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A Short-Term Assessment of Carbon Dioxide Fluxes under Contrasting Agricultural and Soil Management Practices in Zimbabwe

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Abstract

Two of the biggest problems facing humankind are feeding an exponentially growing human population and preventing the accumulation of atmospheric greenhouse gases and its climate change consequences. Refined agricultural practices could address both of these problems. The research addressed here is an exploration of the efficacy of alternative agricultural practices in sequestering carbon (C). The study was conducted in Zimbabwe with the intent to (a) demonstrate the utility of micrometeorological methods for measuring carbon dioxide (CO₂) exchange between the surface and the atmosphere in the short-term, and (b) to quantify differences in such exchange rates for a variety of agricultural practices. Four Bowen ratio energy balance (BREB) systems were established on the following agricultural management practices: (1) no-till (NT) followed by planting of winter wheat (*Triticum aestivum*), (2) NT followed by planting of blue lupin (*Lupinus angustifolios* L.), (3) maize crop residue (*Zea mays* L.) left on the surface, and (4) maize crop residue incorporated with tillage. Over a period of 139 days (from 15 June to 31 October 2013) the winter wheat cover crop produced a net accumulation of 257 g CO₂-C m⁻², while the tilled plot with no cover crop produced a net emission of 197 g CO₂-C m⁻² and the untilled plot with no cover emitted 235 g CO₂-C m⁻². The blue lupin cover crop emitted 58 g CO₂-C m⁻², indicating that winter cover crops can sequester carbon and reduce emissions over land left fallow through the non-growing season. The micrometeorological methods described in this work can detect significant differences between treatments over a period of a few months, an outcome important to determine which smallholder soil management practices can contribute towards mitigating climate change.

Keywords: agricultural management practice, carbon dioxide, CO₂ flux, conservation agriculture, greenhouse gas emissions, smallholder farmer

1. Introduction

Though most greenhouse gas (GHG) emissions are from fossil fuel combustion, agriculture has a unique and important role in mitigating GHG emissions and their relationship to climate change. Agriculture is a source of approximately 10% of total GHG emissions (FAO, 2013), yet it also has the potential to mitigate GHG emissions by sequestering carbon (C). Agriculture's mitigation potential is explained in part by the size of the top three active reservoirs of C in the C cycle. The oceans play an important role in C sequestration and are the largest active reservoir with 38,000 Pg C, though only 700-1,000 Pg C of this total are at shallow depths where interactions with the atmosphere take place. Fossil fuels make up the second largest active reservoir with 5,000-10,000 Pg C. Organic matter in soil is the next largest pool with 1,500 to 2,300 Pg C (Jobbágy & Jackson, 2000; Houghton, 2007). With about 12% of the global land surface under cultivation, agricultural C sequestration is an important low-cost mitigation strategy with substantial co-benefits (Smith et al., 2007).

The United Nations Food and Agricultural Organization (FAO) projects that food production must increase by 70 % to feed over 9 billion people by 2050 (Conforti, 2011). Land degradation and land use change are estimated to

produce between 6 and 20% of global GHG emissions and if agriculture is the biggest driver of land use change due to deforestation and degradation (Blaser & Robledo, 2007; Kissinger, 2011), then directly and indirectly agriculture could be responsible for as much as one third of global GHG emissions. Variations in these estimates reflect a level of scientific uncertainty that hinders the prediction of future trends, a matter that the present research is intended to help resolve. The focus of this study involves quantifying the mitigational impact of improving land use practices in Africa.

The overall GHG mitigation potential of these improved agricultural practices is probably underestimated. Some agricultural practices already address the problems of food security and GHG emissions simultaneously; for example reduced tillage – especially NT – maintains yields through improved soil quality while also sequestering C (Smith et al., 2007; Thierfelder et al., 2013; Thierfelder et al., 2014). Maintaining or improving soil quality and crop yields reduces pressure to convert forests or marginal land into farmland as is the common response to declining agricultural productivity. Thus, such agricultural practices have multiple benefits by increasing food security, soil quality and sustainability, and soil C sequestration while preventing the conversion of forests and grassland soils to cropland (Grieg-Gran, 2010). Finally, several reviews raise the importance of related socio-economic factors since without increases in profitability through improved productivity, mitigation techniques are obviously less likely to be adopted (Smith et al., 2007; Wollenberg, 2012).

Sub-Saharan Africa is a region where conservation agriculture (CA) practices could improve soil quality as well as stabilize or increase crop yield while reducing C emissions. As much as three-quarters of the agricultural land in sub-Saharan Africa has been degraded by erosion and depletion of soil nutrients mostly resulting from poor agricultural practices (Henaio & Baanante, 1999; Bai et al., 2008, 2010). Conservation agriculture practices can reverse soil degradation and improve agricultural productivity by reducing erosion and enhancing soil quality, water holding capacity, soil structure, biological activity and water infiltration (Grieg-Gran, 2010; Thierfelder et al., 2012, 2014).

Cover crops may also play an important role in mitigating GHG emissions by promoting C sequestration (Barthès et al., 2004; Thierfelder et al., 2014). Cover crops reduce erosion by providing soil cover between growing seasons. Leguminous covers add nitrogen to soils thereby sustaining or increasing soil quality. Cover crops can also act as a “catch” or “trap” crop by storing mobile nutrients not used by the preceding crop which are then stored for future mineralization and plant uptake.

The Intergovernmental Panel on Climate Change claims that there is no universally accepted list of best mitigation practices, since their effectiveness varies across climates and soil types (Smith et al., 2007). The FAO submission to the United Nations Framework Convention on Climate Change (UNFCCC) emphasized the challenges in measuring the capacity of agricultural practices and soil to sequester or emit C including variability in soil type and C content within a field, the difficulty measuring small year-to-year changes in soil C, and previous land use practices (FAO, 2009).

Switching from tillage to a NT agricultural management practice has the potential to reduce agricultural CO₂ emissions (Schlesinger, 1999; Halvorson et al., 2002; West & Post, 2002; Govaerts et al., 2009; O’Dell et al., 2014). Tillage increases aeration within the upper soil horizons, fueling organic matter decomposition by microbes and producing soil microbial respiration and CO₂ emissions (Schlesinger & Andrews, 2000). West and Post (2002) found in their review of 67 long-term studies that converting from conventional tillage to NT often produced a significant increase in soil C in the top 7-cm of soil across all experiments with the notable exception under a wheat (*Triticum aestivum* L.) rotation followed by fallow.

In addition to potential C sequestration, NT is considered to have other benefits such as reduced soil erosion, enhancement of soil structure and infiltration, improved resilience to drought and flooding as well as enhanced quality and productivity (Kurkalova et al., 2004; Lal, 2004; Follett et al., 2011; Thierfelder et al., 2014). However, the potential of NT to increase soil C has been questioned (Manley et al., 2005; Baker et al., 2007; Powlson et al., 2011), especially for moist, cool climates (Hermle et al., 2008). Some studies do not identify greater C concentrations under NT as compared to conventional tillage in soil horizons deeper in the profile compared with shallow or surface soil horizons (Angers & Eriksen-Hamel, 2008). Clearly, more research is needed to provide data on the value of NT as an agricultural practice for use in specific climates and soil types.

Accurately measuring soil C is fundamental to understanding sequestration rates and C content in soils managed under different tillage regimes. Due to the slow rate of C sequestration and spatial variation in soils, annual changes in soil C are small and difficult to quantify, especially when relying on measurements of soil C concentrations (Smith, 2004). Methods for measuring C are often tedious, requiring field measurements and high quality, precision analytical laboratories that are rarely available in developing countries.

The objective of this research was to demonstrate that micrometeorological techniques can detect which agricultural practices and environmental conditions have the potential to sequester C. For a three month period from late winter to the beginning of the planting season in Zimbabwe we measured real time CO₂ flux and accumulations of CO₂. Carbon dioxide emissions from land can be determined in real time by measuring the CO₂ exchange between the surface and the atmosphere – the ‘flux’. There are two main approaches for measuring CO₂ exchange over agricultural ecosystems including the use of static or dynamic chambers and micrometeorological techniques (Follett et al., 2011). Among the micrometeorological methods available for use, the Bowen Ratio Energy Balance (BREB) system and eddy covariance have gained considerable popularity (Follett et al., 2011). Dugas (1993) compared three BREB systems with nine soil chambers and found good CO₂ flux agreement between the two methods. He also noted that the micrometeorological methods integrate the soil-atmospheric boundary layer interactions over a much larger area than chamber methods and thus accommodate more of the spatial variability of CO₂ flux from soil thereby allowing high resolution measurements representative of larger areas. Though chamber-based measurements of GHG flux can be less expensive than micrometeorological techniques, they require intense effort and diligence to address spatial and temporal variability (Rochette & Eriksen-Hamel, 2008; Parkin & Venterea, 2010) due to diurnal soil temperatures as well as common changes in atmospheric pressure. Due to the temporal and spatial issues and resulting maintenance challenges in using chamber systems, the BREB approach was selected for this research.

2. Materials and Methods

2.1 Site Description

Soil properties and micrometeorological variables were measured from 15 June 2013 to 31 October 2013 at Mt. Pleasant, Zimbabwe (17.7220° S, 31.0209° E, 1,494 m elevation asl) about 12 km north of the center of the capital city Harare. The study site is located at the International Maize and Wheat Improvement Centre (CIMMYT), an international agricultural research center. The climate is temperate highland tropical with dry winters, with a unimodal average yearly rainfall of 840 mm with approximately 94% of rainfall occurring from November to March.

The soils are classified as *Chromic Luvisols* (Nyamapfene, 1991) in the World Reference Base for Soil Resources international standard taxonomic soil classification system, equivalent to *Rhodustalfs* in USDA Soil Taxonomy (Soil Survey Staff, 1999). The soil texture is predominantly sandy clay loam derived from metamorphosed sedimentary rock parent material. The study site is nearly level with a slope of less than 2%. Prior to the start of the experiment, the study site had been fallow for two years preceded by at least 27 years with conventional maize (*Zea mays* L.) cropping using disc plowing as the land preparation method in rotation with soybean (*Glycine max* L.) with occasional bush fires that eliminated all the plant residues.

2.2 Experimental Design

An area approximately 160 m by 160 m was divided into four square plots about 0.64 ha each. The experimental design is an unreplicated completely randomized design with repeated measures, where the plots are the experimental units. There is one plot per treatment. Five-min micrometeorological measurements were averaged to produce 30-min CO₂ flux calculations which are repeated measures. Two plots were seeded in early May 2013, one with blue lupin (*Lupinus angustifolius* L.) with row spacing of 75 cm created by a tractor drawn ripper at a depth of 10 cm and seeded by hand into the riplines, with an interrow spacing of 30 cm for a target population density of 44,444 plants ha⁻¹. The second plot was seeded with wheat (*Triticum aestivum*) cultivar PAN 3492 (Pannar Seed company, Greytown, South Africa) via Vicon spreader (Kverneland, Norway) broadcasting at a rate of 120 kg ha⁻¹, with shallow disturbance of the soil with a rake by hand after broadcasting. A basal fertilizer application of 7:14:7 nitrogen, phosphorus and potassium was broadcast by hand on the wheat plot at planting and on 28 June, 300 kg ha⁻¹ of N as ammonium nitrate was applied as a top dressing. The blue lupin plot was manually weeded with hoes from 13-18 June and 14-15 August, 2013. During germination and seedling establishment, irrigation was applied by overhead sprinklers for a 6-h period every three days followed by a weekly 6-h sprinkler irrigation to ensure stand establishment on the wheat and blue lupin plots. A description of the four plot treatments and abbreviations used is provided in Table 1. A photograph of each of the plots taken in August, 2013 (Figure 1) provides context for each plot and the site.

Table 1. Summary of experiment treatments

Treatment Description	Abbreviated Name Used in Figures and Tables
No-till planted with wheat cover crop seeded via Vicon broadcast	Wheat
No-till planted with blue lupin cover crop direct seeded by hand following a tractor drawn ripper	Blue lupin
Maize crop residue left on the surface	Untilled
Maize crop residue incorporated with disc plow	Tilled



Figure 1. Photographs of the four plots taken 9 August, 2013, Mt. Pleasant, Zimbabwe

2.3 Micrometeorological Measurements

A BREB micrometeorological station was established near the center of each plot to measure soil and atmospheric properties according to the theory and approach described by Dugas (1993) and implemented in a prior experiment (O'Dell et al., 2014). The plot size and surrounding vegetation provided less than the fetch (uniform upwind surface) normally imposed on micrometeorological studies of this kind – of 100 m in length for every one meter in height of the micrometeorological measurements above the canopy or soil surface. The measurement heights used in the present experiment were 0.2 m and 1.7 m above the canopy and each plot size was 0.64 ha. While this fetch constraint necessarily affected the results and conclusions drawn from them, the magnitude of the resulting uncertainty is thought to be small because measurements close to the surface (such as in the present case) reflect the influence mostly of the nearest surface. The classical 100:1 constraint is intended to be safely conservative and fetch as low as 20:1 has been found acceptable for BREB (Heilman, Brittin, & Neale, 1989). There was one tree approximately 8 m tall located 30 m from the eastern edge of the study site and two trees were located approximately 80 meters from the eastern edge. These are also thought to have had little influence on the micrometeorology affecting the study plots as winds were rarely directly from the east.

The BREB station housed atmospheric sensors at each end of a rotating arm centrally mounted on a frame connected to a vertical pole that could be height adjusted above the soil surface or canopy, as shown in Figure 2. A 12-V DC electric gear motor powered the rotating arm to a near vertical orientation. A shielded horizontal air intake was mounted approximately 1.5 m apart at both ends of the arm facing in the direction of the most prevalent winds (southeast). Humidity probes, air temperature sensors, and CO₂ intake tubes were housed in the horizontal air intakes for measurements at two heights (periodically adjusted to maintain approximately 0.2 and 1.7 m above the soil surface or the top of the growing crop canopy). Air temperature was measured with thermistors. Water vapor pressure was computed using measurements made with temperature and relative humidity probe measurements (model HC2-S3-L, Rotronic, Switzerland supplied by Campbell Scientific, Inc,

Logan, UT). A constant flow of ambient air was drawn over the sensors with fans at a rate of $0.34 \text{ m}^3/\text{min}$. CO_2 concentrations were measured with a non-dispersive infrared gas analyzer (model LI-820, LI-COR Inc., Lincoln, Nebraska). A mechanically activated limit switch was attached to the frame for detecting which arm was up (model XCKL106, Telemecanique, Palatine, IL).



Figure 2. Micrometeorological station with rotating arms at the Mt. Pleasant, Zimbabwe study site

Soil heat flux was measured with a soil heat flux plate (model HFT3-L, Radiation Energy Balance System (REBS), Seattle, WA) at a depth of 0.06 m below the surface. Two Type “T” thermocouples buried at 0.015 m and two buried at 0.045 m measured soil temperature. The soil surface temperature on the tilled and untilled plots was measured with infrared radiometers (model SI-111, Apogee Instruments, Inc., Logan, UT). Volumetric soil moisture content was measured at two depths on the tilled and untilled plots with a water content reflectometer (model CS615, Campbell Scientific, Inc, Logan, UT), at 0.03 m parallel and below the soil surface to measure the average water content for the 0-6 cm layer and at a 45° angle extending from 0.06 m to about 0.15 m below the surface.

A net radiometer (NR Lite2, Kipp & Zonen, Delft, The Netherlands supplied by Campbell Scientific, Inc, Logan, UT) was attached to the mast at a height of 2 m to measure net radiation. A silicon pressure sensor (model SB-100, Apogee, Logan, UT) measured barometric pressure. Wind speed was measured with a three-cup anemometer (model 014A, Met One Instruments, Inc., Grants Pass, OR) at a height of 5 m. Rainfall was measured with a tipping bucket rain gauge (model TE525, Texas Electronics, Dallas, TX) at a height of 3 m above the tilled and wheat plots. Wind direction was measured with a single wind direction sensor mounted at 4 m on the blue lupin instrument tripod (Model 03301 R.M. Young Wind Sentry Vane, R.M. Young Traverse City, Michigan supplied by Campbell Scientific, Inc, Logan, UT). Two 70-W solar panels and two 12-V batteries wired in parallel powered each BREB station.

Except for soil moisture sensors which were interrogated hourly, sensor data were recorded every five seconds using a data logger (Model CR3000, Campbell Scientific Inc.). Following arm rotation there was a 7 s time delay to allow for gas to be purged from the CO_2 analyzer tubing. The data logger calculated and recorded 5 min averages of the 5 s readings. Following the storage of each 5 min average, the data logger initiated rotation of the arms swapping the upper and lower positions of the air inlets housing temperature and humidity sensors and CO_2 intake to remove bias between the sensors measuring temperature, humidity and CO_2 concentration at two heights.

2.4 Data Analysis

The Bowen ratio and the CO₂ flux density were calculated using the following equations based on research refining the BREB approach (Bowen, 1926; Kanemasu et al., 1979; Stull, 1988; Held et al., 1990; McGinn & King, 1990; Dugas, 1993; Perez et al., 1999) and performed using the same method as reported by O'Dell et al., (2014). Five-min water vapor pressure and temperature differences were averaged at 30-min intervals to calculate the Bowen ratio (β):

$$\beta = [P \times C_p(\theta_L - \theta_U)] / [\lambda \times \varepsilon (e_L - e_U)] \quad (1)$$

where P is the measured atmospheric pressure in kPa, C_p the specific heat capacity of air at constant pressure (1,004.67 J kg⁻¹ K⁻¹), θ_L and θ_U are the potential temperatures at the upper (U) and lower (L) positions (K), λ the latent heat of vaporization of water (2.45x10⁶ J kg⁻¹), ε the ratio of the molecular weights of air and water (0.622), and e_U and e_L are the vapor pressures at the upper and lower positions (kPa) (Bowen, 1926; Kanemasu et al., 1979; Stull, 1988; Held et al., 1990; Dugas, 1993).

Potential temperature, θ was calculated from the thermistor air temperature data with equation:

$$\theta = T (P_o/P)^{R/C_p} \quad (2)$$

where T is the measured thermistor temperature (in °C converted to K, i.e., K = °C + 273.16), P_o the reference pressure (100 kPa), P the observed pressure (kPa), R the universal gas constant (8.314 J K⁻¹ mol⁻¹) and C_p the specific heat capacity of air (~29.1 J mol⁻¹ K⁻¹) (Stull, 1988).

Latent heat flux density, LE (W m⁻²) was calculated as:

$$LE = (R_n - G_o) / (1 + \beta) \quad (3)$$

where R_n is the measured net radiation (W m⁻²) and G_o is the soil heat flux at the soil surface (W m⁻²) (Bowen 1926; Kanemasu et al., 1979; Stull, 1988; Held et al., 1990; Dugas, 1993). Since soil heat flux was measured at a depth of 0.06 m below the surface, soil heat flux values were corrected for heat storage in the 0 to 0.06 m soil layer (i.e. $G_o = G_{0.06m} + \Delta S$) via:

$$\Delta S = C (\Delta T / \Delta t) z \times 1 \times 10^6 \quad (4)$$

where ΔS is the change in heat storage above the soil heat flux plate (W m⁻²), C the volumetric heat capacity of the soil (MJ m⁻³ K⁻¹), ΔT the change in temperature (current minus previous) of the soil above the heat flux plate (K) taken from average soil temperature measurements at 0.015 m and 0.045 m depths, Δt is the time step (s), z is the depth of the soil heat flux plate (0.06 m). C was calculated with the following equation:

$$C = C_m (1 - \phi_f) + C_w \times \theta \quad (5)$$

where the volumetric heat capacity for soil is represented by C_m (2.35 MJ m⁻³ K⁻¹), the volumetric heat capacity of water is C_w (4.18 MJ m⁻³ K⁻¹), and soil volumetric water content, θ included measurements from soil moisture sensors on the tilled and untilled plots and was estimated at a higher level of 0.3 on the wheat and blue lupin plots due to irrigation. Soil porosity, ϕ_f , was calculated as:

$$\phi_f = 1 - (\rho_b / \rho_s) \quad (6)$$

where ρ_b is soil bulk density measured at 1.19 and 1.36 Mg m⁻³ for the tilled and untilled plots respectively and estimated at 1.25 Mg m⁻³ for the wheat and blue lupin plots. Soil particle density, ρ_s , was assumed to be 2.65 Mg m⁻³. Sensible heat flux density, H (W m⁻²) was calculated as (Kanemasu et al., 1979; Held et al., 1990; McGinn & King, 1990; Dugas, 1993):

$$H = R_n - G_o - LE \quad (7)$$

Turbulent diffusivity for sensible heat, K_h (m² s⁻¹) was calculated as:

$$K_h = (H / \rho_b C_p) \times (\Delta z / \Delta \theta) \quad (8)$$

$\rho_b C_p$ is the volumetric heat capacity for air (1,200 J m⁻³ K⁻¹), Δz is the sensor separation distance (1.5 m) (McGinn & King, 1990).

A , the CO₂ flux density (kg m⁻² s⁻¹) was calculated as:

$$A = K_c (\Delta \rho_c / \Delta z) \quad (9)$$

where K_c is the turbulent diffusivity for CO₂ (m² s⁻¹) and is assumed to be equal to the turbulent diffusivity for sensible heat (K_h), and $\Delta \rho_c$ is the average difference in CO₂ density between measurement heights converted from the LI-820 CO₂ concentration output of ppm to kg CO₂ m⁻³ (Held et al., 1990; McGinn & King, 1990; Dugas, 1993).

The CO₂ flux was corrected for temperature and vapor density differences at the two measurement heights using the following equation:

$$A_{corr} = A + (\rho_c/\rho_a) \times (0.649 \times 10^{-6} \times LE + 3.358 \times 10^{-6} \times H) \quad (10)$$

where A_{corr} and A are in kg m⁻² s⁻¹, ρ_c is the average CO₂ density at both measurement heights (g m⁻³), ρ_a is the density of dry air (~1,200 g m⁻³) (Webb et al., 1980).

The sign conventions used for this study follow standard micrometeorological practice. Thus R_n is positive when energy is moving down toward the soil surface, H and LE are positive when moving up and away from the surface, and G_0 is positive when moving down from the top of the soil surface (Perez et al., 1999). The sign convention for CO₂ flux is that an upward flux is positive, i.e., a positive A_{corr} number represents CO₂ emissions from the soil and a downward flux is negative, i.e., negative A_{corr} represents C sequestration (Dugas, 1993; Perez et al., 1999).

Because the Bowen ratio definition uses measured vertical temperature and humidity differences, computed CO₂ fluxes are subject to error as the Bowen ratio approaches -1, which often occurs near sunrise, sunset or during rainfall (Perez et al., 1999, Ohmura, 1982). In recognition of this, values of the Bowen ratio in the range $-0.75 < \beta < -1.25$ were replaced using linear interpolation. Data collected during and immediately following precipitation events were omitted because of the questionable performance of R_n and G sensors. Graphs of both 5 min and 30 min averaged raw data and calculated energy fluxes were visually inspected to detect problems with sensors.

BREB measurement recordings began on 14 June 2013 and continued through October. To account for differences in the response times of the rotating sensors, the data logger program was modified to wait for two minutes following the rotation of the arms before collecting five-second readings to determine the five-min average. The program change to delay averaging of five-second readings was installed on 5-6 August 2013.

In the CO₂ flux calculations there were occasionally unexplained large spikes or periods of unusually large values. Some of the spikes in CO₂ flux density could be correlated with events such as irrigation and rainfall, and the small temperature and vapor pressure differences that occur as energy flux changes at sunrise and sunset; however other spikes could not easily be explained. Large spikes in CO₂ flux that were greater than four times the average of the preceding or following flux calculations for a particular instrument (occurring most frequently during sunrise and sunset) were removed and linearly interpolated.

Soil samples were taken on 25 February 2014 to provide further input into the site characterization. Table 2 shows average soil C determined by high temperature catalytic combustion with Primacs-SNC Analyzer (Skalar Analytical, Breda, Netherlands) in the 0-7 cm layer and 7-15 cm of soil for eight samples collected for both layers of each plot for a total of 64 samples.

Table 2. C concentration of soil samples for two soil depths with standard deviation (SD) in parentheses

Plot	Average C concentration ± SD 0-7 cm depth (g/kg)	Average C concentration ± SD 7-15 cm depth (g/kg)
Tilled	0.26 (± 0.062)	0.25 (± 0.091)
Untilled	0.24 (± 0.074)	0.23 (± 0.046)
Wheat	0.23 (± 0.129)	0.19 (± 0.055)
Blue lupin	0.27 (± 0.077)	0.23 (± 0.084)

2.5 Statistical Analysis

Unreplicated experiments provide valuable data in agricultural research when there is a limited number of experimental units (Perrett & Higgins, 2006; Underwood, 1996). In this case cost and logistical circumstances limited the number of instruments and replications. Multiple observations with subsampling and/or repeated measures provide useful data in place of replication (Underwood, 1996; Dugas et al., 1997; Perrett & Higgins, 2006). To determine statistically significant differences among the treatments, t-tests of the half hour CO₂ flux were performed for all pair-wise comparisons. Distributions were compared using the Kolomogorov-Smirnoff (KS) test using the SAS software version 9.3 (SAS, Cary, NC) NPAR1WAY procedure. Distribution means were compared using t-tests. Satterwaithe's degrees of freedom correction was applied when the null hypothesis of

variance equality of the distributions was rejected.

More robust, non-parametric analyses were used to compare the distributions of temporal flux, as well as the carbon accumulation trends over the course of the experiment. A non-parametric bootstrap rolling procedure was developed to simulate 95% confidence intervals for the cumulative distribution of CO₂ by each treatment over the duration of the experiment. The method applied here differs from typical applications of this procedure developed for time series analysis of economic data (e.g., Balcilar & Ozdemir, 2013). In this application the *variance around the accumulation* of CO₂ after t days associated with each treatment is of interest.

The rolling bootstrap procedure follows, noting that the same seed is used to generate random draws to replicate the distributions of each treatment. We resample each $t = 1 \dots 139$ th day of the experiment with replacement to reconstruct the accumulation path observed over the experiment. The block sampling procedure replicates the strong diurnal cycles observed daily, along with idiosyncratic weather events and varying lengths of daylight particular to each day. Resampled units are therefore days, each having, on average 40 records (minimum, 3; maximum, 48). Consider for example set $D = \{d_1, d_2, d_3, \dots, d_t\}$, where d_t is the sub-set of measurements recorded on day t .

Step 1: Randomly sample from set D , with replacement, t days to generate a bootstrap series, D^* .

Step 2: Find the total CO₂-C accumulated from D^* .

Repeat Steps 1 and 2 1,000 times.

Step 3: Determine and save the 2.5% and 97.5% confidence intervals of the bootstrap distribution of the C measurement totals for the simulated series.

Step 4: Update sample space D by appending the observations from day $t + 1$; for example; $D = \{d_1, d_2, d_3, \dots, d_t, d_{t+1}\}$.

The procedure is repeated until set D includes all 139 days of data collected during the experiment. The simulation procedure begins at day 10 to avoid producing singleton bootstrap data sets. The distributions of daily CO₂ accumulations associated with each are compared graphically.

3. Results

3.1 Energy Balance

There is a strong partitioning of available energy to sensible heat in the energy balance in the tilled and untilled fields (Figures 3 and 4) with no vegetation and no irrigation. On the other hand the latent heat flux totally dominates the wheat plot (Figure 5) for this period and to a lesser extent, the blue lupin plot (Figure 6). One noticeable feature of the data record is a consistent association of the CO₂ flux with the latent heat flux. This association is most evident in August and September for the wheat plot and in September and October for the blue lupin plot as these crops achieve maturity. Likewise the latent energy flux on the blue lupin plot (Figure 6) beginning to increase and dominate by the end of this period is also consistent with increasing evapotranspiration and CO₂ sequestration of a growing crop.

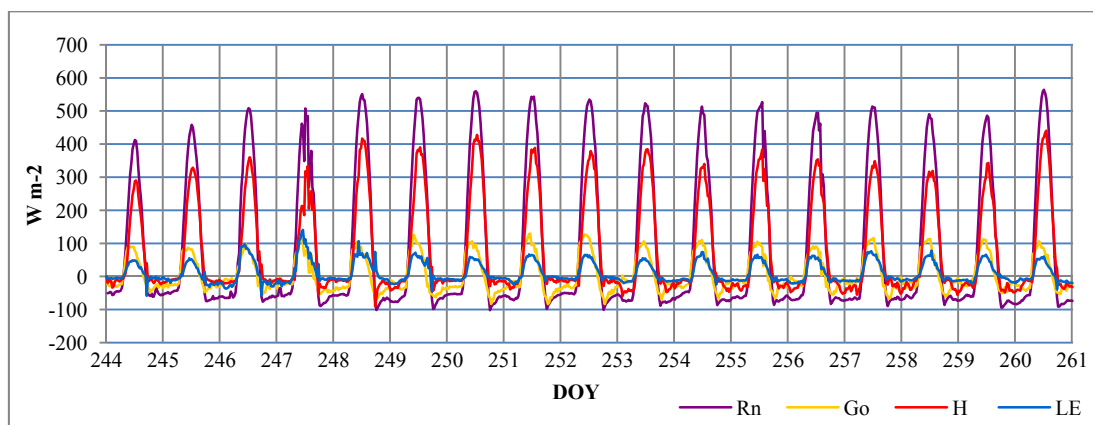


Figure 3. Energy balance for the tilled plot for 1-18 September, 2013 (DOY 244-261), Mt. Pleasant, Zimbabwe. R_n is the net radiation, G_0 the surface soil heat flux, H the sensible heat flux, and LE the latent heat flux

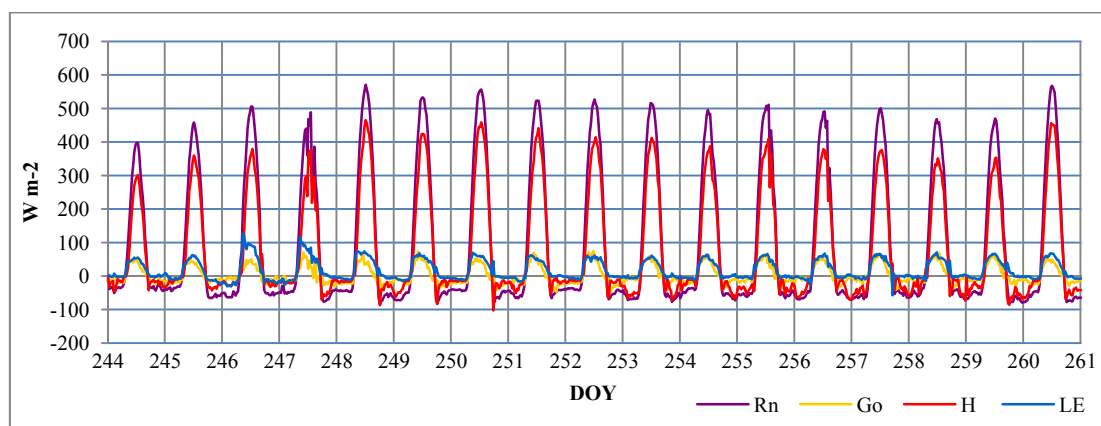


Figure 4. Energy balance for the untilled plot for 1-18 September (DOY 244-261) 2013, Mt. Pleasant, Zimbabwe. R_n is the net radiation, G_o the surface soil heat flux, H the sensible heat flux, and LE the latent heat flux

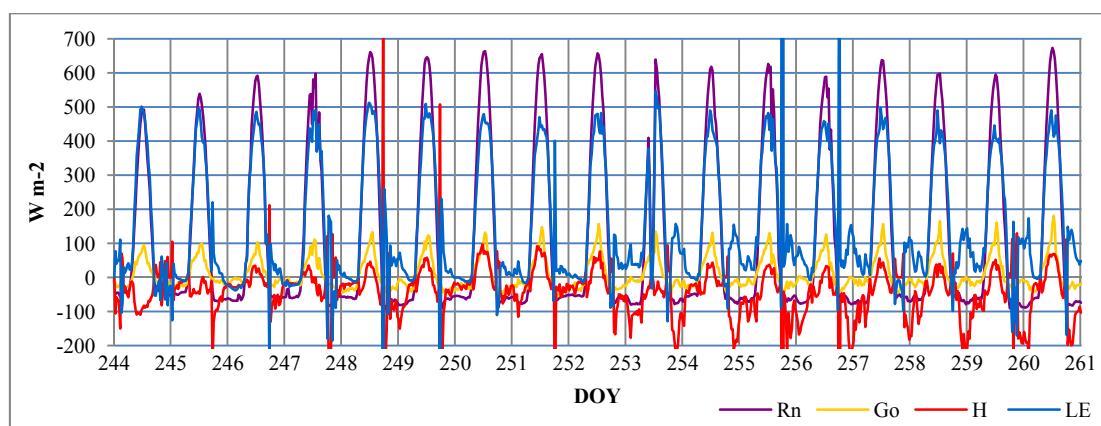


Figure 5. Energy balance for the wheat plot for 1-18 September (DOY 244-261), 2013, Mt. Pleasant, Zimbabwe. R_n is the net radiation, G_o the surface soil heat flux, H the sensible heat flux, and LE the latent heat flux

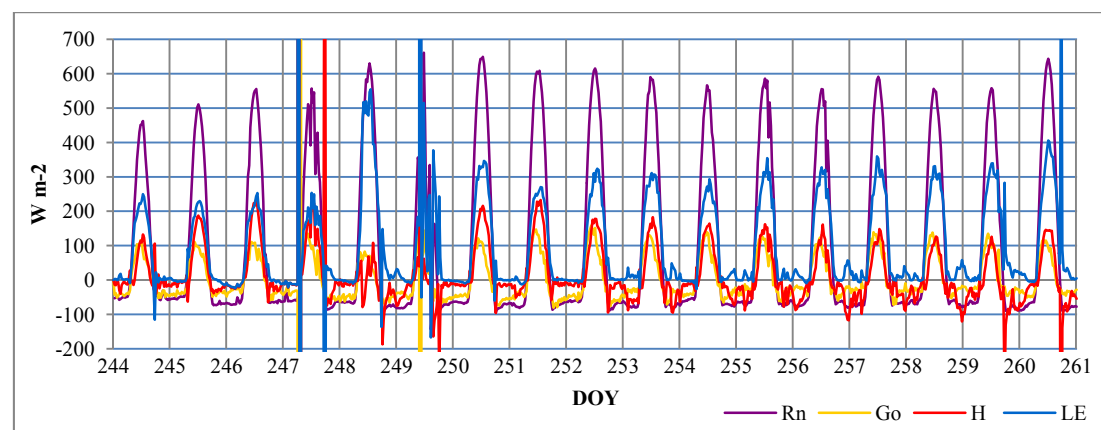


Figure 6. Energy balance for the blue lupin plot for 1-18 September, 2013, Mt. Pleasant, Zimbabwe. R_n is the net radiation, G_o the surface soil heat flux, H the sensible heat flux, and LE the latent heat flux

The net radiation on the tilled and untilled plots (Figures 3 and 4) is noticeably lower (peaking at 620 and 593 $W m^{-2}$ respectively during this period) than the net radiation on the wheat and blue lupin plots (Figures 5 and 6) (peaking at 724 and 682 $W m^{-2}$ respectively) indicating greater reflectance of short wave radiation and emitted long wave radiation, with the untilled having the lowest net radiation (Figure 4) and the tilled having the highest surface temperature. Notably the wheat plot has the greatest net radiation during September (Figure 5), with the

blue lupin exceeding the net radiation of all plots at the end of October. The irregular appearance of both net radiation and latent energy flux on DOY 249 on the blue lupin plot (Figure 6) coincides with irrigation over that plot.

3.2 CO₂ Flux Calculated from Energy Balance

There was a smaller range of CO₂ flux for all plots during June and July as would be expected for the nascent cover crops (Figure 7). From July to September the daily maximum rate of CO₂ uptake by the wheat cover crop increased to more than ten times that of the other plots (Figures 7 and 8). Note that the scale of the wheat graph in Figure 7 is greater than the scale for the other treatments, so that differences among the months can be seen for all of the plots. The CO₂ flux reveals a strong diurnal signal for the wheat crop during this period, and during September as the wheat flux diminishes, the diurnal signal of blue lupin CO₂ flux increases in strength as that crop reaches maturity (Figure 8). The CO₂ flux of both the wheat and the blue lupin treatments from August through October are consistent with observed vegetative growth (Figure 1), showing a peak of CO₂ flux from the wheat crop in September as the wheat reached maturity, while the blue lupin began flowering in mid-August and reached peak CO₂ sequestration levels on 15 October (day of year (DOY) 288) one week following a 2.8 mm rainfall.

On 25 October approximately 2,400 kg of wheat were harvested from the whole plot (3.75 tonnes ha⁻¹) with a combine harvester, leaving the straw residue as mulch on the soil surface. There has not been much research on cover crop yields because there are typically no markets for these crops; they are usually used as fodder, for household fuel or home construction, or green manure. This could be an active area of research, but no regional information is currently available.

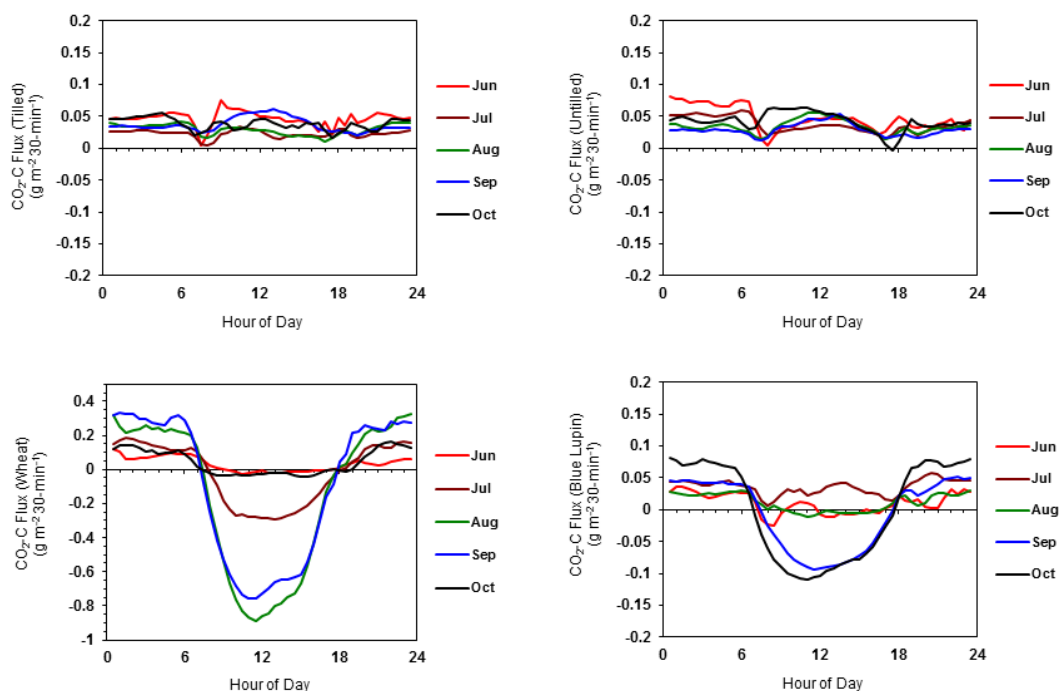


Figure 7. CO₂-C from CO₂ Flux Density for each plot by month from 15 June through 31 October (DOY 166-181), 2013, Mt. Pleasant, Zimbabwe (Note for clarity the figure for the Wheat plot is at a different scale to allow the smaller trends to be visually perceptible on the other plots)

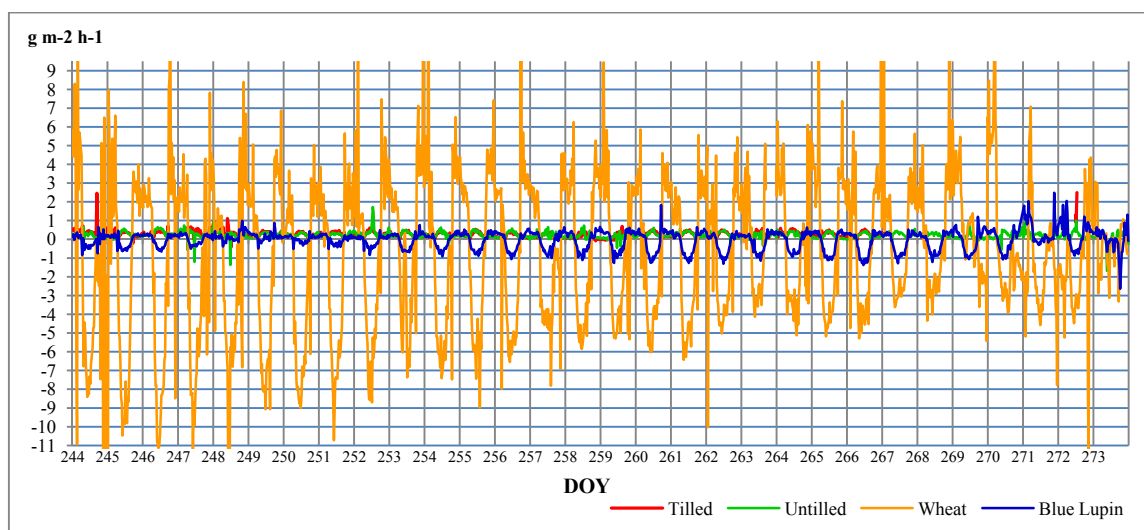


Figure 8. CO₂ Flux Density (A_{corr}) for all plots in September 2013, Mt. Pleasant, Zimbabwe

Carbon dioxide concentration data collected during this period were also analyzed for periodic fluctuations during nighttime hours and were found to have a pattern (Hicks et al., 2015) that could indicate meteorological conditions that could influence nighttime CO₂ flux.

3.3 The Short-Term Cumulative CO₂ Flux

A graphic comparison of the accumulation of 30-min fluxes of CO₂-C for the four treatments (Figure 9) using the bootstrapping procedure, with a lag of 10 days to seed the simulation shows the differences in the treatments. Data were removed for any 30-min period that did not have a value for all four treatments, leaving 77% of original data for the analysis. The shaded areas are 95% bootstrap confidence intervals.

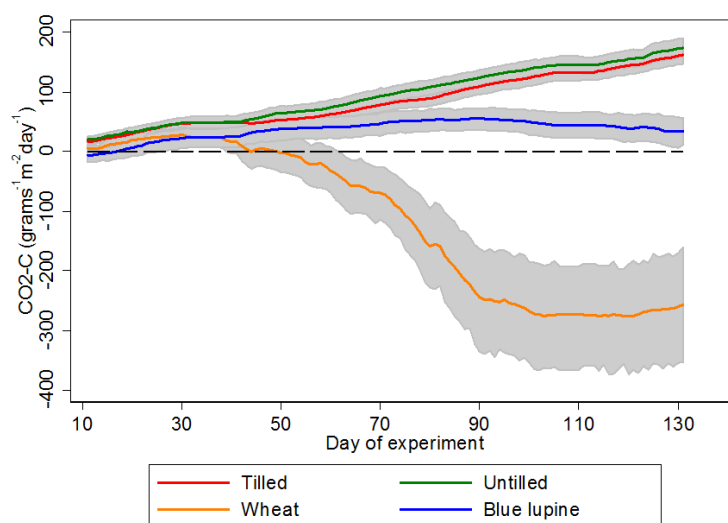


Figure 9. Comparison of accumulated sum of half-hour CO₂-C for all treatments (shaded areas are 95% bootstrapped confidence intervals)

These totals show that the wheat treatment effectively sequestered carbon during this period, while the other treatments did not. The blue lupin treatment did not emit as much CO₂ as the tilled or untilled plots.

Accumulated sums of CO₂-C emitted or sequestered from available data for each month and the entire 139-day period with the percentage of missing values (Table 3) provide comparisons of sums for each treatment in each month. The percentage of observations missing from equipment failures or deleted due to environmental conditions are included for each period. There was a period of 40 days from 8 August through 19 September

when all instruments were working continuously; the hourly average CO₂ flux density for this period is shown for comparison purposes. While about 11% of data for the tilled treatment were missing, the total amount of missing observations across all measurement records was 7.4%, although for about 23% of the time at least one of the four systems was not operational. By comparison FluxNet sites reported an average of 35% of rejected or missing data (Gilmanov et al., 2010). In addition to greater data coverage, this shows a degree of resilience and robustness in instrumentation, process, and maintenance derived in part from prior experience in a remote setting (O'Dell et al., 2014), especially valuable in developing countries.

Table 3. Sum of CO₂-C and percentage of missing values by month and for the total period from 15 June to 31 October, 2013, Mt. Pleasant, Zimbabwe

Period	Tilled Sum of CO ₂ -C (g m ⁻² period ⁻¹)	Tilled Percent Missing Values for Period	Untilled Sum of CO ₂ -C (g m ⁻² period ⁻¹)	Untilled Percent Missing Values for Period	Wheat Sum of CO ₂ -C (g m ⁻² period ⁻¹)	Wheat Percent Missing Values for Period	Blue Lupin Sum of CO ₂ -C (g m ⁻² period ⁻¹)	Blue Lupin Percent Missing Values for Period
June 15-30	36.15	0.0%	36.47	1.2%	24.44	6.3%	7.54	6.2%
July 1-31	0.02	0.0%	-0.08	11.9%	-0.21	20.6%	0.06	31.9%
August 1-31	44.07	0.0%	46.29	8.3%	-189.93	0.0%	17.54	1.7%
September 1-31	41.19	22.8%	41.88	0.0%	-126.26	1.0%	-6.97	0.0%
October 1-31	41.17	27.4%	61.60	0.9%	65.23	0.3%	3.95	0.1%
June 15-October 31	196.62	11.0%	234.71	4.9%	-257.49	5.6%	58.34	8.2%

Note. Significant differences were found for each pair-wise comparison ($p < 0.01$), except for the t-test comparing the tilled and untilled treatments ($p = 0.62$) and the KS procedure comparing the wheat and the blue lupin treatments ($p = 0.56$).

4. Discussion

BREB techniques can detect differences in CO₂ flux and accumulations of CO₂-C among different agricultural practices and environmental conditions. Cover crops reduce CO₂ emissions over bare-fallow, and some cover crops (wheat was tested here) can have a net sequestration of C over the short-term, when sequestration is defined as a stable increase in C storage regardless of residence time (Hutchinson et al., 2007). These results are consistent with other studies found in the literature (Paustian et al., 1997; Chivenge et al., 2007; Barthès et al., 2004; Mapanda et al., 2010, 2011; Thierfelder et al., 2013, 2014). In particular Mapanda's (2011) measurements of CO₂ flux from soil of maize plots using chambers at the nearby University of Zimbabwe research farm from 2007 through 2008 were similar to CO₂ emissions of the blue lupin, tilled and untilled treatments, accounting for the possible underestimation of flux from chamber methods. The current study adds results to Mapanda's work by including the CO₂ flux of the vegetative canopy and providing continuous measurements over a 4-mo period, adding a detailed picture of the flux to reveal differences over shorter periods, such as days, weeks, and months. With continuous sampling, the relationships of other variables such as moisture and temperature can be distinguished, and annual and interannual totals of flux can be measured and compared for various combinations of management practices. These results underscore the problem of bare-fallow for both tilled and land left untilled, and highlights the value of cover crops during the non-growing season.

These results also indicate that BREB micrometeorological systems can be used to distinguish short-term differences in days, weeks, and months between agricultural practices in a temperate and moderately dry climatic regime in Zimbabwe, despite instrument challenges such as remote power and environmental influences such as sporadic turbulence, rainfall, and irrigation. BREB systems could be applied to comparing differences between crops, plant populations, rotations, different stages of growth, senescence, in-between cropping periods, and in different climatic regimes.

Many studies have looked at CO₂ flux from agriculture, and in the last few decades instrument advances have

created a global network of micrometeorology towers that are measuring CO₂, such as FLUXNET (Oak Ridge National Laboratory, 2014) and GRACEnet (USDA ARS, 2014). Most of these sites are in developed countries and integrated with university and government programs. Gilmanov et al. (2010) synthesized data from micrometeorological towers measuring 118 non-forest ecosystems including 28 from cropland, finding that cropland and grassland ecosystems actually serve as a significant C sink, despite current skepticism about agriculture's contributions to the carbon budget. Yet Gilmanov et al. (2010) included only one dataset from Africa which was from a shrubland/savanna ecosystem in South Africa thus providing no information about agricultural practices.

To demonstrate a different view of the role of agriculture and its relative importance to global GHG emissions, recent US estimates can be considered. According to the US EPA (2014), 94% of US CO₂ emissions were from fossil fuel combustion. In contrast, Canadell et al. (2009) report that from 1990 to 2005 48% of CO₂ emissions in Africa were from land use change, of which 89% was attributed to agricultural use (43% was from deforestation for permanent cropland, 48% was from deforestation due to shifting agriculture, and 11% was industrial wood harvest). One method to reduce the pressure to convert forest to cropland by smallholders and industrial agriculture is to increase agricultural productivity and yields through sustainable CA practices. Identifying those practices that sequester C provides a basis for C trading credits to further incentivize CA adoption.

Differentiating the practices and environmental factors that contribute to increased emissions and sequestration provides the data to support optimal practices for reducing emissions in specific climatic regimes. There are many unanswered questions such as quantifying the contributions of a seasonal practice to the net annual emissions or sequestration and measuring the CO₂ flux from practices that sequester C deeper in soil layers and promote the incorporation of residues before decomposition and respiration between cropping cycles.

This data shows that differences can be discerned between management practices on a seasonal basis. It remains (a) to measure and aggregate an entire year's set of practices including the management practices used for the growing season cash crop in addition to the preparation periods between crop planting to determine net annual emissions or sequestration from a sequence of practices, (b) to identify management practices that facilitate consideration of carbon credits, (c) to encourage adoption of sustainable agricultural practices for food security and mitigation of GHG emissions, and (d) to demonstrate the role of subsistence agriculture. Data that show the differences in specific practices and conditions will provide a basis for policies that promote GHG mitigation and provide incentives to smallholders.

5. Summary and Conclusions

Bowen ratio energy balance measured differences in CO₂ flux at the field scale, quantifying the C aggregated by a practice that only lasts for a few months providing data about specific practices. Carbon dioxide flux was significantly lower from cover crops than bare fallow. More importantly a wheat cover crop grown during the dry winter season can sequester a significant amount of C. This experiment provided evidence that micrometeorological techniques can distinguish small differences in CO₂ emissions between agricultural practices and provides feedback and information about contributing factors, such as irrigation, soil water content, and vegetation density. Although the BREB system requires careful attention to instrument maintenance and refinement in implementation, it provided a rich set of micrometeorological variables and soil properties that enabled a closer examination and comparison of energy balance estimates of CO₂ flux for measuring the potential of agricultural practices to sequester carbon in real time over shorter periods. This approach is considerably promising to compare the relative ability of different agricultural practices to sequester C, and may be able to distinguish small differences between specific crops, plant densities and various intensification strategies.

This effort focuses on short-term flux of CO₂ from both soil and crops, which are difficult to quantify by direct measurement of soil organic carbon and can take as long as five years to show statistically significant differences. Hence, confirmation of the present results will be challenging until baseline data can be compared. Possible approaches include replication elsewhere, in different circumstances, and investigating correlations between crops with varying root depth to explore the relationships between BREB CO₂ flux signals and plant/soil properties. Finding the most realistic and effective combinations of specific crops, climate, and moisture regimes provides tremendous opportunity to refine carbon sequestration recommendations.

Smallholder farmers in Africa and other developing countries cannot easily deploy this technology to measure practices that would fit their climatic regimes. Carbon dioxide flux measurements are being collected in Africa but most are not applied to agriculture. This experiment has refined the architecture and support requirements to make this method more accessible to CA researchers seeking co-benefits for specific management practices that

can improve livelihoods on a smallholder scale.

Another important question this research raises is the validation of this approach with alternate methods, data and analysis. While the BREB system can quantify CO₂ flux on a field scale, greater confidence can be achieved comparing the results with other alternative approaches like eddy covariance or canopy chambers, which has been planned for subsequent trials.

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