Cornell Cooperative Extension
Eastern NY Commercial Horticulture Program

HUDSON VALLEY FARM HUB

Cary Institute of Ecosystem Studies

Evaluating Tillage and Cover Crop Impacts on Greenhouse Gas Flux in Annual Vegetable Production Systems in Eastern New York

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2021 Annual Report

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I. Abstract

A small plot randomized complete block design field trial was conducted at the Hudson Valley Farm Hub (Hurley, NY) to evaluate the impact of fertilizer and tillage treatments on greenhouse gas (GHG) flux from plots planted with butternut squash from late April through September 2021. There were three conventionally tilled (CT) treatments that were rototilled in April to terminate the cover crop and rototilled again in June pre-transplant that were replicated four times: an unfertilized treatment, a treatment fertilized with sodium nitrate (Chilean nitrate) in July at a rate of 40 lbs N/acre, and a treatment amended with Sugar kelp meal before transplanting the squash in June at approximately 2,000 lbs/acre to provide an estimated 40 lbs N/acre. There were two additional reduced tillage (RT) treatments that were strip-tilled pre-transplant after terminating the cover crop via roller-crimper in June: an unfertilized treatment and a treatment fertilized with sodium nitrate in July at a rate of 40 lbs N/acre. There was a statistically significant effect of tillage treatment on the average daily GHG flux rate in 2021 with the reduced tillage plots releasing 1.35 times more combined carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) in CO_2 equivalents than the conventional tillage plots (p=0.0057). Much of the difference in greenhouse gas flux rate occurred immediately following the pre-transplant strip tillage from June 15-17; during this period, the reduced tillage plots released 1.59 times more CO_2 (p=0.00193) and 5.51 times more N_2O (p=0.0004) than the conventional tillage plots on average.

Additional data was collected on soil chemical and soil biological characteristics in addition to traditional agronomic data like crop yield and quality. There was a significant effect of the tillage treatment on soil temperature and soil moisture both, with the reduced tillage plots averaging a lower temperature over the season (p=0.0003) and higher soil moisture (p=0.0151) compared to the conventional tillage plots. Despite few differences in soil available nutrient levels over the season, there were significant differences in the concentration of several micronutrients in squash foliar samples evaluating in July (zinc, manganese, and iron). Those differences in nutrient concentration did not translate into any differences in marketable squash yield. Nevertheless, the differences in GHG flux between the conventional tillage and reduced tillage plots described above combined with the yield data did result in a significant difference in the crop yield to flux ratio, with the conventional tillage plots more efficiently producing squash per unit of flux in CO_2 equivalents than the reduced tillage plots on average (p=0.0396).

II. Background

The potential to sequester carbon in well-managed agricultural soils has been extensively studied. However, very little of this body of research has been conducted on the potential to adopt practices to promote carbon sequestration in annual vegetable production systems. While it is generally understood that reducing tillage and using cover crops can increase soil organic matter and promote carbon sequestration, the impacts on complex interactions between soil microbial activity, soil temperature, and soil moisture of reduced tillage systems is less clear. Some studies have demonstrated that, while significantly reducing carbon dioxide flux from soils, some reduced tillage systems can actually promote a net increase in the release of methane and nitrous oxide, resulting in a net increase in the global warming potential (GWP) of some production systems measured in carbon dioxide equivalents, or CO_2eq. Other challenges arise in reducing tillage on organic vegetable farms, such as supplying sufficient nitrogen to crops and effectively managing weeds, that can reduce crop yield to financially unacceptable levels.

With support from the Hudson Valley Farm Hub (HVFH), Cornell Cooperative Extension Eastern New York Commercial Horticulture (ENYCHP) regional vegetable specialist Ethan Grundberg initiated a three-year trial in 2020 designed to compare the greenhouse gas (GHG) flux from different combinations of tillage and fertilizer application rate in winter squash fields located at HVFH. The results from 2020 suggested that reducing tillage in winter squash production had the potential to significantly decrease average daily GHG flux in CO_2eq, but that reducing tillage in an organic system also led to an unacceptable reduction in crop yield (especially when no additional nitrogen fertilizer was added). Based on those results, the 2021 trial was designed to try to answer the following questions:

1. What effect would strip-tilling all of the plots have on GHG flux and yield? Can minimum tillage from strip-tilling preserve the benefit of reducing GHG flux compared to full conventional tillage while also improving the yield in reduced tillage plots?
2. If there are significant differences in yield between tillage and fertility treatments, are there also significant differences in soil nutrient availability, nutrient uptake and tissue concentration, or other soil biological and physical characteristics that may explain the treatment effects on yield?
3. What impact might changing the source of supplemental nitrogen in conventionally tilled plots from Chilean nitrate to kelp meal have on GHG flux, yield, and the other soil chemical and biological characteristics?
4. What combination of tillage and fertility treatments is most efficient at generating crop yield per unit of GHG flux in CO_2-equivalents?

III. Materials and Methods

Trial Design

The researchers used a small plot randomized complete block design with four replicates and five total treatments for this trial. Each treatment plot was 5 feet wide by 30 feet long and consisted of one row of transplanted 'JWS 6823 PMR' butternut squash. Each replicate consisted of five plots, one for each of the five treatments included in the trial. There were three conventional tillage (CT) treatments and two reduced tillage (RT) treatments for a total of five treatments in 2021:

1) **RT HIGH N**: Winter kill cover crop mulch left in place, field peas drilled in early spring, roller crimped and strip-tilled in June before transplant, and amended with a "high" rate of soluble Chilean nitrate applied in July at 40 lbs N/acre
2) **RT LOW N:** Winter kill cover crop mulch left in place, field peas drilled in early spring, roller crimped and strip-tilled in June before transplant, and no supplemental fertilizer
3) **CT HIGH N:** Conventionally tilled (cover crop rototilled in early April, rototilled again in June before transplant and strip-tilled), with a "high" rate of soluble Chilean nitrate applied in July at 40 lbs N/acre
4**) CT LOW N:** Conventionally tilled (cover crop rototilled in in early April, rototilled again in June before transplant and strip-tilled) with no supplemental fertilizer
5) **CT KELP:** Conventionally tilled (cover crop rototilled in in early April, rototilled again in June before transplant and strip-tilled) with addition of 2,000 lbs/acre Sugar kelp meal, or 40 lbs/acre actual N, before June rototilling

Plot Tillage

Conventionally tilled (CT) plots were first tilled on April 9, 2021 using a 6-foot wide tractor mounted rototiller attachment to a depth of approximately four-inches. The CT plots were subsequently tilled using a tractor mounted rototiller to a depth of approximately four-inches on June 15, 2021 prior to all plots being strip-tilled and then hand-planted with butternut squash seedlings. All plots were tilled with an Unverferth ripper-stripper unit disturbing, but not inverting, an approximately 8-inch wide swath in the middle of each plot on June 14, 2021.

Kelp Analysis and Amendment

New York-grown Sugar Kelp (*Saccharina Latissima*) was sourced by GreenWave for processing into kelp meal. Kelp was dried and then milled to approximately 14 mesh before being transported to the research site. Representative samples of the processed kelp meal were sent to Waters Ag Labs (Warsaw, NC) for nutrient analyses conducted on June 3, 2021. The full analysis is presented in the table below. The researchers rounded the 2.23% nitrogen content to 2% for the purposes of calculating the amount of kelp meal to apply per plot. Based on the 2% nitrogen content, 6.89 pounds of kelp meal were broadcast in each of the four 150 sq ft CT KELP plots (approximately 2,000 pounds/acre) on June 15, 2021. The 2,000 pound/acre rate was calculated to provide an additional 40 pounds of nitrogen per acre, equivalent to the target rate of actual nitrogen provided by the supplemental Chilean nitrate in the CT High N treatment plots. The meal was then incorporated with the tractor mounted rototiller and evenly distributed in the top four inches of the soil profile prior to transplanting the butternut squash seedlings.

Table 1: Kelp meal nutrient analysis results

Analyte	Percent (%) (As-Is Basis)	Percent (%) (Dry Basis)	Pounds per Ton (As-Is Basis)
Nitrogen-Total	**2.23**	2.401	44.6
Nitrate Nitrogen	**0.16**	0.172	3.2
Ammonia Nitrogen	**0.05**	0.054	1
P2O5-Total	**0.48**	0.517	9.6
K2O-Total	**11.22**	12.083	224.4
Calcium	**2.25**	2.423	45
Magnesium	**0.74**	0.797	14.8
Sulfur	**0.90**	0.969	18
bron	**0.01**	0.011	0.2
Zinc	**0.01**	0.011	0.2
Manganese	**0.01**	0.011	0.2
Iron	**0.11**	0.118	2.2
Copper	**0.01**	0.011	0.2
Sodium	3.53	3.801	70.6
Aluminum	**0.03**	0.032	0.6

Field Establishment

'JWS 6823 PMR' butternut seedlings were hand transplanted into the trial plots on June 15, 2021 with two-feet of in-row spacing between transplants and six-feet between rows. A single line of drip irrigation was installed alongside each row of plants after transplanting and HVFH staff installed wire hoops and ProtekNet insect exclusion netting to prevent cucumber beetle damage to the crops.

Chilean Nitrate Analysis and Amendment

OMRI-listed sodium nitrate (Chilean nitrate) with a guaranteed analysis of 15-0-2 (15% nitrogen by mass, 0% phosphorous, and 2% potassium) was broadcast in the CT HIGH N plots at a rate of 0.98 pounds per 150 sq ft (approximately 285 pounds/acre) on July 14, 2021. The 285 pound/acre rate was calculated to provide an additional 40 pounds/acre of actual nitrogen to the CT HIGH N plots. The fertilizer was shallowly incorporated using stirrup hoes following application.

Soil Temperature and Moisture Monitoring

Soil temperature and soil moisture readings were taken at each of the 20 in-ground chambers prior to gas sampling beginning on April 27, 2021. Soil temperatures were measured using a six-inch digital soil thermometer. Soil moisture was evaluated using a FieldScout TDR 350 meter. Time domain reflectometry (TDR) sensors use eight-inch long parallel rods to transmit low voltage electrical pulses through the soil. The time that the voltage takes to be reflected back to the rods is used to approximate the total amount of soil pore space filled with water, or the volumetric water content percentage (VWC). Higher VWC readings are associated with wetter soils.

Gas Sampling

Modified five-gallon buckets with gaskets were installed as in-situ gas chamber bottoms on April 23. Chamber tops of a known volume were installed every other week through September and after major disturbance events such as plot tillage and fertilizer application. Gas samples were extracted from each of the closed chambers on four, ten-minute intervals (T=0 min, 10 min, 20 min, and 30 min) during each of the 17 sampling events. 20 ml syringes were used to extract samples that were then injected into 6 ml Exetainer® glass vials secured with standard screw-top caps and cholorbutyl septa. An additional needle was placed through the septa prior to the injection of the gas sample. The first 12 ml of sample was used to purge the vial contents through the second needle. The second needle was removed with 8 ml of gas sample remaining in the syringe, which was then injected into the 6 ml vial to slightly over-pressurize the container to avoid contamination. Chamber bottoms were removed on May 11 in anticipation of the field being roller crimped to terminate the cover crop and were re-installed on May 20, then removed again on June 15 for planting before being re-installed after planting 1-

hour prior to the June 15 sampling event. The full list of sampling event dates and weather conditions is available below (start time and environmental conditions information was not recorded for July 15; wind speed and ambient air temperature at 10:00 AM was later obtained from the weather station data generated at HVFH).

Table 2: GHG sampling event dates and environmental conditions

Sampling Event	**Date**	**Start Time**	**Ambient Air Start (ºF)**	**Ambient Air Finish (ºF)**	**Average wind speed (mph)**	**Relative Humidity (%)**
1	4/27/2021	10:46	54.4	63.7	2.4	17.2
2	5/11/2021	10:15	56.7	60.4	3	44.5
3	5/25/2021	9:45	63.8	67.7	2.8	66.2
4	6/7/2021	9:15	77.5	83.1	1.1	74.2
5	6/15/2021	12:10	72.8	74.6	1.2	58.1
6	6/16/2021	11:00	70.2	73.1	3.3	54.8
7	6/17/2021	10:00	66.4	68.2	0.7	69.9
8	6/30/2021	9:30	83	84.2	0	64.5
9	7/14/2021	10:00	77	78.4	0	94.9
10	7/14/2021	1:25	86.5	89.2	1.2	89.2
11	7/15/2021	X	75.9	X	1.5	X
12	7/16/2021	9:00	77	80.7	0.8	94.7
13	7/27/2021	9:45	75.1	77.5	0	80.8
14	8/11/2021	9:45	87.7	88.6	1.4	78.7
15	8/24/2021	10:15	88.4	92.5	2.2	66.4
16	9/8/2021	9:45	83.8	84.2	1.4	61.2
17	9/21/2021	11:30	83.5	88.5	1.5	78.4

Soil Nutrient and Health Analyses

Aggregate soil samples from each treatment collected across all four treatment plots were extracted using a heavy duty spiral auger soil sampler to a depth of 6-inches. Subsamples were submitted to Waters Ag Labs (Warsaw, NC) on May 3, July 20, August 2, and October 6 for Mehlic III nutrient analysis (Basic Test 4), available soil nitrate, and soil organic matter percentage (specific test protocols available by request from the lab). Additional soil subsamples from each treatment were submitted to Ward Labs (Kearney, NE) on May 3 and August 3 for Haney Soil Health Test analysis (protocol available at https://www.wardlab.com/wp-content/uploads/2019/09/Haney-Rev-1.0-Information.pdf). Individual plot soil samples (4 per treatment) were collected and submitted to Ward Labs for Haney Soil Health Testing on October 6 as well.

Plant Tissue Analyses

Tissue samples from the butternut squash crop in each plot (4 per treatment) were collected according to the protocol recommended by Waters Ag Labs (Warsaw, NC) on July 14 prior to the application of Chilean nitrate described above and again on July 27. Specific lab protocols for the basic plant tissue analysis are available by request from the lab.

Harvest Evaluation

All butternut squash from 10 row-feet per plot were harvested for evaluation on September 20, 2021. Each vine per plant was carefully inspected for squash fruit that were clipped with pruning shears and collected in harvest totes. Individual squash were then weighed and rated for marketability. Squash were classified as unmarketable if they were damaged by sun scald, showed vertebrate pest damage, showed insect feeding damage, were rotten, undersized, or immature (underdeveloped color). The weights of each marketable squash in every plot were added together in order to determine total marketable yields by plot.

Gas Chromatography

The 6 ml exetainer samples were incrementally delivered to The Cary Institute for Ecosystem Studies (Millbrook, NY) and stored at room temperature until they were analyzed by gas chromatography (GC). All GC analysis was conducted by Dr. Peter Groffman's lab manager Lisa Martel. Nitrous oxide, carbon dioxide and methane were analyzed on a Shimadzu GC-14 GC system for greenhouse gas analysis. This GC is equipped with an electron capture detector (N_2O), thermal conductivity detector (CO_2) and a flame ionization detector (CH_4). These detectors have a repeatability of <2% for standards of 600 ppm CO_2, 1 ppm N_2O and 5 ppm CH_4.

Flux Calculations

Fluxes were calculated from the linear rate of change in gas concentration, the chamber internal volume, and soil surface area. Flux rate calculations were corrected for actual in situ temperature, but pressure was assumed to be 1 Atmosphere for all flux calculations. Single points were removed from regressions if they were more than six times higher or lower than the other three values or if they contradicted a clear trend in the other three points. This procedure prevents inclusion of high flux rates based on non-significant regressions. Non-significant regressions were used in flux calculations to avoid biasing the statistical distribution of rates by setting all non-significant regressions to zero.

Nitrous oxide and methane fluxes were converted into carbon dioxide equivalents (CO_2eq). N_2O Flux rates were multiplied by a factor of 298 and CH_4 flux rates were multiplied by 84 to reflect their differing global warming potentials (https://climatechangeconnection.org/emissions/co2-equivalents/). In order for total growing season GHG fluxes to be calculated, rates must be assigned to non-sampled days. This was accomplished by applying the average rates of sampling days that bracket any non-sampled days, and applying it to all non-sampled days in that date range.

Statistics

Unless otherwise noted, all data was analyzed using a generalized linear model in JMP 15.1.0 Pro Software (SAS Institute Inc, Cary, NC) with tillage, fertility, the interaction term (tillage*fertility), and date when applicable as fixed effects with replicate as a random effect. Statistical significance and connecting letter reports were generated following a post-hoc Tukey's Honestly Significant Difference (HSD) test at p= 0.05 to account for multiple means comparisons and a post-hoc Student's t-test at p=0.05 for comparisons of two means.

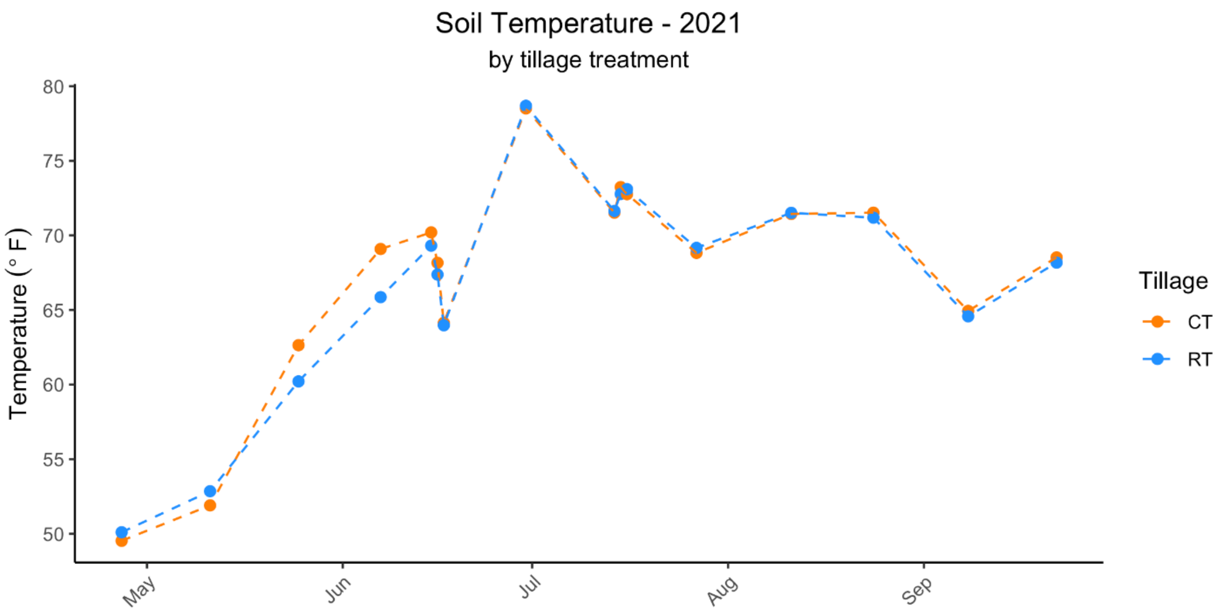
IV. Results

Kelp Treatment

The primary statistically significant effect of adding kelp meal as a nitrogen source and soil amendment was that it increased the amount of soil available potassium (p=0.0345) when compared to the two other conventional tillage treatments. For this reason, the CT Kelp treatment will not be considered in the remaining sections. There is, however, a full report describing the differences between the three conventional tillage treatments (CT Kelp, CT High N, and CT Low N) available here.

Soil Temperature

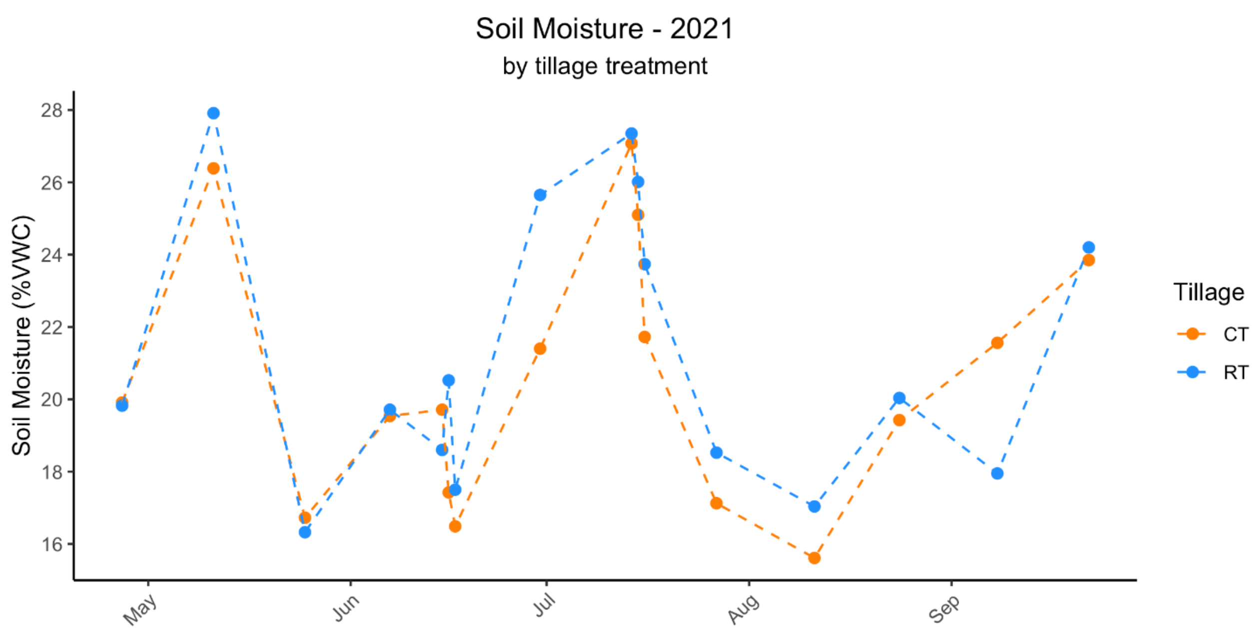
The tillage treatment had a significant impact on the mean soil temperature over the trial period (April 27 through September 22). The conventional tillage plots were warmer on average (67.29 ^{o}F) compared to the reduced tillage plots (66.92 ^{o}F) at p=0.0003. As can be seen in the line graph below, the difference in temperature between the CT and RT plots was greatest during the period from mid-May to mid-June; average soil temperatures were comparable for the two tillage treatments for the rest of the season.



Graph produced by Owen O'Connor, Tributary Data LLC

Soil Moisture

The tillage treatment also had a significant impact on the mean soil moisture over the course of the season (April 27-September 22). The reduced tillage plots maintained a higher average soil moisture in %VWC compared to the conventional tillage plots at p=0.0151.



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Soil Analyses

There were few statistically significant differences in soil nutrient levels, soil biological activity, soil health calculations, and other soil chemical characteristics revealed in the results from the Haney Soil Health testing and Mehlic III analyses. There was a significant effect of the fertility treatment on both H3A nitrate-nitrogen availability and the ratio of Organic Nitrogen : Inorganic Nitrogen from the Haney tests conducted post-harvest in October. The plots that received supplemental Chilean nitrate (RT High N and CT High N) had more available nitrate-nitrogen on average compared to the plots that received no additional nitrogen fertilizer (RT Low N and CT Low N) at p=0.0148. The unfertilized plots also had a higher Organic N : Inorganic N ratio when compared to the high nitrogen plots at p=0.276. Additionally, there was a significant interaction between tillage and fertility treatments on the average amount of potassium available in the soil over the season as measured with the Mehlic III tests; the CT High N plots had a higher average level of soil available potassium (461.00 lbs/acre) compared to the RT Low N plots (363.75 lbs/acre) and the RT High N plots (350.25 lbs/acre) at p=0.0306. All of the soil potassium levels reported were in the excessive range.

Foliar Nutrient Analyses

Similar to the soil analyses described above, there were few significant differences in the concentration of nutrients in the squash foliar samples that were analyzed by Waters Ag Labs in July. There was a significant effect of tillage treatment on the foliar concentrations of manganese (Mn) and iron (Fe); the squash plants in the conventional tillage plots averaged a higher level of Mn (103.31 ppm) and iron (1299.63 ppm) compared to the plants in the reduced tillage plots (87.56 ppm and 653.31 ppm, respectively) at p=0.0310 and p=0.0005. There was also a significant interaction between the tillage and fertility treatments on the zinc (Zn) foliar concentration; the plants in the CT High N plots had a higher concentration of Zn on average (59.38 ppm) than the plants in the RT High N plots (49.25 ppm) at p=0.0299.

Marketable Yield

There was no statistically significant treatment effect on the average marketable squash yield observed in this trial. There was, however, a slight numeric trend toward higher yield in the conventional tillage plots 43.07 lbs/10 row feet) compared to the reduced tillage plots (36.61 lbs/10 row feet).

GHG Flux During the June Pre-Plant Tillage Event

In 2020, the conventionally tilled plots released significantly more CO_2 and N_2O than the reduced tillage plots during the disturbance period immediately following pre-plant tillage. However, the opposite results were observed in 2021 following the rototilling of the CT plots and the strip tillage of both the CT and RT plots in mid-June. The RT plots had a CO_2 flux that was 1.59 times higher than the CT plots (p=0.00193) and N_2O flux in CO_2eq that was 5.5 times higher (p=0.0004) for the period from June 15-17, 2021. Methane flux was negligible across all treatments during the period.

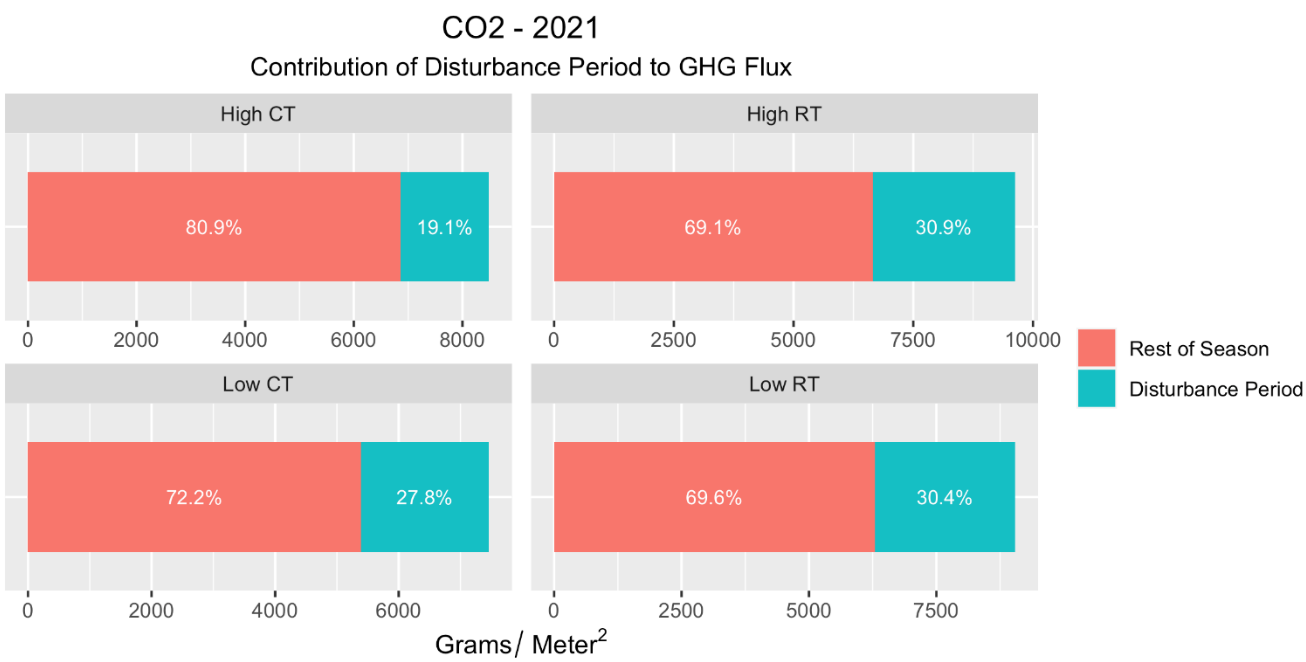
Pre-Plant Tillage (June 15-17) Greenhouse Gas Flux Calculations

	Mean Daily CO2 Flux (g/m2)[y]	Mean Daily N2O Flux in CO2eq (g/m2) [z]	Mean Daily Combined GHG Flux in CO2eq (g/m2)
Conventional Tillage (CT)	25.034 A	2.471 A	27.506 A
Reduced Tillage (RT)	39.709 B	13.606 B	53.308 B
p-value	0.00193	0.0004	0.0005

[y] Numbers within each column followed by the same letter are not significantly different from each other based on Student's t at $p = 0.05$

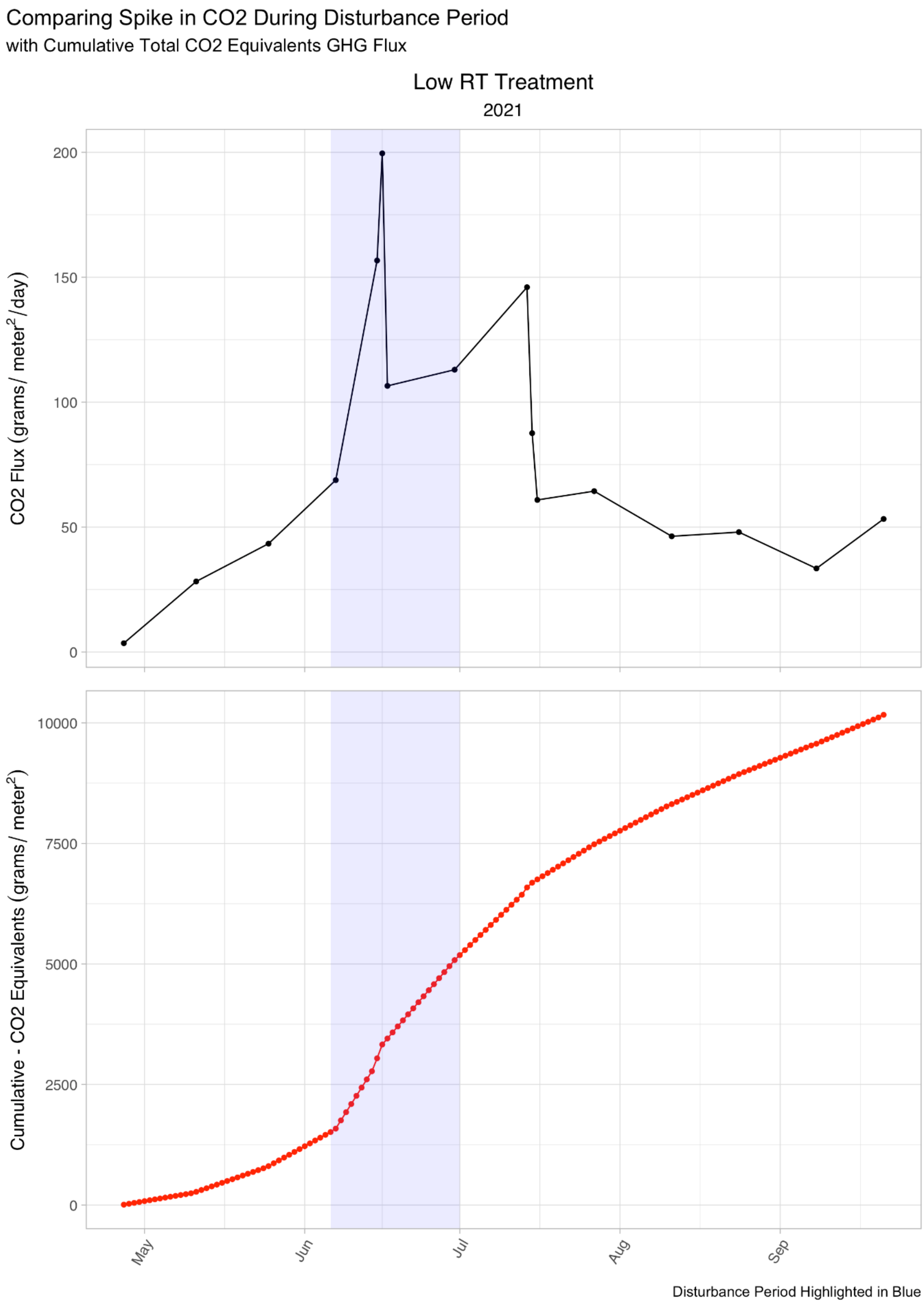
[z] Nitrous oxide data is non-normal; means were log transformed for analysis, but untransformed means are presented in the tables

As can be seen in the graph below, the CO_2 flux during the three-day period was higher than average across all treatment plots; however, the flux during the pre-plant tillage disturbance period was proportionally higher compared to the season total in the RT plots (30.9% and 30.4% of total) compared to the CT plots (19.1% and 27.8% of total).



Graph produced by Owen O'Connor, Tributary Data LLC

A more detailed visualization of the spike in CO_2 flux in the RT Low N treatment plots is displayed in the graph below. The steepness of the curve in the cumulative contribution to season-long CO_2 flux represented in the graph specific to the RT Low N treatments is similar to that graphed for the other trial treatments.



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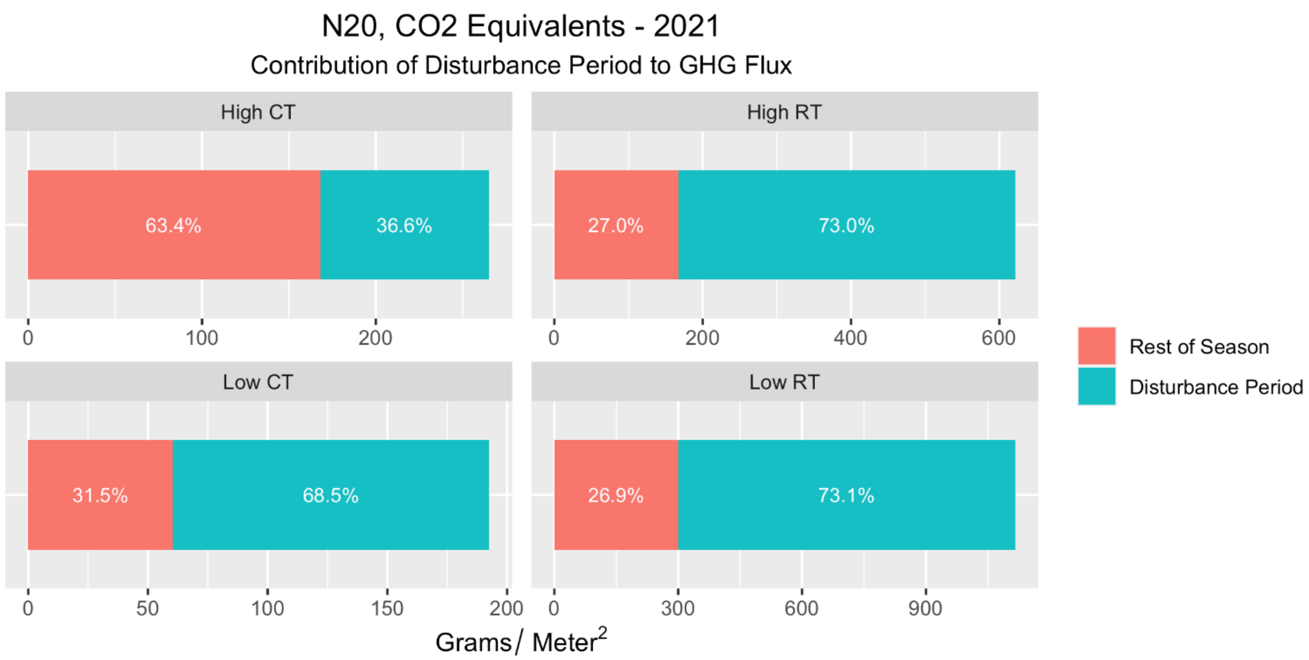
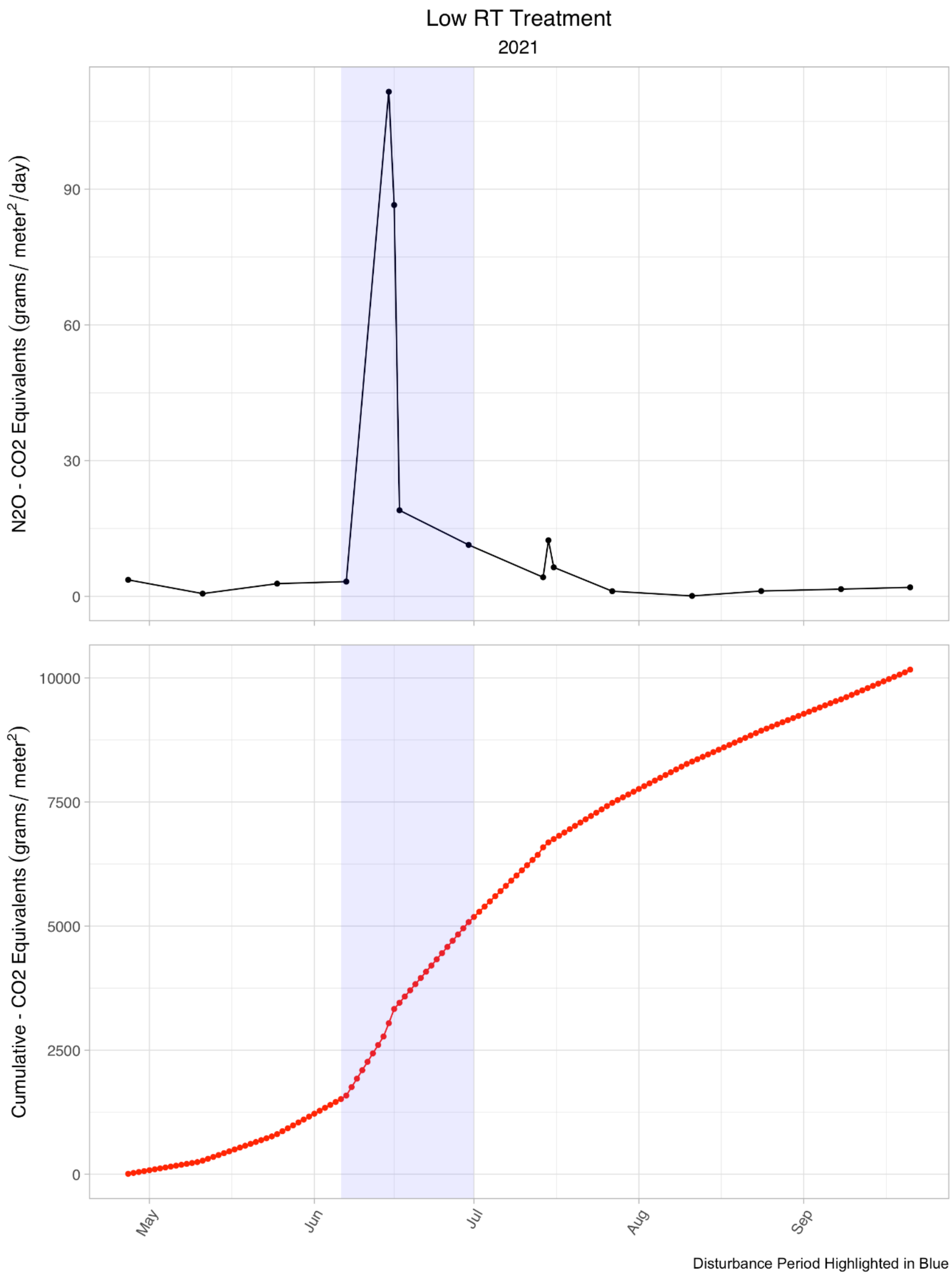
The portion of the season total nitrous oxide flux in CO_2eq was even more greatly elevated during the pre-plant tillage disturbance period compared to CO_2. 73% of the total season N_2O flux occurred during the disturbance period in the RT plots, whereas the N_2O flux during the same period represented just 36.6% of the season total in the CT High N plots and 68.5% of the season total in the CT Low N plots.



Graph produced by Owen O'Connor, Tributary Data LLC

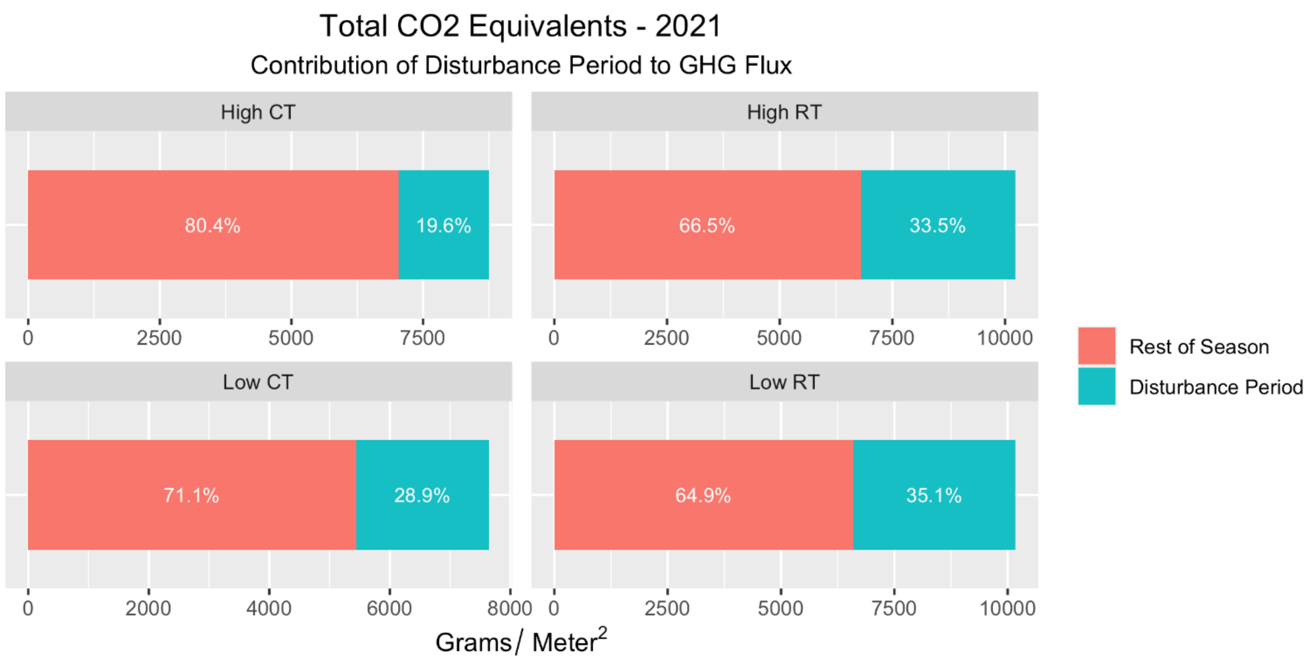
Again, a more detailed visualization of N_2O flux over the sampling season for the RT Low N plots is provided below. The spike in N_2O flux in CO_2eq is more extreme than that observed for CO_2 above, but also reverts to average levels compared to the flux trends for CO_2. While the relative flux of N_2O in the RT plots during the pre-transplant tillage disturbance period was significantly higher than in the CT plots, the spikes in N_2O flux were similar across all treatments. The slope of the curve at the mid-June point in the second graph displaying the cumulative season flux was also similar across all treatments, indicating a much higher than average rate of release of N_2O during that period than at other points in the season.

Comparing Spike in N2O During Disturbance Period
with Cumulative CO2 Equivalents GHG Flux



Graph produced by Owen O'Connor, Tributary Data LLC

The total GHG flux (CO_2, N_2O, and CH_4 combined) in CO_2eq during the period again showed the disproportionately high flux rates compared to the rest of the season. Though the three-day period represented just over 2% of the duration of the season during which flux data was gathered, the total GHG flux for the disturbance period represented over 33% of the season total flux in the RT treatments.



Graph produced by Owen O'Connor, Tributary Data LLC

Season-Long Mean Greenhouse Gas Flux

There was also a significant effect of tillage treatment on the mean daily CO_2, N_2O, and total GHG flux in CO_2eq when averaged over the entire duration of the sampling season (April 27-September 22). Mean daily CO_2 flux in the reduced tillage plots was 1.22 times higher than in the conventional tillage plots (p=0.0276) and N_2O flux in CO_2eq was 4.47 times higher in the reduced tillage plots (p=0.00033) over the duration of the season. As was the case during the disturbance period described above, CH_4 flux rates were negligible over the season.

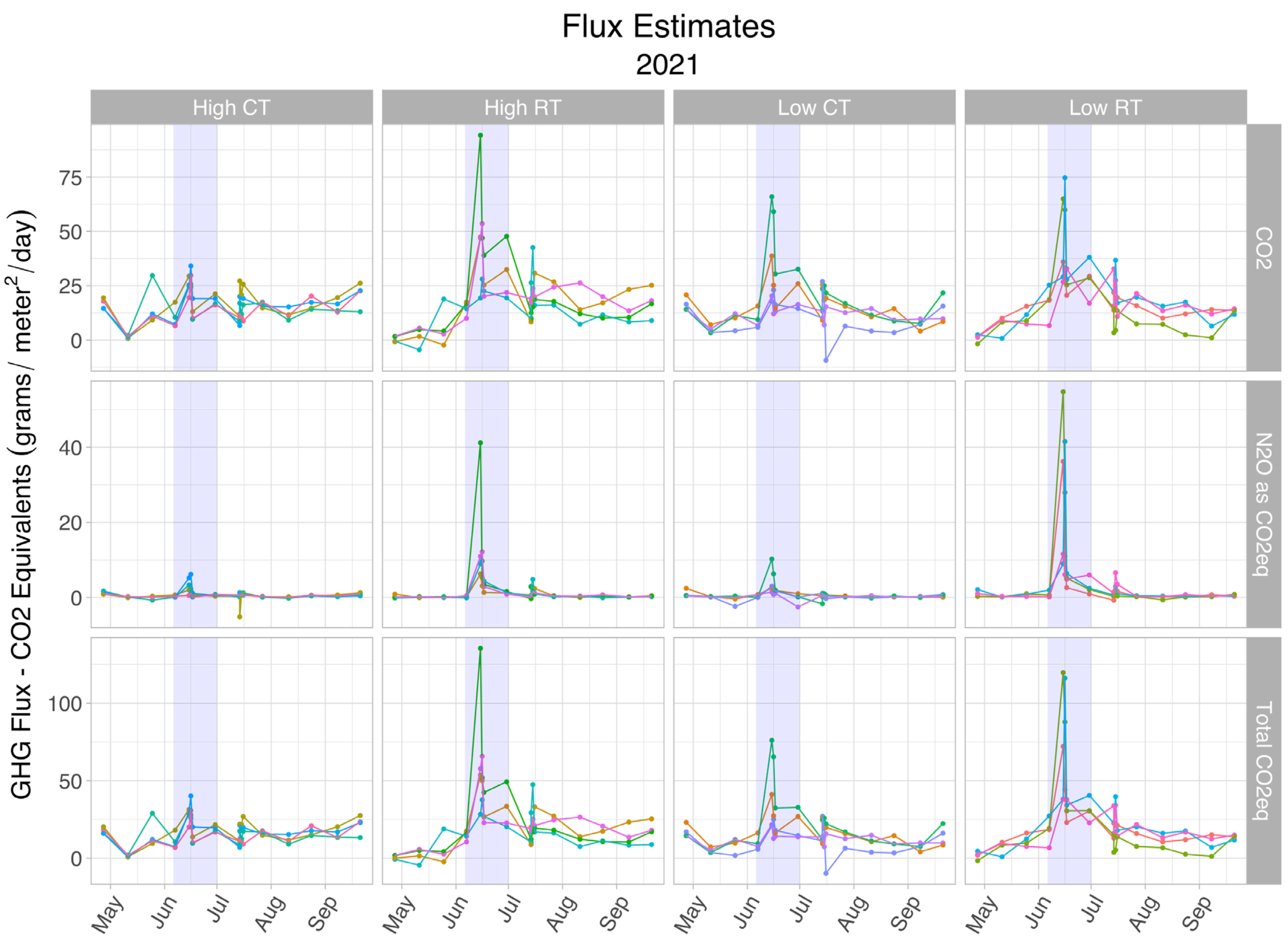
Season Long Mean Greenhouse Gas Flux Calculations

	Mean Daily CO2 Flux (g/m2)[y]	Mean Daily N2O Flux in CO2eq (g/m2) [z]	Mean Daily Combined GHG Flux in CO2eq (g/m2)
Conventional Tillage (CT)	15.678 A	0.683 A	16.355 A
Reduced Tillage (RT)	19.089 B	3.053 B	22.125 B
p-value	0.0276	0.00033	0.0057

[y] Numbers within each column followed by the same letter are not significantly different from each other based on Student's t at p = 0.05

[z] Nitrous oxide data is non-normal; means were logistic transformed for analysis, but untransformed means are presented in the tables

Of course, the season long daily flux means are greatly influenced by the spikes in CO_2 and N_2O flux rates during the pre-transplant tillage disturbance period. The graphs below display the season-long flux rates for CO_2, N_2O, and total GHG flux in CO_2eq of each individual chamber clustered by treatment. The spikes in flux rate during the disturbance period are evident in the four vertical shaded portions, one for each treatment. The more substantial increases in flux rates, especially for N_2O, in the RT plots compared to the CT plots during the disturbance period are especially pronounced in this visualization.

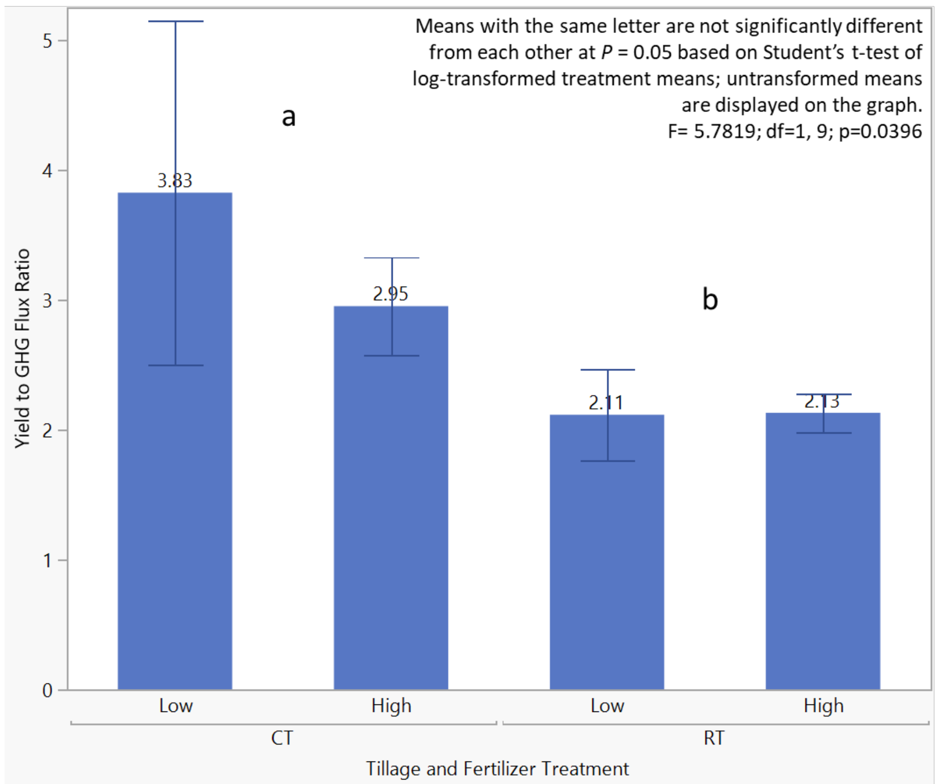


Graph produced by Owen O'Connor, Tributary Data LLC

When the flux totals from the three-day period from June 15 to June 17 are excluded from the calculation of season long daily flux means, the analyses shift slightly. There is no longer a significant difference in CO_2 flux means across all treatments when excluding the disturbance period, but the significant effect of tillage on N_2O flux remains. N_2O flux rates in the reduced tillage plots were still 2.65 times higher than flux rates in the conventional tillage plots on average over the sampling season excluding the disturbance period ($p=0.00030$).

Crop Yield to GHG Flux Ratio

The measure of how efficiently each treatment was able to convert total GHG flux in CO_2eq to squash yield is approximated by calculating the yield to flux ratio. In 2020, the conventional tillage plots produced higher ratios, mostly due to the much higher yield achieved in those plots compared to the reduced tillage plots. In 2021, there was again a statistically significant effect of tillage treatment on the yield to flux ratio despite no significant differences in crop yield across the treatments. The mean yield to flux ratio in the conventional tillage plots was 1.48 times higher than the mean ratio in the reduced tillage plots (p=0.0396).



V. Discussion

Given the breadth of data results presented in the section above, the discussion narrative will attempt to generate answers to the four primary research questions that informed the trial design in 2021 and that were shared in the 'Background' section of the report. Each question will be considered in turn below.

1. *What effect would strip-tilling all of the plots have on GHG flux and yield? Can minimum tillage from strip-tilling preserve the benefit of reducing GHG flux compared to full conventional tillage while also improving the yield in reduced tillage plots?*

The simplest portion of this research question to address is that of the impact of strip tillage on squash yield. Though there were other changes to the production system between 2020 and 2021 (cover crop mixes, winter squash variety, environmental conditions, etc.), the primary change to the RT treatments was the transition away from no tillage to minimal strip tillage. Seemingly as a result, the average squash yield in the RT plots increased sufficiently for there to be no statistically significant difference in the yield between the RT and CT treatment plots in 2021.

However, the increase in crop yield came at the expense of higher rates of GHG flux (especially N_2O) in the RT treatments. In 2021, strip-tilling the RT plots eliminated the benefit of lowering GHG flux rates in the reduced tillage treatments that had been observed in 2020. New research from Debasish Saha, Armen Kemanian, and others at Penn State University may help partially explain why strip-tillage produced such a high N_2O flux rate in the RT plots. Saha et al have found that the act of terminating and incorporating legume cover crops in long-term corn-soy rotations has led to large spikes in the release of N_2O. The hypothesis that the research team has developed to explain the phenomenon revolves around the activation of microbial activity that is triggered by the incorporation of easily accessible carbon that also serves as a rich nitrogen source for microbes. After the crop residue is incorporated (by moldboard plowing in the PSU research, but by strip tillage at HVFH), soil microbes quickly begin to feed on the cover crop. The burst of activity can quickly deplete microbially-available oxygen (O_2) and create anoxic conditions. N_2O release is favored by these low oxygen environments, which can be exacerbated by higher soil moisture content that is often observed in RT environments and was documented in the trial field in 2021 at the time of strip-tillage (Saha et al, 2021).

The decision to seed field peas in the spring into the residue of the winter-killed cover crop mix from 2020 was intended to improve nitrogen availability to the squash crop with the hope of increasing yield. The strategy is commonly employed by organic farmers using both CT and RT production systems. However, the 2021 research findings suggest that the high nitrogen legume cover crop combined with strip-tillage produced the unintentional effect of significantly increasing GHG flux. On-going research from Dr. Kemanian at Penn State University suggests that growers may be able to mix higher rates of grasses into legume cover crop mixes in order to mitigate the increase in N_2O described above. However, this strategy also comes at the expense of reducing the amount of nitrogen that is available for plant-uptake during the squash growing season. It is possible that strip-tilling RT plots may be able to improve crop yield without significantly increasing GHG flux rates if the cover crop mix that is terminated in place in the RT plots includes more grasses in addition to legumes; however, more research is required to better understand the mitigation potential, ideal ratios and species of grasses to mix with field peas, and implication for nitrogen availability to the cash crop.

2. *If there are significant differences in yield between tillage and fertility treatments, are there also significant differences in soil nutrient availability, nutrient uptake and tissue concentration, or other soil biological and physical characteristics that may explain the treatment effects on yield?*

Unlike the results in 2020, there was no significant difference in crop yield measured in 2021 across the different tillage and fertility treatments. Few differences in soil nutrient availability and uptake were observed in 2021, possibly resulting from the decision to move away from a no-till system to a minimal disturbance strip-tillage system in the RT plots.

3. *What impact might changing the source of supplemental nitrogen in conventionally tilled plots from Chilean nitrate to kelp meal have on GHG flux, yield, and the other soil chemical and biological characteristics?*

As was discussed in the 'Kelp Treatment' section of the results, there were no significant differences in GHG flux rates, yield, or most soil chemical and biological characteristics between the kelp amended plots, the Chilean nitrate amended plots, and the conventional tillage plots that received no additional fertilizer. In both 2020 and 2021, the addition of 40 lbs/acre of actual nitrogen as sodium nitrate in July has not resulted in a significant impact on GHG flux despite the risk of contributing to higher N_2O flux rates. It is possible that this trial has not captured any relationship between nitrogen fertilizer rates, sources, and GHG flux since field conditions have been drier than average at the time of fertilization in both trial years. As was discussed above, higher N_2O flux rates are correlated with lower soil O_2 levels that can result after heavy precipitation.

4. *What combination of tillage and fertility treatments is most efficient at generating crop yield per unit of GHG flux in CO_2-equivalents?*

The metric used to evaluate the efficiency of generating crop yield per unit of GHG flux that the researchers have adopted is the yield to flux ratio. In 2020, the two CT treatments had higher yield to flux ratios than the two RT treatments despite lower mean GHG flux rates in the RT plots. The higher ratios for the CT treatments in 2020 was almost exclusively the result of significantly higher yields in the CT plots compared to the RT plots.

The yield to flux ratios were again significantly higher in the CT plots than in the RT plots in 2021. However, instead of differences in yield being the primary driver of that difference in yield to flux ratio, the ratio in the RT plots suffered due to the significant increase in GHG flux that was already described above. Though the fertility treatments did not have a significant impact on either flux rates or yield to flux ratios in 2021, it is noteworthy that the CT Low N treatment had the highest numeric yield to flux ratio in both 2020 and 2021. While there is an abundance of research to support the use of nitrogen fertilizer to increase crop yield, even in organic production systems (see, for example Ogles et al, 2015 and Luna et al 2020), the results from two years of trials at HVFH have not shown a clear yield benefit to the addition of 40 lbs/acre of actual nitrogen as either sugar kelp meal or sodium nitrate. More research is required to better understand the potential impacts of different nitrogen fertilizer rates and sources on crop yield and GHG flux, but the results from this trial indicate that there is potential to reduce fertilizer application rates at HVFH without sacrificing winter squash yield.

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VI. 2022 Planned Research

There are three minor changes anticipated to the 2022 research trial design:

1. Cover crop mix: The trial will be planted in a field seeded with winter rye in October 2021, similar to the system that was evaluated in 2020.
2. Pre-transplant tillage: None of the plots will be strip-tilled in 2022. CT plots will be rototilled in the early spring to terminate the winter rye cover crop and again before transplanting squash in June. However, the RT plots will not receive any pre-transplant tillage like in 2020.
3. Kelp treatment: There are no plans to include a kelp-amended treatment in the 2022 research trial.

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