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Areas of Potential Nitrous Oxide Emission Reduction Obtained Through Geographic Analysis of Different Agricultural Techniques in Corn Production

by

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An abstract of

a thesis submitted to the Faculty of Emory College of Arts and Sciences

of Emory University in partial fulfillment

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Bachelor of Science with Honors

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Abstract

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As of 2016, agricultural processes within the U.S. contribute 9% of the U.S.'s total greenhouse gas emissions. N_2O is the third largest greenhouse gas, and in the U.S., agriculture is the main contributor to N_2O emissions, contributing a total of 80%. Of this, 87% of N_2O emissions from agriculture are due to fertilizer usage. This demands research into cultivation techniques that present an alternative to using fertilizers. To provide scientific evidence for a policy that will promote sustainable and climate-smart agriculture, this paper examines how alternatives to fertilizer may vary in their emission reduction potential across the U.S. The agricultural methods being assessed include white clover living mulch, crimson clover cover crop, cereal rye cover crop, and traditionally fertilized soil. When the estimated % change in emissions after implementation of the different techniques was mapped, the greatest emission reduction potential for cereal rye, crimson clover, and living mulch was within the corn belt and the southeastern U.S.. When fertilizer usage was controlled for, the southeast observed less of an emission reduction potential than the corn belt. Therefore, due to the limitations of this study, including the application of local studies in Georgia to the broader U.S., additional more expansive studies should be conducted to confirm this thesis' results. Following the potential confirmation of this thesis' results, additional studies should be directed towards the analysis of whether the techniques analyzed in this study can reduce emissions in the corn belt. Other potential areas for future study include an analysis of why the southeast may have a smaller emission reduction potential than the corn belt even when controlling for the amount of fertilizer used. Additional local level studies could also be directed towards sharp variations in emission reduction potentials between bordering counties. And finally, further studies would be needed to assess whether N_2O emissions from corn farms are being underestimated due to between row/within row measurement differences.

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Table of Contents

Figures

Tables

Introduction

As of 2016, agricultural processes within the U.S. contribute 9% of the U.S.'s total greenhouse gas emissions (Behnke et al, 2019). Nitrous oxide (N_2O) is the third largest anthropogenic greenhouse gas and has a global warming potential 298 times greater than carbon dioxide (CO_2) over a 100-year time horizon (Fisher et al., 2018, Behnke et al., 2019, EPA). In addition to its effect as a greenhouse gas, N_2O emissions are currently the main contributor to stratospheric ozone depletion (Fisher et al., 2018).

Around 80% of N_2O emissions in the U.S. come from agriculture, and within this, 87 percent of N_2O emissions from agriculture are due to fertilizer usage (Behnke et al., 2019, U.S. Energy Information Administration, EPA). Therefore, finding alternative agricultural techniques that reduce fertilizer input could potentially reduce N_2O emissions. Corn is the largest crop within the U.S., meaning that among all crops in the U.S., the most acres are used to grow corn (Capehart et al., 2019). Corn also uses the largest amount of fertilizer (Economic Research Service: United States Department of Agriculture). This thesis focuses on corn as the crop with one of the largest N_2O emission reduction potentials within the U.S..

Because increased fertilizer use is closely linked to increased N_2O emissions from agricultural sites, agricultural techniques which can reduce the amount of fertilizer used have the potential to mitigate N_2O emissions (Shcherbak et al., 2014). Two potential alternatives to fertilizer include cover crops and living mulch systems. Living mulch crops grow leading up to and throughout the growing season of the cash crop (in this case, corn) they are supporting. They differ from cover crops in that cover crops are terminated before the growing season begins. However, although cover crops and living mulch systems are two potential alternatives to fertilizer, further investigation is needed to discern whether these alternatives emit less N_2O than traditionally fertilized soil. Past studies have shown mixed results on whether cover crops can reduce N_2O (Pimentel et al., 2015, Parkin et al., 2016, de Carvalho et al., 2016). One potential contributing factor to the mixed results on cover crops emission reduction potential is the type of cover crop used. In one study, the use of legumes as cover crops proved somewhat ineffective at limiting N_2O emissions when compared to grass-based cover crops or no cover crops (Pimentel et al., 2015). In addition to this, another study identified little or no change between any cover crop or no cover crop systems (Parkin et al., 2016). However, in another study, legume cover crops were able to reduce N_2O emissions more than traditional fertilizer (de Carvalho et al., 2016). And yet another study identified a positive effect of cover crops in their ability to decrease N_2O (Fisher et al., 2018). So, this begs the question of what could be causing these mixed results? And where would different types of cover crops be most effective in reducing N_2O?

Another potential avenue for reducing N_2O emissions is living mulch. The results on the success of living mulch in reducing N_2O emissions thus far are inconclusive (Turner et al., 2016, Alexander et al., 2019). Therefore, this study assesses where in the U.S. future attention should be paid to the potential success of living mulch systems in reducing N_2O emissions. When used with corn, living mulch has been shown to require additional irrigation (Sanders et al. 2018). Because soil moisture is linked to increased N_2O emissions and continuously provides organic matter to the soil throughout the growing season, the ability for living mulch to reduce N_2O emissions may appear dubious(Pimental et al., 2015). One study analyzed this using kura clover (species abbreviation M. Bieb) and found that, rather than reduce emissions, the living mulch system increased N_2O emissions in comparison to treatments lacking living mulch (Turner et al.

2016). However, this study only took between row emission measurements (Turner et al. 2016). Between row measurements differ from within row measurements. If the chambers measuring emissions from the soil are placed between rows of corn, they constitute between row measurements. If the chambers measuring emissions from the soil are placed within the rows of corn, they constitute within row measurements. Differing from the study which solely collected between row measurements, another study whose methods included both within row and between row measurements of N_2O emissions found little differences between N_2O emissions from living mulch and traditional techniques (Alexander et al. 2019).

The county-level N_2O emissions from corn farms in the U.S. was analyzed by Pelton (2019). His analysis was conducted by collecting data on fertilizer use, yields, and other relevant variables through a variety of databases on the county level, as described in Pelton (2019). This opens the door to further analyze how county level emissions change with different agricultural techniques. Taking this opportunity, this thesis analyzes how crimson clover cover crop, cereal rye cover crop, and white clover living mulch impact county-level N_2O emissions compared to using traditional fertilizer methods from corn farms. Due to this application of regional emission data to national county level statistics, and the therefore necessary assumption that the techniques emit the same amount of N_2O in relation to one another across the U.S., the results of this study cannot be used to see where these four techniques will be successful. However, the results can be used to identify regional variations in where emission reduction is possible. And information on where emission reduction is possible can inform potential avenues to reducing greenhouse gas emissions below the goals outlined in the Paris Agreement. Therefore, the question being asked is, where in the U.S. should future research be directed, in order to discover the most effective N2O emissions mitigation techniques for growing corn.

Methods

For the year of 2017, U.S. county level changes after implementation of the four agricultural techniques was estimated using results from Peters et al. (2020). The measurement was conducted in Watkinsville, Georgia, U.S. within the West Unit of the Phil Campbell Sr. Resource and Education Center at the University of Georgia. The methods include N_2O flux measured between rows of corn for four different agricultural types: crimson clover (trifolium incarnatum) cover crop, cereal rye (secale cereale L.) cover crop, white clover (trifolium repens L.) living mulch, and bare soil with traditional fertilizer (urea) (Young-Mathews, 2013, Casey, P.A., 2012, USDA NRCS Plant Materials Program). White clover was grown over the winter, as were the two cover crops. Both crimson clover and cereal rye were terminated using herbicide prior to the planting of corn. White clover was allowed to grow through the summer. Data collection began prior to the start of the growing season. The corn was planted on April 21st, and data collection ended when the corn was harvested on August 15th.

In order to randomize measurements and increase accuracy, there were three plots of land, each sized at 6.1m by 7.3m, for every agricultural technique being studied. For each plot, three chambers were installed to estimate soil fluxes. In 2017, 15mm irrigation was provided by a Kifco T200L water wheel. Water filled pore space was kept above 40% by adding an additional 20mm water during irrigation when needed. Fertilizer in the form of urea was applied throughout the corn's growing season to a final amount of 50kg/ha for the plot containing white clover, 150kg/ha for the plot containing crimson clover, and 250kg/ha for both the plot containing traditionally fertilized soil and the plot containing cereal rye. Fertilizer was applied within rows of corn.

Static chamber measurements were taken from chambers placed between the rows of corn. The chambers were made using white polyvinyl chloride pipe. The volume of the chambers was 2.92 L and the surface area of the chambers was .0182 m^2. Ten mL measurements were taken using syringes from opaque PVC chambers. Initial measurements were taken upon capping the chambers, and then additional measurements were taken from the same chamber every 3.75 minutes for a total of 15 minutes. This was later analyzed through gas chromatography, specifically Shimadzu Gas Chromatograph (GC)-2014 GHG. To analyze N_2O, an electron capture detector was used.

In order to assess where the four agricultural techniques analyzed by Peters et al. (2020) varied in their emission reduction potential across the U.S., the Pelton (2019) dataset was used. Pelton (2019) included the estimated county level direct N_2O emissions from corn farms across the U.S.. More specifically, this data set compiled national direct N_2O emissions, which include the N_2O emissions, originating from nitrogen input, emitted from the soil. This was obtained using a USDA report that combined both a DAYCENT and a Denitrification and Decomposition model, including soil type and climatic variations, to assess the N_2O emission from different fertilizers in different regions. Background N_2O emissions were deducted from the combined USDA models and fertilizer usage per county. Fertilizer use per county was calculated using the Association of American Plant Food Control (AAPFCO) data containing the amount of fertilizer sold in each county from 2007 to 2012. This calculation was analyzed in conjunction with how many farms use fertilizer and USDA surveys on the breakdown of fertilizer going to different crops. Using the Nutrient Use Geographic Information System (NuGIS) and census data, information was obtained regarding the acres of corn planted and harvested. Using the county level yield statistics from the years 2000 to 2016, Pelton (2019) then estimated 2012 yields. Using this, he reported the number of bushels of corn harvested per acre. Afterwards, the average direct N_2O emissions per acre of corn harvested for each county was presented by the county's FIPS number. Using the USDA's County FIPS Codes, I converted FIPS numbers into county names.

I took the average N_2O flux data across all dates measured for four different agricultural types: crimson clover (CC) cover crop, cereal rye (CR) cover crop, white clover (WC) living mulch, and traditional (TR) bare soil with fertilizer. The emission data from Peters et al. (2020) was first converted from micromol $N/m^2/hr$ to match the 2012 Pelton (2019) study's kgN/acre/yr. For each of the agricultural techniques, the average N_2O emissions was then multiplied by the number of acres of corn farms per county. Next, I divided the emissions, for each estimate per county, by the number of kg of corn harvested within that county. Yields for each agricultural technique were obtained from a comparable 2015 study done on the same plot of land at UGA, from Andrews et al., 2018**.** Yield was incorporated into the four agricultural methods by multiplying the kg/acre corn yield from the four different agricultural techniques by the number of acres in each county. From here, the % difference between the 2012 Pelton-estimated N_2O emissions per kg yield and the emissions per kg yield for each of the agricultural techniques was calculated for each county and mapped.

In addition to using Peters et al. (2020) flux data assessing N_2O emissions for the four different agricultural techniques, in order to assess the difference between within row and between row emission measurements, I analyzed additional data measured throughout 2019. The data collected in 2019 was from the same farm at UGA as was the 2017 Peters et al. (2020)

study. In the year of 2019 N_2O flux was measured both between the rows of corn and within the rows of corn for both traditionally fertilized soil and living mulch. Four chamber locations were dedicated to traditional in row and one chamber location for traditional between row, as well as one chamber location for living mulch in row and one chamber location for living mulch between row (Figure 1). Static chambers were used with Picarro G2508, an instrument which continuously measures N_2O, CO_2, CH_4, and H_2O gas concentrations from the chambers (Figure 1). The chambers used in 2019 were of the same material, white polyvinyl chloride pipe, volume, 2.92 L, and surface area, .0182 m^2, as was used in 2017. Data collection began at the start of the growing season and continued approximately a third of the way through before stopping. The corn was planted on April 26th. An average of 120kg/ha of fertilizer, in the form of urea, was applied within rows of corn, except for on May 27th when fertilizer was applied between rows of corn. In 2019, 15mm irrigation was provided by a Kifco T200L water wheel. Water filled pore space was kept above 40% by adding an additional 20mm water during irrigation when necessary.

Figure 1: Closed chambers connected to Picarro during concentration collection.

Upon completion of data collection, the continuous measurement of N_2O concentrations over time were analyzed using IDL. Picarro presented the concentration of N_2O over time in ppb. For each individual chamber, the N_2O gas accumulated over time once capped. The rate of these accumulations during the one-minute measurement were calculated for each chamber, represented as a slope. Using the slope for the rate of N_2O accumulation, the N_2O flux was calculated by multiplying this slope by the volume of the chamber divided by the surface area of the chamber.

Flux = slope * volume/surface area

For each data collection date, the fluxes for the chambers measuring living mulch between row (LMBR), traditional between row (TRBR), living mulch within row (LMIR) , and traditional within row (TRIR) emissions, were averaged. The average flux for each was then graphed as N_2O flux over time. This graph's (Figure 5) titles and axes were later shifted in Images due to formatting issues in IDL software. This had no impact on the flux data for LMBR, LMIR, TRIR, or TRBR, or the maps and graphs that were later made using these variables' flux data. However, there is some potential for error in the human adjustment of the axes.

For both 2017 and 2019, repeated measurements were taken from each chamber, the methods of which for 2017 are described above. In 2019, the Picarro was used to measure N_2O gas concentrations from each chamber one at a time. To do so, Picarro continuously withdrew the accumulating gas within each chamber for a full minute before switching to the next chamber. As it pulled gas from the chambers it measured the concentrations of CO_2, N_2O, CH_4, and H_2O within that gas. Picarro would then present this data as ppb of N_2O over time. After measuring the gas concentration within each individual chamber, Picarro would cycle back to the first chamber and repeat the process. This continued until Picarro had conducted five cycles, with each cycle having measured each chamber for one minute. Each round is characterized by five of these cycles. In 2019, between two and four rounds were measured. For both 2017 and 2019 weather would at times limit the number of rounds that could be conducted. In 2019 there were seven chambers measured for each cycle. Within each round only cycles three through five were used to calculate N_2O fluxes, in order to reduce error, due to the later three cycles displaying the change in N_2O concentrations over time more clearly.

Using the results of the 2019 data showing the difference for in row and between row measurements, the flux for each date was averaged for LMBR, LMIR, TRBR, and TRIR. Using the averages for TRBR and TRIR, the % difference between the TRBR and TRIR N_2O emission value and the Pelton (2019) county level N_2O emissions were each mapped. The % difference for each county in the state of Georgia was then averaged to obtain the average % difference between 2012 Pelton (2019) emission data, and 2019 between row and within row emissions.

In order to assess how the 2017 emission data for traditional soil from Peters et al. (2020) compared to the 2012 Pelton (2019) county level emission data within the state of Georgia, the two average N_2O fluxes for TRBR and TRIR were averaged to obtain the average TR emissions. The average TR emissions was divided by the averaged TRBR emissions, resulting in the conversion factor to convert TRBR to the averaged TRBR and TRIR. This process was repeated for LMBR and LMIR to obtain the conversion factor to convert LMBR to the averaged LMBR and LMIR. These conversion factors display what the between row measurement needs to be multiplied by in order to match the averaged in row and between row flux. The calculated TRBR conversion factor was 1.58, and the LMBR conversion factor was .95. The TRBR conversion factor/LMBR conversion factor was then multiplied by the respective 2017 averaged traditional soil/living mulch N_2O emissions, from Peters et al. (2020), per kg yield. Due to the traditional between row measurements more closely matching the 2012 Pelton (2019) dataset within the state of Georgia, the 2012 Pelton (2019) per county emissions were also multiplied by the TRBR conversion factor to obtain what the N_2O emissions would be if both within row and between row measurements had been taken. This assumes that the 2012 Pelton (2019) county level emission data heavily favors between row measurements. The difference between the adjusted for between row and within row 2012 Pelton (2019) county level emissions and the adjusted for between row and within row 2017 traditional emission data, and living mulch emission data from Peters et al. (2020) were then both mapped.

In order to direct future research and explore avenues to reduce the U.S. GHG emissions below the goals outlined within the Paris Agreement, geographic differences in where the different agricultural techniques have the potential to reduce emissions the most are assessed. To control for fertilizer usage variation, the N_2O emissions per kg yield for each county was divided by the amount of fertilizer used for every kg of corn yield. Using adjusted-for-between-and-within-row traditional and living mulch emissions, along with crimson clover and cereal rye emissions, per kg yield, these emission averages were divided by the kg of fertilizer used per kg of corn yielded. Using these numbers, which account for how much fertilizer was used to produce every kg of corn, a map was created depicting the % difference between the 2012 Pelton (2019) county level N_2O emissions per kg of fertilizer used for each kg of corn yielded, and the four agricultural techniques' N_2O emissions per kg of fertilizer used for each kg of corn yielded.

In order to assess whether future studies should look closer at local level variations in addition to larger regional variations in emission reduction trends, this thesis looks closer at counties that share a border, and despite their close proximity, have sharp differences in the degrees with which a certain agricultural technique can reduce emissions. To do this, select counties neighboring one another with a large difference in % differences in emissions between the 2012 Pelton (2019) dataset and the 2017 emission data were looked at more closely. Specifically, within the corn belt, the counties of Morgan County, Cass County, and Macoupin County in Illinois were compared. These counties were selected due to Morgan county presenting a % difference of 649.9% within the living mulch graph in comparison to its surrounding counties. This was done based on the % difference between the adjusted-for-between-row 2012 Pelton (2019) emission estimates and the adjusted-for-between-row living mulch and traditional measurements from 2017, as well as the % difference between the 2012 Pelton (2019) emission estimates and the 2017 emission data for crimson clover and cereal rye from Peters et al. (2020).

Results

The averaged flux per hour across the entire growing season for each agricultural type in 2017, obtained from Peters et al. (2020), revealed that traditionally fertilized soil emitted the least at 0.771kgN/m^2/hr with a p-value of .457, followed by crimson clover at .879kgN/m^2/hr with a p-value of .398, then cereal rye at 1.295kgN/m^2/hr with a p-value of .222, and finally, living mulch at 2.283kgN/m^2/hr with a p-value of .043(Figure 2). All p-values were calculated in excel using two tailed tests. Each agricultural type had an n value of 12, where n represents the number of days flux data was available for. Due to the flux variations throughout the growing season, each technique has a large standard deviation. Only living mulch's averaged flux was statistically significant when compared across the flux for each agricultural type per day measured. Therefore, while the 2017 averaged fluxes measured throughout the growing season will be used in this thesis, further studies are needed to support the trends observed in Peters et al. (2020). Due to the small n value both in limited chamber placements and time, prior to any policy recommendations or future studies assessing the implication of this thesis's results, a more expansive study must be done to first confirm the results of the 2017 emissions data from Peters et al. (2020). However, despite the small n values, variations in emission reduction potential across the U.S. can still be assessed using the relative differences between different agricultural techniques.

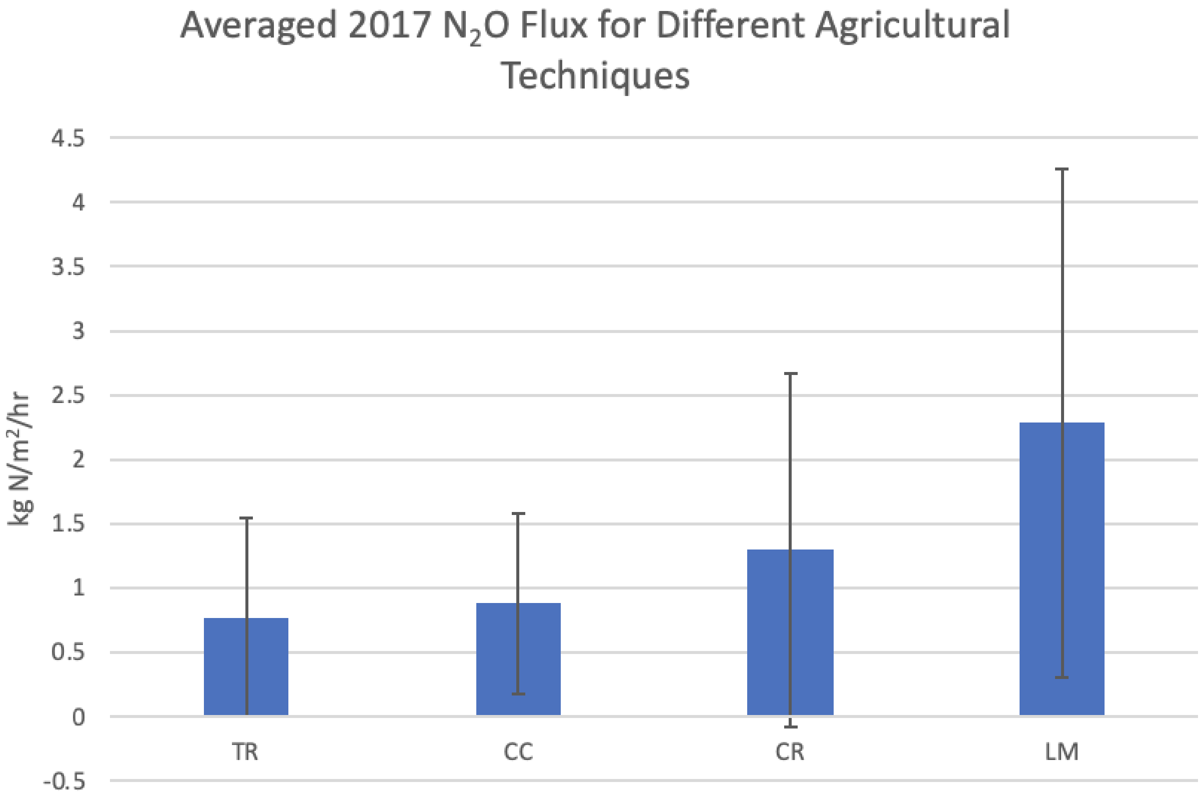


Figure 2: The averaged fluxes and standard deviations across all measured dates for cereal rye (CR), crimson clover (CC), living mulch (LM), and traditional (TR), calculated from Peters et al. (2020) data.

Based on corn yields per hectare for each of the four agricultural techniques, obtained from a 2015 study by Andrews et al. (2018), I then calculated the yield based N_2O emissions for each different agricultural technique. The 2015 corn yields in Mg/ha from Andrews et al., 2018, are displayed below in Figure 3. Plots with crimson clover resulted in a yield of 5766.8 kg/acre, plots with cereal rye resulted in a yield of 5232.6 kg/acre, plots with living mulch resulted in a yield of 4730.8 kg/acre, and traditionally fertilized plots resulted in a yield of 4572.95 kg/acre.

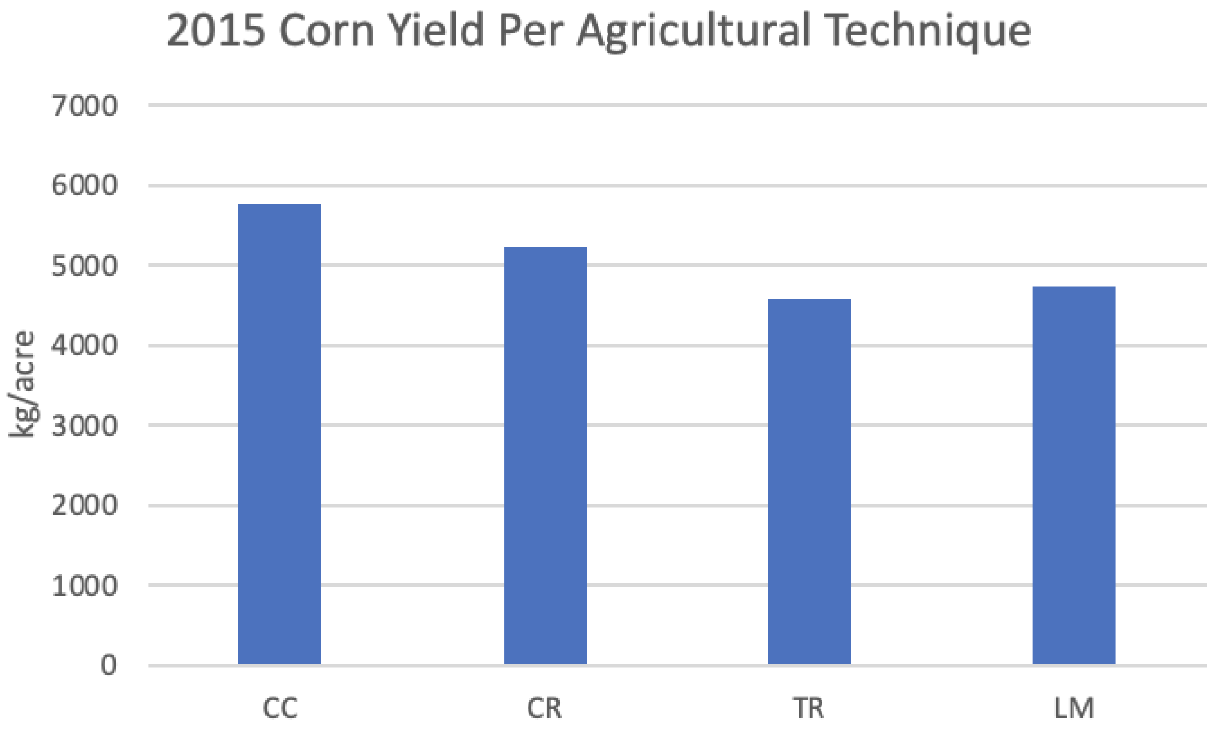


Figure 3: Yield for different agricultural techniques, including living mulch (LM), cereal rye (CR), crimson clover (CC), and traditional (TR). Data obtained from Andrews et al. (2018).

I mapped the % difference between 2017 county level N_2O emissions per kg yield for traditionally-fertilized soil and 2012 estimate of county level emissions per yield from Pelton (2019). Figure 4 shows this map within the state of Georgia. By mapping the % difference between 2012 estimated N_2O emissions per kg yield from Pelton (2019) and the N_2O emissions from traditional soil from Peters et al. (2020), I found a 18.52% difference in the county of Oconee, where the 2017 and 2019 measurement collection occurred. I also found a -0.224% difference for the entire state of Georgia. However, this does not definitively show that the 2017 traditional data was representative of corn emissions within the state as recorded by the Pelton (2019) dataset.

County Level % Change With Traditional Fertilizer in Georgia

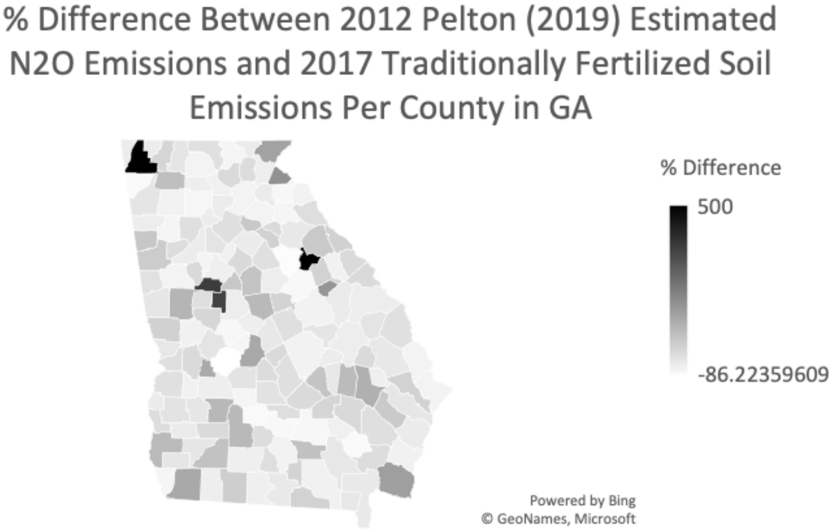


Figure 4: County level % difference between 2012 Pelton (2019) N_2O emission estimates and 2017 N_2O emissions calculated from Peters et al. (2020), from fertilized soil, across the state of Georgia. Yield data factored in from Andrews et al. (2018).

However, in order to further explore potential differences between the Pelton (2019) data on estimated emissions in 2012 and traditional fertilized soil emissions from Peters et al. (2020), further analysis was conducted into differences in where on corn farms emissions were being measured. To do so, Figure 5 displays the 2019 flux analysis from the farm at UGA analyzing the difference for between row and in row measurements for both traditional soil and living mulch. Following fertilization on April 27th, intensive measurements were taken for the eight days after. The flux analysis found that, due to how the fertilizer was applied, the N_2O emissions from between the rows of corn was significantly less than the N_2O emissions within the rows of corn. There is some variation over time, with a general trend of, following fertilizer application there is an immediate spike in N_2O emissions, and then another spike around a week after this initial spike. May 28th is missing from the above graph due to complications with how the data was coded. Due to the variability in fluxes for each date, further studies should be completed to confirm these results.

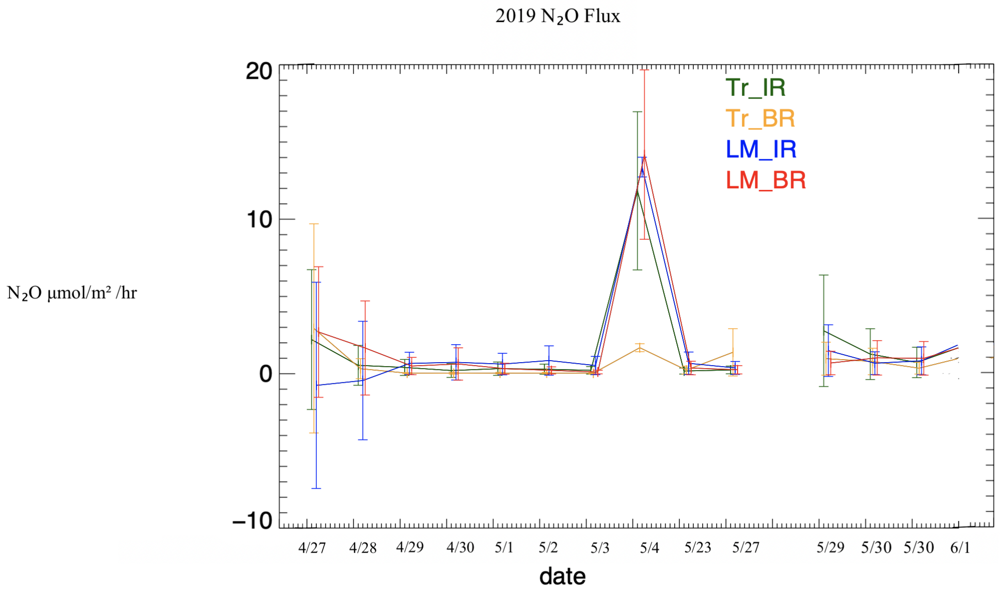


Figure 5: N_2O flux across time for traditional within row (TrIR), traditional between row (TrBR), living mulch in row (LMIR), and living mulch between row (LMBR).

It should be noted that although the averages support the notion that LMIR emits less than LMBR (Figure 6), this seems to be skewed by a few select dates. For 4/27 and 4/28, LMBR displays a greater flux than LMIR. The same is true for TRIR and TRBR, where the general trend for the averages is flipped due to TRBR being fertilized instead of TRIR. However, for traditional this difference is to a lesser degree, and the later spike on May 4th favors the traditional trend of within row measurements emitting more than between row measurements, due to TRIR being fertilized in May. It is also possible that depending on the time of the year and the status of the crop that this trend reverses. So, before April 29th this trend could switch where the BR emits more than the IR. This switch in trends is also seen for the 27th and the 28th of May. However, soon after it reverts to the original trend. This could be due to improper fertilization on the 27th of May, where it was applied between the rows of corn. Therefore, when analyzing the differences between the averaged fluxes, it is possible that TRBR emits less than shown in Figure 6.

The fluxes were averaged across all calculated dates for the between row and within row flux measurements of corn for the two techniques, as shown in Figure 6. The p-values were calculated for each agricultural type's averaged flux using two tailed tests and an n value of 14, where n represents the number of days flux data was available for. The results, shown in Figure 6, show that TRIR emitted more than TRBR. TRIR had an averaged flux of 1.753 kgN/m^2/hr and a p-value of 0.118. TRBR had an averaged flux of 0.8738 kgN/m^2/hr with a p-value of 0.415. On the other hand, LMIR emitted less than LMBR. LMIR had an averaged flux of 1.656 kgN/m^2/hr with a p-value of 0.117. LMBR had an averaged flux of 1.953 kgN/m^2/hr with a p-value of 0.073. For living mulch, the between row measurements resulted in greater N_2O emissions, yet for traditional in row measurements showed greater N_2O emissions. However, the traditional between row averages were not statistically significant, when compared across the flux for TRBR per day measured, using a two tailed test. Therefore, while the averages found for traditional between row will be used throughout this study, further studies are needed to establish a significant difference between measurements taken between and within row for traditional and living mulch agricultural types. Following the event of a future more expansive study confirming the average flux differences between TRIR, TRBR, LMIR, and LMBR, the results of this study can be re-assessed.

In 2017 the majority of measurements were taken in between rows of corn. Due to between row measurements in traditionally fertilized soil presenting with lower N_2O emissions, it would also be possible that the 2017 emission data is skewed towards lower emitting between row measurements. Therefore, despite higher emission data coming from living mulch plots in 2017 when compared to traditional, further investigation is needed to determine whether this general increase in emissions holds across the U.S. if both within row and between row emissions are estimated. To do this, the averaged between row and within row emissions are estimated for both living mulch and traditional and compared to 2012 estimates from Pelton (2019).

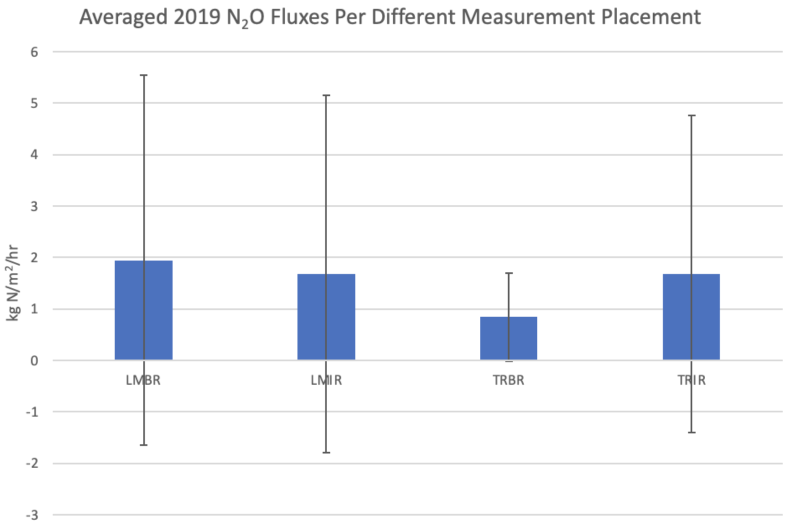
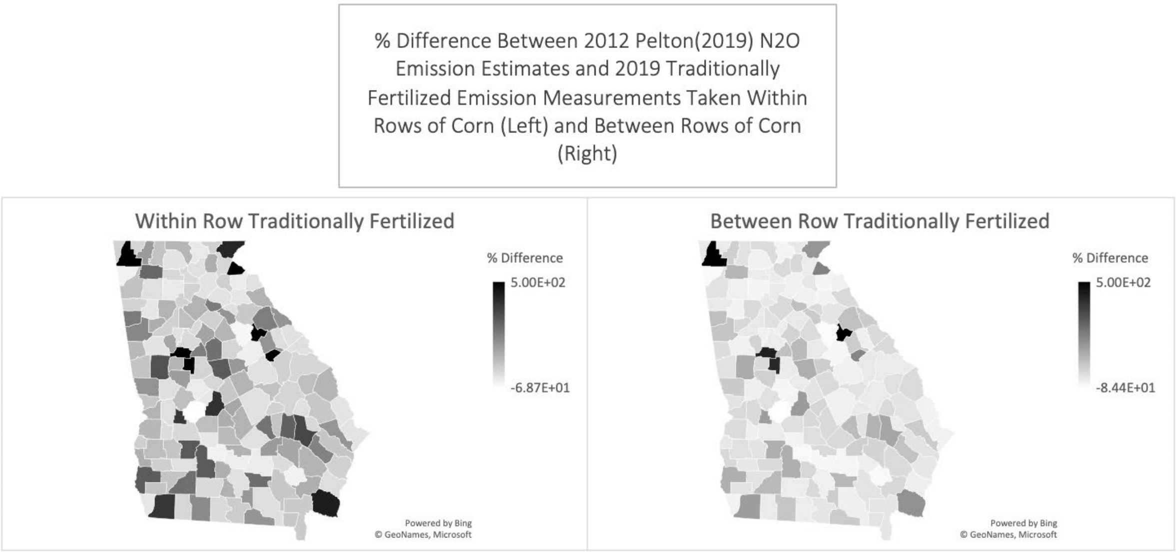


Figure 6: The averaged 2019 fluxes and standard deviations across all measured dates for living mulch between row (LMBR), living mulch within row (LMIR), traditional between row (TRBR), and traditional within row(TRIR).

Following this, a map comparing the % difference between 2012 emission estimates from Pelton (2019) and 2017 traditional soil emission was created to assess whether Pelton (2019) was weighted towards either between row or within row. Figure 7 shows an average % difference of 5.2% in the state of Georgia for the map depicting the % difference between the 2012 estimated emissions from Pelton (2019) and the 2019 between row emissions. Whereas the map depicting the % difference between the 2012 estimated emissions from Pelton (2019) and the 2019 within row emissions show an average % difference of 121.80% for the state of Georgia. This displays a bias within the 2012 data towards between row measurements.

County Level % Change (TR Between or Within Row Measurements) in Georgia



% Difference Between 2012 Pelton(2019) N2O Emission Estimates and 2019 Traditionally Fertilized Emission Measurements Taken Within Rows of Corn (Left) and Between Rows of Corn (Right)

Within Row Traditionally Fertilized

Between Row Traditionally Fertilized

Figure 7: Maps depicting the county level % difference between 2012 N_2O emission estimates from Pelton (2019), and 2019 N_2O emissions for traditional between row (right) and traditional within row (left) within the state of Georgia. Yield data factored in from Andrews et al. (2018).

Figure 8 depicts a map of the % difference between the adjusted-for-between-row and within-row 2012 emission data from Pelton (2019), and the adjusted-for-between-row and within-row for living mulch and traditional fertilized soil, using 2017 emission data from Peters et al. (2020). Additionally, maps were created to assess the distribution of the % change between the 2012 emissions data from Pelton (2019) and the 2017 emissions for CC and CR from Peters et al. (2020). The maps for CC and CR are not adjusted for in row and between row due to a lack of data on the differences between their in row vs between row emissions. Within the southeastern U.S. and the corn belt there are multiple counties with emission reduction potential within the map in the upper right depicting the county level % difference in 2012 estimates from Pelton (2019) adjusted for between row and within row, and 2017 living mulch emission values averaged for between row and within row. When estimating the effect of implementing the two cover crop agricultural techniques nationally, the crimson clover cover crops showed large scale decreases in emissions in both the southeastern U.S. and the corn belt. And cereal rye, similar to living mulch, showed modest emission reduction potential in the corn belt and in the southeastern U.S.. However, across all four maps, there is a general trend connecting the degree of emission reduction potential and elevation (GIS Geography). Elevation within this paper is defined as the number of ft a point of land rises above sea level. Higher elevations, such as within the Appalachian Mountains, corresponds to lower emission reduction potential.

County Level % Change for CC, CR, and Adjusted TR and LM in the U.S.

Figure 8: County level maps depicting, for the two graphs on the right, the % difference in emissions between the adjusted for in row & between row 2012 emission estimates from Pelton (2019) and adjusted for in between row & between row emissions for living mulch (top graph) and traditional soil (bottom graph). For the left two graphs, the % difference in emissions between 2012 emission estimates from Pelton (2019) and emissions for cereal rye (top graph) and crimson clover (bottom graph). Used Peters et al. (2020) emission data, and Andrews et al. (2018) yield data in calculations.

In order to assess whether a limited emission reduction potential within higher elevations was due to increased fertilizer usage, new maps were created to account for the amount of fertilizer used. The per kg yield of corn N_2O emissions for the Pelton (2019) emissions as well as the 2017 emission data for LM, TR, CR, and CC were divided by the average amount of fertilizer being applied per kg yield. The % difference between these new adjusted-for-fertilizer-usage emissions data for CC, LM, and CR and the TR emission data was then calculated and mapped. When adjusting for fertilizer usage, this largely eliminated the correlation between increased emissions and elevation. Therefore, it is possible that higher elevations lead to increased fertilizer usage per kg yield. Generally, across all maps, the southeast observed less of a decrease than the corn belt and the northeast. Therefore, on a broad national scale, additional research should be conducted to discern what might be causing the reduced potential for emission reduction within the southeast as compared to the corn belt.

The living mulch map shows no potential for emission reduction. However, due to the map's assessment of emissions per kg of fertilizer used for each kg of corn yielded, this does not factor in the degree to which the different techniques would reduce the amount of fertilizer used. Therefore, these maps are not representative of where future studies should be conducted to assess mitigation strategies.

Fertilizer Controlled County Level % Change Per Technique in the U.S.

% Difference Between 2012 Pelton (2019) N2O Emissions Per kg Fertilizer Applied Per kg Corn Yield, and 2017 Emission Per kg Fertilizer Applied Per kg Corn Yield for Cereal Rye (top) and Crimson Clover (bottom)

% Difference Between Adjusted-for-Between-and-Within-Row 2012 Pelton (2019) N2O Emissions Per kg Fertilizer Applied Per kg Corn Yield, and Adjusted-for-Between-and-Within-Row 2017 Emission Per kg Fertilizer Applied Per kg Corn Yield for Living Mulch (top) and Traditional (bottom)

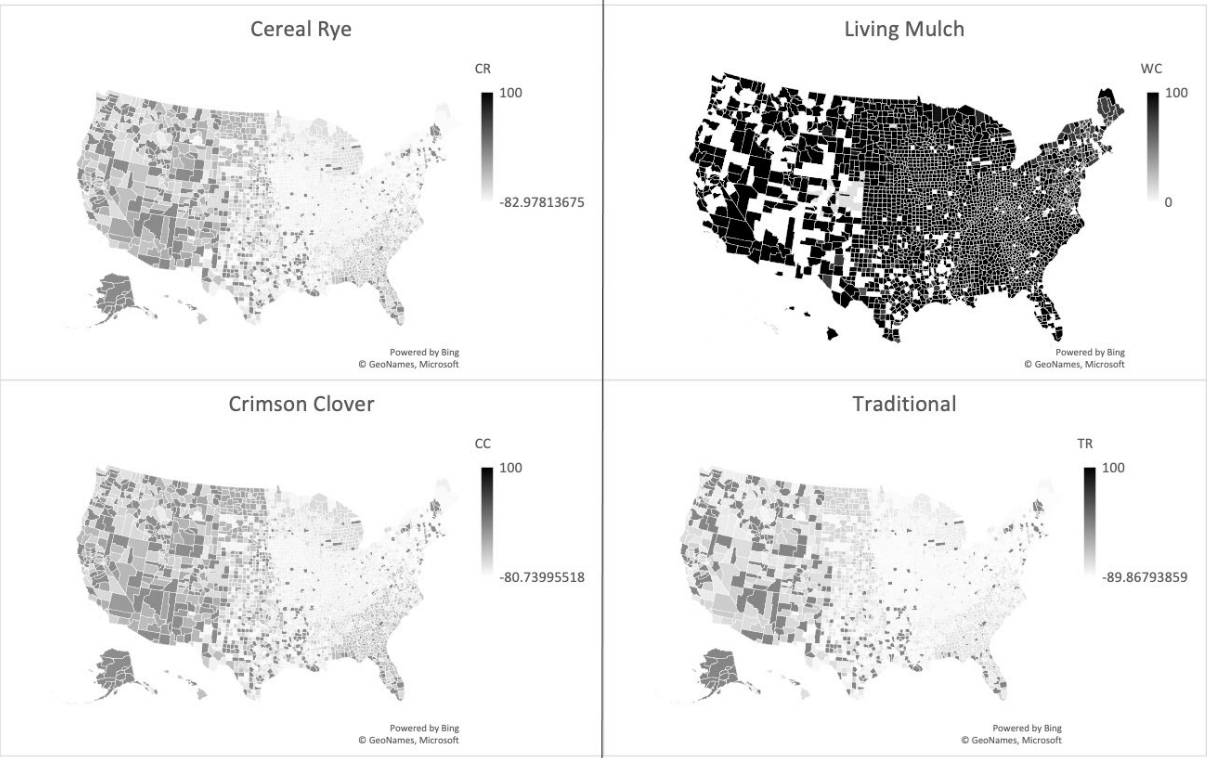
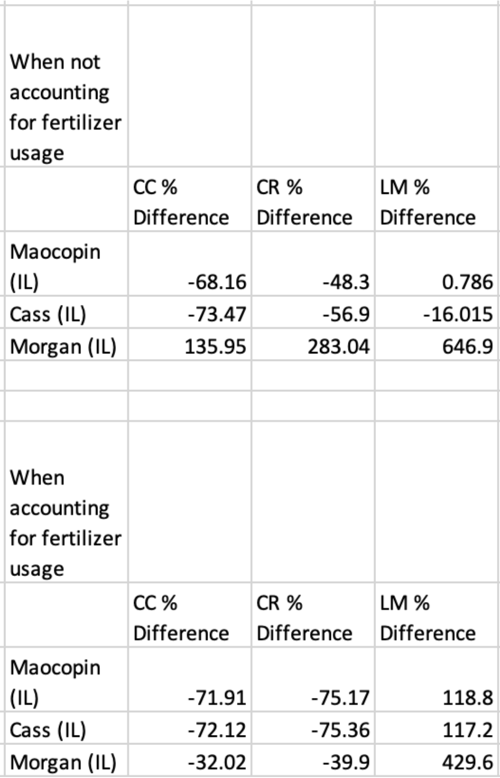


Figure 9: County level maps depicting N_2O emissions per kg yield of corn divided by the amount of fertilizer used for each kg yielded, for the two graphs on the right, the % difference in emissions between the adjusted for in row & between row 2012 emission estimates from Pelton (2020) and adjusted for in between row & between row emissions for white clover (top graph) and traditional soil (bottom graph). For the left two graphs, the % difference in emissions between 2012 emission estimates from Pelton (2020) and emissions for cereal rye (top graph) and crimson clover (bottom graph). Used Peters et al. (2020) emission data, and Andrews et al. (2018) yield data in calculations.

The results of this study indicate that additional research should also be directed towards adjacent counties with staggeringly different % differences. The assumption in analyzing adjacent counties is that their emission reduction potential will be similar due to similar geography, climate, and soil conditions. However, there are multiple counties in Figure 8 and Figure 9 that, even after accounting for the amount of fertilizer used in each county, show large differences in their emission reduction potentials. This study looks closer at one example of three counties which are close in proximity and yet differ in their emission reduction potentials. The counties analyzed include Morgan County, Illinois, Macoupin County, Illinois, and Cass County, Illinois. Across all three agricultural types, Morgan County had the smallest potential for emission reduction, followed by Macoupin County and then Cass County which had the largest potential for emission reduction. To assess whether this was due to different levels of fertilizer used between the counties, these same three counties were compared again. And although this led to the difference between Macoupin County and Cass County's emission reduction potential becoming almost nonexistent, Morgan County still displayed a significantly lesser emission reduction potential.

Table 1: Table depicting the % differences between, on the top half, the 2012 Pelton (2019) dataset and the 2017 emission data for CC and CR, and the 2012 Pelton (2019) dataset adjusted for between row and within row and the 2017 emission data for LM adjusted for between row and within row. On the bottom half is the % difference between the 2012 Pelton (2019) dataset's emission data per kg fertilizer used per kg yield and the 2017 emission data per kg fertilizer used per kg yield for CC and CR, and the 2012 Pelton (2019) dataset , emission data per kg fertilizer used per kg yield, adjusted for between row and within row and the 2017 emission data per kg fertilizer used per kg yield for LM adjusted for between row and within row. Used Peters et al. (2020) emission data, and Andrews et al. (2018) yield data in calculations.

County Level Emission Reduction Potential Variations



When not accounting for fertilizer usage			
	CC % Difference	CR % Difference	LM % Difference
Maocopin (IL)	-68.16	-48.3	0.786
Cass (IL)	-73.47	-56.9	-16.015
Morgan (IL)	135.95	283.04	646.9
When accounting for fertilizer usage			
	CC % Difference	CR % Difference	LM % Difference
Maocopin (IL)	-71.91	-75.17	118.8
Cass (IL)	-72.12	-75.36	117.2
Morgan (IL)	-32.02	-39.9	429.6

Discussion

Due to the limited measurements taken and potential yearly differences between the data used in 2012, 2015, 2017, and 2019, first this study should be repeated on a larger scale. After replication, a similar analysis as used in this thesis can discern where future research should be directed. When analyzing, on a smaller scale, the differences between Macoupin, Cass, and Morgan county, there is some variable not controlled for within this study leading to Morgan County's limited emission reduction potential. Therefore, following replication confirming these results, directing future research towards studies which investigate what might be causing Morgan County's decreased emission reduction potential, could uncover further avenues to mitigate N_2O emissions.

These between-county differences would not be caused by differences in fertilizer usage due to the bottom half of Figure 10 depicting the % changes adjusted to account for emissions per kg of fertilizer used for each kg corn yielded.

In addition to county-level variations, the broader country-level variations should be explored as indicators of areas for potential emission reduction. The Appalachian mountains present with a larger % difference than the rest of the country within all four agricultural techniques in Figure 8. The trend connecting decreased emission reduction potential to higher elevations, observed within the Appalachian mountains, disappeared when fertilizer usage is accounted for in Figure 9. Therefore rather than elevation leading to increased N_2O emissions, higher elevations more likely lead to increased fertilizer use due to decreased yields and therefore result in increased emissions. One study, supporting this idea, found that elevation did in fact have a large impact on corn yield (Machado et al., 2002).

As the trend in the results connecting decreased emission reduction potential to higher elevations decreased significantly when fertilizer usage was controlled for, one potential causal factor that led to decreased emission reduction potential within the southeast in Figure 9 is soil pH. The concentration of great emission reduction potential within the corn belt, as seen in Figure 8, aligns with a regional soil pH level of 6-6.5, which suggests this specific pH range could be conducive to lower N_2O emissions (Oregon State University). The pH of the soil may affect which microbes can survive. Therefore, further study is needed as to whether a pH range of 6-6.5 supports the survival of microbes that in nitrification and denitrification emit less N_2O. This could also be one potential explanation for the small scale variations between Morgan County and Cass County/Macoupin County.

The variations in pH are not observable in Figure 9 for living mulch due to the large positive % difference across most of the country. This large positive % difference for white clover across the U.S., in comparison to the legume cover crop, crimson clover, which decreased emissions in the southeast, could be because of white clover’s continuous provision of nitrogen to the soil throughout the growing season, whereas crimson clover is terminated prior to planting the corn. And in addition to being a legume and fixing nitrogen into the soil as the corn is growing, another explanation for their emission reduction potential difference is that living mulch, through intermittently decomposing and regrowing, provided organic matter, including nitrogen, to the soil as the crop was growing. In addition to the difference between white clover and crimson clover, white clover presents with a lower emission reduction potential than traditionally fertilized soil despite less fertilizer being applied.

One additional possibility for why living mulch had limited emission reduction potential across the U.S. in comparison to the other techniques is its prevention of runoff. One study done in Iowa analyzing both the loss of NO_3 below the soil and N_2O emissions discovered that in a winter wheat cover crop field with both corn and soybean as the crops, the cover crop model had 60% less N leaching in comparison to soil lacking any cover crops (Gillette et al., 2018). Another study showed that greater N leaching resulted in lower N_2O emissions (Benoit et al., 2015). These past studies provide some support for why living mulch resulted in higher emission levels. It could very well be due to its prevention of NO_3 leaching. In blocking the runoff of NO_3, the living mulch increases the amount of nitrogen present in the soil. Therefore, through preventing leaching, it would increase emissions.

In addition to explaining living mulch emissions, nitrogen levels within the soil also help explain the results depicting the elevated emission reduction potential for the two cover crops. Cereal rye is not a legume and therefore doesn’t provide nitrogen before or after being incorporated into the soil. However, cereal rye has a lower emission reduction potential than crimson clover. This difference could be caused by cereal rye receiving more fertilizer than crimson clover. Another potential explanation could be differences in between row vs within row measurements, which were not taken into account for crimson clover and cereal rye within this study.

Between row and within row emission measurements were analyzed for living mulch and traditionally fertilized soil. The mapping analysis within Figure 7 shows a bias towards between-row measurements within the 2012 dataset. It is possible that due to a lack of attention to the difference between in row emissions and between row emissions that N_2O emissions from corn farms across the U.S. have been underestimated. Therefore, additional research should be directed towards uncovering whether corn N_2O emissions contribute greater to the U.S. GHG emissions than previously thought. Results indicating an underestimation of corn farm N_2O emissions would demand stronger mitigation policies aimed at corn farms in order to reduce the U.S. GHG emissions below the goals outlined within the Paris Agreement. Both the 2017 and 2019 data were primarily of peak-level emissions, whereas the 2012 data set also included background emissions. This is due to the 2017 and 2019 data being collected solely during the corn growing season, with the 2017 data being collected throughout the entire growing season and the 2019 data being collected throughout the first month of the growing season. It would be useful to further extend this study and assess whether or not the difference in emissions within-row and between-row holds both until the corn is harvested and after the growing season.

All together, due to the potential for living mulch, crimson clover, and cereal rye to reduce emissions within the corn belt and the southeastern U.S. in Figure 8, additional research should be directed towards studies assessing whether emission trends between the techniques hold within these regions. Figure 8 and Figure 9 accounts for yield, meaning that if the emission reduction trends hold against further studies, within the corn belt, emissions could be reduced while maintaining current yields if usage of cover crops and living mulch systems are supported.

Future research could identify where subsidies should be provided to which agricultural techniques in which county. This could help farms implement certain techniques with both the greatest emission reduction potential and no additional costs. Potential costs from the different agricultural techniques include seeds and maintenance of the cover crops/living mulch systems. Due to both crimson clover and cereal rye being terminated prior to the growing season, they need to be replanted in the winter. However, white clover is a perennial and will therefore regrow on its own in the winter. Therefore additional subsidizing may be needed for crimson clover and cereal rye in comparison to white clover. Further studies are needed to assess the magnitude, location, and specific mitigation technique future subsidies target.

Limitations

There are multiple potential limitations in this study, as well as opportunities for further research. Multiple assumptions were made that need to be looked further into to assess the accuracy of these results. However, despite these assumptions, the trends uncovered within this study would still indicate areas for further research. The first assumption was that emission values for the growing season will be representative of the entire years' emissions. For all maps, emission values from either the growing season in 2017 or 2019 were compared to full year long emission estimates in 2012. This means the 2017 and 2019 data could be weighted towards greater N_2O emissions.

In addition to differences between the growing season emissions and background emissions, another potential limitation in this study was the number of chamber measurements taken in both the 2017 Peters et al. (2020) study, and the 2019 data measurements.

Another potential limitation is the differences in agricultural practices across the U.S.. Different bioengineered strains of corn could theoretically support different microbial growth within the soil, leading to a potential for different levels of N_2O being emitted in the nitrification and denitrification process. Because the data being compared to the 2012 estimates were taken from a small farm that was not characterized as a monoculture, and only used one strain of corn, it is possible that this would cause small differences in emissions in comparison to those that do.

Potentially more important than variations in strains of corn is the varying levels in which herbicide or pesticide is used across the U.S. (Hussain et al., 2009). Pesticide can affect the microbes involved in nitrification, which could then affect N_2O emissions (Hussain et al., 2009). If some regions use insecticide or herbicide more than others then this could potentially cause some regions to emit more than others.

And there are a few smaller potential errors such as the errors mentioned in the results section for Figure 5, where there is missing data for May 28th, the day after the second round of fertilizer was applied. This missing data was caused by some failing in the coding of the graph. This could mean that there are other potential errors in the code. However, due to complications with the software and access to the data leading up to the end of this thesis, this possibility could not be further investigated. As for the 28th, due to fertilizer being mistakenly applied between rows of corn on the 27th rather than within, the trend within this peak would be predicted to support greater emissions for TRBR.

And finally, one potential error is yearly differences. The yields used in Figure 3 were from 2015 which may not precisely align with yields for 2017 and 2019. However, the climatic conditions during corn's growing seasons between the years were similar. There may also be differences between the 2012 climatic conditions within the state of Georgia and the 2017 and 2019 climatic conditions within the state of Georgia.

Conclusion

Climate change cannot be fought with one solution, but rather, needs a million small solutions. Due to the small scale of the 2017 Peters et al. (2020) study and the small scale of the measurements behind the 2019 data used to analyze the between row and within row differences, applying one study within Georgia to the entire country isn’t reasonable for making policy decisions aimed at mitigation strategies.

However, it can be used to direct further research. And based on the findings within this thesis, additional research needs to be directed towards county level variation in agricultural technique success in mitigating N_2O emissions as well as broader geographical differences, potentially caused by elevation and soil pH levels. Overall, the results of this study indicate that emission reduction is possible within the corn belt and southeastern U.S., and should be further explored in future studies. Confirmation of emission reduction potential could then inform potential avenues for reducing greenhouse gas emissions below the goals outlined in the Paris Agreement.

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