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Conservation agriculture as a climate change mitigation strategy in Zimbabwe

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Conservation agriculture as a climate change mitigation strategy in Zimbabwe

Abstract

There is a need to quantify agriculture's potential to sequester carbon (C) to inform global approaches aimed at mitigating climate change effects. Many factors including climate, crop, soil management practices, and soil type can influence the contribution of agriculture to the global carbon cycle. The objective of this study was to investigate the C sequestration potential of conservation agriculture (CA) (defined by minimal soil disturbance, maintaining permanent soil cover, and crop rotations). This study used micrometeorological methods to measure carbon dioxide (CO₂) flux from several alternative CA practices in Harare, central Zimbabwe.

Micrometeorological methods can detect differences in total CO₂ emissions of agricultural management practices; our results show that CA practices produce less CO₂ emissions. Over three years of measurement, the mean and standard error (SE) of CO₂ emissions for the plot with the most consistent CA practices was $0.564 \pm 0.0122 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$, significantly less than $0.928 \pm 0.00859 \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ for the conventional tillage practice. Overall CA practices of no-till with the use of cover crops produced fewer CO₂ emissions than conventional tillage or fallow.

Keywords

Conservation agriculture; carbon dioxide (CO₂) emissions; no-till; micrometeorology; climate change mitigation

Introduction

Reducing CO₂ emissions from fossil fuel combustion is a critical step towards not exceeding the 1.5°C threshold in global temperature above pre-industrial levels set by the UN Paris Agreement at COP21 (IPCC-SR15, 2018). Amongst other land uses, the role of agriculture in the global context of climate change cannot be ignored. Smith (2016) concluded that agriculture offers several strategies that could help moderate the expected increases in atmospheric CO₂ concentrations. He proposed employing wide-scale changes in soil management that would promote soil C sequestration including degraded land restoration, reduced tillage, crop residue retention, cover crops, diverse crop rotations, utilization of organic amendments, deeper rooting plant varieties, and optimizing both population densities and nutrient management. Obviously, it is necessary to account for site-specific factors such as climate, soil type, and previous land use.

Following atmospheric convention, a flux is deemed to be positive when CO₂ is emitted from plants or soil to the atmosphere. The rate of exchange is considered to be negative when CO₂ is extracted from the atmosphere and “sequestered” into ecosystem plants or soil (D Baldocchi et al., 2001). Soil C reserves are accumulated over millennia, from the decay and assimilation of the organic matter deposited on and within the soil as plants and roots die and decay, such as in prairie/grassland soils, wetlands, peatlands, marshes and the topsoil under forests. The organic C that plants produce from the sequestration of atmospheric CO₂ is transferred to the soil after plant necrosis with both root and plant residue mineralization being fundamental to soil C formation (Kirschbaum, 2000). From the soil ecosystem perspective, the C cycle continues with CO₂ released (emitted) back into the atmosphere through decomposition

of both soil and plant organic matter by microorganisms (respiration) and can be accelerated by tillage (Schlesinger & Andrews, 2000).

Modifying agricultural practices would appear to be an obvious choice for climate change mitigation, since cropland occupies 11% of the earth's land surface (FAO, 2011) and is intensively managed. Like forests, crop production produces plants that remove CO₂ from the atmosphere. Though Smith (2016) points out that some agricultural practices have the potential to sequester C—i.e., to be a negative emission strategy—the current assessment of agriculture is that it is generally a net emitter of CO₂ and other greenhouse gases because of the dominant contribution of CO₂ emissions from soils (Smith, 2008).

The three principles of Conservation Agriculture (CA)—minimal soil disturbance, maintaining soil cover with crop residue and/or mulch, and crop rotation (Hobbs, 2007)—are among the crop management practices described by Kassam et al. (2009) that sequester soil C. However, field studies have not always confirmed that these practices sequester soil C (Powlson et al., 2014) as they vary with context; soil C sequestration depends on the site management, crop, yield, climate, soil type, and agro-ecologies involved (Cheesman et al., 2016).

Many soil C sequestration uncertainties result from challenges in measuring soil C stocks, which are made especially difficult considering soil spatial and temporal variability as well as the time needed to measure changes on a mass or volume basis (Eswaran et al., 1993). Increasingly researchers question the comparability of soil C measurements from soils with different bulk densities, which could mislead assessments of CA systems as compared to tillage practices (Palm et al., 2014). Considering the temporal and spatial variability of soil C, small annual changes in soil C can take greater than five years to detect (Smith, 2004; Nectpálová et al., 2014). Taking into account the impact of both climate and the combination of agricultural

management practices on soil organic C, it is understandable that many studies do not show consistent soil C sequestration results (Powlson et al., 2016).

Micrometeorological (micromet) methods allow measurement of the exchanges of physical quantities—such as heat and mass—in the atmospheric boundary layer and can be used to estimate the movement of CO₂ and other trace gases between the surface (vegetation canopy, soil or soil cover) and the atmosphere at the field scale (Arya, 2001). By measuring CO₂ flux using micromet methods (e.g., eddy covariance (EC) or Bowen ratio energy balance (BREB)) (Kanemasu et al., 1979), we can estimate the net ecosystem exchange of CO₂ (NEE) between a surface and the atmosphere for a given agricultural management practice over a given period of time. The NEE summarizes whether an ecosystem is a CO₂ source or sink for a season or a year. Measuring CO₂ flux over several years can provide information about climate and agricultural management impacts on NEE not available from other experimental methods. Negative NEE (net removal of CO₂ from the atmosphere to the ecosystem for a time period) does not always translate into soil C sequestered. However, NEE can be used to show both the short- and long-term CO₂ sink and source potential of an ecosystem and the comparative benefits of factors such as climate and management practice that contribute to the overall CO₂ exchange. For example, the global and regional networks of more than 900 EC measurement stations distributed around the world have produced more than 7000 site-years of data, all of which shed light on factors such as the disturbance of vegetation or soil, plant phenology and climate, which contribute to NEE (Baldocchi, 2014; Chu et al., 2017).

Mixed results have been reported from EC micromet studies that have measured the C sequestration potential of soils managed using CA principles. Baker and Griffis (2005) measured the NEE of a spring cover crop using conventional tillage (CT) and compared it to a

site using strip tillage for two years of a maize (*Zea mays* L.)-soybean (*Glycine max* L.) rotation near Minneapolis, MN. They found no significant reduction of emissions from the strip tillage practice and both systems were net sources of atmospheric C, suggesting that larger differences may be observed when CT is compared to continuous no-till. Hollinger et al. (2005) found a six-year no-till maize-soybean rotation near Champaign, IL to be a net C sink overall, though during soybean years, the ecosystem was a net source. In a three-year no-till study, Verma et al. (2005) found that a rainfed maize-soybean rotation was C neutral, while an irrigated continuous maize field was close to C neutral or a small C source. Additionally Verma et al. (2005) found that an area of irrigated maize-soybean rotation emitted more C than the irrigated continuous maize. When expanding the study to eight years, Suyker and Verma (2012) found that a rainfed maize-soybean rotation remained C neutral, while an irrigated maize-soybean rotation moved closer to being C neutral from being a C source. During a four-year maize-soybean rotation that included tillage near Ames, IA, Hernandez-Ramirez et al. (2011) concluded that maize appeared to be C neutral while soybean may have been a net source. These EC studies show that no-till maize can range from being a C sink to a slight C source, while the addition of soybean rotations, irrigation and tillage practices generally increased emissions. These studies also support other soil C measurements showing that soybean residues decompose faster than maize due to a lower C:N ratio reducing soil C sequestration (de Moraes Sá et al., 2013; Reicosky et al., 1995; West & Post, 2002).

Several chamber studies have examined CO₂ emissions over agriculture in Africa (Kim et al., 2016; Rosenstock et al., 2016). Studies using chambers confront many challenges, including spatial and temporal variability and cumbersome sample processing (Kimaro et al., 2016; Rosenstock et al., 2016). Hence, several studies in Africa have used micromet methods to

measure CO₂ exchange rates, though most have been over savanna ecosystems (Tagesson et al., 2015; Williams et al., 2009) with no studies over agricultural cropland. Ciais et al. (2011) reviewed the C balances of African ecosystems and reported a need for more observations of C fluxes and stocks, recommending a network of EC flux towers for agroecosystems as well as other terrestrial ecosystems. There are also fewer micromet stations measuring CO₂ flux in subtropical climates as opposed to temperate climates.

Few micromet studies have measured NEE over CA in Africa and most experiment durations have been for less than a year (e.g., O'Dell et al., 2014; 2015). This three year study evaluates cross-seasonal micromet data near Harare, Zimbabwe. The objective was to compare the CO₂ exchange consequences of CA practices with conventionally tilled controls to investigate their potential for soil C sequestration. Measurements used the BREB method due to its ability to enable relevant data to be obtained close to the surface and because of its demonstrated utility for measuring trace gas exchange (Gilmanov et al., 2017).

Materials and Methods

Site Description

This study was conducted from 15 June 2013 to 1 May 2016 at the International Maize and Wheat Improvement Centre (CIMMYT) Southern Africa Regional Offices in Harare, Zimbabwe (17.7220° S, 31.0209° E, 1494 m asl) at the same location and using the same instrument setup as previously described by O'Dell et al. (2015).

The site is located in Zimbabwe's Natural Region II agro-ecological zone (Mugandani et al., 2012) and the climate is classified as temperate highland tropical, with a unimodal rainfall pattern of dry winters and rainfall between 700–1000 mm during the six-month growing season.

Annual average temperature ranges between 16-19 °C (Mugandani et al., 2012). The soils are classified as Chromic Luvisols (IUSS Working Group WRB, 2015), which correspond to Rhodustalfs in the USDA soil taxonomic classification system (Soil Survey Staff, 2014). The soil texture is clay and the study site has a slope of less than 2%. The study site was fallow for two years prior to the beginning of micromet measurements in June 2013.

The study site included four square plots approximately 80m x 80m (0.64 ha) in size upon which different tillage and crop treatments were applied. Plots were identified by number and treatment sequence summary as is shown in Figure 1. BREB stations were established a few meters downwind of the center of each plot; the predominant wind direction from the southeast.

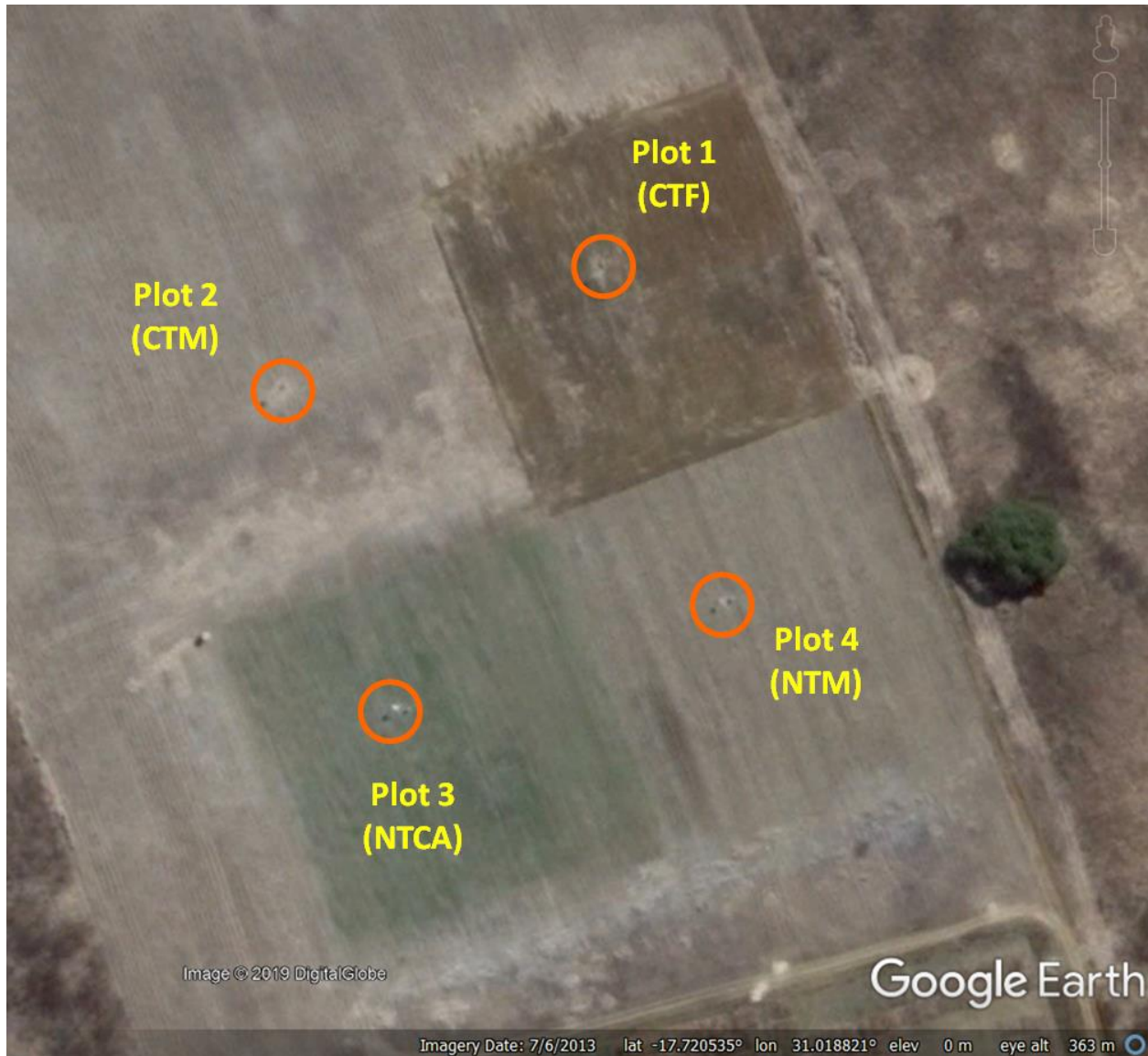


Figure 1. Plot layout image (imagery date 6 July 2013) about 2 months following initial planting in 2013, showing BREB station locations in orange circles (Google Earth Pro v7.3.2.5491; data provider DigitalGlobe 2018). The plot abbreviations refer to the sequence of treatments including conventional tilled fallow (CTF), conventional tillage maize (CTM), no-till CA (NTCA), and no-till maize (NTM).

Treatment applications

The analysis that follows distinguishes between wet and dry seasons by year (Figure 2). The wet season is considered the same as the cropping season described by Mhlanga et al. (2015). For the purposes of this experiment, the wet season is assumed to start on 1 November

and end 30 April of the following year and the dry season is assumed to start on 1 May and end 31 October. An exception is that the dry season experimentation for 2013 was delayed until 15 June when micromet measurements began and was the only season that included irrigation of plots 3 and 4 that were planted with cover crops. Otherwise, the wet and dry season rainfall pattern was similar across years providing comparable environmental conditions by season and year.

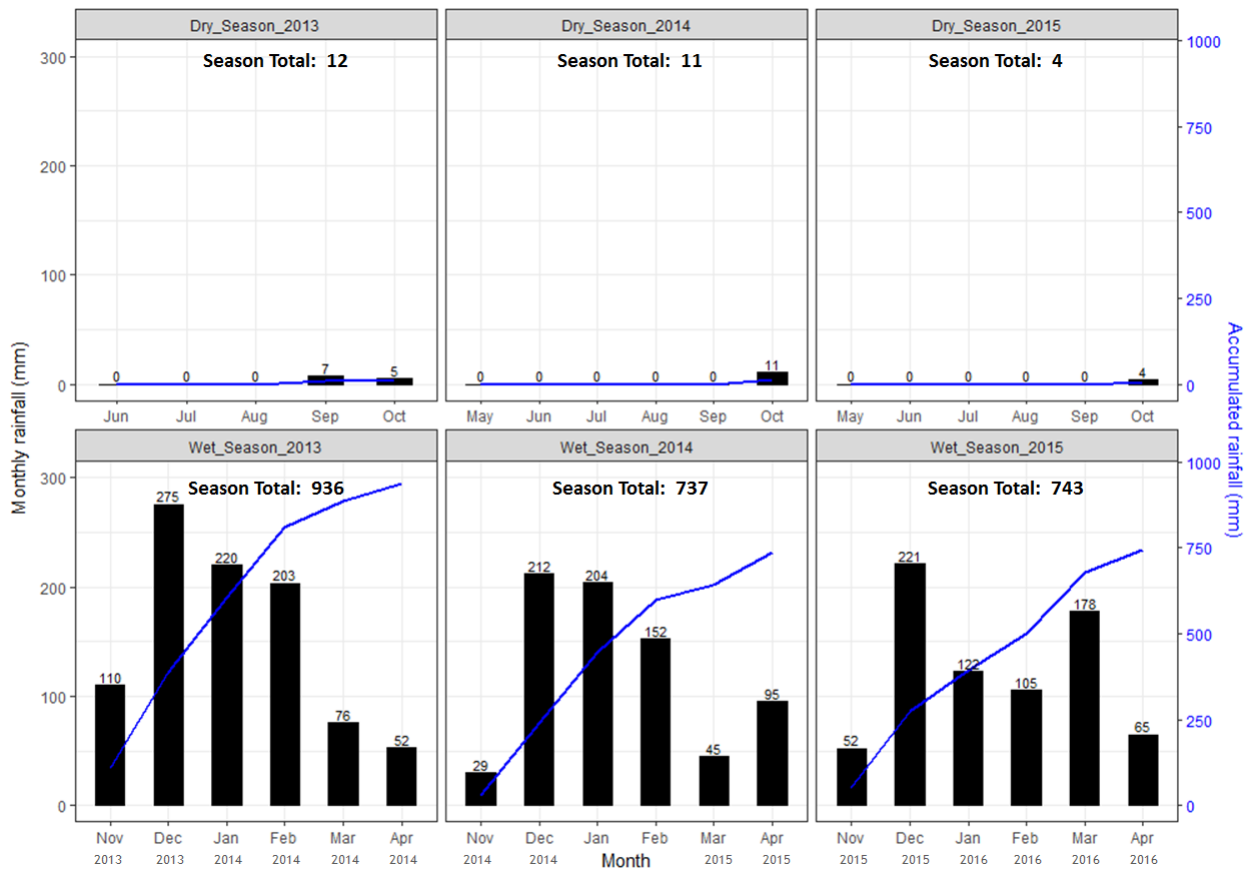


Figure 2. Total rainfall by month for each season-year with rainfall amounts (mm) displayed above each bar. The blue curves show cumulative rainfall during each season.

Table 1 provides a description of the experiment treatments, with the following acronyms preceding each season crop such as maize or fallow: conventional tillage (CT), no-till (NT), velvet bean intercrop (VBI), and staggered planting for maize trial (SP). CA treatments were selected to compare the net CO₂ flux between conventional tillage and CA practices such as no-

till, with and without intercropping. For example, during the first wet season in 2013, plot 2 (2-CTMaize) was plowed with a disc plow and planted with maize in a conventional tillage approach, while plots 3 (3-NTMaize) and 4 (4-NTMaizeVBI) were planted maize using no-till with a velvet bean (*Mucuna pruriens* L.) intercrop added (4-NTMaizeVBI) for rotation/cropping system intensification. During the second and third wet seasons in 2014 and 2015, a maize trial was conducted on plot 4, which staggered the planting of maize.

Table 1. Plot treatment operations and dates by season-year.

Treatment Period	Plot #	Treatment Abbreviation	Treatment Operation	Date
Dry season 2013	1	1-CTFallow	Conventional tillage followed by fallow	13 Jun 2013
	2	2-NTFallow	No-till fallow with maize and grass residue	
	3	3-NTWheat	No-till wheat (<i>Triticum aestivum</i> L.)	Early May 2013
	4	4-NTBlueLupin	No-till blue lupin (<i>Lupinus angustifolios</i> L.)	Early May 2013
Wet season 2013	2	2-CTMaize	Tillage	05 Oct 2013
	2	2-CTMaize	Maize planting	08 Nov 2013
	3	3-NTMaize	No-till planted with maize	20 Nov 2013
	4	4-NTMaizeVBI	No-till planted with maize	20 Nov 2013
	4	4-NTMaizeVBI	Velvet bean (<i>Mucuna pruriens</i> L.) intercrop	30 Jan 2014
	1	1-CTFallow	Tillage of weed growth followed by fallow	20 Feb 2014
Dry season 2014	1-4	1-4-NTFallow	None (all plots fallow)	
Wet season 2014	1	1-CTFallow	Tillage followed by fallow	17 Jan 2015
	1	1-CTFallow	Hand weeding with hoes	2 Feb 2015
	2	2-CTMaize	Tillage followed by maize planting	17 Jan 2015
	3	3-NTMaize	No-till planted with maize	23 Jan 2015
	4	4-NTMaizeSP	No-till staggered planting for maize trial	11 Dec 2014
	4	4-NTMaizeSP	No-till remainder of plot planted with maize	23 Jan 2015
Dry season 2015	1	1-CTFallow	Tillage followed by fallow	17 Jul 2015
	2-4	2-4-NTFallow	Plots 2-4 left fallow	
Wet season 2015	3	3-NTJackBean	No-till planted with jack bean (<i>Canavalia ensiformis</i> L.)	18 Dec 2015
	4	4-NTMaizeSP	No-till staggered planting for maize trial	18 Dec 2015
	1	1-CTFallow	Herbicide application followed by fallow	6 Jan 2016
	2	2-NTPigeonpea	No-till with pigeonpea (<i>Cajanus cajan</i> Millsp.)	6 Jan 2016
	4	4-NTMaizeSP	No-till remainder of plot planted with maize	18 Jan 2016
	1	1-CTFallow	Tillage followed by fallow	20 Jan 2016
	2	2-NTPigeonpea	Additional pigeonpea planted to fill in gaps	29 Jan 2016

Ideally, planting dates should be scheduled for similar calendar dates on each year, but optimal planting dates vary due to onset of seasonal rainy periods at the trial site as growing season planting is rainfed. Simba and Chayangira (2017) describe how small holder farmers in Zimbabwe schedule planting based on the mean start of the growing season that varies on the district and is usually dictated solely by the onset of effective planting rains, determined as rainfall of 30-50 mm falling after 15 November.

The experimental environment was challenging, and maintaining all sensors in a properly calibrated fashion was sometimes difficult and affected the continuity of measurement over the whole trial period. However, we accomplished a data recovery rate of 73% even in a remote environment, a value consistent with other BREB/EC data (Falge et al., 2001).

Agronomic management

During the first dry winter season wheat was seeded into plot 3 and blue lupin in plot 4 (Table 1). Wheat was broadcasted with a Vicon fertilizer distributor, lightly harrowed and irrigated thereafter. Blue lupin was seeded into 45 cm rip-lines at a 20 cm in-row spacing. Plot 1 and 2 remained as fallow in this first winter season. Crop residues were retained in all NT treatments on the surface. A uniform spray of glyphosate (N-(phosphonomethyl)glycine, 41% ai) for an initial weed control was sprayed at a rate of 3 L ha⁻¹ at the trial onset and before each new seeding. Emerging weeds were controlled when small with hand hoes producing marginal soil disturbance, consistent with smallholder farming in Southern Africa (Muoni et al., 2013). This was specifically necessary on plot 4 (with blue lupin). Ammonium nitrate was applied to the wheat crop at a rate of 200 kg ha⁻¹ (at a nutrient content of 34.5% N, this was equivalent to 69 kg ha⁻¹ N).

In November 2013, a commercial maize variety (var. Pristine 601) was seeded into rip-lines in plots 2-4 at a plant population of 53,000 plants ha⁻¹ (75cm row x 25 cm in-row spacing with 1 seed per station). In plot 4 a velvet bean intercrop was established between maize rows. The velvet bean crop was seeded in 75cm rows at a 50 cm in-row spacing with 2 seeds per planting station. A basal dressing of 165 kg ha⁻¹ NPK (7-14-7) was applied at planting and top-dressed at 4 and 7 weeks after planting with 200 kg ha⁻¹ of urea applied as split application. Plot 1 was tilled and stayed as an un-seeded fallow. In the growing season of Year 2, maize was again planted in plots 2-4, however part of plot 4 was used for a maize trial planted in December 2014 with the remaining part of plot 4 planted along with plots 2 and 3 in January 2015.

In year 3, the treatments changed to pigeon pea in plot 2, jack bean in plot 3 and maize in plot 4. All crops were seeded into rip-lines spaced at 75 cm apart and an in-row spacing of 50cm. The legumes received a basal fertilization of 165 kg ha⁻¹ NPK (7-14-7), applied at planting and maize was top-dressed at 4 and 7 weeks after planting with 200 kg ha⁻¹ of urea applied as split application. Plot 1 was tilled and stayed as an un-seeded fallow. The whole cropping sequences are described in Table 2.

Harvest procedures

Maize was harvested at physiological maturity (10 samples of 4 rows by 5; 15 m²). Harvest samples were cut, both cobs and biomass weighed in situ, subsamples taken for moisture determination of both grain and biomass and later calculated as grain yield in kg ha⁻¹ at 12.5% moisture content. Biomass was also expressed in kg ha⁻¹ dry weight.

CO₂ Flux Measurements

BREB is a relatively simple methodology and it has an application advantage over smaller sized plots often used in agricultural experiments. To obtain in-air measurements that

are indeed relevant for studying the characteristics of the surface underneath, it is clearly best to make the measurements close to the soil surface or top of the crop canopy. In this regard, the BREB approach is better than alternative EC because BREB measures meteorological properties closer to the surface (frequently less than 0.5 m) while EC instruments typically measure at heights generally many meters above the surface. Due to the fact that BREB measurements are closer to the surface, they are more likely to be representative of it. The BREB analysis procedure does not impose a need for determination of an eddy viscosity with which to derive fluxes from measured gradients. Instead, it assumes equality of these eddy diffusivities and apportions heat fluxes according to the gradients based on the assumption that the contributing diffusivities are the same. Whereas a fetch/height ratio of 100 might well be appropriate for the use of eddy correlation methods, studies elsewhere confirm that consistent flux estimates can be obtained using the BREB method at fetch to height ratios as low as 20:1 (Heilman et al., 1989).

Our BREB sensor outputs were recorded at five-second intervals. To eliminate sensor biases, the present BREB measurements were made with a rotating arm system designed to switch the level of measurement by temperature, humidity, and CO₂ sensors every five minutes, yielding five-minute averages of differences in temperature, humidity and CO₂ concentration between the levels accessed by the arms (O'Dell et al., 2015). The resulting five-minute averages were then combined to produce 30-min averages, used as input for the BREB analysis routine (Bowen, 1926; Dugas, 1993; Kanemasu et al., 1979). CO₂ fluxes were then derived as described by O'Dell et al. (2015). Data have been excluded for which the apparent 30-min turbulent diffusivity was negative (Savage et al., 2009). Occasions in which CO₂ flux spikes exceeded four times the standard deviation of the running average, flux data were removed and linearly interpolated (Vickers & Mahrt, 1997).

Statistical Analysis

Graphical representations of data were developed using the R programming language, environment, and packages including dplyr and ggplot2 (R Core Team, 2018). Statistical analysis of variance (ANOVA) was conducted with the GLIMMIX procedure (SAS V9.4, SAS Institute, Cary, NC). The above-ground maize biomass and grain yield data were available for the 2013 wet season and a one-way ANOVA was used to analyze treatment effects with mean separation analysis performed using Fisher's least significant difference (LSD) test with mean separations converted to letter groupings using the PDMIX800 macro (Saxton, 1998). Maize grain yield was adjusted to 12.5% moisture content. The mean CO₂ flux by season and for the entire experiment period was analyzed using a repeated measures ANOVA with Tukey's honest significant difference (HSD) mean separation test. Data are presented as mean or sum \pm one SE.

Results and Discussion

Table 2 provides the treatment sequence for each plot over the six seasons of the experiment, using abbreviated plot-treatment names for subsequent reference. In addition to tillage type, the total period sequence name label summarizes all three growing season crop treatments, with the following acronyms used: conventional tillage with fallow (CTF), conventional tillage mostly planted to maize (CTM), no-till with CA planting of maize or jack bean (NTCA), and no-till with planting of maize (NTM). Note that plot 4 had staggered maize planting during the 2014 and 2015 growing seasons.

Table 2. Sequence of treatments for each plot by season-year using abbreviated plot-treatment labels, with capital letters representing the following acronyms: conventional tillage (CT), no-till (NT), velvet bean intercrop (VBI), and staggered planting for maize trial (SP). Total treatment sequence labels include: conventional tilled fallow (CTF), conventional tillage maize (CTM), no-till CA (NTCA), and no-till maize (NTM).

Season - Year	Plot 1	Plot 2	Plot 3	Plot 4
Dry Season 2013	1-CTFallow	2-NTFallow	3-NTWheat	4-NTBlueLupin
Wet Season 2014	1-NTFallow	2-CTMaize	3-NTMaize	4-NTMaizeVBI
Dry Season 2015	1-CTFallow	2-NTFallow	3-NTFallow	4-NTFallow
Wet Season 2013	1-CTFallow	2-CTMaize	3-NTMaize	4-NTMaizeSP
Dry Season 2014	1-CTFallow	2-NTFallow	3-NTFallow	4-NTFallow
Wet Season 2015	1-CTFallow	2-NTPigeonpea	3-NTJackBean	4-NTMaizeSP
Total Sequence Name	1-CTF	2-CTM	3-NTCA	4-NTM

Table 3 provides a summary of CO₂ fluxes by season-year and treatment. The NEE for all seasons are positive, indicating net emissions for all of the study periods. Results during the 2013 dry season are greater than the estimates previously reported by O’Dell et al. (2015) due to the present rejection of flux evaluations when the indicated turbulent diffusivity was negative. Thus, negative nighttime fluxes were rejected—making total nighttime emissions greater. Table 3 shows plot 3 (3-NTJackBean) in the 2015 wet season produced significantly fewer emissions than all of the other plots. For four of the six seasons (dry seasons 2014 and 2015 and wet seasons 2013 and 2015), plot 1 (1-CTFallow) produced significantly greater emissions than all the other plots (Table 3). In general, dry seasons produced lower emissions than wet seasons, except for plot 3 which sequestered more C during wet seasons, which is likely a result of less microbial activity during drier conditions.

Table 3. Net ecosystem exchange (NEE), standard error (SE), number (N) of 30-min measurements, and mean CO₂ flux followed by Tukey's honest significant difference letter group for each treatment by season-year as compared with repeated measures ANOVA. Capital letters within plot-treatment abbreviations correspond to following acronyms including: conventional tillage (CT), no-till (NT), velvet bean intercrop (VBI), and staggered planting for maize trial (SP).

Season	Year	Plot-Treatment Abbreviation	NEE (kg CO ₂ m ⁻² season ⁻¹)	SE of the NEE	N	Mean NEE (g CO ₂ m ⁻² h ⁻¹)
Dry	2013	1-CTFallow	3.05	0.0451	6120	0.987 a
		2-NTFallow	2.72	0.0443	6200	0.860 a
		3-NTWheat	1.41	0.112	5587	0.427 b
		4-NTBlueLupin	1.02	0.0258	5672	0.375 b
	2014	1-NTFallow	4.47	0.0465	8277	1.096 a
		2-NTFallow	3.66	0.0485	8347	0.874 b
		3-NTFallow	3.15	0.0363	8431	0.737 c
		4-NTFallow	2.01	0.0384	5153	0.814 bc
	2015	1-CTFallow	2.16	0.0376	5042	0.833 a
		2-NTFallow	2.52	0.0345	7077	0.707 b
		3-NTFallow	2.55	0.0587	8347	0.610 c
		4-NTFallow	2.23	0.0443	6418	0.629 c
Wet	2013	1-TFallow	4.65	0.0764	5776	1.80 a
		2-CTMaize	2.15	0.113	6160	0.941 b
		3-NTMaize	1.67	0.136	6170	0.908 b
		4-NTMaizeVBI	2.12	0.0999	6372	0.915 b
	2014	1-TFallow	3.61	0.0731	6476	1.30 ab
		2-CTMaize	2.54	0.0507	3769	1.42 a
		3-NTMaize	1.27	0.0601	3111	1.01 b
		4-NTMaizeSP	4.19	0.0637	6658	1.38 a
	2015	1-TFallow	3.69	0.0625	5027	1.60 a
		2-NTPigeonpea	3.32	0.0736	6513	1.42 b
		3-NTJackBean	1.85	0.115	6021	1.00 c
		4-NTMaizeSP	3.02	0.0601	5272	1.40 b

Table 3 shows that there were differences among the treatments. To examine the cause of emission disparity, a closer examination of the data is needed. Comparisons of the CO₂ flux plotted by time of day for each season-year and each treatment are shown in Figure 3. CO₂ flux differences are most clearly observed during the daytime, while nighttime emissions rates often overlap. All plots yielded emissions during the night. For the wet growing seasons, only 2013

shows net sequestration during the day for all three plots planted to maize, while during the 2014 and 2015 wet seasons, only 3-NTMaize and 3-NTJackBean show net daytime sequestration.

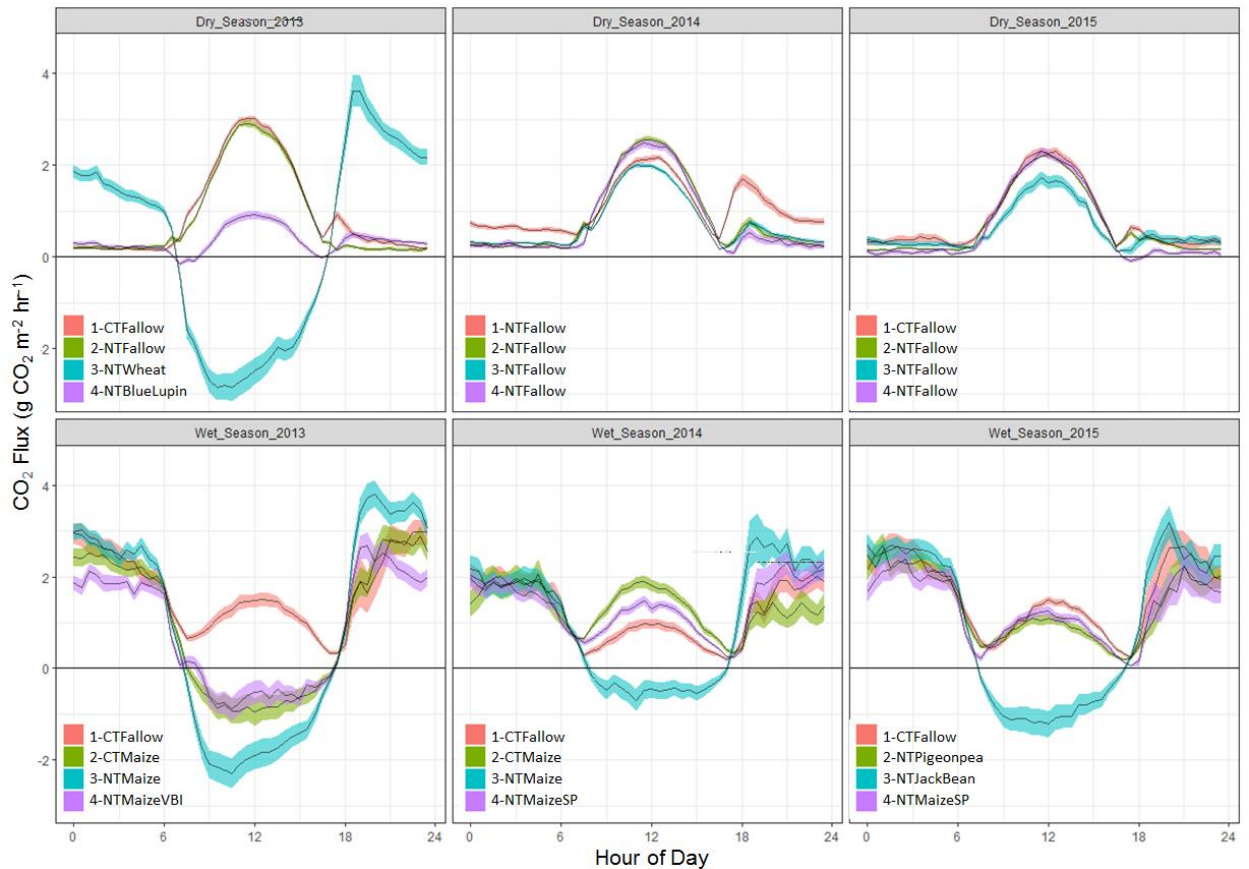


Figure 3. Mean CO₂ flux by time of day and season-year for each treatment \pm one SE shown in translucent colors. Negative values represent uptake of CO₂ by the canopy and positive values represent emissions from the surface to the atmosphere. Capital letters within plot-treatment abbreviations correspond to following acronyms including: conventional tillage (CT), no-till (NT), velvet bean intercrop (VBI), and staggered planting for maize trial (SP).

The 2013 dry season was different from the other dry seasons; cover crops were planted on plots 3 and 4 (3-NTWheat and 4-NTBlueLupin) and those plots were irrigated. For the 2013 dry season, only 3-NTWheat had net C sequestration during the day. The other three plots had net daytime emissions. The 2014 and 2015 dry seasons show very little difference in emissions

between treatments, except for lower daytime (during the hours of 0800 to 1600) emissions for 3-NTFallow during the final 2015 dry season.

All wet seasons (Figure 3) show the greatest daytime C sequestration (negative values) for plot 3 (3-NTCA), which had the most consistent CA treatment. During the 2013 dry season, 3-NTWheat showed the greatest daytime sequestration and 3-NTFallow showed the lowest daytime emissions during the 2014 and 2015 dry seasons.

Harvest data was available during the 2013 wet season for the total grain yield and above-ground biomass which was harvested 14 April 2014 (Table 4). The above-ground biomass for 3-NTMaize was significantly greater than both 2-CTMaize and 4-NTMaizeVBI (maize with velvet bean intercrop), while the grain yield for 3-NTMaize was only significantly greater than the grain yield for 2-CTMaize. The results for grain yield are consistent with the mean CO₂ flux for this season, which shows significantly greater emissions from 2-CTMaize than 3-NTMaize, and no significant difference between and mean CO₂ flux for 3-NTMaize and 4NTMaizeVBI (Table 3).

Table 4. Mean and SE (Mg ha⁻¹) for grain yield (at 12.5% moisture content) and above-ground biomass for the 2013 wet season harvest for three maize treatments (plots 2-4). Means with different letters were significantly different (P<0.05, ANOVA Fisher LSD, N = 10).

Plot#-Treatment Abbreviation	Grain yield (Mg ha⁻¹)	SE	Above-ground biomass (Mg ha⁻¹)	SE
1-CTFallow				
2-CTMaize	5.67 b	0.274	9.29 b	0.429
3-NTMaize	6.55 a	0.262	11.6 a	0.542
4-NTMaizeVBI	5.92 ab	0.251	9.34 b	0.387

Latent heat flux (LE) by time of day and season-year illustrates an association between water and daily CO₂ flux patterns (Figure 4). Daytime LE was considerably greater during the

2013 dry season due to irrigation for the two cover crops (3-NTWheat and 4-NTBlueLupin) than during the 2014 and 2015 dry seasons.

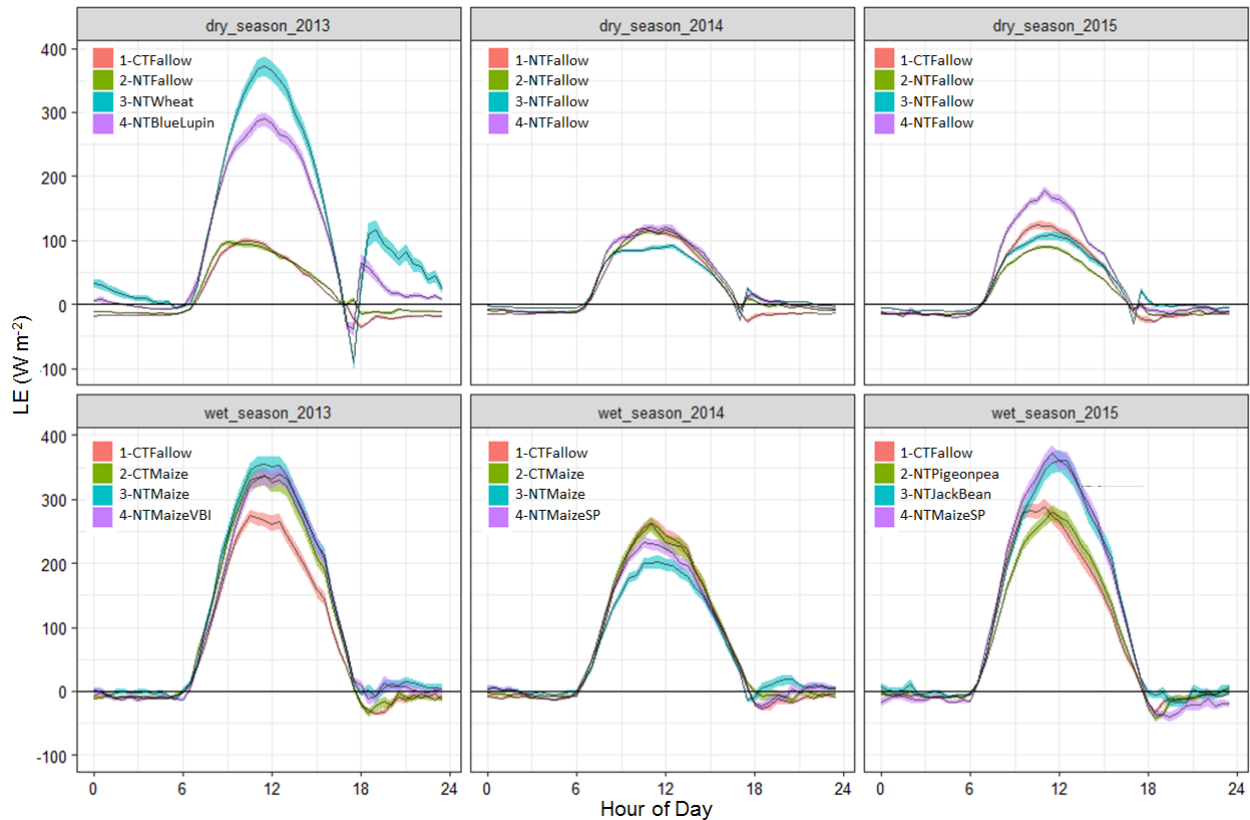


Figure 4. Mean latent heat flux (LE) (W m^{-2}) by time of day and season-year for each treatment \pm one SE shown in translucent colors.

The nighttime data illustrated in Figures 3 and 4 are particularly informative, since the high exchange rates evident for the CO_2 results are not mirrored in the LE data. The negligible nighttime LE in the wet season, when water was plentiful, is as expected. The ability of the BREB methodology to reproduce this expected LE can be interpreted as an indication that the approach is working. The high CO_2 flux at night, especially during wet seasons (Figure 3), can be attributed primarily to sub-surface biotic factors (soil microbes and root respiration). However, given that available heat energy becomes very small at night, the magnitude of

positive nighttime CO₂ flux can be uncertain when quantified by turbulence-based micromet methods, such as BREB (Dugas et al., 1999).

In the dry seasons, the outstanding feature that highlights the association between water and CO₂ flux is exemplified by the irrigated NTWheat crop of 2013 (Figure 3). It is evident, that the high CO₂ emission rates at night are associated with enhanced autotrophic and heterotrophic respiration associated with greater soil moisture. Irrigation not only provides for cover crop growth during the dry season, but also enhances microbial activity as shown during nighttime hours in Figure 3 (Liu et al., 2010; Orchard & Cook, 1983). A closer inspection of Figure 4 shows that it is only for the irrigated plots in 2013 that the LE at night indicates respiration. Elsewhere the nighttime LE rates are low, as expected, and indicative of the conventional curtailment of plant transpiration at night.

Examples of distinctive LE and CO₂ flux relationships include the greatest daytime sequestration found in 3-NTMaize (blue) along with the greatest daytime LE during the 2013 wet season (Figure 5). Another relationship that can be seen when comparing LE with CO₂ flux is apparent during the 2013 wet season where the greatest daytime CO₂ emissions occurs over the 1-TFallow (red) with the smallest daytime LE during that period showing that total evapotranspiration is decreased without plant transpiration, while daytime respiration rates contribute to total evaporation from the soil (Figure 5).

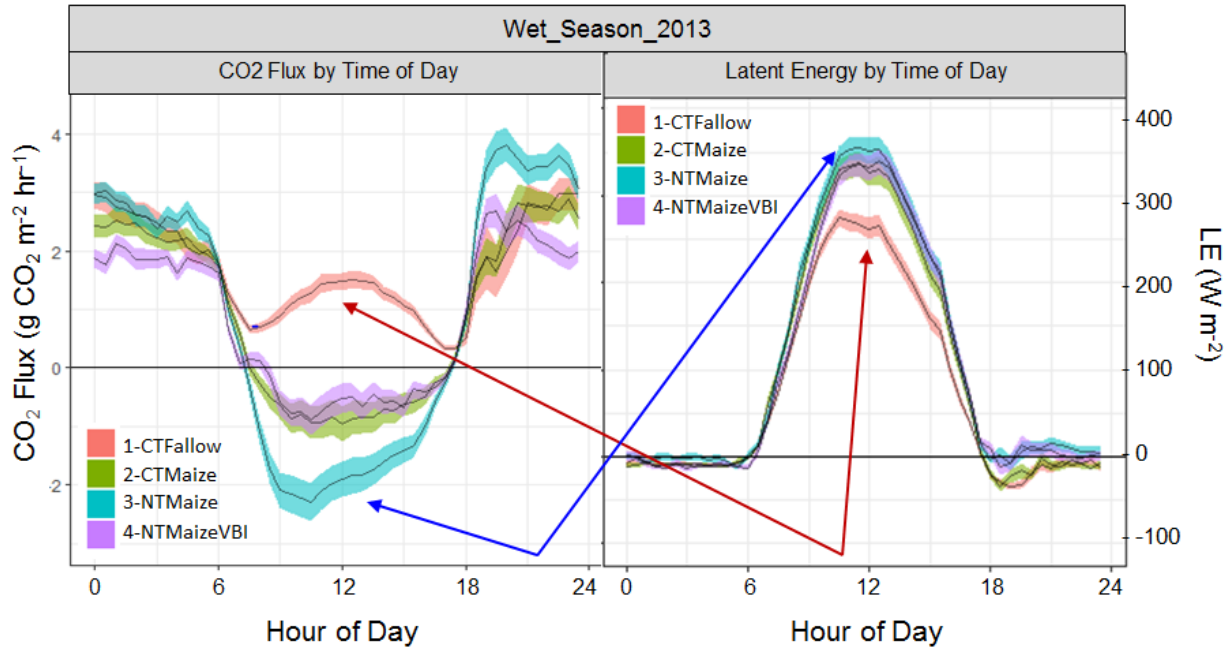


Figure 5. CO₂ flux and latent heat flux (LE) by time of day for wet season 2013 with blue arrows showing the relationship between CO₂ flux and LE for 3-NTMaize and red arrows showing the relationship between CO₂ flux and LE for 1-CTFallow.

During the first dry season in 2013, the total NEE for the two cover crops, 3-NTWheat ($1.41 \pm 0.113 \text{ kg m}^{-2}$) and 4-NTBlueLupin ($1.02 \pm 0.0258 \text{ kg m}^{-2}$) were significantly less than the two fallow plots and not significantly different from zero (at the 90% probability level), i.e., the cover crops were essentially in carbon-cycle equilibrium. The negative mean daytime fluxes (Figure 3) indicate strong photosynthesis by 3-NTWheat, while the greater nighttime flux indicates greater respiration for the wheat cover crop at night.

Several micromet studies reported that winter wheat sequestered C (Gebremedhin et al., 2012; Moureaux et al., 2008), while Gilmanov et al. (2014) found that many legume crops, such as soybean, peanut (*Arachis hypogaea* L.) and pea (*Pisum sativum* L.), were net sources of C—though the perennial legume, alfalfa (*Medicago sativa* L.), sequestered more C than wheat. In a seven-year experiment comparing the effects of N fertilization with leguminous and non-leguminous cover crops, Sainju et al. (2002) found that the non-legume, rye (*Secale cereale* L.),

produced greater SOC concentrations than two legumes, hairy vetch (*Vicia villosa* Roth.) and crimson clover (*Trifolium incarnatum* L.), supporting greater C sequestration shown for wheat in this experiment as compared to blue lupin.

During the first wet season in 2013, the total NEE was less in 3-NTMaize treatment ($1.67 \pm 0.136 \text{ kg m}^{-2}$) than 4-NTMaizeVBI ($2.12 \pm 0.0999 \text{ kg m}^{-2}$) though the velvet bean intercrop was expected to increase total sequestration (Table 3). This is counter-intuitive and may be a result of the greater residue cover left by the preceding wheat cover crop (on plot 3), which may have provided a catch crop releasing nutrients for the following maize crop. It is also possible that the preceding blue lupin cover crop (on plot 4) provided a more labile substrate for greater decomposition and respiration during the 2013 wet season. Interestingly, it appears that 3-NTMaize had greater daytime C sequestration, while 4-NTMaize-VBI had lower nighttime emissions (Figure 3). The 2-CTMaize treatment, which had the advantage of nutrient mineralization from tillage (Lupwayi et al., 2004; Reicosky et al., 1995), did not produce significantly greater total CO₂ emissions ($2.15 \pm 0.0113 \text{ kg m}^{-2}$) for the 2013 wet season than both CA no-till maize plots (3-NTMaize at $1.67 \pm 0.0136 \text{ kg m}^{-2}$ and 4-NTMaizeVBI at $2.12 \pm 0.0999 \text{ kg m}^{-2}$). Though the daytime mean flux for the 2-CTMaize (Figure3) was within one SE of the 4-NTMaizeVBI, both 2-CTMaize and 4-NTMaizeVBI show more than 2 SEs greater daytime flux than the 3-NTMaize treatment.

The dry seasons in 2014 and 2015 are comparable in environmental conditions representing a typical cool non-growing dry season; all treatments were no-till fallow with no cover crops or irrigation, except for plot 1 which was tilled in 2015. CO₂ flux by time of day for these seasons were very similar (Figure 3). The final 2015 wet/growing season showed differences in daytime CO₂ flux with the 3-NTJackBean treatment sequestering CO₂ while all the

other plots emitted CO₂ (Figure 3). The total NEE for 3-NTJackBean of $1.85 \pm 0.115 \text{ kg m}^{-2}$ for the season was more than 3 SEs and significantly less than 4-NTMaizeSP at $3.02 \pm 0.0601 \text{ kg m}^{-2}$ (Table 3). While 3-NTJackBean produced the lowest NEE for this season, there was still a net CO₂ emission on this plot, suggesting that even with CA practices, it is possible that many crops will still be a net source of C.

It is important to note that precipitation was close to 200 mm less during the 2014 and 2015 growing seasons than the 2013 growing season. While some crops like jack bean and maize are known for rapid growth, it is also possible that the buildup of plant residues from the previous CA treatments also contributed to reduced evaporation at the soil surface and greater water use efficiency during a growing season with less rainfall (Mupangwa et al., 2007). This example provides evidence that CA may help farmers adapt to climate change under reduced rainfall conditions.

The total CO₂ flux sum (NEE) and mean for each plot for the 34.5-month period of measurement provide information about the impact of a sequence of treatments on CO₂ flux over time (Table 5). Consistent with individual seasons, the plot with the greatest NEE (1-CTF, $21.6 \pm 0.341 \text{ kg CO}_2 \text{ m}^{-2} \text{ period}^{-1}$) was the fallow, which received more conventional tillage than any other plot, while the plot with the least total emissions (3-NTCA, $10.6 \pm 0.518 \text{ kg CO}_2 \text{ m}^{-2} \text{ period}^{-1}$) had the most systematic applications of CA treatments.

Table 5. Total NEE and SE (kg CO₂ m⁻² period⁻¹), number of 30-min measurements, mean NEE (g CO₂ m⁻² h⁻¹) followed by Tukey's Honest Significant Difference (HSD) letter group and SE of the mean (g CO₂ m⁻² h⁻¹) for each plot over the 34.5-month experiment period.

Plot # - Treatment Sequence Name	Accumulated NEE (kg CO₂ m⁻² period⁻¹)	SE of the NEE	N	Mean NEE (g CO₂ m⁻² h⁻¹)	SE of the mean
1-CTF	21.6	0.341	36718	1.18 a	0.00794
2-CTM	17.7	0.365	38066	0.928 b	0.00859
3-NTCA	10.6	0.518	37667	0.564 c	0.0122
4-NTM	14.6	0.332	35545	0.821 b	0.00845

Plot 3 (NTCA) had the most consistent CA practices and the lowest mean CO₂ flux (0.564 ± 0.0122 g CO₂ m⁻²) for the three-year period, which was significantly different than all other plots (Figure 6, Table 5). Plot 4 (NTM) also included CA practices, however, its mean CO₂ flux (0.821 ± 0.00845 g CO₂ m⁻²) was lower and significantly different than 3-NTCA (Figure 6). Several possible explanations may account for this difference, including that 4-NTM had staggered planting, which may have contributed to increased emissions. Additionally, 4-NTM was planted with maize for three consecutive years, and continuous maize deviates from CA's third principle of crop rotation. Plot 1 (CTF), which was fallow and received the most tillage, had a greater mean CO₂ flux and was significantly different than the other three plots for the experiment period.

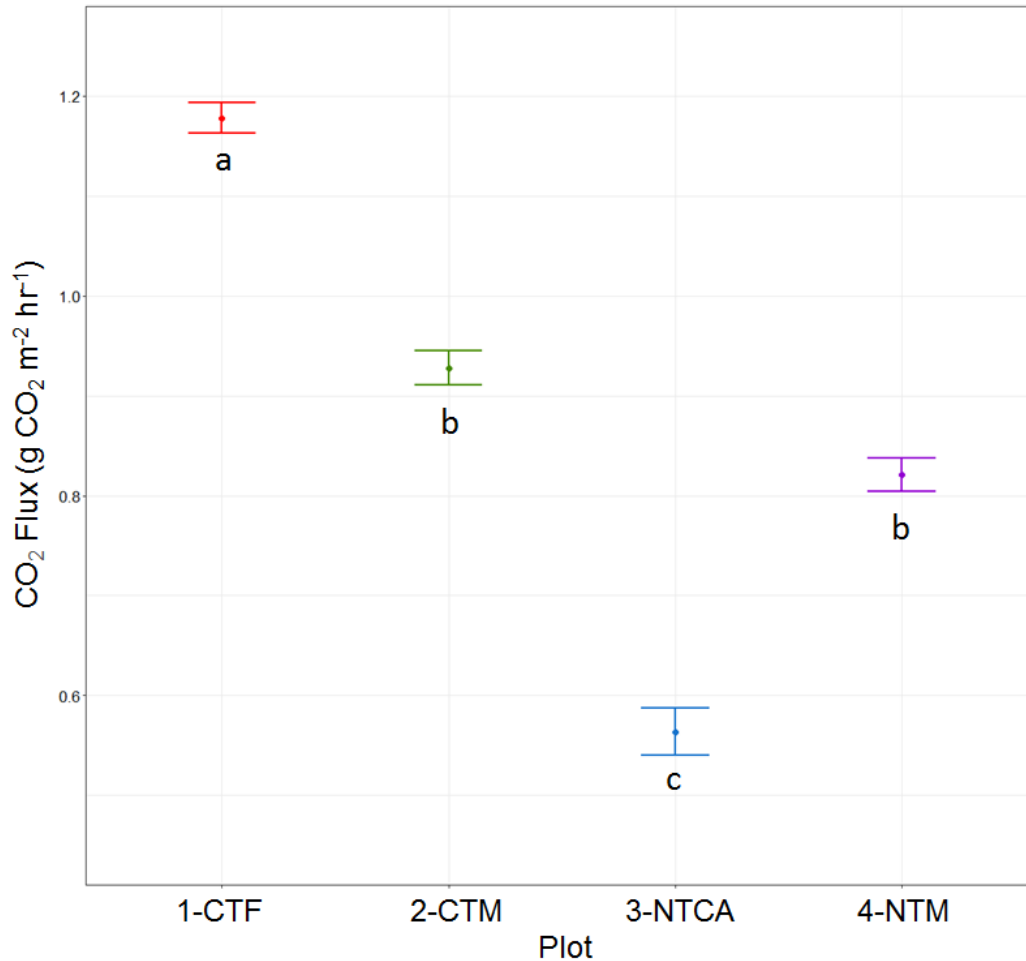


Figure 6. Mean CO₂ flux (g CO₂ m⁻² h⁻¹) with 95% confidence intervals for the 34.5-month experiment period and the ANOVA least squares mean separation output converted to letter grouping using Tukey’s HSD.

The most consistent application of CA principles was on plot 3, and this plot produced significantly fewer CO₂ emissions than all the other treatment combinations as well as almost half the total emissions as compared to the tilled fallow treatment (1-CTF). This can be viewed in Figure 3 for all blue shaded daytime CO₂ flux, which showed the lowest (positive) emissions during dry seasons 2014 and 2015 and the greatest (negative) sequestration during the remaining seasons. These results suggest that effective rainfall utilization—as is common with CA practices—can be used to reduce total CO₂ emissions as evidenced by results from plot 3

(NTCA), indicating that CA may be able to improve water use efficiency and crop yields in semi-arid climates in Africa. More research into the types, timing, and density of cover crops may increase knowledge of the cover crop impact on subsequent cropping seasons and water use efficiency. Of interest is plot 4 (NTM), which also had CA treatments, though its total emissions were not much lower than plot 2 (CTM) with conventional tillage, suggesting that if not implemented effectively, CA practices may not sequester significantly more than conventional practices.

Conclusions

While there are intense constraints imposed on agriculture in a unimodal wet season/dry season climate, there is potential to reduce GHG emissions using CA practices. Micrometeorology—as with BREB methods used here—can detect differences between soil and cropping practices both in the short term (by season) and over longer terms (multiple years). This study found that basic no-till CA practices coupled with cover crops produced healthy crop stands that emitted less CO₂ than tilled treatments. This experiment suggests that CA enhanced with a dense cover crop and its subsequent thick residue cover may reduce evaporation losses and trap nutrients, which will promote greater productivity in the following crops. Furthermore, this research provides data regarding CA's potential to reduce C emissions. The data show CO₂ emissions that appear related to the effects of reduced soil organic matter from tillage and surface residue that can impact evaporation, respiration, and crop productivity. These results indicate that CA may help to mitigate the consequences of climate change and adapt to climate change impacts such as reduced rainfall in tropical and/or semi-arid regions like southern Africa. This study also provided evidence that CA may not sequester more C over time than

conventional practices when all CA principles are not fully implemented such as without crop rotation and insufficient soil cover.

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