Cornell Cooperative Extension
Eastern NY Commercial Horticulture Program
Cary Institute of Ecosystem Studies

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

---

2020 Annual Report

Ethan Grundberg, Lisa Martel, Sarah Tobin, and Erik Schellenberg

June 29, 2021

I. 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. 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) in 2020, Cornell Cooperative Extension Eastern New York Commercial Horticulture (ENYCHP) regional vegetable specialist Ethan Grundberg along with Cornell Cooperative Extension Orange County Natural Resources Educator Erik Schellenberg initiated a three-year trial designed to compare the greenhouse gas (GHG) flux from four different combinations of tillage and fertilizer application rate in winter squash fields located at HVFH. The 2020 trial was designed to generate data to help answer the following research questions:

1. What impact, if any, does reducing tillage have on total GHG flux and squash yield compared to using conventional tillage in an organic production system?
2. What impact, if any, does reducing nitrogen fertilization rates have on total GHG flux and squash yield compared to using a standard sidedress application of 40 pounds per acre of nitrogen as Chilean nitrate in an organic production system?
3. Is there any significant interaction between the tillage effect and the nitrogen fertilizer effect on total GHG flux and squash yield?
4. Are there significant differences in measured soil temperature and soil moisture between the tillage and fertilizer rate treatment plots?

The 2020 trial results used to help answer these questions will be discussed in the following sections.

II. Methods

Trial Design

The researchers used a randomized complete block design with four replicates and four treatments for this trial. Each treatment plot was 6 feet wide by 30 feet long and consisted of one row of transplanted 'Waltham' butternut squash. Each replicate consisted of four plots, one for each of the four treatments included in the trial. The four treatments included in 2020 were:

1) **RT HIGH N**: Roller crimp terminated winter rye with a "high" rate of soluble Chilean nitrate
2) **RT LOW N**: Roller crimp terminated winter rye with a "low" rate of soluble Chilean nitrate
3) **CT HIGH N**: Conventionally tilled (winter rye cover crop tilled in in early May, disced, harrowed, then maintained bare) with a "high" rate of soluble Chilean nitrate
4) **CT LOW N**: Conventionally tilled (winter rye cover crop tilled in in early May, disced, harrowed, then maintained bare) with a "low" rate of soluble Chilean nitrate

Plot Tillage and Roller Crimping

Conventionally tilled (CT) plots were first tilled on March 10, 2020 using a six-foot offset disc harrow attached to a tractor drawbar in order to prevent the densely seeded winter rye (approximately 180 pounds/acre) from establishing in those plots.

The result of the first primary tillage pass with a disc harrow on 3/10/2020

The CT plots were subsequently tilled using a BCS walk-behind tractor rototiller attachment to a depth of approximately three-inches on June 10, 2020 prior to transplanting the butternut squash.

The winter rye was allowed to continue to grow in the reduced tillage (RT) plots until pollen shed. HVFH used a tractor-mounted roller crimper to terminate the rye cover crop on June 5, 2020 and again on June 10, 2020 to improve the kill rate of the grass.

Field Establishment

'Waltham' butternut seedlings were hand transplanted into the plots on June 12, 2020 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.

Soil Temperature and Moisture Monitoring

Soil temperature and soil moisture readings were taken at each of the 16 in-ground chambers prior to gas sampling beginning on June 30, 2020. 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 in-ground gas chamber bottoms on May 12, 2020. Chamber tops of a known volume were installed every other week through October and after major disruption 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 18 sampling events. 20 ml syringes were used to extract samples that were then injected into 10 ml vials with crimped septa. An additional needle was placed through the vial septa prior to the injection of the gas sample. The first 8 ml of sample was used to purge the vial contents through the second needle. The second needle was removed with 12 ml of gas sample remaining in the syringe, which was then injected into the 10 ml vial to slightly over-pressurize the container to avoid contamination.

Chamber bottoms were removed on May 27 in anticipation of the field being roller crimped to terminate the rye cover crop and were re-installed on June 11 one-hour prior to gas sampling. Chambers were also removed on October 8 after a morning gas sampling to allow for post-harvest fall tillage. The chambers were reinstalled late morning on October 8 and gas samples were collected again that afternoon and following morning. The full list of sampling event dates and weather conditions is available below.

Date	Start Time	Ambient Air Start	Ambient Air Finish	RH %	Disruption Event Notes
5/12/2020	10:20	50	54	45	
5/27/2020	10:20	79	81	70	Chambers removed in prep for roller crimper
6/11/2020	3:05	88	87	50	Rye roller crimped 6/5 and again 6/10. CT plots rototilled 6/10
6/12/2020	9:30	75	79	62	Squash hand transplanted 6/12 after gas sampling
6/16/2020	11:00	76	79	53	
6/30/2020	9:30	67	69	96	
7/13/2020	10:00	80	87	62	Hand weeding in conventional till plots 7.6.2020 1.5 hours
7/21/2020	11:40	92	95.5	61.9	Weeded. Applied N and disrupted soil in chambers
7/22/2020	9:10	78.6	82.5	60.7	
7/23/2020	9:00	78.4	83	71.4	
8/6/2020	9:15	71.2	71.8	67.1	
8/20/2020	9:15	71.1	65.6	65.2	
9/4/2020	10:20	72.1	80.1	89.1	
9/17/2020	9:30	57.8	73.91	87.7	
10/1/2020	10:00	64.9	70.2	78.4	
10/8/2020	9:30	56.1	60.2	59	Removed chambers. Field disced.
10/8/2020	2:50	60.1	59.5	49.2	Chambers reinstalled 1130 am after disced twice
10/9/2020	9:20	49.9	58.6	85.5	

Harvest Evaluation

All butternut squash from 10 row-feet per plot were harvested for evaluation on September 21, 2020. Each vine per plant was carefully inspected for squash 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, were undersized, or were 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

Gas from the 10 ml sample vials was transferred to lab evacuated 6 ml exetainers on January 26, 2021 to accommodate the specifications of the chromatograph housed in Dr. Peter Groffman's lab at The Cary Institute for Ecosystem Studies. The 6 ml exetainer samples were delivered to The Cary Institute on February 23, 2021 and stored at room temperature until they were analyzed in batches from February 23 through March 23, 2021 by gas chromatography (GC) operated by Dr. 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

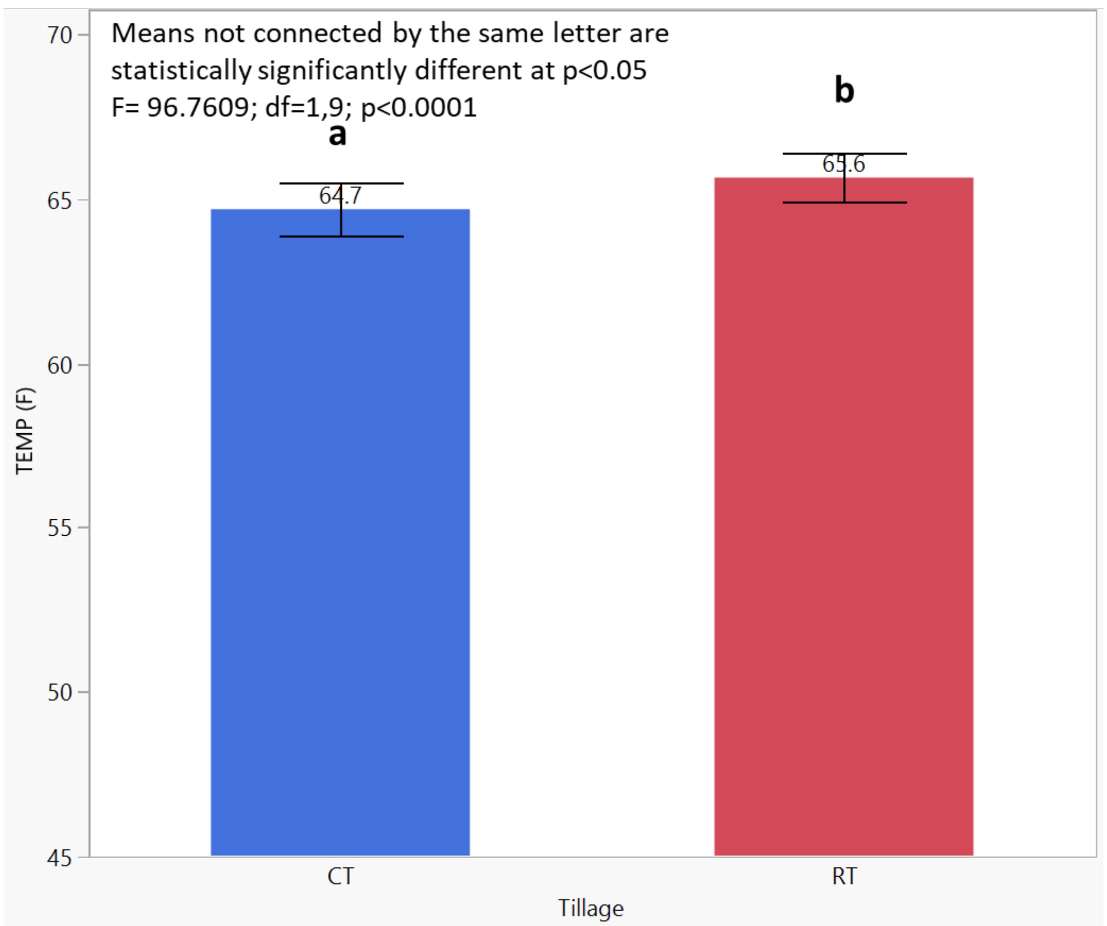
Fluxes were calculated from the linear rate of change in gas concentration, the chamber internal volume and soil surface area. Flux rate calculations were corrected for actual in situ temperature, but pressure was assumed to be 1 Atmosphere for all flux calculations. Single points were removed from regressions 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. 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.

III. Results

Soil Temperature

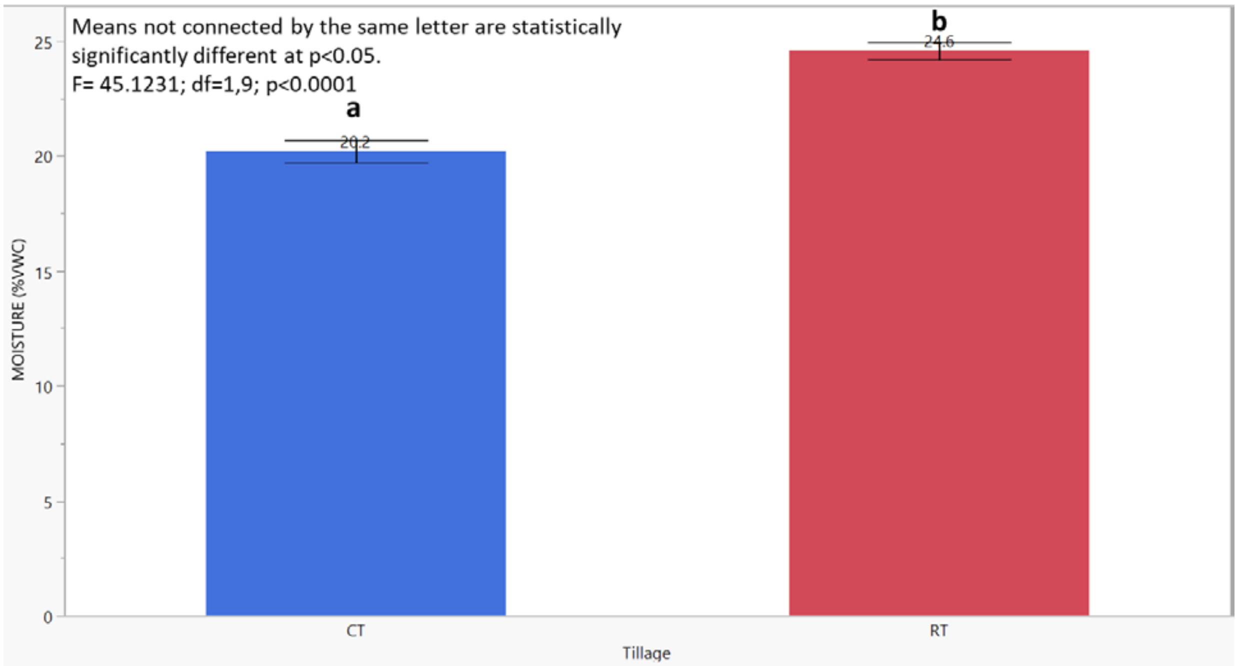
The response variable of season long mean soil temperature at a depth of 6-inches was analyzed using a generalized linear model where fertilizer rate, tillage, and the interaction term of fertilizer and tillage (fertilizer rate * tillage) were fixed effects. Both the replicate and the chamber nested in the replicate (chamber[rep]) were assigned as random variables in the statistical model. Only the tillage treatment was found to have a statistically significant effect on mean soil temperature in this trial at the 95% confidence interval ($p<0.001$). The reduced tillage plots in this trial had a higher mean season long soil temperature at 65.63 °F than the mean soil temperature in the conventionally tilled plots at 64.68 °F. The results will be discussed in more detail below in the “Discussion” section.



2020 season mean soil temperature by tillage treatment

Soil Moisture

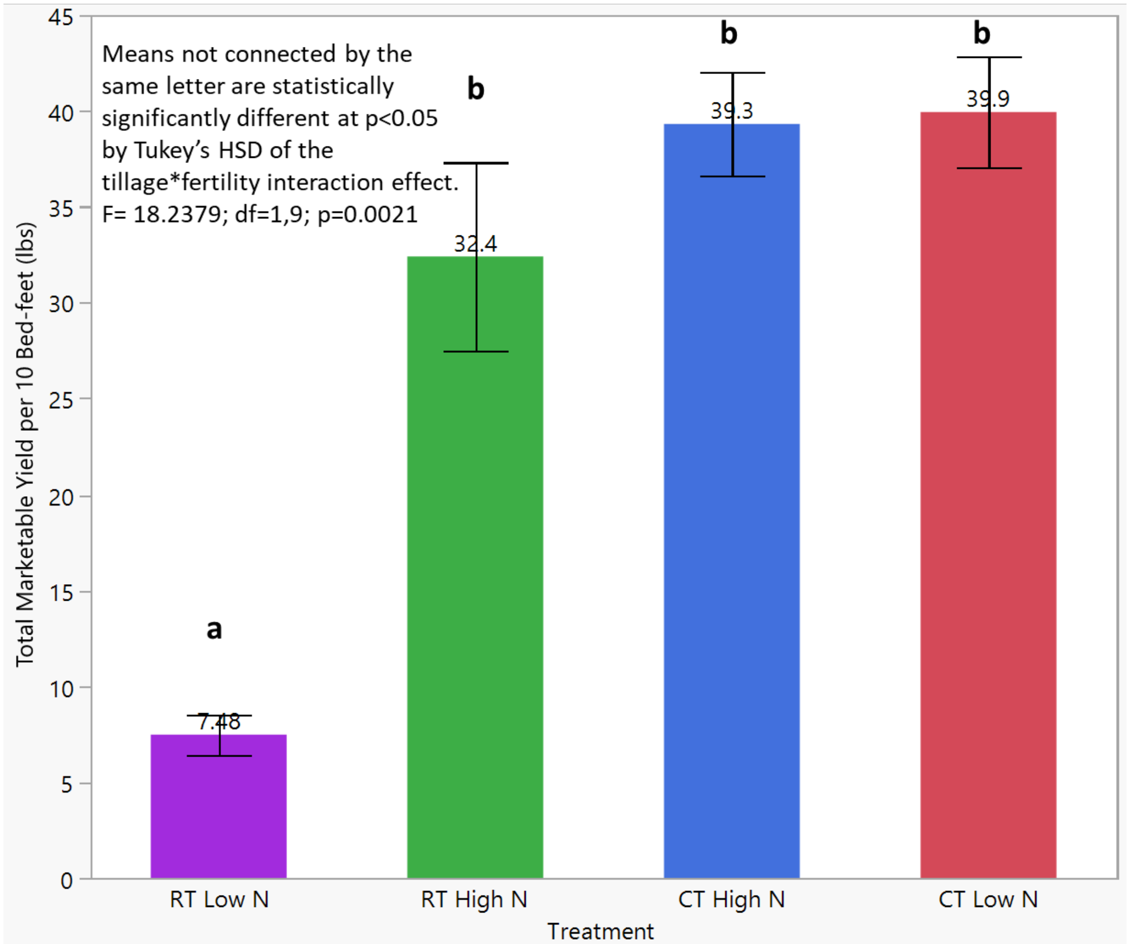
Using the same statistical model described above for soil temperature, the season long mean soil moisture (measured as a percent of volumetric water content) was found to be statistically significantly different by tillage treatment (p=0.00009), but not fertilizer rate or the interaction between fertilizer and tillage treatment. The reduced tillage plots maintained a higher season average soil moisture at 24.6% (VWC) compared to 20.2% (VWC) in the conventionally tilled plots.



2020 Season Mean Soil Moisture by Tillage Treatment

Marketable Yield

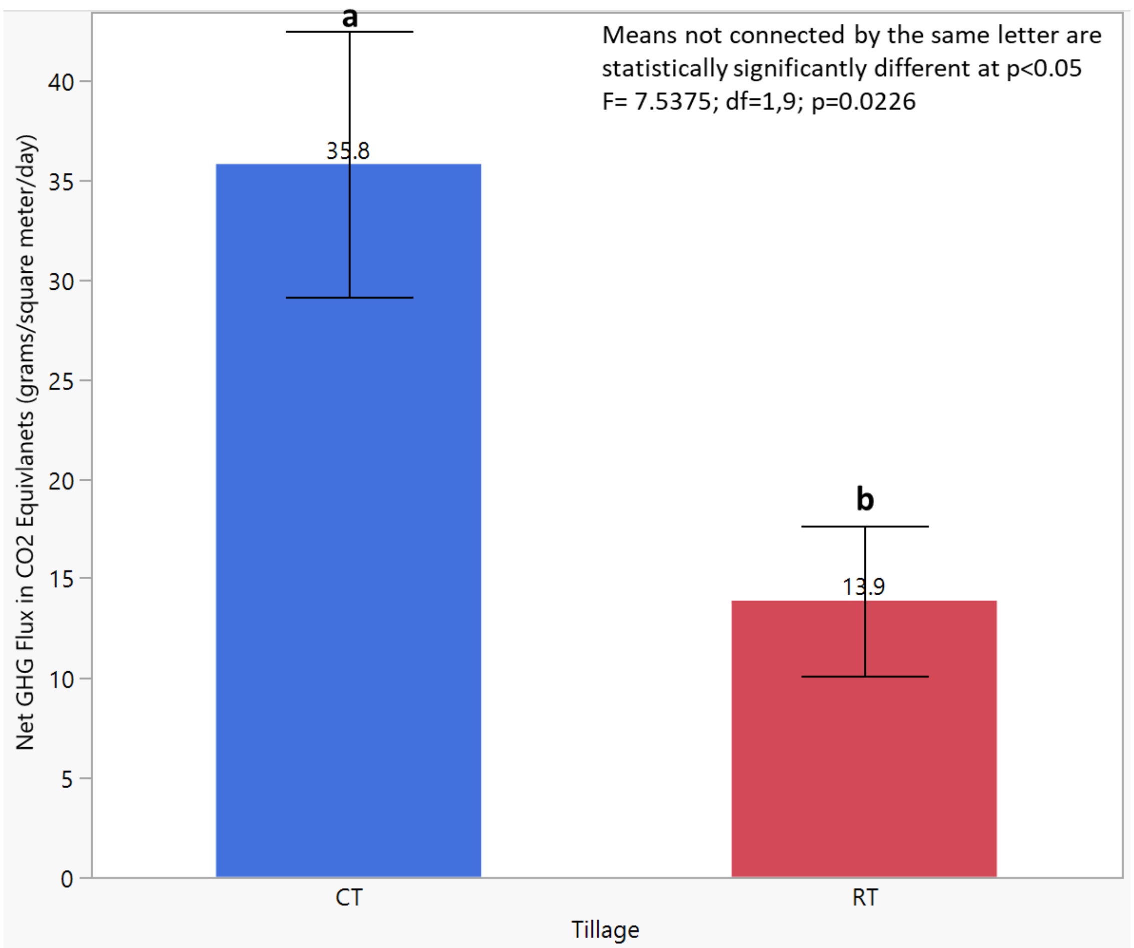
The marketable yield per 10 bed feet per plot was analyzed using a similar statistical model to those described in the previous two sections, but without the chamber nested in the replicate included as a random variable. There was a significant effect of the interaction term between fertility and tillage (fertility*treatment) on marketable yield in this trial (p=0.0021), so the significant effects of tillage and fertility will not be presented individually. After a Tukey-Kramer HSD post-hoc analysis, it was found that the reduced tillage-low nitrogen treatment had significantly lower yield than the other three treatments (reduced tillage-high nitrogen, conventional tillage-low nitrogen, and conventional tillage-high nitrogen). The average marketable yield in pounds per 10 bed feet is presented by treatment in the graph below. Yield in the RT-LOW N plots was just 7.48 lbs/10 feet compared to 32.4 lbs in the RT-HIGH N plots and nearly 40 lbs in the plots belonging to the two CT treatments.



2020 marketable squash yield per 10 bed feet

Greenhouse Gas Flux During June Pre-Plant Tillage Event

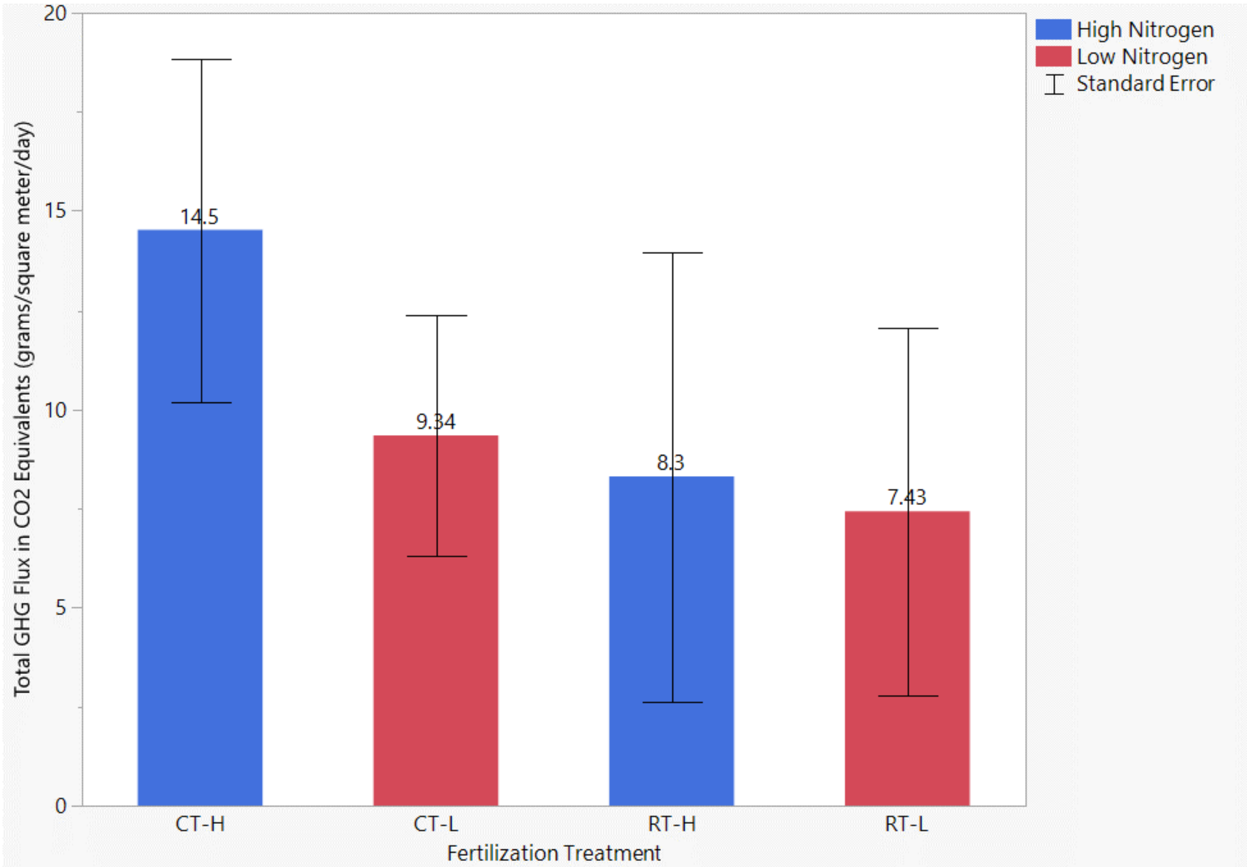
Following the rototiller pass in the conventional tillage plots on June 10, 2020, gas samples were collected on June 11 and June 12. The total GHG flux in CO_2 equivalents was calculated using the methods described above just for the period of June 11-12 to assess the impact of the tillage event on total seasonal GHG flux. Using the same statistical model described in the "marketable yield" section above, it was found that there was a statistically significant effect of tillage on net GHG flux in CO_2 equivalents (p=0.02264), but not fertilization or the interaction of tillage and fertilization.



Net GHG flux in CO2 equivalents for the June 10-12 tillage event

Greenhouse Gas Flux During July Chilean Nitrate Application Event

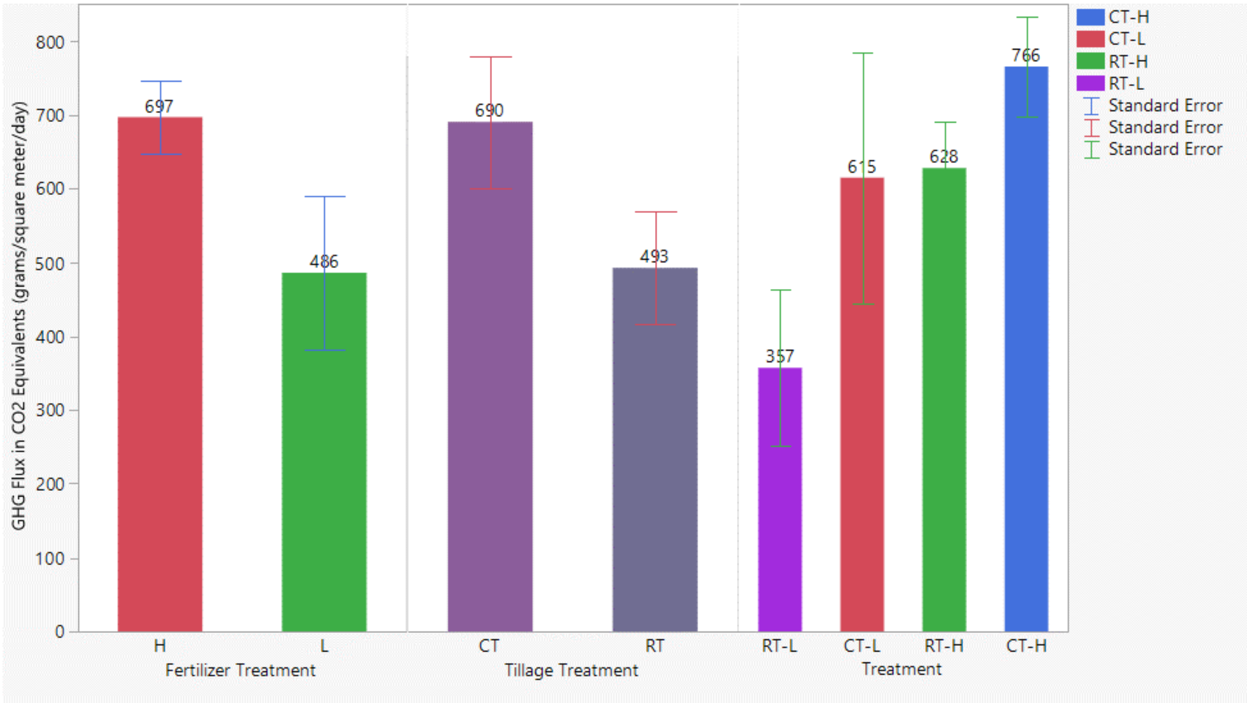
After the application of Chilean nitrate to "high N" plots on July 21, 2020, gas samples were collected from the chambers on three consecutive days July 21-July 23. The total GHG flux in CO_2 equivalents was calculated using the methods described above just for the period of July 21-23 to assess the impact of the fertilization event on total seasonal GHG flux. Using the same statistical model described in the "marketable yield" section above, it was found that there was no statistically significant effect of fertilization (p=0.56111), tillage (p=0.43889), or the interaction between the two (p=0.67818) on net GHG flux in CO_2 equivalents for the three-day period. Despite the lack of statistical significance, there was a numerical trend toward slightly elevated N_2O flux in the conventionally tilled high nitrogen treatment, but not in the reduced tillage high nitrogen treatment, during the period as illustrated in the graph below.



Net GHG flux by treatment from July 21-23 after fertilizer application to "high N" plots

Total Seasonal Greenhouse Gas Flux in CO2 Equivalents

Using the same statistical model described in the other GHG flux sections above, it was determined that there was no statistically significant effect of tillage, fertilization, or the interaction between the two terms on the average total GHG flux in CO_2 equivalents in grams per square meter per day observed in this trial. There was, however, a numeric trend toward higher net GHG flux in conventionally tilled plots compared to reduced tillage plots ($p=0.14188$ for the tillage effect) and higher flux in high nitrogen plots compared to low nitrogen plots ($p=0.12005$ for the fertilizer effect). Those trends can be observed in the graph below.

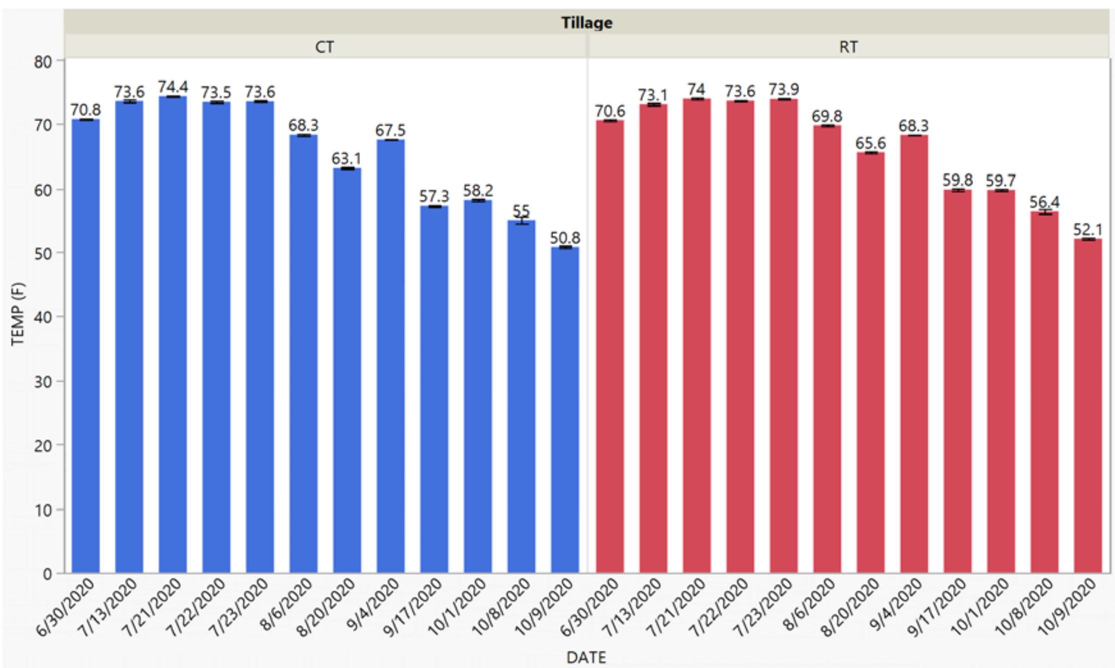


2020 season-long daily mean GHG flux in CO2 equivalents by fertilizer treatment, tillage treatment, and the combination of fertilizer and tillage treatments

IV. Discussion

Soil Temperature

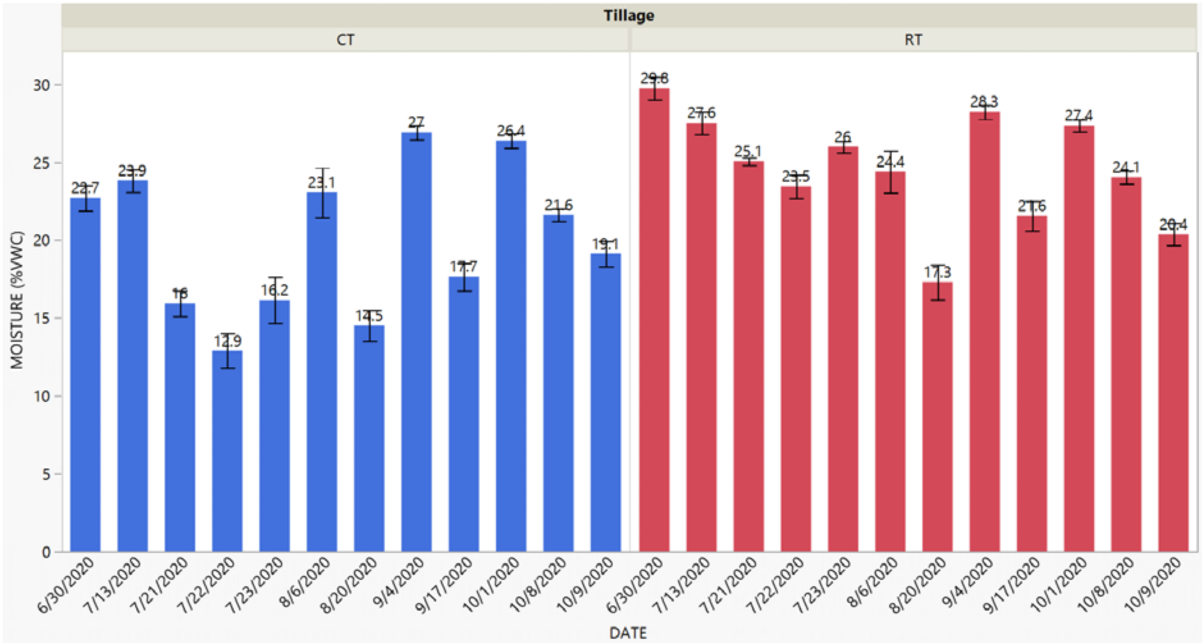
Despite the statistically significant effect of tillage on soil temperature observed in the trial, the actual measured difference was fairly small in practice at just 0.95 ^{o}F. Since temperature measurements did not begin until late June, it is also likely that the season long mean temperature was actually much closer between to two tillage treatments. Soil temperatures in plots with residue tend to be cooler in the spring compared to conventionally tilled plots that warm faster with direct soil exposure to the sun. However, the trend observed in the 2020 data set is noteworthy in that it illustrates the insulating effect of residue left on the reduced tillage plot soil surfaces that helps to maintain slightly warmer temperatures later into the season compared to conventionally tilled soils. That trend toward higher soil temperatures in reduced tillage plots in September and October can be seen in the graph below.



Mean 2020 soil temperatures by tillage treatment and date

Soil Moisture

In addition to the insulating effect of the residue that maintains higher soil temperature later into the season in reduced tillage plots, the residue also has a buffering effect on soil moisture levels and maintains higher mean soil moisture over the season compared to conventionally tilled plots. Not only was the soil moisture higher on average in the reduced tillage plots over the season, the fluctuation from dry to wet was less severe in the reduced tillage plots compared to the conventionally tilled plots. The reduction in soil moisture variability should, theoretically, support the growth and development of healthier, less-stressed plants.



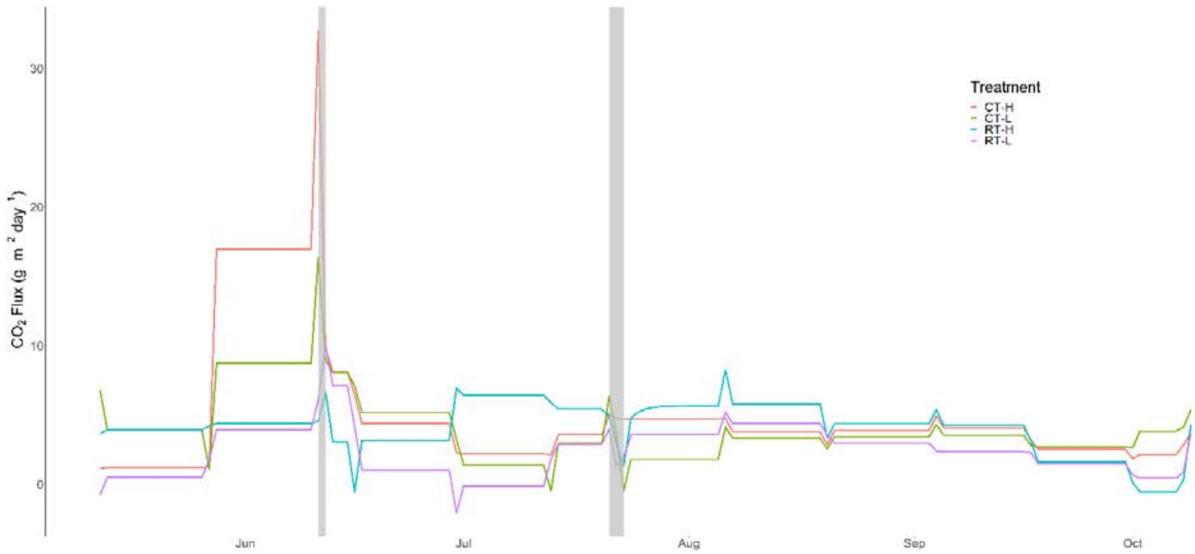
Mean 2020 soil moisture as volumetric water content percentage by tillage treatment and date

Marketable Yield

The statistically significant reduction in yield in the reduced tillage-low nitrogen (RT-L) plot was not unexpected; however, the severity of the yield decline was surprising. Though there was a trend toward lower net GHG flux in the RT-L treatment, the loss in yield would be economically unsustainable for commercial operations. It is also noteworthy that the addition of 40 pounds per acre of actual nitrogen by Chilean nitrate did not produce a statistically significant increase in yield in this trial in the conventionally tilled plots, but did result in a significant increase in the reduced tillage plots. Data collected in 2021 should help to provide more information on whether nitrogen is more scarce in reduced tillage plots and whether the lack of a yield response from supplemental nitrogen in the conventionally tilled plots in 2020 was an anomaly.

Greenhouse Gas Flux During June Pre-Plant Tillage Event

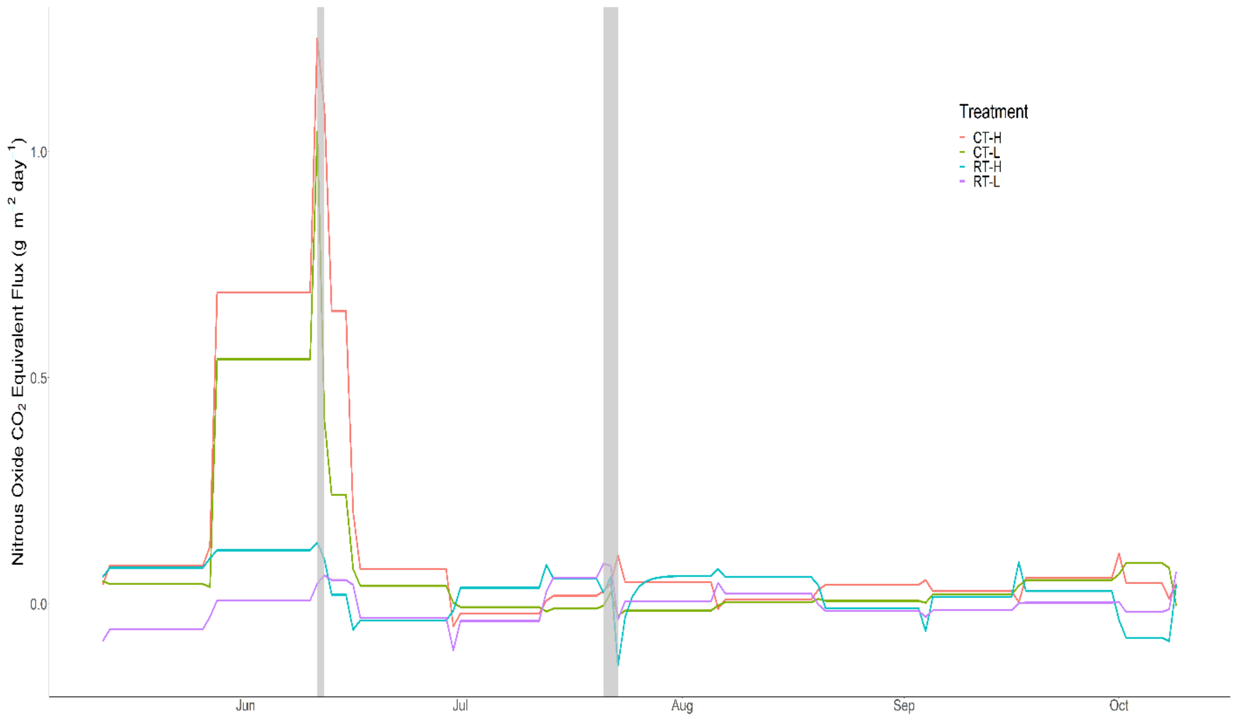
As hypothesized in the trial design, the pre-plant tillage event produced the largest spike in GHG flux during the season. Not only did the conventionally tilled plots that were rototilled release significantly more CO_2, but N_2O flux also increased post-tillage compared to the reduced tillage plots. As the graph below illustrates and the statistical analysis presented above in the "results" section confirms, the conventionally tilled plots released more than 2.5 times the amount of CO_2 over the two-day period in mid-June than the reduced tillage plots. The net GHG flux in CO_2 equivalents released during the tillage event accounted for nearly 5% of the estimated annual total GHG flux in the conventionally tilled plots, whereas total flux in the reduced tillage plots over the same period accounted for just 3.14% of the annual total.



CO2 flux over the 2020 season by treatment

Greenhouse Gas Flux During July Chilean Nitrate Application Event

The research team anticipated that the high nitrogen plots would show a significant increase in N_2O release following the application of 286 pounds per acre of Chilean nitrate (40 pounds of actual nitrogen) in July. However, the gas samples collected for the three-day period following fertilization showed no significant difference in either N_2O flux or total GHG flux in CO_2 equivalents between the treatments. This trend can be observed in the graph below; the fertilization event period is highlighted with the gray band near the middle of the X axis. It is possible that the lack of rain following the application of the Chilean nitrate resulted in negligible N_2O release post-fertilization and that the nitrogen volatilized more gradually over time. The graph below does show an increase in N_2O release from the two high nitrogen treatments (CT-H and RT-H) beginning in late July through early August that may be the result of the Chilean nitrate application. Nevertheless, the 2020 data suggest that the addition of 40 pounds of nitrogen per acre as Chilean nitrate to reduced tillage squash systems has the potential to significantly increase yield without significantly increasing N_2O release rates in the short term or net GHG flux over the season compared to unfertilized reduced tillage plots.



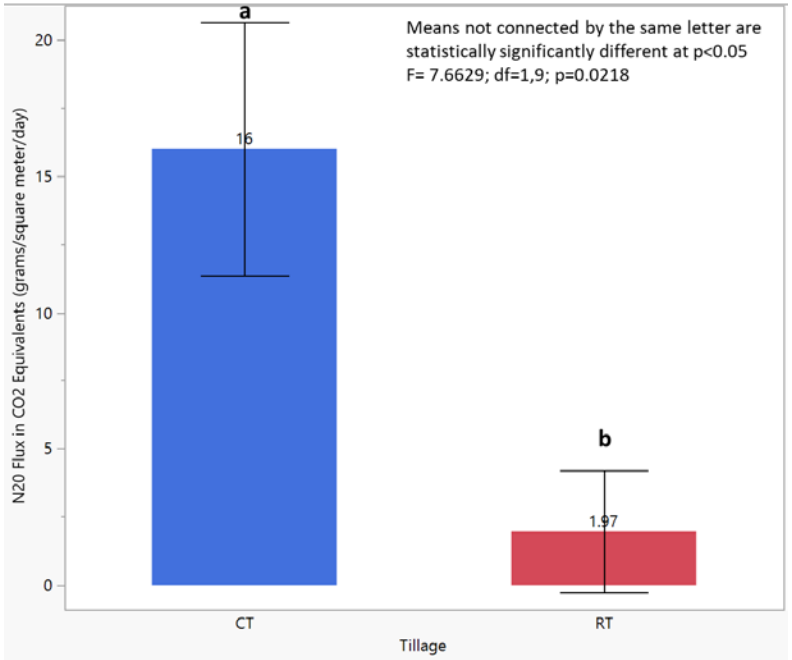
N2O flux in CO2 equivalents over the 2020 season by treatment

Total Seasonal Greenhouse Gas Flux in CO2 Equivalents

Despite the significant difference in GHG flux between the tillage treatments observed after the pre-plant rototilling in June 2020, the season-long mean daily net GHG flux in CO_2 equivalents was not significantly different between treatments. As previously discussed, though, there were numeric trends toward lower GHG flux rates in the reduced tillage-low nitrogen plots (RT-L) compared to the other treatments. As can be seen in reviewing the values in the table below, CO_2 accounted for the majority of the GHG flux in all of the plots and also represented the largest numeric difference between the RT-L treatment plots and the others. While methane release was negligible over the season, there was a statistically significant effect of tillage on daily mean N_2O flux over the season ($p=0.0218$). The conventionally tilled plots averaged a flux of approximately 16 grams of N_2O per meter squared per day in CO_2 equivalents over the season compared to just 1.97 grams in the reduced tillage plots—an over 8-fold difference. As implied in the discussion above, it was incorrectly hypothesized that the fertility treatment, not the tillage treatment, would have a greater impact on N_2O release.

Treatment	Mean Growing Season CO_2 Flux ($g\ m^{-2}\ day^{-1}$)	Mean Growing Season N_2O Flux, CO_2 equivalent ($g\ m^{-2}\ day^{-1}$)	Mean Growing Season CH_4 Flux, CO_2 equivalent ($g\ m^{-2}\ day^{-1}$)	Mean Total Growing Season GHG Flux, CO_2 equivalent ($g\ m^{-2}\ day^{-1}$)
Conventional Tillage, High N fertilization	745 (130) 42.5 (6.81)	19.4 (9.9) 2.34 (1.53)	1.57 (2.01)	766 (134)
Conventional Tillage, Low N fertilization	605 (323) 25.3 (21.6)	12.5 (16.5) 1.45 (2.05)	-2.29 (3.98)	615 (341)
Reduced Tillage, High N fertilization	626 (114) 11.2 (10.7)	4.85 (7.66) 0.23 (0.05)	-0.61 (3.20)	628 (125)
Reduced Tillage, Low N fertilization	360 (212) 16.2 (11.5)	-0.91 (3.46) 0.11 (0.14)	-1.83 (3.03)	357 (212)

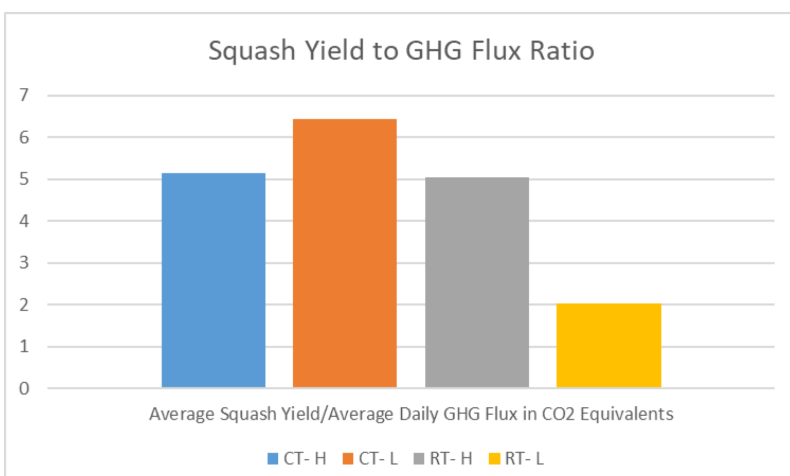
Treatment means and standard deviations of growing season sums of CO2, N2O, CH4 and total GHG flux. Sums and standard deviations in red are the totals over the tillage disturbance from June 11th – 12th. Sums and standard deviations in blue are for the fertilization disturbance from July 21st – 23rd.



2020 mean daily N2O flux by tillage treatment

Squash Yield Per Unit of GHG Flux

In an effort to synthesize the crop yield data and the GHG flux data, a ratio of average crop yield per plot (in pounds per 150 sq ft) to average daily GHG flux in CO_2 equivalents (converted to pounds per 150 sq ft) can be calculated. This ratio represents the pounds of squash generated per unit of GHG flux in the different treatments; a higher value suggests a more efficient conversion of GHG flux to pounds of food. Though no statistical analysis was applied to these figures in 2021, the ratios for the four treatments in order from highest to lowest are Conventional Tillage- Low Nitrogen (6.43997), Conventional Tillage- High Nitrogen (5.15113), Reduced Tillage- High Nitrogen (5.05402), and Reduced Tillage- Low Nitrogen (2.02892).



V. Ongoing Research

The GHG flux research will continue in 2021 with several minor changes and additions:

1. Soil analyses:
    a. Nutrient availability: Standard soil nutrient level analyses, including nitrate-nitrogen, will be conducted from aggregate samples from each of the four plots per treatment in May, July, and September 2021 to evaluate potential differences in nutrient availability by treatment over the season.
    b. Haney Soil Health Test: The same sampling schedule and protocol will be used to submit samples for Haney Soil Health testing in 2021. The Haney test will provide data on potential differences in active carbon, microbial respiration rate, soil organic matter, and more that may account for differences in crop yield and overall soil health between the treatments.
2. Plant tissue testing: In addition to the soil testing, leaf samples from each of the treatment plots will be submitted to Waters Ag Labs three times during the growing season in an effort to better understand potential differences in nutrient uptake in the squash plants growing in the different tillage and fertilizer treatments.
3. Kelp meal treatment: In collaboration with the non-profit GreenWave, the researchers have added a fifth treatment to the trial in 2021. The new treatment is a conventionally tilled plot amended with the equivalent of 2,000 pounds per acre of dried and milled sugar kelp grown on Long Island. The kelp will provide 40 pounds of actual nitrogen per acre prior to transplanting the squash in addition to additional potassium to the crop. However, the main question being studied with the additional treatment is whether the addition of kelp meal to the soil may have a buffering effect on GHG flux compared to the other conventionally tilled plots.
4. Formalized partnership with The Cary Institute: Given the proximity of the institute and the responsiveness of Dr. Groffman's lab manager Lisa Martel to the needs of the trial, the research team is thrilled to have formalized the relationship with The Cary Institute for 2021. All GC work will be completed by Lisa Martel, who will also calculate fluxes and generate both GC data and interpretation. The Walter Lab at Cornell University will still remain involved in the project in an advisory capacity and will provide additional interpretation and analysis support after year three of the research.