Soil Trace Gas Fluxes in Living Mulch and Conventional Agricultural Systems

Samuel JW Peters[1], Eri Saikawa[1,2], Daniel Markewitz[3], Lori Sutter[3], Alexander Avramov[2], Zachary P Sanders[4], Benjamin Yosen[2], Ken Wakabayashi[2], Geoffrey Martin[2], Joshua S Andrews[4], Nicholas S Hill[4]

[1]Department of Environmental Health, Rollins School of Public Health, Emory University, 1518 Clifton Rd, Atlanta, GA, 30322

[2]Department of Environmental Sciences, Emory University, 201 Dowman Dr, Atlanta, GA, 30322

[3]Warnell School of Forestry and Natural Resources, University of Georgia, 180 E Green St, Athens, GA, 30602

[4]College of Agricultural and Environmental Sciences, University of Georgia, 137 Cedar St, Athens, GA, 30602

Abbreviations: Living mulch system (LMS), greenhouse gas (GHG), climate-smart agriculture (CSA), potentially mineralizable nitrogen (PMN), soil organic carbon (SOC), infrared gas analyzer (IRGA), gas chromatography (GC), permanganate oxidizable carbon (POXC), white clover (WC), crimson clover (CC), cereal rye (CR), conventional no cover crop (Tr)

Corresponding author email: eri.saikawa@emory.edu

Core Ideas

White clover living mulch plots had higher overall CO_2, N_2O, and NH_3 fluxes.

High N_2O and NH_3 fluxes in living mulch lasted through the late growing season.

Rates of CO_2 flux were partially explained by soil moisture and temperature.

Rates of N_2O flux were partially explained by soil moisture and extractable NO_3.

Abstract

Row crop agriculture is a significant source of two major greenhouse gases (GHGs) – carbon dioxide (CO_2), nitrous oxide (N_2O), and the air pollutant precursor, ammonia (NH_3). Fluxes of these naturally-occurring trace gases are often augmented by agricultural practices, such as fertilizer application and crop systems management. A living mulch system (LMS) maintains a live cover crop year-round and is an emerging agricultural system that can reduce pesticide and fertilizer use, while maintaining yields. Multiple trace gas fluxes of GHGs and NH_3 had never been measured together in an LMS of corn and white clover previously. This study compared soil gas fluxes in a white clover LMS with two other cover crop systems and a no cover crop system. Infrared and gas chromatography measurements were taken over two years in northern Georgia, USA. Mean soil CO_2 and N_2O fluxes (159.7 kg ha^{-1} day^{-1} and 0.027 kgN ha^{-1} day^{-1}, respectively) observed in LMS plots exceeded those from other treatments. Soil temperature, moisture, potentially mineralizable nitrogen, and nitrate partially explained these differences. Mean soil NH_3 emissions were greater in LMS (0.089 kgN ha^{-1} day^{-1}) compared to no cover crop (0.038 kgN ha^{-1} day^{-1}). Increased N_2O and NH_3 fluxes could be from release of nitrogen (N) from decomposition of clover and release of N into the soil as the corn shades the clover. While LMS plots did not reduce trace gas emissions, labile carbon content was at least 100 mg kg^{-1} greater than other treatments after two years, improving soil health.

Introduction

Carbon dioxide (CO_2) and nitrous oxide (N_2O) are the first and third most prevalent anthropogenic greenhouse gases (GHGs) (Myhre et al., 2013). Over 20% (10-12 Gt CO_2 eq yr^{-1}) of anthropogenic GHG emissions come from agriculture, forestry, and land use change (Smith et al., 2014) with agriculture being the largest contributor of the three since 2010 (Tubiello et al., 2015). 30-38% of agricultural GHGs and the largest anthropogenic contributions of N_2O come from soils in response to inputs such as manure and synthetic nitrogen (N) fertilizer application (Smith et al., 2014, Galloway et al., 2008, Montzka et al., 2011, Park et al., 2012). Agricultural practices that mitigate GHG emissions have the potential to reduce overall GHG emissions and increase the feasibility of meeting the 2°C increase limit outlined in the Paris Agreement within the United Nations Framework Convention on Climate Change (Paustian et al., 2016, Wollenberg et al., 2016).

N loss through N-based fertilizer application and green manure decomposition produce ammonia (NH_3) (Anderson et al., 2003, Sommer et al., 2004, Larsson et al., 1998, Ruijter et al., 2010). These emissions contribute to increased levels of secondary inorganic aerosols (SIA) which cause respiratory, cardiovascular, and other health issues (Kampa et al., 2008). Using agricultural systems that reduce soil NH_3 emissions could decrease surface SIA formation (Bauer et al., 2016) and lower indirect N_2O emissions (Bhatia et al, 2004).

Climate-Smart Agriculture (CSA) is a new paradigm for climate-risk management in agriculture that seeks to mitigate climate change, promote adaptation to climate change impacts, and enhance farm productivity and food security (Bryan et al., 2013). Using a cover crop, i.e. replacing bare fallow in the winter with crops that are suppressed and plowed as green manure in the spring, is a CSA management technique that increases soil organic carbon (SOC), offsetting GHG emissions and improving soil health (Poeplau et al., 2015).

Studies have shown reduced soil GHGs in cover crops compared to conventional tillage and no-till agricultural systems (Robertson et al., 2000, Abdalla et al., 2014, Kaye et al, 2017). However, a meta-analysis demonstrates that N_2O reductions are only present in experiments lasting less than a year, so further long-term studies are needed to determine overall effects of cover crops on N_2O (Basche et al., 2014).

A living mulch system (LMS) is a modified cover crop system where a legume cover crop grows throughout the cash crop's growing season, while contributing enough N to the soil pool to satisfy the needs of the cash crop (Zemenchik, et al., 2000). These systems have been shown to provide a variety of benefits, compared to bare soil and full cover crop suppression, including reduced erosion, nitrate leaching, and fertilizer use (as much as 75% less in some field trials), but function best in areas with ample available water (Zemenchik, et al., 2000, Nakamoto et al., 2006, Hartwig et al., 2002, Ochsner et al., 2010, Sanders et al., 2018). Due to these benefits, the LMS is being promoted as a potential sustainable alternative to conventional row crop agriculture, but the environmental impacts are relatively unknown.

Two studies have measured soil gas flux in an LMS, examining N_2O and NH_3 emissions in a kura clover (*Trifolium ambiguum*) and corn (*Zea mays*) production system (Turner et al., 2016, Alexander et al, 2019). Turner et al. (2016) found that cumulative area-scaled N_2O emissions over one growing season were higher in the LMS (2.3 ± 0.1 kgN ha^{-1}) despite lower fertilizer inputs, compared to conventional corn production (1.3 ± 0.1 kgN ha^{-1}). The majority of this increase came later in the growing season due to clover mineralization (Turner et al., 2016). Conversely, Alexander et al. (2019) found no significant differences in NH_3 or N_2O flux between management systems, indicating there is no consensus on how an LMS affects trace gas fluxes. N-rich cover crops, such as those used in LMS, can lower N loss as NH_3 from fertilizer applications (Larsson et al., 1998).

In order to better understand the broader impacts of an LMS, we aimed to analyze additional GHGs and NH_3. We also wanted to explore how a different species of clover could affect these trace gases. In white clover and corn LMS, N biomass pools in clover are mineralized later in the growing season and N uptake increases in the corn (Andrews et al., 2018). In addition, white clover grows faster than the kura clover used in previous studies (Speer et al., 1985, Zemenchik et al., 2001), and thus can have greater N decomposition rates (Tribouillois et al., 2015). Decomposition is the driving factor for N_2O production in a leguminous LMS (Turner et al., 2016), so the white clover and corn LMS may contribute to higher fluxes later in the growing season. Flux values should be analyzed with concurrently measured soil parameters to understand the soil processes contributing to GHG fluxes.

This study measured the CO_2, N_2O, and NH_3 soil fluxes and potential causal parameters in a white clover and corn LMS. We compared these fluxes to two other no-till cover crop systems (crimson clover and cereal rye) and one no cover crop system over two growing seasons. We hypothesized that in LMS plots: 1. CO_2 fluxes would be largest in LMS plots due to increased root and microbial respiration, but would be offset by increased SOC; 2. Overall N_2O fluxes in LMS would be greater than other techniques using dead mulches or bare soil. Additionally, an LMS with white clover would have higher N_2O fluxes than one with kura clover, due to greater N decomposition rate of white clover; and, 3. NH_3 fluxes would be lower than other management techniques due to reduced urea fertilizer application outweighing N loss from the green manure.

Materials and Methods

Site Description and Field Preparation

Over the 2016 and 2017 summer growing seasons, we measured the CO_2, N_2O, and NH_3 soil fluxes associated with four different management techniques for growing corn: 1) a

no-till system with crimson clover as the cover crop (CC), 2) a no-till system with cereal rye as the cover crop (CR), 3) a no-till white clover LMS (WC), and 4) a no cover crop conventional system (Tr) (Figure S1). There were three 6.1 × 7.3 m plots of each management technique located at the West Unit of the University of Georgia's J. Phil Campbell Sr. Resource and Education Center in Watkinsville, GA, USA, on a soil classified as a Cecil sandy loam (fine, kaolinitic, thermic type Kanhapludults) (Figure S2). Details regarding field treatment can be found in the Supplementary Material (Table S1). 15 mm irrigation was applied using a Kifco (Havana, IL) T200L portable water wheel. Each irrigation event applied 20 mm water when water-filled pore space dropped to 40% or lower to increase it to 90%.

Static Chamber Measurements of GHGs

Gaseous CO_2 and N_2O fluxes were measured weekly over each growing season in opaque PVC static chambers (Collier et al., 2014). Chamber design followed previous studies with size and material modifications explained in Figure S3 (Parkin et al, 2010, Collier et al., 2014). Three chambers were inserted in March, 2016 into each plot (Figure S2).

In WC chambers, there was living clover biomass, but biomass in CC and CR chambers had been previously killed by herbicides (Roundup for crimson clover and Dicamba for cereal rye) and was on the surface of the soil. One chamber from each of the 12 plots was sampled weekly by extracting five 10 mL samples midmorning via syringe (Collier et al., 2014). Chamber tops were placed over collars and a time 0 measurement was taken. Samples were then drawn from chambers over 30 minutes at 7.5-minute intervals for the 2016 season and over 15 minutes at 3.75-minute intervals for the 2017 season. The time interval changed in 2017 to save time and reduce potential temperature effects on the chambers after initial analysis of 2016 data showed a 15-minute measurement would provide

an accurate estimate of the flux. To account for heterogeneity in soil fluxes, each week we selected in rotation one of the three collars to sample. Gas samples were analyzed using a Shimadzu Gas Chromatograph (GC)-2014 GHG using a flame ionizing detector and methanizer for CO_2 and an electron capture detector for N_2O.

Background flux samples were taken on August 12th, November 5th, and December 28th, 2016 and February 1st, 2017 in the same 12 plots and with the same sampling techniques as in the growing season. During this time, there was no corn planted. This set of data were assumed to be minimally affected by management techniques and used as a reference to control for baseline fluxes in regression analysis.

Following GC analysis, we plotted concentrations of each gas species over time and calculated fluxes using the following formula:

$$F = m \times V/A$$

[1]

Where F is soil flux in μmol m^{-2} sec^{-1} or μmol m^{-2} hr^{-1} for CO_2 and N_2O respectively, m is the rate of GHG concentration change over 30 or 15 minutes in μmol m^{-3} sec^{-1} or μmol m^{-3} hr^{-1}, V represents chamber volume in m^3, and A is the chamber surface area in m^2. Only fluxes with a slope with an R^2 of 0.75 or greater were included for analysis. This followed Collier et al. (2014), which states that a linearity protocol can be determined via visual inspection when using the static chamber method. It is known that gas fluxes are sometimes non-linear (Parkin, et al., 2010), but due to the clear visual linearity of fluxes observed in this study, a simple approach was taken. Additionally, sensitivity analyses were carried out using R^2 values of 0.8 and 0.9 and we found minimal changes in significance of key study findings (Supplemental Tables S4-S7).

CO_2 In-Field Infrared Gas Analyzer Measurements

A Licor-6400XT Portable Photosynthesis System Infrared Gas Analyzer (IRGA) was used to measure CO_2 in 2016 due to data extending beyond acceptable limits of the GC calibration curve (Doff Sotta et al., 2004). Samples from the IRGA were not taken directly in PVC chambers, but next to them, to allow for simultaneous sampling.

Measurements from the IRGA were taken from every plot each week and recorded as an average of continuous individual measurements over a minimum change of 10 ppm CO_2. IRGA measurements were collected directly in corn rows (areas with no white clover biomass) and half way between corn rows (areas with white clover biomass) to determine if there were differences in respiration.

NH_3 Acid Trap Measurements

Ammonia fluxes were measured with a static chamber and a vacuum pump acid trap in an open system configuration. Acid trap designs came from previously tested methods (Misselbrook et al., 2005), with modifications including a Balston NH_3 filter instead of an additional tube of acid before the chamber inlet for the ambient air. Flow rate was also reduced to match different chamber volume. Sampled air came from inside the chamber and was then bubbled through a fritted Midget impinger at a flow rate of 2 L min^{-1} for two hours. Due to only having two acid traps, only WC and Tr plots were sampled each week, rotating chambers and plots randomly to obtain a high sample size for the two systems hypothesized to be most different. Samples were analyzed colorimetrically in duplicate using EPA method 350.1 (O'Dell, 1993).

Soil and Environmental Parameters

Soil water content and temperature were measured using CS625 reflectometers (Campbell Scientific, Logan, UT) placed at two different soil depths (0-15 cm and 15-30 cm) between the corn rows. The rods were 30 cm in length and installed at an angle of 30 degrees

from the surface. Water content data and temperature were measured and recorded on 10-min intervals, stored on data loggers, and downloaded weekly. A soil moisture release curve based on the van Genuchten equation (Van Genuchten, 1980) was created using the evaporation method (Arya, 2002) with a HYPROP device (Decagon, Pullman, WA) from soil collected from the plot area.

Corn canopy light interception was measured weekly until the tasseling (VT) stage of corn development. A line quantum sensor (Model LI 191sb, Li-Cor, Lincoln, NE) measured the amount of light above the corn canopy and the amount of light reaching the clover canopy in the WC plots, the surface of the cover crop residue in the CC and CR plots, or the soil surface in the Tr plots, at four locations in each plot. The percentage of light intercepted by the corn canopy was calculated using the following formula:

% light interception = [1-(light at lower surface / light above corn canopy)] × 100 [2]

Soil cores were taken from eight locations at a depth of 15 cm using a 1.5-cm inside diameter handheld soil probe within the center two rows of each plot. Two of the cores were taken from random locations within the rows and three cores were taken from random locations between the rows. These samples were taken weekly throughout the growing season (April 26th – July 20th 2016, and May 4th – July 12th 2017). The cores were combined, air-dried, and stored at 4°C. Five grams of soil from each sample was extracted at 21°C with 40 mL of 1M KCl (cold extraction) and at 100 °C with 40 mL of 2M KCl (hot extraction) for NO_3^- and NH_4^+ analysis (Campbell et al., 1994). Soil extracts were analyzed for NO_3^- and NH_4^+ concentration using a TL-2800 Ammonia and Nitrate Analyzer. Soil potentially mineralizable nitrogen (PMN) was calculated as the difference between cold and hot NH_4^+ extractions. Two soil pits were dug on the periphery of the plots and 5 × 5 cm brass rings were inserted into the top 15-cm of soil. The rings and soil were dried at 105°C and the soil

bulk density was calculated. Bulk density, saturated hydraulic conductivity (Ksat), and total porosity were measured according to the core method, constant head method, and calculation from particle and bulk densities, respectively (Grossman et al., 2002, Klute et al., 1986, Flint, et al., 2002). Labile C was quantified by measuring permanganate oxidizable carbon (POXC) from six soil samples per system taken from the brass rings in August, 2017, following the methodology in Weil et al. (2003).

Soil N compounds were measured in paired plots directly across one irrigation lane to those where gas fluxes were measured in 2016 due to location of soil sampling equipment, and were taken within two days of flux sampling. In 2016, soil NO_3^-, NH_4^+, and PMN data for the linear model were averaged over the three paired plots of corresponding management technique as opposed to individual data points in 2017, when soil data were taken directly from plots where flux was measured. Management system was assumed to be the limiting factor, as both sampling locations had been identically-treated experimental plots for the three years prior to the inception of this experiment. Finally, clover biomass data were measured weekly in all WC plots. Biomass measurements were used along with soil temperature to estimate the amount of respiration coming from clover versus soil in an attempt to infer soil-only respiration in following analysis.

Statistics and Missing Data

All statistics were carried out using R version 3.4.1. Observed N_2O and NH_3 fluxes were converted to N_2O-N and NH_3-N for statistical analysis. All fluxes were log transformed prior to statistical test after failing normality testing with a Shapiro-Wilks test (Das & Imon, 2016). An initial ANOVA of all individual flux observations determined that there were significant differences in CO_2 and N_2O fluxes between treatments. To specify these differences, mean GHG fluxes were compared between all four management techniques

using Tukey's pair-wise comparison. N_2O comparisons used static chamber GC data for all time points. For IRGA data, an average of three replicates of both in-row and between-row measurements from each plot every week was used for data analysis. Comparisons of CO_2 used between-row IRGA data for 2016 and GC data for 2017. A student's T-test compared mean NH_3 fluxes in WC and Tr plots. Cumulative sums for the growing seasons were also calculated by extrapolating the average from all plots for the days between sampling.

A multiple linear regression of log-transformed individual observations of flux was performed. The goals of the regression were to determine which soil and climatic parameters were related to differences in soil GHG fluxes found in the pair-wise comparisons, and which management techniques were still significantly different after controlling for these parameters. Management technique was included as a categorical variable in part, to control for differences in fertilizer application. Single variable, season specific, and management-technique specific regressions were conducted initially to develop the final model for N_2O and CO_2 as displayed below:

$$Y_s = \beta_0 + \beta_1 Tech_1 + \beta_2 Tech_2 + \beta_3 Tech_3 + \beta_4 Season_{2016} + \beta_5 Season_{2017} + \beta_6 Temp + \beta_7 Mois + \beta_8 LightInt + \beta_9 NO_3 + \beta_{10} NH_4 + \beta_{11} PMN + \varepsilon$$

[3]

Where $\mathbf{Y}_s$ denotes soil trace gas emissions with s for separate log transformed gas species (N_2O or CO_2). The independent variables are as follows: $\mathbf{Tech_1}$ is CC, $\mathbf{Tech_2}$ is CR, $\mathbf{Tech_3}$ is WC compared to Tr as a reference, $\mathbf{Season_{2016}}$ and $\mathbf{Season_{2017}}$ compared to background measurements as a reference, **Temp** is soil temperature in °C at 15 cm, **Mois** is soil moisture between corn rows at 15 cm depth in volumetric water content, **LightInt** is light interception as the inverse of the percentage of light reaching the soil, $\mathbf{NO_3}$ is soil nitrate in

μg/g, **NH_4** is soil ammonium in μg/g, and **PMN** is potentially mineralizable N in μg/g. Multicollinearity was tested for in all final models and was not found.

Percent change for each coefficient was calculated using the following formula:

$$\% \, Change = 100 \times (e^{\beta - 1})$$

[4]

For all final CO_2 and N_2O models (N=292 and 203 respectively), an estimate of soil temperature, moisture, and N compound were calculated for Tr plots from the average of all CR plots over the same time period. This was because instrumentation for these parameters was set up from previous experiments before Tr plots were created for this one. Plots without cover crops had similar labile C to CR plots (Table S2) and had equivalent fertilization amounts each year (Table S1). Missing values for soil temperature, moisture, and N compound data were replaced with averages of the measurements taken the week before and the week after in plots with the same corn production system. This could bias results towards the null, and underestimate the effects of these parameters in the linear regression.

Model parameters other than soil temperature and moisture were not measured during background sampling. Averages from the end of the 2016 season and the beginning of the 2017 season were paired with observed background fluxes. Light interception was considered to be zero during background periods, as no corn was present to shade the soil. Data from IRGA (2016) and GC (2017) measurements were combined for the CO_2 model.

In order to estimate CO_2 fluxes from soil without clover respiration, emissions were estimated by subtracting clover respiration rates from total CO_2 flux observed. The clover respiration rates were derived, using measured clover biomass and soil temperature and a previously developed curve of clover respiration over various temperatures (Beinhart, 1962). The formula for the clover respiration estimation is shown below:

$$CO_2Clover = \frac{(m*T+b)*BM*1{,}000{,}000/3600*P}{A*R*T_k}$$

[5]

Where **CO_2Clover** is the estimated CO_2 flux from clover in µmol m^{-2} sec^{-1}, **b** and **m** are the intercept in respiration rate in µL O_2 mg^{-1} $hour^{-1}$ (-8.2) and slope in respiration rate of the respiration (0.48) function derived from Beinhart (1962), respectively, **T** is soil temperature in °C, **BM** is the clover biomass in kg within the chamber, **P** is the surface pressure in atm, **A** is the area of the chamber in m^2, **R** is the gas constant in L atm K^{-1} mol^{-1}, and $\mathbf{T_k}$ is the soil temperature in Kelvin.

Results

CO_2

Soil porosity, Ksat, and labile C were greater in WC plots compared to all other systems (by at least 7.4, 431, 22.9 % respectively), while bulk density was lower by at least 8.8% (Table S2). Between-row measurements from GC and IRGA correlated well (R^2=0.73) in 2016, with IRGA measurements greater than GC measurements in the same plot. Only GC measurements were obtained in 2017 due to IRGA instrument failure, possibly leading to an underestimation of CO_2 flux during the 2017 growing season.

Mean CO_2 fluxes for both 2016 and 2017 from between-row measurements were higher in WC plots compared to Tr plots, with a difference of 1.72 µmol m^{-2} sec^{-1} (p-value <0.001). This effect was not found in corn rows in 2016, where clover biomass was not present in the chamber (Table 1). Fluxes were greatest in WC plots in the middle of the growing season (Figure 1).

Heterotrophic estimates did not match well with corn row measurements early in the growing season (Figure S5), potentially leading to the higher fluxes observed after

subtraction. The CO_2 fluxes in corn rows and between rows in WC plots differed significantly, unlike for other treatments (Figure S5), indicating clover respiration was occurring when the clover switched from photosynthesis to respiration in the opaque chambers. Cumulative sums for CO_2 fluxes were higher in WC plots for both growing seasons (Table 1) and were greater than total SOC sequestered per year in WC plots (2.27 kg m^{-2} versus 0.62 kg m^{-2}).

The multiple linear regression of individual log-transformed between-row CO_2 fluxes showed greater flux in CC, CR, and WC plots compared to Tr plots (p-value<0.001), with WC plots having the greatest increase (Table 2), confirming the results of the post-hoc ANOVA analysis for between-row measurements. Soil moisture and light interception were correlated with higher CO_2 flux (p-value <0.001 and 0.04).

N_2O

Mean N_2O flux was higher in WC plots with differences of 1.15, 1.09, and 1.05 μmolN m^{-2} hr^{-1} for WC-CC, WC-CR, and WC-Tr, respectively (Table 1, p-value ≤ 0.001 for all). The N_2O fluxes were near background levels at the beginning and end of the growing season and greater, following fertilizer application. The largest fluxes were in the WC plots for both years and in Tr plots following fertilizer application in 2016. There were greater fluxes in CC, CR, and Tr plots in 2017 in the weeks following fertilizer application (Figure 2). Cumulative sums for N_2O were also higher in WC plots for both growing seasons compared to all other techniques (Table 1).

The multiple linear regression of individual log-transformed N_2O fluxes indicated that WC plots had a larger N_2O flux than Tr plots (Table 3, p-value < 0.001), confirming the results of the post-hoc ANOVA analysis. Higher N_2O fluxes compared to Tr plots were not observed in CC and CR plots (Table 3). Soil moisture and soil NO_3 were correlated at the

α=0.05 level with higher N_2O fluxes (p-values of < 0.001 and 0.016 respectively) and soil NH_4 was corelated at the α=0.10 level (p-value of 0.063).

NH_3

Mean NH_3 fluxes were significantly higher in the WC plots (21.8 nmolN m^{-2} hr^{-1}, 95% CI (13.8, 29.7)) compared to the Tr plots (9.22 nmol m^{-2} hr^{-1}, 95% CI (6.25, 12.2)) during the 2017 growing season. NH_3 fluxes were higher towards the middle of the growing season in both Tr and WC plots with large fluxes in the weeks following fertilizer application (maximum flux of 75 nmolN m^{-2} hr^{-1}) (Figure 3).

Discussion

CO_2

Higher CO_2 fluxes in WC plots were observed in between rows, where clover biomass was present, but not within corn rows, where no clover biomass was present in 2016. This indicates a large amount of the flux between corn rows could be due to clover respiration. The discrepancy between estimated heterotrophic respiration and measurements in corn rows likely arose from an underestimation of clover respiration in the early growing season (Figure S5). Future studies should directly measure clover respiration and how it changes when the chamber is closed or open to better account for light effects on clover respiration. More in-row measurements could also avoid clover respiration masking responses in heterotrophic soil respiration. The increase in soil labile C in LMS plots indicates minimal C sequestration in comparison to increased emissions. However, labile C has rapid turnover rates, and future studies should assess total SOC at different depths to get a better measure of sequestration in an LMS (Table S2) (Martens, 2000).

Decomposition of clover could have increased CO_2 fluxes (Singh et al., 1977) and soil respiration can increase with higher C:N ratios in litter layers (Spohn, 2015). Future studies should include cover crop C:N ratios to explore these relationships further in an LMS compared to other systems.

Soil moisture was positively correlated with CO_2 flux in the linear model and has previously been shown to be an important factor altering CO_2 flux within no-till systems (Harper et al., 2005, Linn et al., 1984, Harmanjit et al., 2015).

Previous studies have shown that systems with N-rich legume biomass residue have higher soil respiration compared to systems without residue on the soil surface (Hendrix et al., 1988). This effect could be amplified in the WC plots, with clover depositing biomass throughout the entire growing season. This study showed that a WC LMS had higher soil heterotrophic respiration after subtracting estimated autotrophic clover respiration. However, this did not corroborate measurements from in corn rows, especially early in the growing season. Future studies should calculate a complete net C equivalence using inputs and outputs including irrigation, fertilizer production, and carbon sequestration.

N_2O and NH_3

Between-row fluxes of N_2O and NH_3 were significantly higher in WC plots compared to the other cover crops and no cover crop systems. Higher NH_3 fluxes in WC plots compared to Tr plots was contrary to the original hypothesis, based on the fact that a lower amount of urea-based fertilizer was applied on WC plots versus Tr plots (Table S1). Cereal grain cover crops have been shown to decrease NH_3 and N_2O emissions due to enhanced N retention (Parkin et al., 2006). The difference in LMS versus common cover crop methods could be related to the timing of N fertilization in between rows from the clover biomass. Large NH_3 fluxes tend to be restricted to short time periods after fertilizer application (Herrmann, 2001).

N_2O fluxes tend to increase exponentially following fertilizer application, then become greater than pre-fertilizer application (Hoben et al., 2011). In an LMS, more of the N is supplied from cover crop decomposition versus inorganic fertilizer, which is the main N source for the other plots (Andrews et al., 2018, Table S1), potentially causing the overall increases in N fluxes in WC plots. In-row measurements of N_2O and NH_3 fluxes should be sampled in future studies to account for potential effects of clover on flux.

Soil moisture, NO_3^-, and NH_4^+ have all been proven as drivers of N_2O flux (Marquina et al., 2015). The correlations presented here with N_2O and NO_3^-/NH_4^+ suggest both nitrification and denitrification are contributing to N_2O fluxes (Stevens et al., 1997). Plots with WC had the lowest total NH_4^+ and NH_4^+:NO_3^- ratio. This potentially indicates more NO_3^- is available for denitrification than NH_4^+ is available for nitrification in these systems, and denitrification could be the greater source of N_2O formation. However, denitrification and nitrification are complex processes, so techniques such as stable isotope and acetylene inhibition (Bateman et al., 2005) should be used in future studies to quantify the amount of N_2O from both processes (Butterbach-Bahl, et al., 2013). One limitation of this study is that the 2016 soil N compound data is in paired plots, rather than in the same plots as flux measurements. Regressions with only 2017 data showed NH_4^+ as a stronger driving force than NO_3^- (Table S3), so future studies should maintain consistency in measurement locations. Soils with higher SOC (as observed in WC plots) can have greater overall N_2O emissions, compared to less fertile soils (Bouwman et al., 2002).

The higher N_2O flux in WC plots compared to Tr plots supports the findings in Turner et al. (2016). Additionally, cumulative sums for LMS systems were similar between the two studies (220.2 in 2016 and 229.9 mg N m^{-2} in 2017 versus 226.5 mg N m^{-2} in Turner et al. (2016)), indicating that white clover and kura clover affect soil fluxes similarly despite different growth rates. Both studies observed the largest N_2O fluxes late in the growing

season, likely due to clover decomposition and mineralization. While the current study originally hypothesized that NH_3 fluxes would be decreased in WC plots due to a lower fertilizer application rate, the results suggest that the continuous release of N outweighed the reduced fertilizer amount.

Conclusion

This study found greater mean CO_2, N_2O, and NH_3 soil between-row fluxes in WC plots compared to three conventional agricultural systems. However, for CO_2, these increased fluxes were not observed from measurements in the corn rows, indicating further study is necessary to elucidate if the increased respiration is autotrophic, heterotrophic, or a combination. N_2O and NH_3 fluxes were higher in LMS plots despite reduced fertilization. Nitrification and denitrification rates should be explored to better understand the specific sources of N_2O fluxes. This study illustrates the complexity of developing a CSA system. A net C equivalence should be calculated from future studies, including soil flux measurements of CO_2, N_2O and NH_3, soil C sequestration, and agricultural inputs to assess the mitigation potential of an LMS.

References

Abdalla, M., Hastings, A., Helmy, M., Prescher, A., Osborne, B., Lanigan, G., … Jones, M. B. (2014). Assessing the combined use of reduced tillage and cover crops for mitigating greenhouse gas emissions from arable ecosystem. *Geoderma*, *223–225*(1), 9–20. https://doi.org/10.1016/j.geoderma.2014.01.030

Alexander, J. R., Venterea, R. T., Baker, J. M., & Coulter, J. A. (2019). Kura Clover Living Mulch : Spring Management Effects on Nitrogen. *Agronomy*, *9*(69), 1–14. https://doi.org/10.3390/agronomy9020069

Anderson, N., Strader, R., & Davidson, C. (2003). Airborne reduced nitrogen: Ammonia emissions from agriculture and other sources. *Environment International*, *29*(2–3), 277–286. https://doi.org/10.1016/S0160-4120(02)00186-1

Andrews, J. S., Sanders, Z. P., Cabrera, M. L., Saha, U. K., & Hill, N. S. (2018). Nitrogen dynamics in living mulch and annual cover crop corn production systems. *Agronomy Journal*, *110*(4), 1309–1317. https://doi.org/10.2134/agronj2017.10.0609

Basche, A. D., Miguez, F. E., Kaspar, T. C., & Castellano, M. J. (2014). Do cover crops increase or decrease nitrous oxide emissions ? A meta-analysis, *69*(6), 471–482. https://doi.org/10.2489/jswc.69.6.471

Bateman, E. J., & Baggs, E. M. (2005). Contributions of nitrification and denitrification to N2O emissions from soils at different water-filled pore space. *Biology and Fertility of Soils*, *41*(6), 379–388.

Bauer, S.E., Tsigaridis, K., Miller, R. (2016). Significant atmospheric aerosol pollution caused by world food cultivation. *Geophys. Res. Lett.*, *43*, 5394–5400. https://doi.org/10.1002/2016GL068354

Beinhart, G. (1962). Effects of Temperature & Light Intensity on CO2 Uptake, Respiration, & Growth of White Clover. *Plant Physiology*, *37*(6), 709–715.

Bhatia, A., Pathak, H., & Aggarwal, P. K. (2004). Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. *Current Science*, *87*(3), 317–324.

Bryan, E., Ringler, C., Okoba, B., Koo, J., Herrero, M., & Silvestri, S. (2013). Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? insights from Kenya. *Climatic Change*, *118*(2), 151–165. https://doi.org/10.1007/s10584-012-0640-0

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., & Zechmeister-Boltenstern, S. (2013). Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Philosophical Transactions of the Royal Society B: Biological Sciences*, *368*(1621), 20130122–20130122. https://doi.org/10.1098/rstb.2013.0122

Campbell, C. A., Jame, Y. W., Akinremi, O. O., & Beckie, H. . (1994). Evaluating potential nitrogen mineralization for predicting fertilizer nitrogen requirements of long-term field experiments. In *Soil testing: Prospects for improving nutrient recommendations soiltestingpros* (pp. 81–100).

Collier, S. M., Ruark, M. D., Oates, L. G., Jokela, W. E., & Dell, C. J. (2014). Measurement of greenhouse gas flux from agricultural soils using static chambers. *Journal Of Visualized Experiments: Jove*, (90), e52110–e52110. https://doi.org/10.3791/52110

Das, K. R., & Imon, A. H. M. R. (2016). A Brief Review of Tests for Normality. *American Journal of Theoretical and Applied Statistics*, *5*(1), 5–12. https://doi.org/10.11648/j.ajtas.20160501.12

Doff Sotta, E., Meir, P., Malhi, Y., Donato Nobre, A., Hodnetts, M., & Grace, J. (2004). Soil CO2 efflux in a tropical forest in the central Amazon. *Global Change Biology*, *10*, 601–617. https://doi.org/10.1111/j.1529-8817.2003.00761.x

Flint, L. E., & Flint, A. L. (2002). Porosity. In J. H. Dane & G. C. Topp (Eds.), *Methods of Soil Analysis: Part 4, Physical Methods* (pp. 241–242). Madison, WI: SSSA.

Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z., Freney, J. R., … Sutton, M. A. (2008). Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. *Science*, *320*(5878), 889–892. https://doi.org/10.1126/science.1136674

Grossman, R. B., & Reinsch, T. G. (2002). Bulk density and linear extensibility. In J. H. Dane & G. C. Topp (Eds.), *Methods of Soil Analysis: Part 4, Physical Methods* (pp. 201–208). Madison, WI: SSSA.

Harmanjit, S. D., Brar, B. S., & Black, T. A. (2015). Influence of Crop Growth and Weather Variables on CO2 Emissions in a Maize-Wheat Cropping System. *Agric. Res. J.*, *52*(10), 28–34.

Harper, C. W., Blair, J. M., Fay, P. A., Knapp, A. K., & Carlisle, J. D. (2005). Increased rainfall variability and reduced rainfall amount decreases soil CO2 flux in a grassland ecosystem. *Global Change Biology*, *11*(2), 322–334. https://doi.org/10.1111/j.1365-2486.2005.00899.x

Hartwig, N. L., Ammon, H. U., Science, W., Hartwig, N. L., & Ammon, H. U. (2002). Cover Crops and Living Mulches. *Weed Science*, *50*(6), 688–699.

Hendrix, P. F., Han, C. R., & Groffman, P. M. (1988). Soil respiration in conventional and no-tillage agroecosystems under different winter cover crop rotations. *Soil and Tillage*

Research, *12*(2), 135–148. https://doi.org/10.1016/0167-1987(88)90037-2

Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, *151*(2), 362–367. https://doi.org/10.1016/j.envpol.2007.06.012

Kaye, J. P., & Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, *37*(1).

Klute, A., & Dirksen, C. (1986). Hydraulic conductivity and diffusivity: Laboratory methods. In A. Klute (Ed.), *Methods of Soil Analysis: Part 1* (2nd ed., pp. 687–734). Madison, WI: SSSA.

Larsson, L., Ferm, M., Kasimir-Klemedtsson, A., & Klemedtsson, L. (1998). Ammonia and nitrous oxide emissions from grass and alfalfa mulches. *Nutrient Cycling in Agroecosystems*, *51*(1), 41–46.

Linn, D. M., & Doran, J. W. (1984). Effect of Water-Filled Pore Space on Carbon Dioxide and Nitrous Oxide Production in Tilled and Nontilled Soils. *Soil Science Society of America Journal*, *48*(1961), 1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x

Marquina, S., Pérez, T., Donoso, L., Giuliante, A., Rasse, R., & Herrera, F. (2015). NO, N2O and CO2soil emissions from Venezuelan corn fields under tillage and no-tillage agriculture. *Nutrient Cycling in Agroecosystems*, *101*(1), 123–137. https://doi.org/10.1007/s10705-014-9659-0

Martens, D. A. (2000). Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. *Soil Biology and Biochemistry*, *32*, 361–369.

Misselbrook, T. H., Powell, J. M., Broderick, G. A., & Grabber, J. H. (2005). Dietary

Manipulation in Dairy Cattle : Laboratory Experiments to Assess the Influence on Ammonia Emissions. *Journal of Dairy Science*, 1765–1777.

Montzka, S. A., Dlugokencky, E. J., & Butler, J. H. (2011). Non-CO2 greenhouse gases and climate change. *Nature*, *476*(7358), 43–50. https://doi.org/10.1038/nature10322

Myhre, G., Shindell, D., Bréon, F. ., Collins, W., Fuglestvedt, J., Huang, J., … Nakajima, T. (2013). *Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. Midgley, Eds.). United Kingdom and New York, NY, USA.: Cambridge University Press Cambridge.

Nakamoto, T., & Tsukamoto, M. (2006). Abundance and activity of soil organisms in fields of maize grown with a white clover living mulch. *Agriculture, Ecosystems and Environment*, *115*(1–4), 34–42.

Ochsner, T. E., Albrecht, K. A., Schumacher, T. W., Baker, J. M., & Berkevich, R. J. (2010). Water balance and nitrate leaching under corn in kura clover living mulch. *Agronomy Journal*, *102*(4), 1169–1178. https://doi.org/10.2134/agronj2009.0523

O'Dell, J. W. (1993). Method 350.1 Determination of ammonium nitrogen by semi-automated colorimetry. *USEPA Environmental Monitoring Systems Lab, Cincinnati, OH*, *August*(Revision 2.0), 1–15.

Park, S., Croteau, P., Boering, K. A., Etheridge, D. M., Ferretti, D., Fraser, P. J., … Trudinger, C. M. (2012). Trends and seasonal cycles in the isotopic composition of nitrous oxide since 1940. *Nature Geoscience*, *5*(4), 261–265. https://doi.org/10.1038/ngeo1421

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174

Robertson, G. P., Paul, E. A., & Harwood, R. R. (2000). Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere. *Science*, *289*(Table 1).

Ruijter, F. J. De, Huijsmans, J. F. M., & Rutgers, B. (2010). Ammonia volatilization from crop residues and frozen green manure crops. *Atmospheric Environment*, *44*(28), 3362–3368. https://doi.org/10.1016/j.atmosenv.2010.06.019

Sanders, Z. P., Andrews, J. S., & Hill, N. S. (2018). Water use efficiency in living mulch and annual cover crop corn production systems. *Agronomy Journal*, *110*(3), 1128–1135. https://doi.org/10.2134/agronj2017.08.0475

Smith, P., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., … Ravindranath, N. H. (2014). Agriculture, forestry and other land use (AFOLU). In O. Edenhofer (Ed.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 813–922). Cambridge University Press.

Sommer, S. G., Schjoerring, J. K. Denmead, O. T. (2004). Ammonia emission from mineral fertilizers and fertilized crops. *Advances in Agronomy*, *82*(557622).

Spohn, M. (2015). Microbial respiration per unit microbial biomass depends on litter layer carbon-to-nitrogen ratio. *Biogeosciences*, *12*, 817–823. https://doi.org/10.5194/bg-12-817-2015

Stevens, R. J., Laughlin, R. J., Burns, L. C., Arah, J. R. M., & Hood, R. C. (1997). Measuring the contributions of nitrification and denitrification to the flux of nitrous oxide from soil.

Soil Biology and Biochemistry, *29*(2), 139–151. https://doi.org/10.1016/S0038-0717(96)00303-3

Parkin, T. B., Kaspar, T. C., & Singer, J. W. (2006). Cover crop effects on the fate of N following soil application of swine manure. *Plant and Soil*, *289*(1–2), 141–152. https://doi.org/10.1007/s11104-006-9114-3

Parkin, Timothy B. and Venterea, Rodney T.. (2010). USDA-ARS GRACEnet Project Protocols Chapter 3. Chamber-Based Trace Gas Flux Measurements. *Flux*, *2010*(April 2003), 1–39.

Tribouillois, H., Fort, F., Cruz, P., Charles, R., Flores, O., Garnier, E., & Justes, E. (2015). A Functional Characterisation of a Wide Range of Cover Crop Species : Growth and Nitrogen Acquisition Rates , Leaf Traits and Ecological Strategies. *PLoS ONE*, *10*(3), 1–17. https://doi.org/10.1371/journal.pone.0122156

Tubiello, F. N., Salvatore, M., Ferrara, A., Rossi, S., Biancalani, R., Condor Golec, R. D., … Srivastava, N. (2015). The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2010: Not as high as in the past. *Global Change Biology*, 2655–2660.

Turner, P. A., Baker, J. M., Griffis, T. J., & Venterea, R. T. (2016). Impact of Kura Clover Living Mulch on Nitrous Oxide Emissions in a Corn–Soybean System. *Journal of Environment Quality*, *45*(5), 1782. https://doi.org/10.2134/jeq2016.01.0036

Weil, R. R., Islam, K. R., Stine, M. a, Gruver, J. B., & Samson-Liebig, S. E. (2003). Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *American Journal of Alternative Agriculture*, *18*(1), 3–17. https://doi.org/10.1079/ajaa2003003

Wollenberg, E., Richards, M., Smith, P., Havlk, P., Obersteiner, M., Tubiello, F. N., … Campbell, B. M. (2016). Reducing emissions from agriculture to meet the 2C target. *Global Change Biology*, *22*(12), 3859–3864. https://doi.org/10.1111/gcb.13340

Zemenchik, R. A., Albrecht, K. A., Boerboom, C. M., & Lauer, J. G. (2000). Corn production with kura clover as a living mulch. *Agronomy Journal*, *92*(4), 698–705.

Zemenchik, R. A., Albrecht, K. A., & Schultz, M. K. (2001). Nitrogen replacement values of kura clover and birdsfoot trefoil in mixtures with cool-season grasses. *Agronomy Journal*, *93*(2), 451–458.

Figure Captions

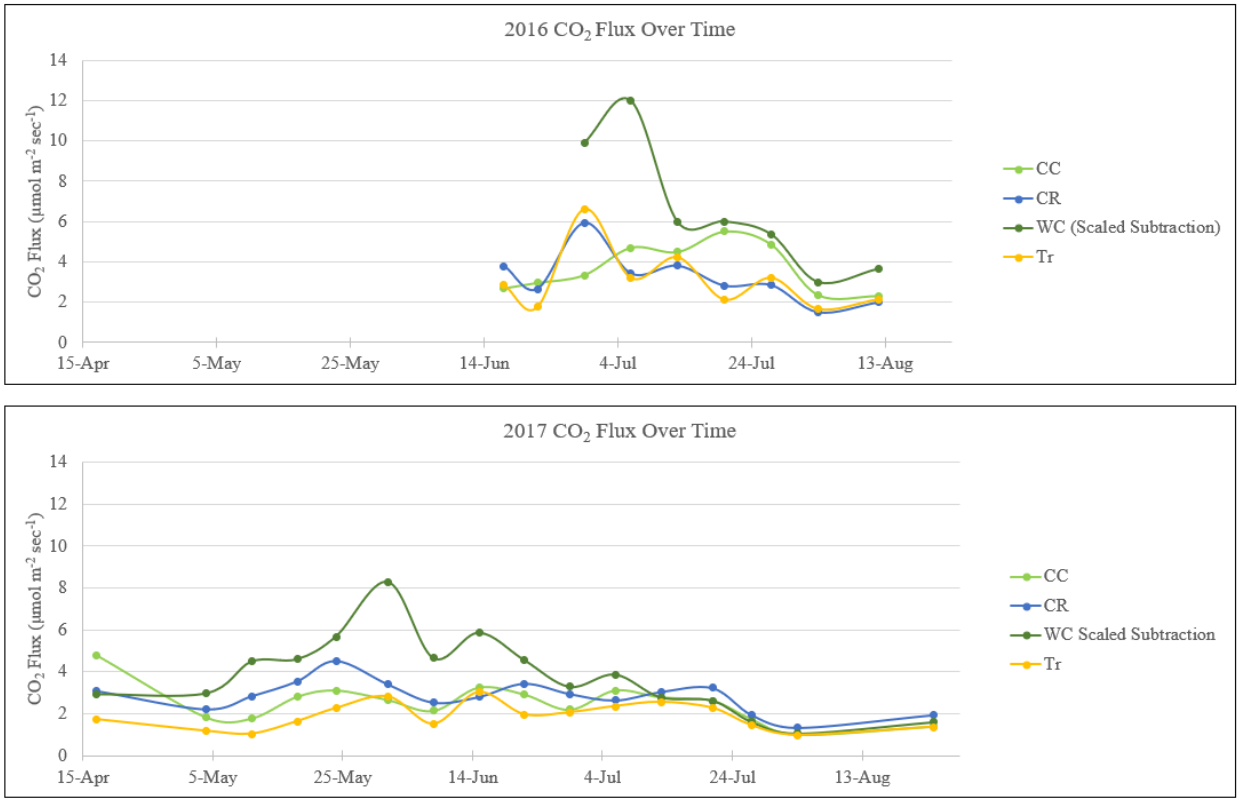

Figure 1: Time series of daily average flux measurements between the corn rows of CO_2 in µmol m^{-2} sec^{-1} during the 2016 (A) and 2017 (B) growing seasons for crimson clover (CC), cereal rye (CR), white clover living mulch (WC), and conventional (Tr) treatments. CO_2 flux was higher in WC plots for both seasons. No error bars are included due to weekly sample sizes of three or less.

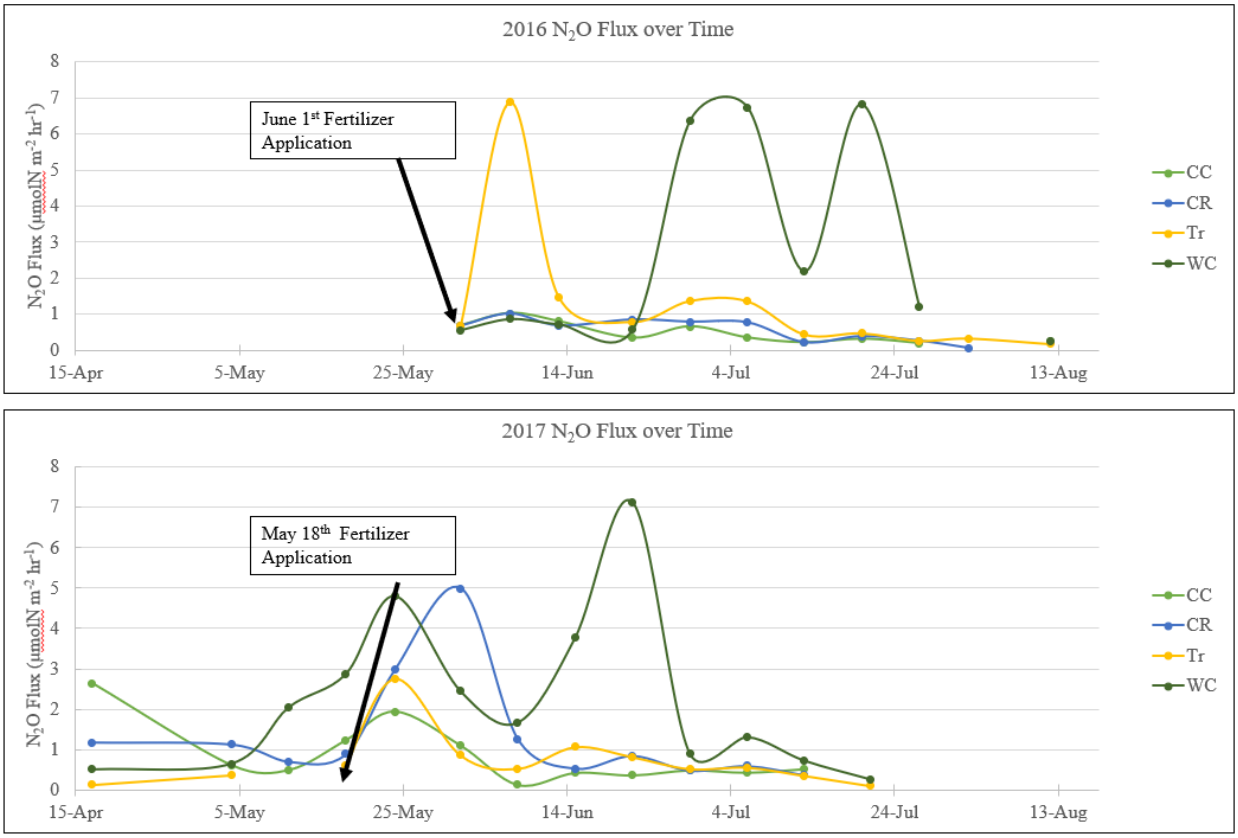

Figure 2: Time series of daily average flux measurements between the corn rows of N_2O in µmolN m^{-2} hr^{-1} during the 2016 (A) and 2017 (B) growing seasons for crimson clover (CC), cereal rye (CR), white clover living mulch (WC), and conventional (Tr) treatments.

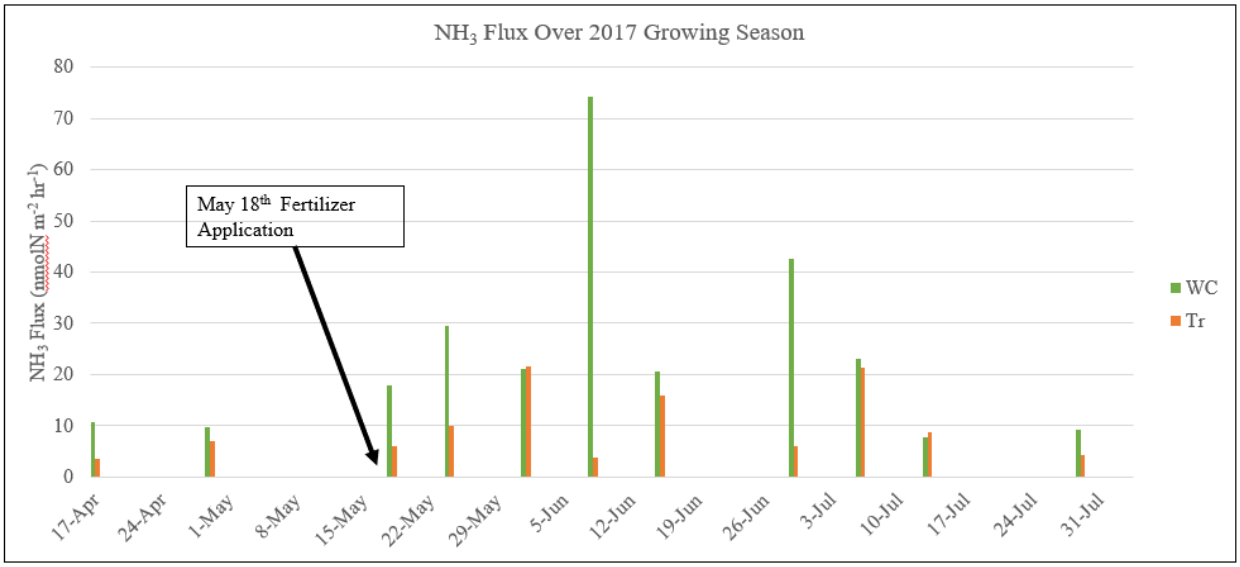

Figure 3: The NH_3 flux measurements in white clover living mulch (WC) and conventional (Tr) treatments over the 2017 growing season. Fertilizer was applied on May 18th.

Tables

Table 1: Flux Rate Means and Comparisons for CO_2 and N_2O

Overall Means				
Mean Gas Flux	*CC (95% CI)*	*CR (95% CI)*	*WC (95% CI)*	*Tr (95% CI)*
CO_2 (µmol m^{-2} sec^{-1})	2.79 (2.43, 3.15)	2.78 (2.50, 3.06)	4.20 (3.41, 4.99)	1.98 (1.73, 2.24)
N_2O (µmolN m^{-2} hr^{-1})	0.50 (0.37, 0.64)	0.56 (0.40, 0.73)	1.65 (1.09, 2.21)	0.60 (0.32, 0.89)
NH_3 (nmolN m^{-2} hr^{-1})	NA	NA	21.8 (13.8, 29.7)	9.22 (6.25, 12.2)

Cumulative Flux Sums (in kg ha^{-1} yr^{-1})

Gas	CC-2016	CC-2017	CR-2016	CR-2017	WC-2016	WC-2017	Tr-2016	Tr-2017
CO_2	8,010	12,000	6,830	12,800	16,567	17,094	6,620	8,320
N_2O-N	0.16	0.32	0.17	0.38	0.67	0.68	0.52	0.20

Mean Log CO_2 Flux Comparisons from Between-Row Measurements (2016 & 2017)

Comparison	*Difference in µmol m^{-2} sec^{-1}*	*95% CI Lower Bound*	*95% CI Upper Bound*	*P-value*
WC-Tr	0.54	0.24	0.83	<0.001*
WC-CR	0.22	-0.06	0.49	0.19
WC-CC	0.19	-0.09	0.47	0.28
Tr-CR	-0.32	-0.61	-0.03	0.03*
CR-CC	-0.02	-0.29	0.25	0.99
Tr-CC	-0.34	-0.64	-0.05	0.02*

Mean Log CO_2 Flux Comparisons from In-Row Measurements (2016)

Comparison	*Difference in µmol m^{-2} sec^{-1}*	*95% CI Lower Bound*	*95% CI Upper Bound*	*P-value*
WC-Tr	0.18	-0.29	0.65	0.74
WC-CR	0.18	-0.15	0.51	0.49
WC-CC	0.16	-0.18	0.50	0.61
Tr-CR	-0.002	-0.47	0.46	0.99
CR-CC	-0.02	-0.35	0.32	0.99
Tr-CC	-0.002	-0.49	0.45	0.99

Mean Log N_2O Flux Comparisons from Between-Row Measurments (2016 & 2017)

Comparison	*Difference in µmol m^{-2} hr^{-1}*	*95% CI Lower Bound*	*95% CI Upper Bound*	*P-value*
WC-Tr	0.91	0.41	1.40	<0.001*

WC-CR	0.86	0.41	1.30	<0.001 *
WC-CC	0.93	0.47	1.39	<0.001 *
Tr-CR	-0.05	-0.55	0.45	0.99
CR-CC	0.07	-0.39	0.55	0.97
Tr-CC	0.03	-0.49	0.54	0.99

* Significant differences at α=0.05 level using Tukey's comparisons of log transformed fluxes.
White living mulch (WC), conventional no cover crop (Tr), cereal rye cover crop (CR), crimson clover cover crop (CC)

Table 2: Linear Regression of Weekly Log Transformed CO_2 Flux

With Autotrophic Scaled Subtraction (N=282, R^2=0.40)				
Variable	*Estimate (β) (95% CI)*	*Standard Error of Estimate*	*Percent Change (%) (95% CI)*	*P-value*
Intercept	-0.68	0.33	NA	<0.001***
CC	0.40 (0.21, 0.59)	0.096	49.5 (23.7, 80.6)	<0.001***
CR	0.33 (0.14, 0.52)	0.095	38.8 (15.1, 67.4)	<0.001***
WC	0.61 (0.42, 0.81)	0.099	84.8 (52.2, 124.4)	<0.001***
Season 2016	0.68 (0.42, 0.95)	0.13	98.3 (52.2, 158.4)	<0.001***
Season 2017	0.20 (-0.06, 0.45)	0.13	21.8 (-5.41, 56.9)	0.13
Temp	-0.007 (-0.03, 0.016)	0.012	-0.71 (-2.94, 1.57)	0.54
Soil Moisture	6.71 (4.97, 8.45)	0.88	6.94 (5.10, 8.82)	<0.001***
Light Interception	0.23 (0.007, 0.45)	0.11	25.7 (0.69, 56.9)	0.04*
Soil NO_3	0.006 (-0.002, 0.01)	0.004	0.59 (-0.16, 1.34)	0.12
Soil NH_4	-0.002 (-0.007, 0.002)	0.002	-0.25 (-0.70, 0.21)	0.29
PMN	-0.02 (-0.05, 0.004)	0.012	-1.99 (-4.35, 0.43)	0.11

***p<0.001, **p< 0.01, *p< 0.05, $^{\#}$p<0.10
White living mulch (WC), conventional no cover crop (Tr), cereal rye cover crop (CR), crimson clover cover crop (CC)

Table 3: Linear Regression of Weekly Log Transformed N_2O Flux, (N=203, R^2=0.48)

Variable	*Estimate (β) (95% CI)*	*Standard Error of Estimate*	*Percent Change (%) (95% CI)*	*P-value*
Intercept	-4.58	0.76	NA	<0.001***
CC	0.12 (-0.21, 0.45)	0.17	12.8 (-18.9, 56.8)	0.47
CR	0.092 (-0.23, 0.41)	0.16	9.66 (-20.5, 50.7)	0.57
WC	1.19 (0.86, 1.52)	0.17	228.5 (136.3, 357.2)	<0.001***
Season 2016	0.75 (0.15, 1.36)	0.31	112.4 (16.2, 289.6)	0.015*
Season 2017	0.68 (0.079, 1.28)	0.31	97.4 (8.22, 259.7)	0.027*
Temp	0.03 (-0.029, 0.089)	0.030	3.07 (-2.86, 9.31)	0.31
Soil Moisture	11.94 (8.73, 15.2)	1.63	12.69 (9.12, 16.4)	<0.001***
Light Interception	-0.12 (-0.46, 0.23)	0.17	-10.0 (-36.9, 25.9)	0.50
Soil NO_3	0.014 (0.0025, 0.025)	0.0056	1.38 (0.25, 2.53)	0.016*
Soil NH_4	0.0062 (-0.00034, 0.013)	0.0033	0.62 (-0.034, 1.31)	0.063$^{\#}$
PMN	0.0024 (-0.008, 0.13)	0.0053	0.24 (-0.80, 13.9)	0.65

***p<0.001, **p< 0.01, *p< 0.05, $^{\#}$p<0.10

White living mulch (WC), conventional no cover crop (Tr), cereal rye cover crop (CR), crimson clover cover crop (CC)

Acknowledgments

This research was supported in part by the Emory University Research Committee and by the United States Department of Agriculture National Institute of Food and Agriculture Foundation Program. We thank Carla Gann, MS for technical assistance with gas chromatography, the editor and the anonymous reviewers for their helpful comments.