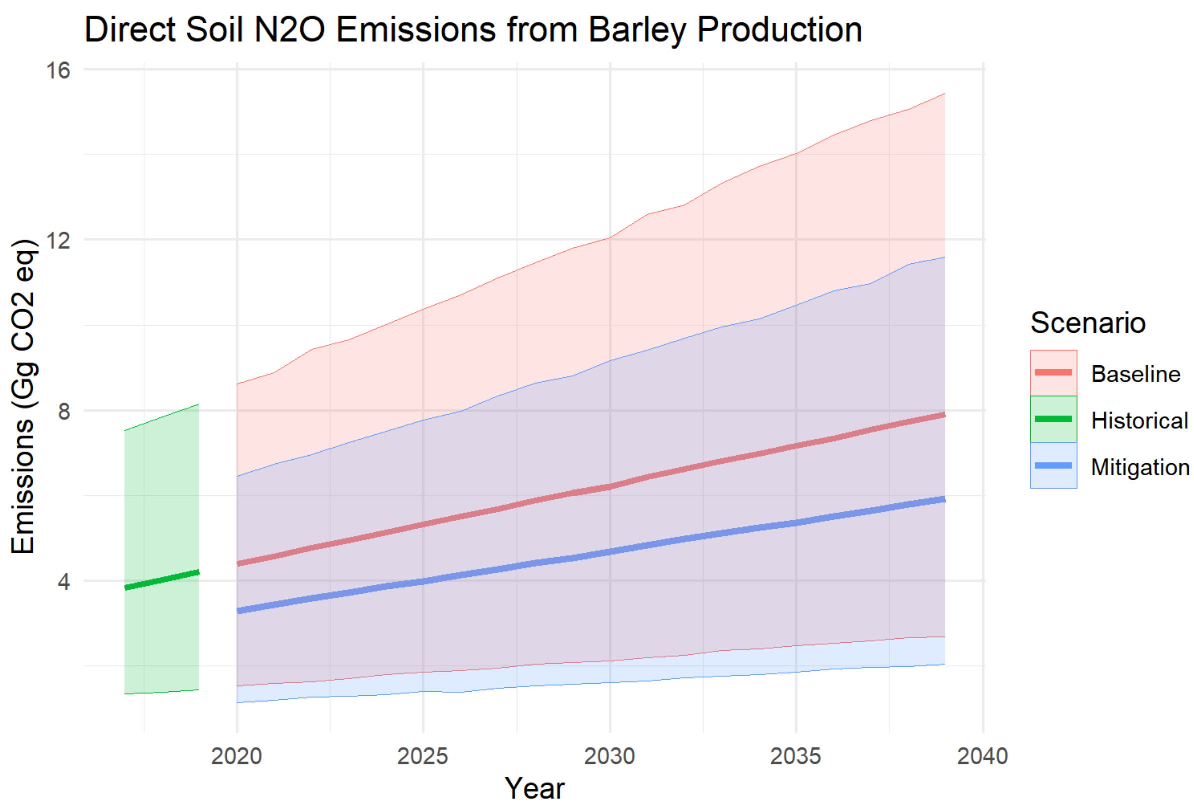

Figure 2

Direct Soil N_2O Emissions from Barley Production (shaded areas represent 95% confidence intervals derived from Monte Carlo simulations)

Indirect soil N_2O emissions also showed a consistent upward trend, increasing from 1.431 Gg of CO_2 equivalence in 2017 to 1.496 Gg in 2018 and 1.571 Gg in 2019. Confidence intervals were slightly more precise than for direct emissions, ranging from 0.534 to 2.664 Gg for 2017, 0.548 to 2.774 Gg for 2018, and 0.575 to 2.883 Gg for 2019 (Figure 3). Though smaller in magnitude, indirect emissions remain important in identifying upstream mitigation opportunities.

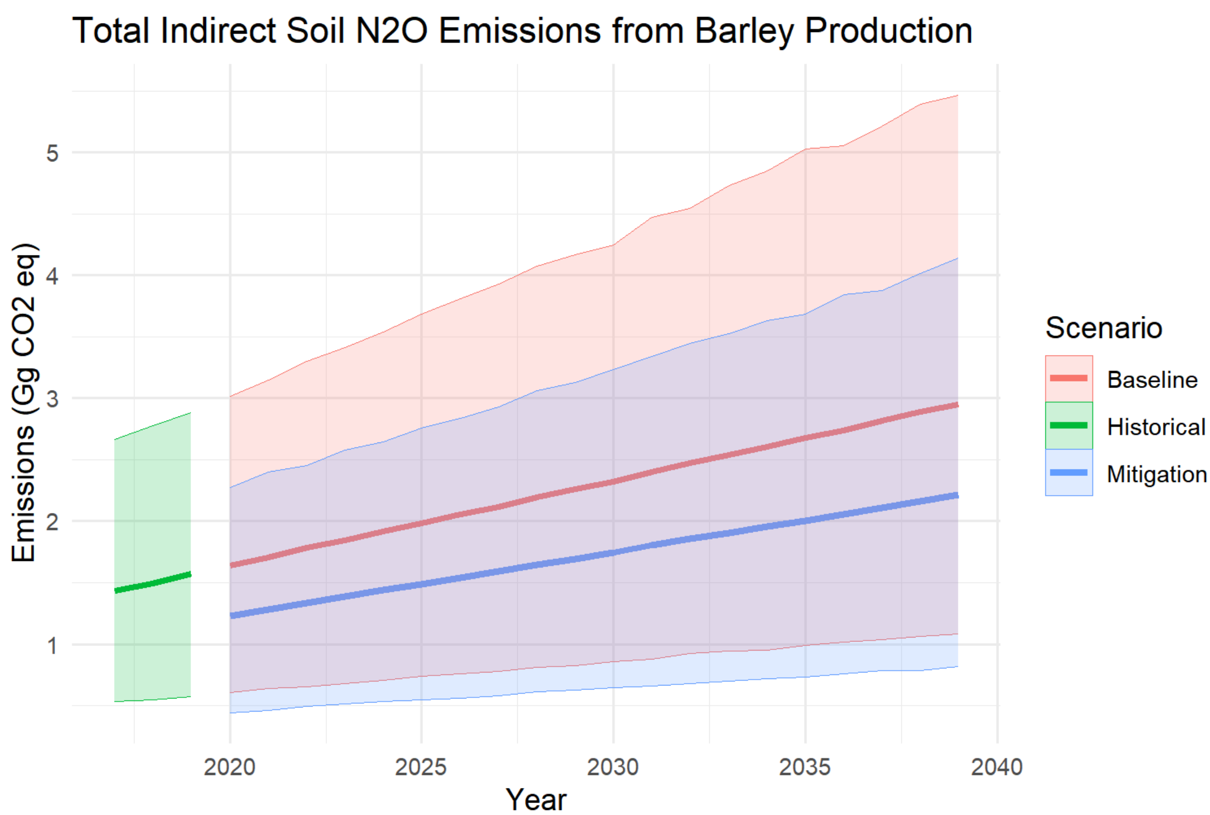

Figure 3

Total Indirect Soil N_2O Emissions from Barley Production (emissions from leaching and volatilization; shaded areas represent 95% confidence intervals derived from Monte Carlo simulations)

Emissions from on-farm diesel use for tillage followed a similar trend, increasing with production area from 1.234 Gg of CO_2 equivalence in 2017 to 1.290 Gg in 2018 and 1.354 Gg in 2019. These estimates include emissions from CO_2, CH_4, and N_2O generated through fuel combustion. Confidence intervals were slightly more precise over time as diesel use estimates began to stabilize, ranging from 0.970 to 1.523 Gg in 2017, 1.008 to 1.589 Gg in 2018, and 1.065 to 1.666 Gg in 2019 (Figure 4).

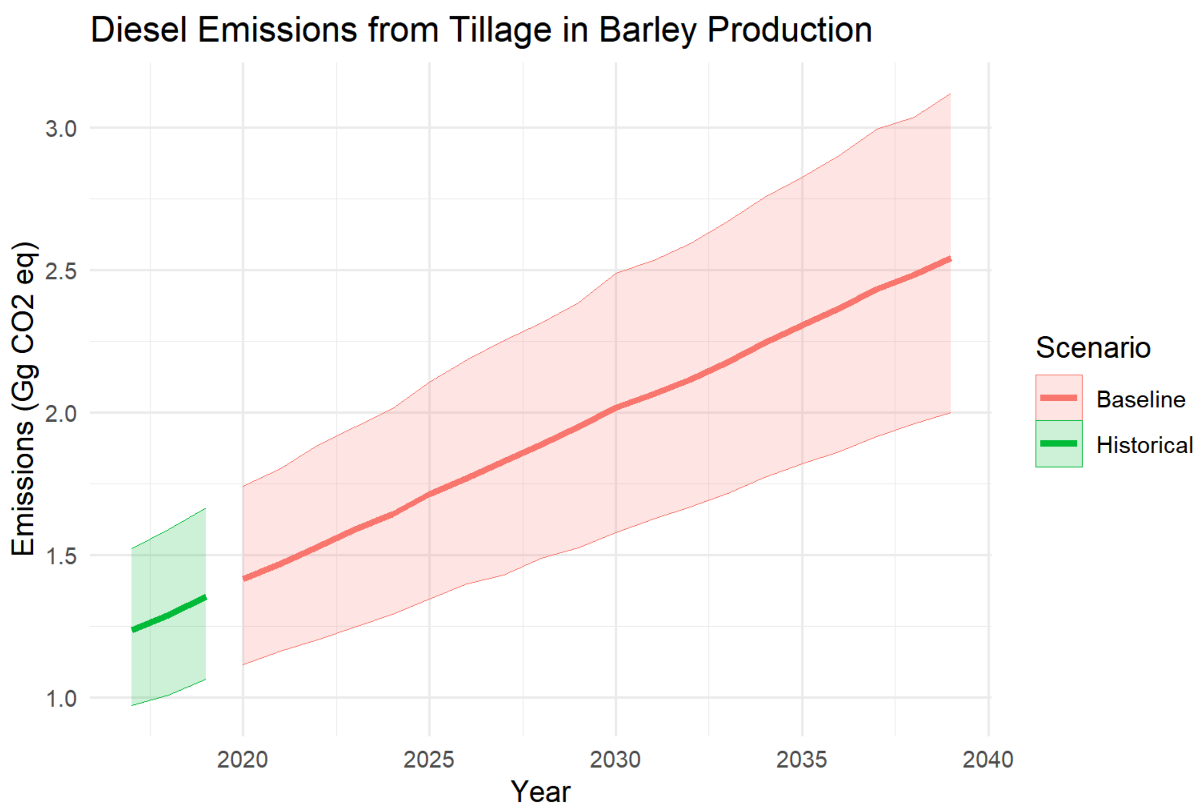

Figure 4

Diesel Emissions from Tillage in Barley Production (CO_2, CH_4, and N_2O emissions; shaded areas represent 95% confidence intervals derived from Monte Carlo simulations)

The results of this analysis suggest that reducing nitrogen fertilizer application in barley production offers a promising mitigation pathway, with substantial estimated additionality and low risk of leakage. The approach is likely to deliver durable climate benefits, particularly when paired with conservation practices that support permanence. However, the uncertainty surrounding current emissions estimates, particularly for indirect N_2O emissions and future fertilizer use, remains too high to justify immediate crediting or large-scale implementation. Additional field-based research, improved data on fertilizer management practices, and refinement of region-specific emission factors are recommended to reduce uncertainty and strengthen the scientific basis for mitigation claims.

Appendix: Quality Control Measures and Improvement Plan

To ensure transparency and consistency, all activity data, emission factors, and methodological choices followed IPCC Guidelines and were sourced from peer-reviewed or institutional reports. Each emission estimate includes a 95% confidence interval, with uncertainty quantified using Monte Carlo simulations and combined based on IPCC Approach 1 (2006, Volume 1, Chapter 3). Input validation checks were built into each R function, including tests for negative or zero fertilizer and diesel values, and confirmation that emission factors fell within prescribed bounds.

Deterministic estimates were compared to probabilistic intervals to verify consistency, and automated warnings were triggered if expected values fell outside the 95% confidence range. For example, a coding error was discovered in the estimation of 2019 diesel emissions because the deterministic estimate did not fall within the bounds of the probabilistic spread. Confidence interval labeling, originally omitted, was also improved, ensuring full 2.5-97.5% bounds were displayed for additionality and buffer pool results.

Variable names and units were reviewed for internal consistency across direct, indirect, and diesel emission scripts. Emission factors from the IPCC (2006) were applied consistently, using triangular distributions for uncertainty. In addition to individual quality control measures, multiple versions of this report were completed over approximately three months, and I continually received and applied outside input from peers and industry experts.

Several improvements could be made in future iterations. Most importantly, this report should be refined with farm- and brewery-level data to reduce uncertainty, making carbon credits real and the presented mitigation strategies more viable. Incorporating farm-level data could also enable a full accounting of on-farm energy use, including emissions from planting, pesticide application, harvesting, irrigation, and grain drying. Similarly, moving from Tier 1 to Tier 2 methods would allow for more accurate, location-specific emissions estimates. The use of brewery-level data would help to make estimates more realistic into the future; while Odell grew relatively constantly between 2017 and 2019, this rate of growth is not sustainable for two more decades. A strongly correlated set of surrogate data would increase the usability of this report enormously.

Strategies could also be built upon to include some relating to emissions from diesel use for tillage, possibly including the implementation of no tillage practices (which require fewer passes by farm machinery, therefore reducing fuel combustion emissions) or electric farm vehicles, especially those charged using renewable energy. Future inventories should also consider emissions from crop residues and other inputs such as manure, lime, or urea. Expanding the scope beyond the farm gate to include upstream production of seed and fertilizer, transportation, malting, and downstream brewing processes would support full Scope 3 reporting. Additional modeling of non-CO_2 greenhouse gases and the interactions among emissions drivers would further strengthen the analysis.

Finally, it is worth mentioning that soil carbon stock changes were modeled using Agriculture and Land Use (ALU) software and Tier 1 methods from the IPCC, and results indicated net carbon sequestration between 2017 and 2019, suggesting a similar trend in extrapolated years (Colorado State University, n.d.). However, these values were ultimately excluded from the final inventory due to methodological constraints. Specifically, ALU assumes static land management over time, which introduces bias when modeling year-to-year cropland expansion without corresponding management change. Additionally, estimates carried substantial uncertainty due to limited recent data on local residue and irrigation practices. These limitations reduced the comparability and interpretability of results across categories. Future inventories could revisit soil carbon modeling with more granular farm-level management data and consider Tier 2 or hybrid methods to better reflect dynamic land-use trends and improve confidence in sequestration estimates.

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