Cornell Cooperative Extension
Eastern NY Commercial Horticulture Program

HUDSON VALLEY FARM HUB

Cary Institute of Ecosystem Studies

Evaluating Potential Impacts of Biochar on Greenhouse Gas Flux Rates and Annual Vegetable Crop Production in Organic Reduced Tillage Systems

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2024 Annual Report

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I. Main Findings

- There was a significant effect of tillage on the average total greenhouse gas (GHG) flux rate measured in 2024. Plots that were conventionally tilled (CT) had higher rates of GHG flux than reduced tillage (RT) plots on average over the season ($p=0.0038$). This difference is mostly the result of a nearly 17.29% reduction in carbon dioxide (CO_2) flux in the RT treatments compared to the CT treatments.
- Biochar also had a significant effect on the average GHG flux rate in 2024. Plots that were amended with biochar had a lower GHG flux rate than those that were not amended with biochar on average over the season ($p=0.0297$). This difference is mostly driven by an approximately 23.13% reduction in CO_2 flux in the biochar-amended treatments compared to the treatments that were not amended with biochar in 2023.
- Crop yield in the conventionally tilled treatment plots was 2.67 times higher than in the reduced tillage plots ($p=0.0185$). The average marketable yield per plant was 4 times higher in the CT treatments than in the RT treatments ($p=0.0048$). Crop yield has consistently been higher in conventionally tilled treatments in previous years of GHG flux research.
- There was a strong numeric trend toward higher crop yield to GHG flux ratio in the CT treatments as a result of the significant difference in marketable yield described above ($p=0.0633$). Despite the measured lower GHG flux in the RT treatments, the reduction in crop yield in those treatments results in a comparatively inefficient conversion of GHG flux to crop yield when compared to the CT treatments.
- Weed management is a serious barrier to maintaining long term reduced tillage systems on organic farms. All of the treatment plots, both conventional tillage and reduced tillage, were rototilled in mid-September 2024 before seeding hairy vetch in an effort to manage intense weed pressure, especially from crabgrass, in the RT plots.

II. Abstract

A small plot randomized complete block design field trial designed to evaluate the impact of applying biochar in combination with different tillage treatments on greenhouse gas (GHG) flux is being conducted at the Hudson Valley Farm Hub (Hurley, NY) in permanent plots from fall 2022 through fall 2025. Plots were established in fall 2022 by seeding winter rye in the trial area. Biochar and compost amendments were added to the trial plots in June 2023 before direct seeding butternut squash as described in the 2023 Annual Report. The four treatments evaluated in this trial are 1) a conventionally tilled (CT) treatment amended with compost only (CT), 2) a CT treatment amended with a biochar/compost mix (CT Biochar), 3) reduced tillage treatment amended with compost only (RT), and 4) a reduced tillage RT Biochar treatment amended with a biochar/compost mix (RT Biochar). The RT Biochar treatment was managed the same as the CT Biochar treatment in 2023 to allow for the incorporation of the biochar/compost mix, but transitioned to a true RT system after being amended. Trial plots were seeded with winter rye again in fall 2023. The CT and CT Biochar treatments were rototilled April 30, 2024 to terminate the cover crop and rototilled again in June before seeding green beans on June 5. Winter rye in the RT and RT Biochar treatments was allowed to continue to grow until anthesis and was roller crimped on both June 4 and June 5.

Greenhouse gas (GHG) flux data was collected January through December 2024. There were significant treatment effects of both tillage type and biochar amendment on the average rate of GHG flux in 2024. RT treatments had a significantly lower GHG flux rate than CT treatments (p= p=0.0038) and biochar-amended treatments had a significantly lower GHG flux rate than unamended treatments (p=0.0297). Those differences were predominantly driven by significant differences in CO_2 flux rates, especially following tillage events. There were also significant differences in N_2O flux rate between the tillage treatments in 2024 with higher rates of nitrous oxide flux being measured in the CT treatments compared to the RT treatments (p=0.0269).

Green bean yield data was collected on July 31. Marketable yield in the CT plots was 2.67 times higher than in the RT plots on average (p=0.0185). This yield drag in RT plots has been observed consistently in GHG flux research trials at HVFH in other cash crops like butternut squash. Despite the significant reduction in GHG flux rate observed in the RT treatments, the decrease in crop yield resulted in an unfavorably low yield to flux ratio in the RT plots (p=0.0633). The numeric difference in yield to flux ratio suggests that the RT systems are less efficient at generating yield per unit of GHG flux, a trend that has been observed in previous years of this research.

There were few significant differences in the soil health metrics that were measured via Haney Soil Health Test and POX-C test in 2024. Water extractable organic carbon levels were preserved better in the RT treatments than in the CT treatments in 2024 (p=0.0091). POX-C, a measurement of the pool of labile soil carbon, was highest in the RT treatment plots that have been under reduced tillage management for the longest time (p=0.0227).

III. Materials and Methods

Trial Design

The trial is a small plot randomized complete block design with four replicates and four total treatments. Trial plots were established in fall 2022 and maintained continuously in situ through 2025. Each treatment plot is 5 feet wide by 30 feet long and was planted with two rows of direct seeded 'Greenback' snap beans as described below. Each replicate consists of four plots, one for each of the four treatments included in the trial that are outlined below:

1) **RT**: Amended with compost via broadcast surface application at 1.6 tons/acre (approximately 2.58 cubic yards/acre) in June 2023. Overwintered cereal rye cover crop roller crimped in June 2024 prior to no-till planting of green beans.
2) **RT Biochar:** Amended with biochar mixed with compost on June 13, 2023 at 0.4 tons/acre biochar (approximately 2.33 cubic yards/acre) and 1.6 tons/acre (approximately 2.58 cubic yards/acre) compost before being rototilled. Transition to reduced tillage system after biochar incorporation. Overwintered cereal rye cover crop roller crimped in June 2024 prior to no-till planting of green beans.
3) **CT:** Amended with compost via broadcast surface application at 1.6 tons/acre (approximately 2.58 cubic yards/acre) in June 2023. Overwintered cereal rye cover crop terminated with a rototiller April 30, 2024. Rototilled again June 5 before direct seeding green beans.
4**) CT Biochar:** Amended with biochar mixed with compost on June 13, 2023 at 0.4 tons/acre biochar (approximately 2.33 cubic yards/acre) and 1.6 tons/acre (approximately 2.58 cubic yards/acre) compost before being rototilled. Overwintered cereal rye cover crop terminated with a rototiller April 30, 2024. Rototilled again June 5 before direct seeding green beans.

Plot Tillage



Conventionally tilled (CT) and CT Biochar plots were first tilled on April 30, 2024 using a 6-foot-wide tractor-mounted rototiller attachment to a depth of approximately four-inches to terminate the winter rye cover crop. The CT and CT Biochar plots were subsequently tilled using a tractor-mounted rototiller to a depth of approximately four-inches on June 5 in preparation for seeding green beans. CT and CT Biochar plots were mowed and rototilled again post-harvest on August 15. The entire trial area was rototilled on September 11 in an effort to manage weeds, especially annual crabgrass.



Field Establishment

Winter rye in the RT treatments was roller crimped using a front mounted I&J roller crimper on June 4 and on June 5 before planting. 'Greenback' snap beans were direct seeded into the trial plots on June 5, 2024 using a four-row John Deere MaxEmerge 2 no-till planter.

Compost Analysis and Amendment

Compost from Vermont Compost was broadcast in the CT and RT plots at a rate of 1.6 tons/acre (approximately 2.58 cubic yards/acre) on June 13, 2023. A full compost analysis from Soil Control Labs (Watsonville, CA) was completed in March 2023 and is available in the appendices of the 2023 Annual Report.

Biochar Analysis and Amendment

Biochar sourced from NY Carbon (www.nycarbon.co, Saugerties, NY) at a cost of $500/cubic yard was mixed with compost (same as described above) on May 11, 2023 and allowed to sit for 4.5 weeks prior to application in the RT Biochar and CT Biochar plots on June 12, 2023. The biochar/compost mix was applied at a rate of 0.4 tons dry weight/acre biochar (approximately 2.33 cubic yards/acre) and 1.6 tons wet weight/acre (approximately 2.58 cubic yards/acre) compost. A sample of the biochar was submitted to Control Laboratories (Watsonville, CA) in March 2023; the analysis can be found in Appendix II of the 2023 Annual Report.

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 January 26, 2024 and ending on December 10, 2024. 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 in 2023. Chamber tops of a known volume were installed monthly during the winter months, every other week during the production season, and daily for three days after plot tillage events. 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 15 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 April 30 from the conventionally tilled plots in anticipation of rototilling to terminate the winter rye cover crop and were re-installed three hours before sampling on that same date. All chambers were removed on May 22 in preparation for the field being roller crimped to terminate the remaining cover crop and were re-installed on June 4 after plot tillage and one hour prior to the June 4 sampling event. All chambers were again removed on August 13 in advance of post-harvest mowing and tillage; they were reinstalled on August 15 almost two hours before the sampling event that day. Finally, all chambers were again removed on September 11 before full field rototilling and reinstalled one hour before gas sampling the same day. The full list of sampling event dates and ambient air temperatures is available below. The sampling event sequence begins at 16 since there were 15 sampling events in 2023. Sampling events 19 and 24 were skipped due to errors in printing labels for the Exetainer® vials.

Table 1: GHG sampling event dates and ambient air temperatures

Sampling Event	Date	Start Time	Ambient Air Temp (ºF)
16	1/26/2024	10:45	39.2
17	3/8/2024	11:45	50.5
18	4/17/2024	1:45	62.6
20	4/30/2024	3:00	65.5
21	5/1/2024	10:30	62.6
22	5/2/2024	10:30	69.7
23	5/17/2024	9:45	66.9
25	6/4/2024	12:30	85.6
26	6/5/2024	9:15	74.8
27	6/6/2024	10:45	76.5
28	6/18/2024	9:45	86.9
29	7/2/2024	10:20	74.5
30	7/16/2024	10:00	80.5
31	7/30/2024	9:15	80.5
32	8/13/2024	12:00	78.0
33	8/15/2024	12:15	83.9
34	8/16/2024	9:00	71.3
35	8/28/2024	9:30	77.8
36	9/11/2024	1:05	61.0
37	9/12/2024	11:45	65.8
38	9/13/2024	10:45	67.6
39	9/25/2024	1:00	59.8
40	10/15/2024	10:35	44.2
41	11/14/2024	10:45	32.6
42	12/10/2024	11:30	40.3

Soil Nutrient and Health Analyses

Soil samples from each trial plot were collected July 9 and September 25 for submission to Ward Labs (Kearney, NE) for the Haney Soil Health Test analysis (protocol available at https://www.wardlab.com/wp-content/uploads/2019/09/Haney-Rev-1.0-Information.pdf). Additionally, the permanganate-oxidizable carbon (POX-C), a measure of the labile or active fraction of soil carbon, was also analyzed by Ward Labs.

Plant Tissue Analyses

Tissue samples from the green bean crop in each plot were collected according to the protocol recommended by Waters Ag Labs (Warsaw, NC) on July 19 and July 29, 2024. Specific lab protocols for the basic plant tissue analysis are available by request from the lab.

Harvest Evaluation

All plants in the middle 10 bed feet of each plot were counted on July 31 before being harvested. All beans of marketable size and quality were picked by hand and weighed using an Ohaus Catapult 1000 bench scale with 0.01 lb readability. The total marketable yield and crop stand values were used to calculate the average marketable yield per plant in addition to the marketable yield per 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 were analyzed using a generalized linear model in JMP 17.2.0 Pro Software (SAS Institute Inc, Cary, NC) with tillage, biochar, the interaction term (tillage*biochar), and date when applicable as fixed effects with replicate as a random effect and, when appropriate, plot (replicate) as a random effect as well. 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 except where noted and Fisher's Protected Least Significant Difference (LSD) was used instead. A post-hoc Student's t-test at p=0.05 was used for all comparisons of two means.

IV. Results

Soil Temperature

As has been the case in previous years, soil temperatures in the RT plots were significantly lower than in CT plots through mid-July. The season-long average soil temperature in the RT plots was also statistically significantly lower than the CT treatments in 2024 ($p<0.0001$). A subset of average soil temperatures is presented below that represent the period of greatest difference between the RT and CT plot temperatures from early June through July.

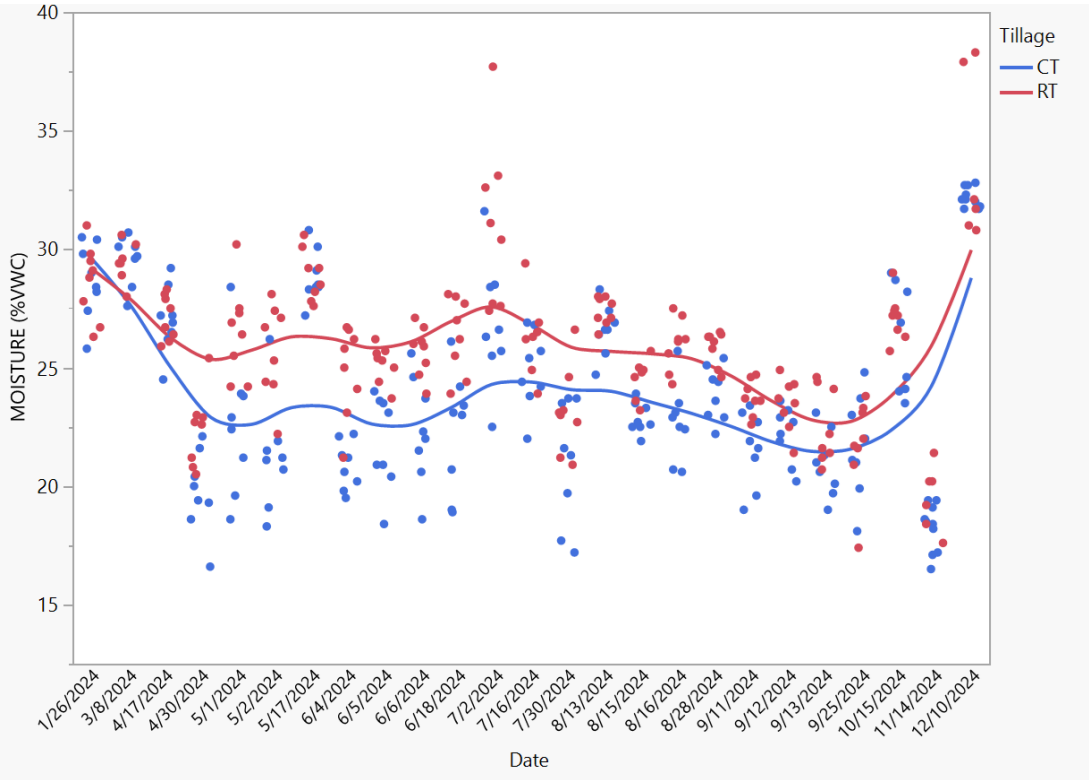
	2024 Mean Soil Temperature (F) by Date					
Treatment	**5-Jun**	**18-Jun**	**2-Jul**	**16-Jul**	**30-Jul**	**Mean Temp (F) over Season**
CT	69.83 a	77.14 a	68.87 a	79.43 a	73.06 a	62.72 a
RT	67.99 b	72.19 b	67.28 b	75.88 b	72.29 b	61.52 b
P-Value	0.0433	<0.0001	0.0028	<0.0001	0.0058	<0.0001

Soil Moisture

The RT plots were significantly moister on average than the CT plots in 2024 ($p<0.0001$). As can be seen in the graph below, the largest difference in soil moisture between the RT and CT plots was observed from early April through mid-July.

	2024 Soil Moisture (%VWC) by Date						
Treatment	**5-Jun**	**18-Jun**	**2-Jul**	**16-Jul**	**30-Jul**	**13-Aug**	**Season Mean Soil Moisture**
CT	21.85 b	22.30 b	26.89 b	24.9	21.05	26.56	23.87 b
RT	25.16 a	26.35 a	30.95 a	26.375	23.1625	27.39	25.85 a
P-Value	0.0033	0.0084	0.0169	0.1137	0.1322	0.0827	<0.0001

Figure 1: 2024 Soil Moisture (%VWC) by Date



Soil Carbon Analyses

Microbially Active Carbon (MAC) and Soil Organic Matter

MAC is calculated by dividing the soil respiration rate by the water extractable organic carbon. Values in the 50-75% range are ideal and reflect that there is sufficient available carbon to support microbial activity in the soil. Values over 80% suggest that the available soil carbon may be limiting to support the microbial population. Neither the tillage nor biochar had a significant effect on MAC on either sampling date or on the change in MAC over the season in 2024. Similarly, there were no significant differences in soil organic matter between the treatments in 2024. Changes in MAC and organic matter over the season are reported in the table below with the delta symbol (Δ).

Tillage	MAC (%) 9-July	MAC (%) 25-Sep	Δ MAC (%)	Season Mean MAC (%)	Organic Matter (%) 9-July	Organic Matter (%) 25-Sep	Δ Organic Matter (%)	Season Mean Organic Matter (%)
RT	65.00	90.33	25.33	77.66	2.15	2.20	0.05	2.18
CT	69.28	83.74	14.46	76.51	2.19	2.20	0.01	2.18
P-Value	0.4704	0.2892	0.0974	0.8092	0.6275	1.00	0.6727	0.741

Water Extractable Organic Carbon (WEOC) and CO_2-C Soil Respiration

WEOC is intended to measure the pool of soil carbon that is more readily available as a food source for the soil microbial biomass; most agricultural soils are in the 100-300 ppm C range. Soil respiration is a measure of how much CO_2 is released from a soil sample over a 24-hour period; higher values correspond to greater microbially activity with most agricultural soils averaging around 50 ppm. As in 2023, both WEOC and respiration measurements were lower in the trial plots than most agricultural soils. While there were some observed statistically significant differences in WEOC and soil respiration on individual sampling dates, the only trend that was consistent in both 2023 and 2024 was the greater decrease in WEOC over the season in the CT plots compared to the RT treatments (data presented in the second table below).

Treatment	WEOC (ppm C) 9-July	WEOC (ppm C) 25-Sep	Δ WEOC (ppm C)	Season Mean WEOC (ppm C)	CO2-C (ppm) 9-July[Y]	CO2-C (ppm) 25-Sep	Δ CO2-C (ppm)	Season Mean CO2-C (ppm)
CT	59.75 a	46.25	-13.5	53.00 ab	35.93	40.5	4.58	38.21
CT Biochar	62.25 a	48.67	-13.58	55.46 a	43.38	45.33	1.96	44.35
RT	57.25 ab	53.25	-4	55.25 a	41.75	40.75	-1.00	41.25
RT Biochar	51.00 b	47.75	-3.25	49.38 b	33.05	42.5	9.45	37.78
P-Value	0.0313	0.1338	0.8723	0.0161	0.0384	0.5428	0.0716	0.1041

Y- There was no separation between the treatment means after both the Tukey's HSD and Fisher's Protected LSD post-hoc tests

Treatment	WEOC (ppm C) 7-July	WEOC (ppm C) 25-Sep	Δ WEOC (ppm C)	Season Mean WEOC (ppm C)
CT	61.00 a	47.46	-13.54 a	54.23
RT	54.13 b	50.5	-3.63 b	52.31
P-Value	0.0031	0.2166	0.0091	0.2124

Permanganate-Oxidizable Carbon (POX-C)

As described above in the methods, permanganate-oxidizable carbon (POX-C) is a measure of the labile or active fraction of soil carbon. Despite statistically significant differences between the treatment means observed on July 9, there was no clear trend in the POX-C data in 2024. POX-C values measured in September were all much higher than the values measured in July. As was the case in 2023, all POX-C values in 2024 were in the "potential constraint" range as defined by Andrews et al (2004) for New York soils. The data has yet to support findings from other research that have demonstrated large increases in POX-C from adopting reduced tillage practices.

Treatment	POX-C (ppm C) 9-July[Z]	POX-C (ppm C) 25-Sep	Δ POX-C (ppm C)	Season Mean POX-C (ppm-C)
CT	288.25 b	527.75	239.50	408.00
CT Biochar	345.75 ab	589.00	243.25	467.38
RT	403.50 a	497.25	93.75	450.38
RT Biochar	298.50 b	600.25	301.75	449.38
P-Value	0.0227	0.6194	0.1044	0.4262

Z- Connecting letters reflect differences in treatment means following a post-hoc Fisher's Protected LSD test at p=0.05

Foliar Nutrient Analysis

There were many significant differences in the foliar concentration of nutrients between treatments in 2024. Green bean plants in the RT Biochar plots had the lowest numeric concentrations of potassium (K), sulfur (S), zinc (Zn), and copper (Cu) when compared to the other treatments. There was a significant effect of tillage with the CT treatments having higher concentrations of foliar magnesium (Mg), calcium (Ca), boron (B), and iron (Fe) than the RT treatments.

	Season Average Foliar Nutrient Concentrations				
Treatment	N%	K%	S%	Zn (ppm)	Cu (ppm)
CT	3.86 b	2.00 ab	0.24 ab	28.00 a	8.88 ab
CT Biochar	4.13 ab	2.07 a	0.25 a	30.25 a	10.25 a
RT	4.24 a	2.12 a	0.23 ab	24.13 b	7.75 bc
RT Biochar	3.94 ab	1.75 b	0.22 b	22.13 b	7.00 c
P-Value	0.0166	0.0344	0.0329	0.0329	0.0203

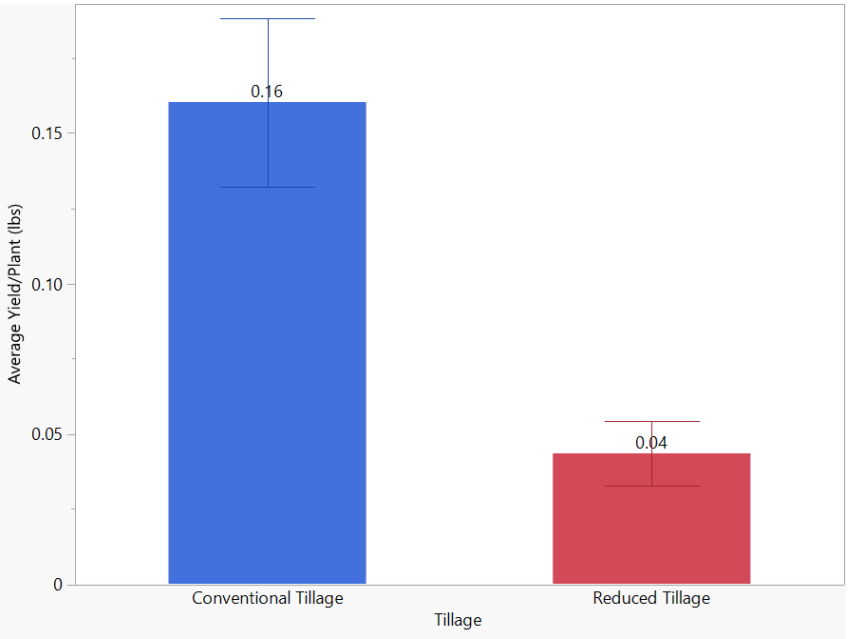
Treatment	Mg%	Ca%	B (ppm)	Fe (ppm)
CT	0.58 a	2.40 a	27.69 a	372.81 a
RT	0.43 b	1.59 b	25.19 b	137.81 b
P-Value	<0.0001	<0.0001	0.0102	0.0005

Harvest Evaluation

As has been the case in previous years of reduced tillage research at HVFH, the marketable yield in the RT treatments was significantly lower than in the CT treatments (p=0.0185). Yield was four times higher per plant on average in the CT treatments than in the RT treatments.

	2024 Harvest Data		
Treatment	Avg # of Plants/10 ft	Avg Marketable Yield (lbs)	Avg Marketable Yield /Plant (lbs)
CT	9.13	1.41 a	0.16 a
RT	10.88	0.53 b	0.04 b
P-Value	0.7207	0.0185	0.0048

Figure 2: Average Marketable Yield Per Plant



GHG Flux Rates Following Tillage Events

Spring Tillage

Higher rates of CO_2 flux following tillage events were measured in 2024 as they have been in previous years of this research. CO_2 flux was 3.75 times higher in the CT treatments than in the RT treatments for the three days following spring tillage on April 30 to terminate the winter rye cover crop in the CT plots (p=0.0010). N_2O flux was also significantly higher in the CT treatments than the RT treatments during that same period (p=0.0310), but accounted for less than two percent of the overall GHG flux for that period.

Pre-Plant Tillage

CO_2 was again the primary driver of GHG flux rates following the pre-plant tillage and roller crimping completed on June 4. There were significant treatment effects of both tillage type and biochar amendment on CO_2 flux rates for the three-day period following tillage and roller crimping. CT treatments were the source of CO_2 flux rates that were approximately 1.28 times higher than in the RT treatments (p=0.0271). Similarly, plots that were not amended with biochar in 2023 had CO_2 flux rates that were about 1.27 times higher than in the plots that were amended by biochar (p=0.0304). Tillage also had a significant effect on the N_2O flux rates during the same period with CT treatments releasing nitrous oxide at over twice the rate of the RT treatments (p=0.021), but again N_2O flux accounted for just a fraction of the total GHG flux in early June.

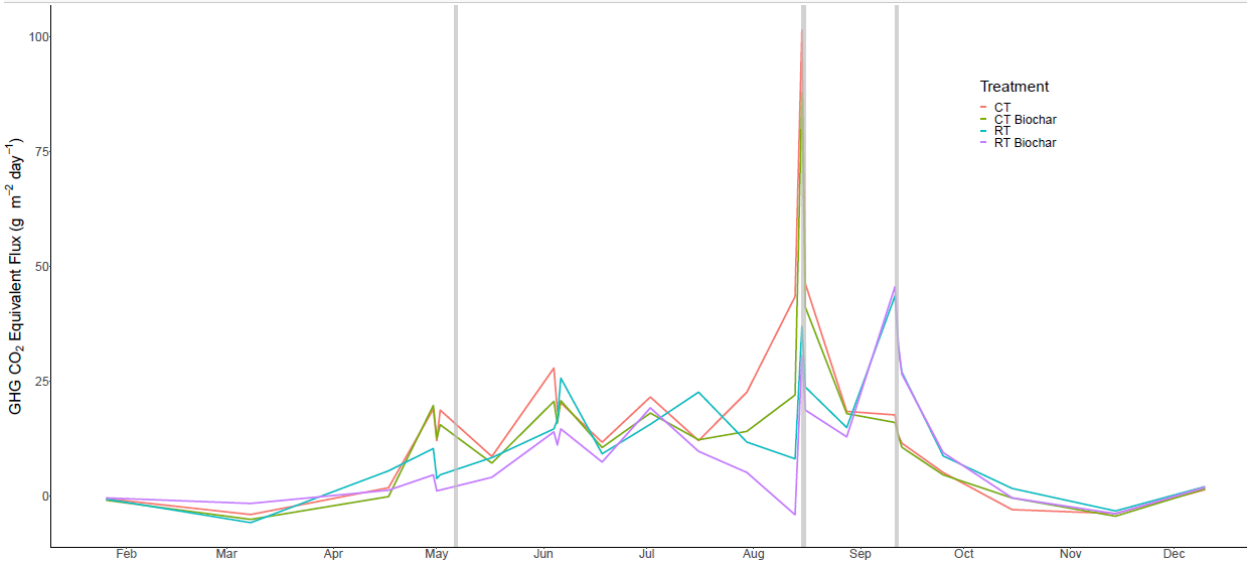
Post-Harvest Mowing and Tillage

The largest difference in CO_2 flux rates in 2024 was measured during the three-day period following post-harvest mowing and tillage on August 13. During that period, the CT treatments had a CO_2 flux rate that was 2.99 times higher than in the RT treatments ($p<0.0001$). There was a smaller, but still statistically significant, effect of biochar amendment on CO_2 flux rates following post-harvest tillage as well. Plots that were not amended with biochar in 2023 released CO_2 at about 1.32 times the rate of plots that did receive biochar ($p=0.0465$).

Pre-Cover Crop Seeding Tillage

As mentioned in the methods section above, the entire trial field was rototilled on September 11 in an effort to control crabgrass in all of the plots before seeding hairy vetch. Since there was more organic material in the RT treatment plots compared to the CT plots, this tillage event resulted in a significantly higher CO_2 flux rate in the RT plots than in the CT plots. For the three-day period following fall tillage, CO_2 flux rates in the RT treatments were 2.53 times higher on average than in the CT treatments that had been tilled less than a month prior ($p=0.0006$). The line graph below highlights the spikes in total GHG flux following tillage events throughout the season.

Figure 3: Total GHG Flux Rates Over the 2024 Season by Treatment



Season Average GHG Flux

Largely driven by the differences in CO_2 flux rates following the tillage events discussed above, there were significant treatment effects of both tillage type and biochar amendment on the season average CO_2 flux rate and the total GHG flux rate in 2024. CO_2 flux in the CT treatments was 1.21 times higher than the RT treatments on average over the season ($p=0.004$). Though N_2O flux totals were inconsequential in 2024 compared to CO_2 flux totals, N_2O flux totals were more than twice as high in CT treatments as they were in RT treatments ($p=0.0269$).

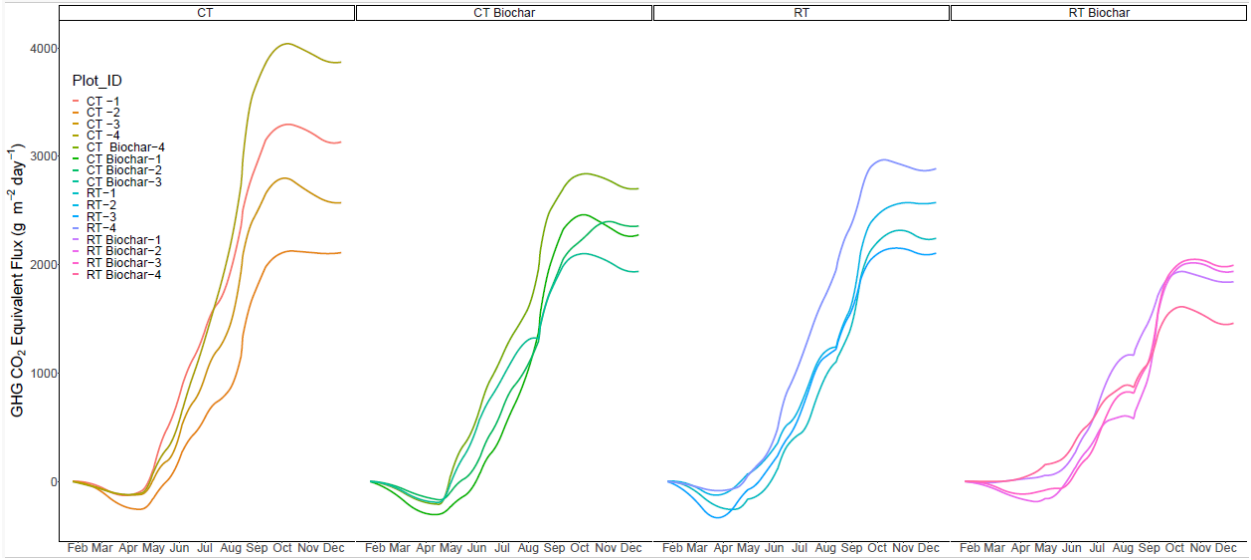
Treatment	Mean Total Flux CO_2eq (g/m^2)	Mean CO_2 Flux CO_2eq (g/m^2)	Mean N_2O Flux CO_2eq (g/m^2)	Mean CH_4 Flux CO_2eq (g/m^2)
CT	2620.03 a	2550.06 a	71.33 a	-1.36
RT	2131.00 b	2109.03 b	30.96 b	-8.99
P-value	0.0038	0.004	0.0269	0.477

The same effect observed in 2023 of biochar suppressing CO_2 flux was again measured in 2024. As can be seen in the table below, 2024 CO_2 flux totals were 1.3 times higher in the treatments that were not amended with biochar compared to the treatments that did receive biochar (p=0.0272). Biochar amendment did not have a significant effect on the rate of nitrous oxide or methane flux in 2024.

Treatment	Mean Total Flux CO_2eq (g/m^2)	Mean CO_2 Flux CO_2eq (g/m^2)	Mean N_2O Flux CO_2eq (g/m^2)	Mean CH_4 Flux CO_2eq (g/m^2)
None	2687.19 a	2634.15 a	58.09	-5.05
Biochar	2063.84 b	2024.94 b	44.20	-5.30
P-value	0.0297	0.0272	0.2947	0.3136

The interaction term between tillage and biochar amendment was not significant in determining GHG flux rates in 2024. However, the graph below demonstrates the cumulative GHG flux totals over the season by treatment. It is clear from the graph that the RT Biochar treatment had the lowest flux rates of any treatment over the season. However, it is also clear that there was little difference in average flux rate between the CT Biochar treatment and RT treatment. The highest average flux rates were measured in the CT plots.

Figure 4: Cumulative Total GHG Flux Over Time by Treatment



Yield to Flux Ratio

The yield to flux ratio is calculated by dividing the average marketable yield (lbs) of each treatment by the average daily total flux rate in CO_2eq ($g/m^2/day$). This ratio approximates how efficiently each treatment generated crop yield per gram of GHG released over the season. In 2024, there were no statistically significant differences in the yield to flux ratio treatment means. However, there was a strong numeric trend toward a higher ratio in the CT treatments when compared to the RT treatments (p=0.0633). Despite the measured lower GHG flux in the RT treatments, the reduction in crop yield in those treatments results in a comparatively inefficient conversion of GHG flux to crop yield and a yield to flux ratio nearly half of the ratio calculated for the CT treatments.

Treatment	Daily Total Average Flux CO_2eq (g/m^2)	Green Bean Marketable Yield (lbs)	Yield: Flux Ratio
CT	16.579 a	1.408 a	0.085
RT	12.117 b	0.528 b	0.044
P-value	0.0038	0.0185	0.0633

V. Discussion

Soil Temperature and Moisture

It has been extensively documented both in other research trials and in previous work at the Hudson Valley Farm Hub that soils in high residue reduced tillage systems, like the one using roller crimped rye in this trial, take longer to warm up in the spring and early summer since the crop residue both insulates the cool soil and prevents direct solar radiation contact of the soil. This impact on soil temperature was clearly observed in 2024 as well. However, the 2024 trend in soil moisture levels was the opposite of that measured in 2023. Soils under high residue RT management often remain drier into the summer since the high biomass cover crop extracts water from the soil to support plant growth. However, soil moisture levels were higher and less variable over the season in the RT treatments compared to the CT treatments. The residue left on the soil as a mulch in these RT systems can also help preserve soil moisture during dry periods of the season; it appears as if the RT plots were more effective at preserving soil moisture than the CT plots during dry spells in the early summer and in the fall of 2024.

Nutrient Uptake

The most consistent difference in foliar nutrient concentrations recorded in this research over the past several years has been significantly lower iron uptake in RT treatments. The other trends in foliar nutrient concentrations were less clear in 2024. However, it is worth noting that there have been no significant effects of biochar on nutrient uptake in either 2023 or 2024. Many growers express concern that biochar applications will tie up nutrients, especially nitrogen, in the soil for multiple seasons after application. The process of “charging” or “activating” biochar by mixing it with compost at least a month in advance of application as was done in 2023 seems to have been an effective strategy for mitigating potential nutrient tie up.

Soil Carbon

Quantifying impacts on soil carbon in a one to three year period is a known challenge. Previous research conducted at HVFH failed to demonstrate any significant changes to soil carbon measurements with annual rotational reduced tillage systems (2021 and 2022). The POX-C test is designed to better evaluate shorter term impacts of management practices on the labile pool of soil carbon. Though the 2024 trends in POX-C data are difficult to attribute to any management practice, it is encouraging that the two biochar treatments recorded the highest numeric increases in POX-C over the season. The significant effect of reducing tillage on the preservation of water extractable organic carbon over the season also aligns with other research findings. It is somewhat discouraging, however, that POX-C, soil respiration, and WEOC rates continue to register below average for agricultural soils despite years of intentional soil carbon building practices undertaken at HVFH combined with the addition of biochar in this trial.

Crop Yield

The average marketable yield per plant in the RT treatment plots was just 25% the average marketable yield per plant in the CT treatment plots. This yield drag in organically managed reduced tillage plots has been observed in every year of this research with the exception of the strip tillage experiment in 2021. Many factors are responsible for causing this reduction in yield including slower crop establishment resulting from lower soil temperatures in the early summer, increased weed pressure, and impacts on soil nutrient availability and uptake that are inconsistent from year to year. Regardless, the 50-75% reduction in yield that has been measured in this research over the years presents a serious challenge for adopting organic reduced tillage systems.

GHG Flux

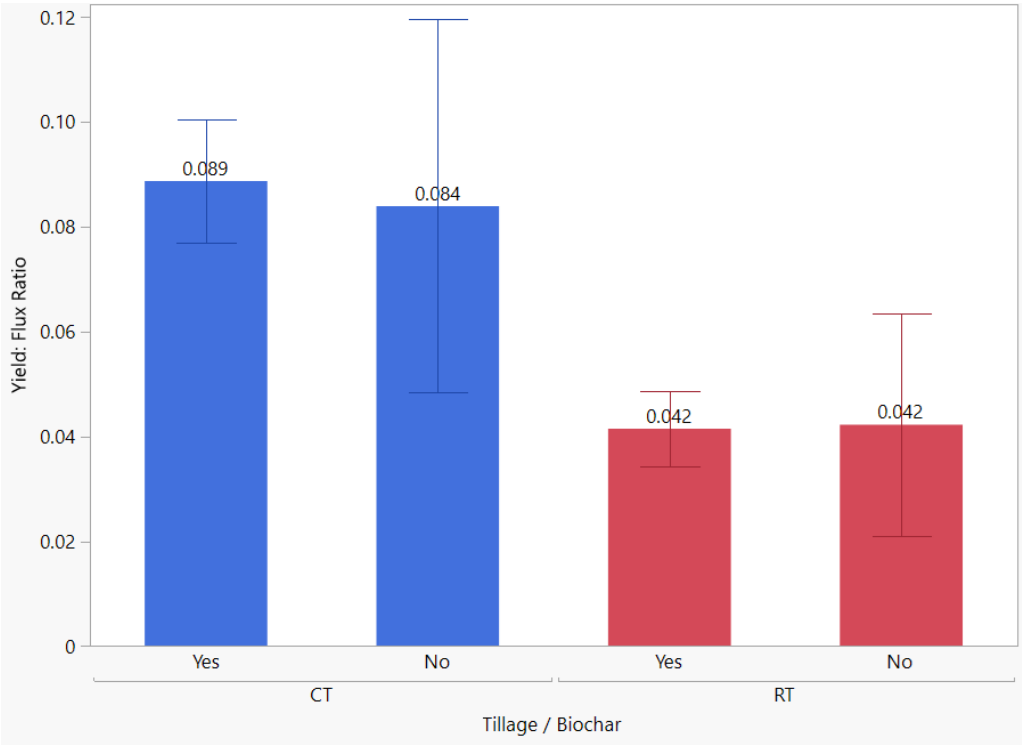
As has been observed in most years of the GHG flux research at HVFH, reducing tillage significantly decreased CO_2 and N_2O flux rates in 2024. CO_2 flux in the CT treatments was 1.21 times higher than the RT treatments on average over the 2024 season largely because of the spikes in flux rate following tillage events. With the exception of the strip tillage experiment in 2021, N_2O flux totals have been minimal in the past several years of research compared to CO_2 flux totals. In 2024, N_2O flux totals were more than twice as high in CT treatments as they were in RT treatments, but only accounted for approximately 2.15% of the total GHG flux averaged across all treatments.

Biochar application is most often associated with reductions to both nitrous oxide and methane flux rates. There was a numeric decrease in N_2O flux in the biochar amended plots in 2024, but the difference was not statistically significant. The most notable impact of the biochar amendments in this research both in 2023 and 2024 was the mitigation of CO_2 flux. CO_2 flux totals were 1.3 times higher in the treatments that were not amended with biochar compared to the treatments that were amended with biochar. In fact, the total GHG flux was numerically lower in the CT Biochar treatment plots on average than in the RT treatment plots in 2024. This may be the result of the spike in CO_2 flux rates in the RT treatments following the September 11 tillage event that was intended to manage the growing crabgrass issue in the trial area. Nevertheless, the 2024 trial data suggest that adding biochar to conventionally tilled systems may reduce GHG flux rates as much as reducing tillage without some of the challenges presented by organic reduced tillage systems, such as weed management and soil cooling.

Yield to Flux Ratio

Both reducing tillage and adding biochar were effective strategies to mitigate GHG flux rates from research plots in 2024. However, GHG flux reduction benefits must always be balanced with potential impacts on crop yield. As discussed above, average marketable yield per plant in the RT plots was just 25% of the per plant marketable yield in the CT plots on average in 2024. The yield to flux ratio represents an effort to calculate how efficiently different production systems generate yield per unit of GHG flux. The yield to flux ratio has consistently been higher in the CT treatments than in the RT treatments over the years largely as a result of the huge yield reductions in the RT treatments. Though the differences were not statistically significant in 2024, there was a clear trend toward higher yield to flux ratios in the CT treatments compared to the RT treatments. As can be seen in the bar graph below, the addition of biochar to trial plots had no measurable impact on the yield to flux ratio; in fact, the treatment that most efficiently produced crop relative to the amount of GHG released from the soil was the CT Biochar treatment in 2024. As discussed above, the 2024 trial data suggests the potential for biochar to effectively reduce GHG flux rates in conventionally tilled soils without the negative impacts on crop yield that have been observed in organic reduced tillage systems at HVFH.

Figure 5: 2024 Yield to Flux Ratio by Treatment



VI. Acknowledgements

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