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Measuring Carbon Dioxide (CO2) Flux of Agricultural Practices in Sub-Saharan Africa

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I am submitting herewith a thesis written by Debra Blumberg O'Dell entitled "Measuring Carbon Dioxide (CO2) Flux of Agricultural Practices in Sub-Saharan Africa." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental and Soil Sciences.

Neal S. Eash, Major Professor

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Measuring Carbon Dioxide (CO2) Flux of Agricultural Practices in Sub-Saharan Africa

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Debra Blumberg O'Dell

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ABSTRACT

Agriculture has an important role in addressing two of the world's most pressing problems: meeting global food demand and mitigating climate change. If agriculture is not practiced sustainably it will fail to meet future food demand and likely intensify the pace of global climate change. There are some agricultural practices, such as Conservation Agriculture, that can produce food sustainably and have the potential to mitigate climate change. However it is not clear which agricultural practices contribute to climate mitigation and by how much. By measuring the carbon dioxide (CO_2) emissions of specific agricultural practices, the ability of practices to sequester or emit carbon can be quantified and used in climate mitigation policies. Since there is a lack of data showing the flux of CO_2 for agricultural practices in developing countries, there is a great need to apply experimental methodologies to address this deficiency. Research was conducted using Bowen Ratio Energy Balance (BREB) instrumentation to quantify the energy balance and CO_2 flux of agricultural practices in Lesotho and Zimbabwe. BREB micrometeorological systems were set up to compare and contrast tillage versus no-till practices and the effects of cover crops. The results demonstrated that with a vigilant approach, BREB micrometeorology provides real time measurements of CO_2 flux that can measure and distinguish the differences between agricultural practices in southern Africa. The results generally confirmed that two of the major tenants of Conservation Agriculture i.e., reduced tillage (specifically no-till) and cover crops, sequester carbon more than tillage and fallow practices. Because the role of agriculture's mitigation potential for climate change is not understood by the wider society, it is critical not only to communicate the results of this research but to raise awareness of the role of Agriculture in addressing two of the biggest problems that humankind will face in the future: feeding a burgeoning human population and preventing catastrophic climate change from record concentrations of atmospheric greenhouse gases. To that end, this thesis also touches on research investigating how to increase awareness and interest in agriculture by college students.

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INTRODUCTION

This thesis presents research conducted to measure CO_2 flux over agricultural practices in southern Africa and to increase awareness of Agriculture's role in climate change and food security. Chapter 1 is a reprint of the paper entitled, "Bowen Ratio Energy Balance Measurement of Carbon Dioxide (CO_2) Fluxes of No-Till and Conventional Tillage Agriculture in Lesotho," published in the Open Journal of Soil Science in March 2014. The paper summarizes the initial implementation of an approach to use micrometeorological instruments to quantify CO_2 fluxes in a rural area of Lesotho. The paper describes research comparing and estimating the emissions and sequestration of CO_2 between two tillage practices in a mountainous country of Southern Africa, finding that no-till sequestered more carbon (C) than conventional tillage. The paper also discusses the challenges of refining the instrumentation and process in a rural, remote setting in Africa.

Chapter 2 is a paper being developed for publication that describes a more recent experiment using the same micrometeorological approach as discussed in Chapter 1 to compare CO_2 flux of cover crops and tillage practices in Zimbabwe. This experiment compared the flux of four different agricultural practices from June to October 2013 at the International Maize and Wheat Improvement Center (CIMMYT) in Harare, Zimbabwe, including (1) no-till followed by planting of winter wheat (*Triticum aestivum*), (2) no-till followed by planting of blue lupin (*Lupinus angustifolios* L.), (3) maize crop (*Zea mays* L.) residue left on the surface, and (4) maize residue incorporated with tillage. This study found that micrometeorological methods were able to detect significant differences in CO_2 exchange rates between treatments.

Chapter 3 is a paper entitled, "Soils and Civilizations: Using a General Education Course to Teach Agricultural Relevance," published in a special September 2013 issue of the North American Colleges and Teachers of Agriculture (NACTA) Journal featuring 24 peer-reviewed manuscripts dealing with the theme of "Globalization: Implications for teaching and learning in postsecondary agricultural education." This paper summarizes an investigation of college student awareness of agriculture's role in both food security and the environment to address student misconceptions about agriculture and the decline in enrollment of students to soil science and other the major scientific disciplines related to agriculture. This study measured changes in student perception of population growth, food security and civilization stability and the relationship these concepts have with environmental sustainability in a general education college course called “Soils and Civilizations.” The study showed that such a course can have an impact in student perception of agriculture and could be an important tool in raising awareness about the role of agriculture in food security and environmental sustainability and increasing enrollment in agricultural disciplines.

CHAPTER I

BOWEN RATIO ENERGY BALANCE MEASUREMENT OF CARBON DIOXIDE (CO2) FLUXES OF NO-TILL AND CONVENTIONAL TILLAGE AGRICULTURE IN LESOTHO

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Abstract

Global food demand requires that soils be used intensively for agriculture, but how these soils are managed greatly impacts soil fluxes of carbon dioxide (CO_2). Soil management practices can cause carbon to be either sequestered or emitted, with corresponding uncertain influence on atmospheric CO_2 concentrations. The situation is further complicated by the lack of CO_2 flux measurements for African subsistence farms. For widespread application in remote areas, a simple experimental methodology is desired. As a first step, the present study investigated the use of Bowen Ratio Energy Balance (BREB) instrumentation to measure the energy balance and CO_2 fluxes of two contrasting crop management systems, till and no-till, in the lowlands within the mountains of Lesotho. Two BREB micrometeorological systems were established on 100-m by 100-m sites, both planted with maize (*Zea mays*) but under either conventional (plow, disk-disk) or no-till soil management systems. The results demonstrate that with careful maintenance of the instruments by appropriately trained local personnel, the BREB approach offers substantial benefits in measuring real time changes in agroecosystem CO_2 flux. The periods where the two treatments could be compared indicated greater CO_2 sequestration over the no-till treatments during both the growing and non-growing seasons.

Keywords

CO_2 flux; CO_2 emissions, Soil, Soil Carbon, Tillage, Till, No-till, Bowen ratio, Micrometeorology, Agriculture, Climate change, Lesotho, Africa

Introduction

Although some aspects of climate change arguments remain contentious, there is general scientific acceptance of the conclusion of the Intergovernmental Panel on Climate Change (IPCC) that increases in atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gasses (GHGs) have contributed to increases in global temperatures and associated climate change. The IPCC report summarized the extent and cause of this increase, noting that human activities have increased atmospheric CO_2 by approximately 40 percent since the mid-1700s [1]. While most anthropogenic CO_2 emissions result from fossil fuel combustion, the U.S. Council for Agricultural Science and Technology (CAST) Task Force Report stated that agriculture produces 13.5 percent of GHG emissions world-wide [2]. According to Denef et al. [3] CO_2 emissions from agriculture in the U.S. result primarily from practices that reduce the amount of organic carbon in the soil, e.g., fallow or intensive tillage.

After the lithosphere and oceans, soil organic matter represents the earth's third largest pool of carbon (C), greater than the C pools in the atmosphere and biosphere [4]. An increasing amount (presently ~ 12 percent, see Wood et al. [5]) of the world's land area is used for food production. The CAST Task Force reports that modified agricultural practices could help reduce agricultural CO_2 emissions. The United Nations Food and Agriculture Submission to the United Nations Framework Convention on Climate Change (UNFCCC) supports this view, stating that agriculture has the potential to contribute to the mitigation and stabilization of the concentration of atmospheric GHGs by promoting the use of agricultural management practices that enhance C sequestration in soils while discouraging the use of agricultural practices that promote the emission of CO_2 from soil to the atmosphere [6]. At the same time, such practices would increase the amount of carbon in soils, to the benefit of plant growth.

Converting from tillage to no-till (NT) as an agricultural management practice has been identified as having potential to reduce CO_2 emissions [7, 8, 9]. Tillage-induced disturbance increases aeration within the top soil horizons, which fuels microbial decomposition of organic matter, increasing soil respiration and CO_2 emissions [10]. West and Post [9] found in their meta-analysis of 67 different long-term (greater than five years) studies that a change from conventional tillage to NT generally produced a significant increase in soil organic carbon (SOC) in the top 7-cm of soil in all experiments except under a rotation of wheat followed by fallow treatment [9].

However, the potential of NT to increase soil C has been contested [11, 12, 13], especially for moist, cool climates and for heavy, textured soil [14]. Many studies have found that soil samples deeper in the profile do not show the effects of different tillage practices affecting shallower soil layers. Clearly, more research is needed to provide data on the value of NT as an agricultural practice in specific climates and soil types.

Measuring soil C is fundamental to understanding sequestration rates and amounts in soils managed under contrasting tillage regimes. Under high intensity tillage, C can be lost in a relatively short amount of time whereas NT systems sequester C but at very low rates with estimates ranging from 97 kg C ha^{-1} yr^{-1} in a dry climate after 20 years [15] to the mean rate of 480 kg C ha^{-1} yr^{-1} that West and Post found from long-term experiments in various climates around the globe [9]. It is critical to measure the impact of tillage, because it has been implicated as the key contributor to CO_2 emissions from soil.

Due to the slow rate of C sequestration and spatial variation in many soils, annual changes in soil C are small and can be difficult to quantify. Interannual climactic variability also impacts carbon emissions from soils and soil carbon measurement over time. The Food and Agriculture Organization of the United Nations (FAO) submission to the UNFCCC [16] summarized the challenges in measuring the capacity of agricultural practices and soil to sequester or emit C. These challenges entail variability in soil type and C content within a field; the need to measure small year-to-year changes in soil C; and previous land use practices. There is presently insufficient understanding to warrant confident assessment, or even to design definitive field studies, particularly for developing countries. Even though the C content of agricultural soils increases slowly, can be reversed, and can only play a minor role in comparison with the CO_2 emissions of fossil fuels, Smith [17] suggests that concerted efforts to reduce agricultural CO_2 emissions – including enhanced soil carbon sequestration – will be required to achieve desired global reductions in emissions.

Developing countries in sub-Saharan Africa represent a region where conservation agriculture (CA) practices improve soil quality as well as stabilize or increase yield while reducing C emissions. In brief, the FAO describes CA as a farming system that prescribes minimal soil disturbance such as no tillage, maintains organic cover on the soil surface and crop rotations [18]. As much as three-quarters of the agricultural land in sub-Saharan Africa has been degraded by erosion and depletion of soil nutrients [19, 20, 21]. The Kingdom of Lesotho in particular is said to have the highest rate of soil erosion in both central and southern Africa [22]. Consequently Lesotho has declined from a net grain exporter in the 1800s [23] to producing less than 30 percent of its own national grain demand in the present day [24]. Increasing soil organic C using CA could improve agricultural production and ecosystem protection by enhancing soil fertility, water holding capacity, aggregate stability and water infiltration [25].

Since C emissions from land are variable and occur in minute quantities over large scales, they are hard to quantify with confidence. There are two main approaches for measuring CO_2

exchange over agricultural ecosystems including the use of static chambers and micrometeorological techniques [2]. The two primary micrometeorological methods are the Bowen ratio energy balance (BREB) system and eddy covariance. Of these two, the latter requires much more complex instrumentation, and usually requires more expert on-site technical attention than the former. Dugas [26] compared three BREB systems with nine soil chambers and found good CO_2 flux agreement between the two methods. He also noted that the BREB method integrates the soil-atmospheric boundary layer interactions over a much larger area than the chamber method and thus accommodates more of the spatial variability of CO_2 flux from soil, allowing high resolution measurements representative of larger expanses. Since there are substantial temporal, spatial, and maintenance challenges in using chamber systems, the BREB approach has been favored for present use. The study reported here is viewed as a field test of the BREB approach, conducted in demanding circumstances in a very mountainous area.

The present study was designed to test the hypothesis that there are no significant differences between long-term net emissions of CO_2 over an area of conventional tillage (Till) and an otherwise similar NT area typical of traditional small scale farming methods in Lesotho. The study compared CO_2 flux between Till and NT treatments over an eighteen month period.

Materials and Methods

Site Description

BREB measurements of soil and micrometeorological properties were collected from December 2010 to June 2012 in Maphutseng (30°12.828’S, 27°29.747’E for the Till plot and 30° 12.788’ S, 27° 29.718’ E for the NT, 1,457 m elevation) in the district of Mohale’s Hoek in southern Lesotho [27]. The study site was located in the Maphutseng river valley on the first terrace above the alluvial floodplain. The study site is in a very mountainous region, but is delineated as the southern lowlands of Lesotho.

Approximately 85 percent of the annual rainfall occurs during the warm season months, from October through March/April. Annual precipitation in the district of Mohale’s Hoek averages less than 700 mm yr^{-1} [28]. Snow and rain occur during the cold season between May and July. Extreme weather conditions such as high winds and hail can occur throughout the year.

The soil was classified as the Phechela series (fine, montmorillonitic, mesic Typic Pelludert); the site was level, with a slope not exceeding 2 percent. While the site classifies as a udic soil moisture regime, there are significant dry periods after crop harvest and through the winter months.

Two adjacent one ha fields were selected for the experimental plots. The NT plot was untilled pasture for almost 30 years until 2008 prior to the start of the present study while the Till plot was kept in sustained tillage over the same period, with a minimal number of non-crop years. The average pH for four soil samples taken February 24, 2011, of the top five cm and 5-10 cm depth of soil for the NT plot was 6.83, while the pH of the top 0-5 cm and 5-10 cm averaged 6.87 and 6.85 respectively in the Till plot (1:1 soil:water ratio) [29]. The bulk density for the Till plot was measured in July 2012 at 1.21 and 1.23 g/cm3 for 0-5 cm and 5-10 cm depths respectively. The bulk density for the NT plot, measured in August 2013 was 1.10 and 1.13 g/cm3 for 0-5 cm and 5-10 cm depths respectively. The average yield for the Till and NT plots during the 2012/2013 planting and harvest season was not significantly different at 7.02 and 6.59 tonnes/ha respectively and the plots were under similar cropping management throughout the experiment.

The NT field was seeded with maize (*Zea mays* L.) using a 2-row Vence Tudo Planter in November 2011. The Till field was prepared with conventional tillage methods using a moldboard plow with two cultivation passes using a tandem disk before planting maize with a 2-row Vence Tudo Planter in November of 2011. Interrow spacing was 90 cm for both plots with population densities seeded at approximately 29,600 plants ha^{-1} [27].

Micrometeorological Measurements

Soil and atmospheric properties were measured and recorded using a BREB system following the theory and experimental procedures laid out by Dugas [26]. The one ha size of the plots and the vegetation and topography surrounding the plots provided a sufficient uniform measurement area (fetch) for micrometeorology measurements. A BREB micrometerological station was built for each plot, with a rotating arm center-mounted on an aluminum mast for height adjustment above the canopy and anchored by a tripod, as shown in Figure 1. The arm rotated on a shaft powered by a 12 V DC electric gearmotor (model 4Z834, Dayton), until it came to rest in a near-vertical position. A horizontal shielded air intake was mounted at both ends of the arm, approximately 1.5 m apart. Each air intake housed humidity and temperature sensors and CO2 intake tubes for measurements at two heights (adjusted routinely so as to be 0.2 and 1.7 m above the top of the growing maize canopy). Air temperatures were measured using thermistors (designed and supplied by TJ Sauer). Water vapor pressure was calculated from hygroclip humidity and temperature probe data (model HC2-S3-L; Rotronic, Switzerland supplied by Campbell Scientific, Inc, Logan, UT). Fans drew air into the intakes, providing a constant flow of ambient air over the sensors at 0.34 m3/min. Carbon dioxide concentrations were measured with an absolute, non-dispersive infrared (NDIR) gas analyzer (model LI-820, LI-COR Inc., Lincoln, Nebraska, USA). Air intake openings faced in the direction of the most prevalent winds (near North).

Figure 1 Photograph of micrometeorological station in Maphutseng

Net radiation was measured with a net radiometer (model Q-7.1, Radiation Energy Balance Systems (REBS), Seattle, WA) that was attached to the mast at a height of 2 m. A soil heat flux plate (model HFT3, REBS) at a depth of 0.06 m was used to measure soil heat flux . Soil temperature was measured with two Type “T” thermocouples buried at 0.02 m and 0.04 m. Barometric pressure was measured using a silicon pressure sensor (model SB-100, Apogee, Logan, UT). A three-cup anemometer (model 014A, Met One Instruments, Inc., Grants Pass, OR) was installed at each BREB location at a height of 5m to measure wind speed and a recording rain gauge (model TE525, Campbell Scientific Inc.) was installed nearby.

A data logger (Model CR23X, Campbell Scientific Inc.) read sensor data every five seconds. After arm rotation there was a time delay of seven seconds to allow for gas to be purged from the tubing. The data logger computed and stored 5-min averages of these readings. After each 5 min average was stored, the data logger prompted the rotation of the arm swapping the lower and upper positions of the air intakes inlets that housed the temperature and humidity sensors. Moving the sensor arms allowed each sensor to measure the two positions thereby cancelling accuracy issues with each sensor and provided the precision necessary to derive accurate measurements of differences in temperature, humidity and CO_2 concentration between the two heights. Two 70 W solar panels and three 12V batteries wired in parallel powered each BREB unit.

Soil samples were collected to measure soil organic carbon concentrations towards the beginning of BREB measurements on February 4, 2011 for the NT field and February 24, 2011 for the Till field. Total organic C concentration was determined by dry combustion at 900C (VarioMax CNS macro elemental analyzer, Elementar, Hanau, Germany).

Data analysis

The following equations were used to calculate the Bowen ratio and the CO_2 flux density based on research developing and refining the BREB approach [26, 30, 31, 32, 33, 34, 35. 36] in a protocol assembled by Dr. T.J. Sauer (personal communication, 2011). Five-min temperature and water vapor differences were averaged at 30-min intervals to calculate the Bowen ratio (β):

$$\beta = \left[P \times C_P(\theta_L - \theta_U)\right] / \left[\lambda \times \varepsilon(e_L - e_U)\right] \qquad (1)$$

where P is the atmospheric pressure in kPa (measured), C_P is the specific heat capacity of air at constant pressure (1004.67 J kg^{-1} K^{-1}), θ_L and θ_U are the potential temperatures at the lower (L) and upper (U) positions (K), λ is the latent heat of vaporization of water (2.45×10^6 J kg^{-1}), ε is the ratio of the molecular weights of air and water (0.622), and e_L and e_U are the vapor pressures at the lower and upper positions (kPa) [30, 31, 32, 33, 35].

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

$$\theta = T(P_O / P)^{R/Cp} \tag{2}$$

where T is the thermistor temperature (measured in °C and converted to K, i.e., K = °C + 273.16), P_o is the standard reference pressure (100 kPa), P is the observed pressure , and R is the gas constant (8.314 J K^{-1} mol^{-1}) and C_p is the specific heat capacity of air (~29.1 J mol^{-1} K^{-1}) [35].

Latent heat flux density, LE (W m^{-2}) was calculated as:

$$LE = \left(R_n - G_0\right) / \left(1 + \beta\right) \tag{3}$$

where R_n is the measured net radiation (W m^{-2}) and G_0 the soil heat flux at the soil surface (W m^{-2}) [26,31, 32, 33, 34]. Since soil heat flux was measured with flux plates at a depth of 0.06 m below the surface, measured soil heat flux values were corrected for heat storage in the 0 - 0.06 m soil layer (i.e. $G_0 = G_{0.06m} + \Delta S$).

$$\Delta S = C\left(\Delta T / \Delta t\right) \times z \times 1 \times 10^6 \tag{4}$$

where ΔS is the change in heat storage above the soil heat flux plate (W m^{-2}), C is the volumetric heat capacity of the soil (MJ m^{-3} K^{-1}), ΔT is the change in temperature (current minus previous) of the soil above the heat flux plate (K) taken from average soil temperature measurements at 0.02-m and 0.04-m depths, Δt is the time step (s), z is the depth of the flux plate (0.06 m) and $1x10^6$ converts from MJ to J. The volumetric heat capacity (C) is calculated for each time step.

Sensible heat flux density, H (W m^{-2}) was calculated as [26, 33, 35]:

$$H = R_n - G_0 - LE \tag{5}$$

The sign conventions used for this study are that 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 is positive when moving down from the top of the soil surface [26, 34].

Turbulent diffusivity for sensible heat, K_h (m^2 s^{-1}) was calculated as:

$$K_h = \left(H/\rho_a C_p\right) \times \left(\Delta z/\Delta\theta\right) \tag{6}$$

where $\rho_a C_p$ is the volumetric heat capacity for air (1200 J m^{-3} K^{-1}), Δz is the sensor separation distance (1.5 m) [35].

A, the CO_2 flux density (kg m^{-2} s^{-1}) was calculated as:

$$A = K_c(\Delta\rho_c / \Delta z) \tag{7}$$

where K_c is the turbulent diffusivity for CO_2 (m^2 s^{-1}) which is assumed to be equal to the turbulent diffusivity for sensible heat (K_h), and $\Delta\rho_c$ is the average difference in CO_2 density between measurement heights converted from the LI-820 CO_2 concentration output of ppm to kg CO_2 m^{-3} [26, 32, 33]. The sign convention for CO_2 flux is that an upward flux is positive and a downward flux is negative.

The CO_2 flux was corrected for temperature and vapor density differences at the two measurement heights using the following equation:

$$A_{corr} = A + (\rho_c / \rho_a) \times (0.649 \times 10^{-6} \times LE + 3.358 \times 10^{-6} \times H) \tag{8}$$

where A_{corr} and A are in kg m^{-2} s^{-1}, ρ_c is the average CO_2 density at both measurement heights (g m^{-3}), ρ_a is the density of dry air (~1200 g m^{-3}) [36]. The CO_2 flux density presented in this paper follows customary sign conventions where a positive A_{corr} number represent CO_2 emissions from the soil and a negative A_{corr} represents C sequestration [26].

Based on research examining conditions where the BREB method fails [34], raw data were rejected that came within the range of the thermistor sensors' resolution, which was: $|\text{Thermistor } \Delta T| < 0.02°C$. While the sensor resolution range for vapor pressure was 0.01 kPa, over one third of the vapor pressure differences, Δe, fell within that range, so raw data was rejected within the range of $|\Delta e| < 0.004$ kPa. These data were removed and replaced by values computed by linear interpolation [34].

Similarly, because of the Bowen ratio definition using measured vertical temperature and humidity differences, computed CO_2 fluxes are subject to large error as the ratio approaches -1, which frequently occurs near sunrise, sunset, or during rainfall [34, 37]. In recognition of this, values of the Bowen ratio in the range $-0.95 < \beta < -1.05$ were replaced via linear interpolation. Data collected during precipitation events were omitted because of the questionable performance of R_n and G sensors during and immediately after rainfall. Graphs of both 5-min and 30-min averaged raw data and calculated energy fluxes were visually inspected to detect problems with sensors.

Results and Discussion

The BREB system as used here provides redundancy for some sensors to allow data collection when instruments stopped working. For example when the net radiometer on the Till unit malfunctioned (due to birds pecking a hole in the dome), the sensor values on the NT unit were used. When thermistor temperature data were not available for analysis, the ambient air temperatures recorded by the Rotronic HC2-S3 humidity and temperature probe at the two heights were used. However, the HC2-S3 sensors are more slowly responsive than the thermistors, which affects the calculations. This also meant that to calculate flux for the Till instrument, the NT net radiometer had to be working. ΔS calculations were made with the average of the top two thermocouples at 0.02-m and 0.04-m depth below the surface, so a malfunction of the lower soil thermocouples on the Till unit necessitated reliance on the top soil thermocouple during the period of malfunction.

Due to sensor and data collection issues, there was not sufficient data to provide conclusive comparisons between the two treatments, however some data are available for analysis. Data from one five-day period that could be viewed as being representative of the non-growing season are presented in Figures 2 and 3. These figures show the energy balance for both NT and Till treatments during a 5.5 day period starting at 12 noon on August 29th through September 3rd 2011 (Decimal Day of Year (DOY) 241-247), about 2 months before crops were planted. The abscissa is ordered according to local time (two hours ahead of GMT). The graphs of the energy balance (Figures 2 and 3) show similar trends between the two treatments, though the No-Till shows shorter and wider peaks of sensible heat than the Till, which would be consistent with greater absorption capacity of the denser organic residue on the NT surface.

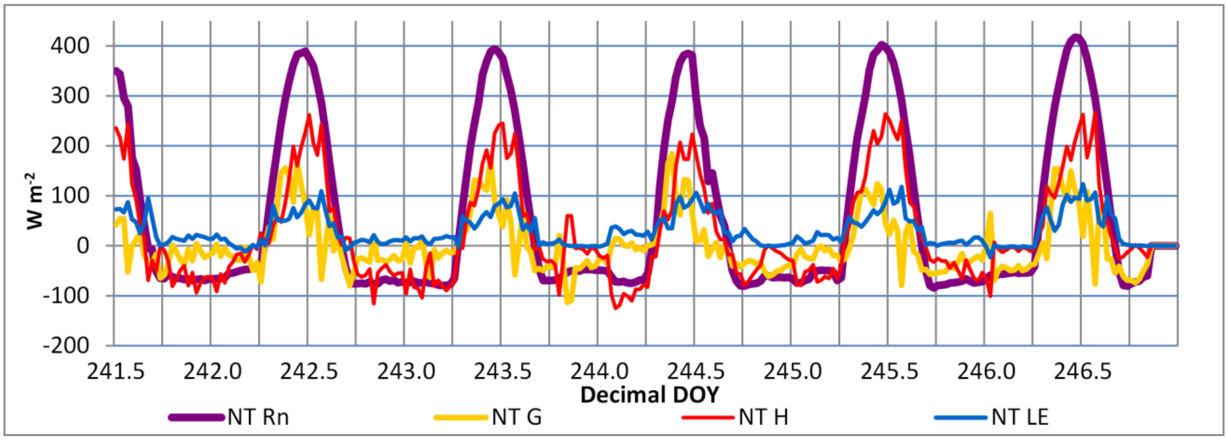

Figure 2 Energy Balance for NT Treatment at Maphutseng from August 29 through September 3

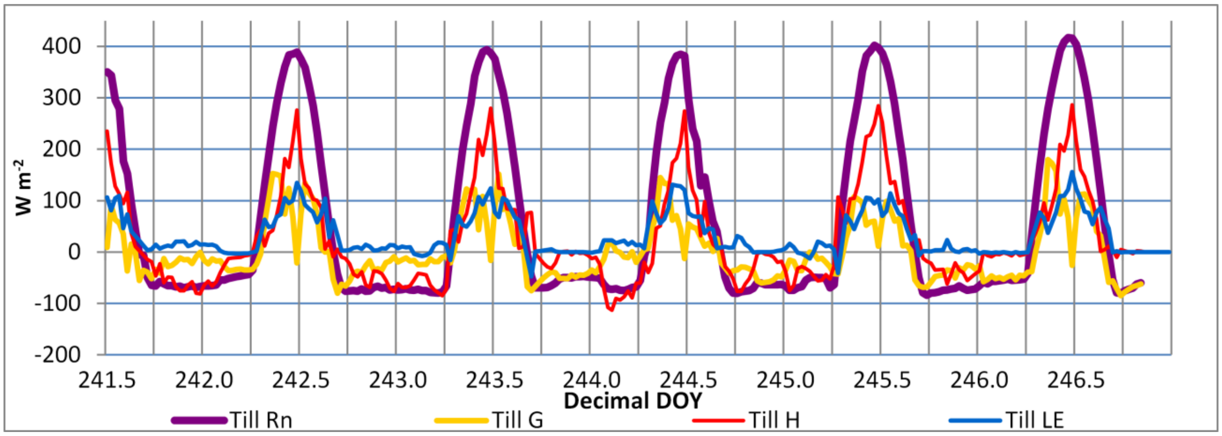

Figure 3 Energy Balance for Till Treatment at Maphutseng from August 29 through September 3

A graph of the CO_2 flux density for this period is shown in Figure 4. Combined with two additional days in September, 2011, the average CO_2 flux density for seven days between DOY 242 and 250 was -0.104 and -0.033 g m^{-2} hr^{-1} for the NT and Till plots respectively. A standard t-test results in the conclusion that the average fluxes were significantly different for the last two days in September, but there was no significant difference for the first 5 days shown in the graph (alpha = 0.10). Cumulative values of CO_2 for these seven days total -17.4 and -5.47 g m^{-2} indicating greater C sequestration by the NT plot.

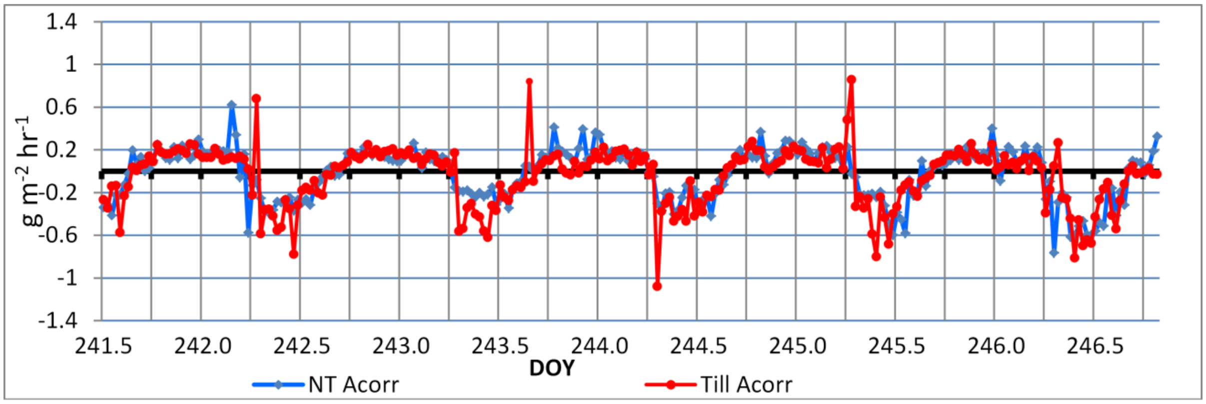

Figure 4 CO2 Flux Density for NT and Till plots for DOY 241-247 (August 29-September 3, 2011)

The CO_2 flux was calculated for one period during the growing season in January 2012 as shown in Figure 5. Extreme CO_2 flux values (less than -4 g m^{-2} hr^{-1} and greater than 4 g m^{-2} hr^{-1}) were considered erroneous and were removed and interpolated. These values occurred most often at sunrise and sunset or when the temperature gradient was opposite in sign from the vapor pressure gradient [36]. Twenty-nine percent of the Till data for this period and twenty percent of the NT data were removed and interpolated. The interpolated average CO_2 flux densities for this period are -1.11 and -0.22 g m^{-2} hr^{-1} for the NT and Till plots respectively and result in cumulative values of -106.49 and -21.47g m^{-2} for the NT and Till plots respectively. A contributing factor to reduced data collection during the growing season was rainfall, which is a reason to reject raw data for BREB calculations [34, 37].

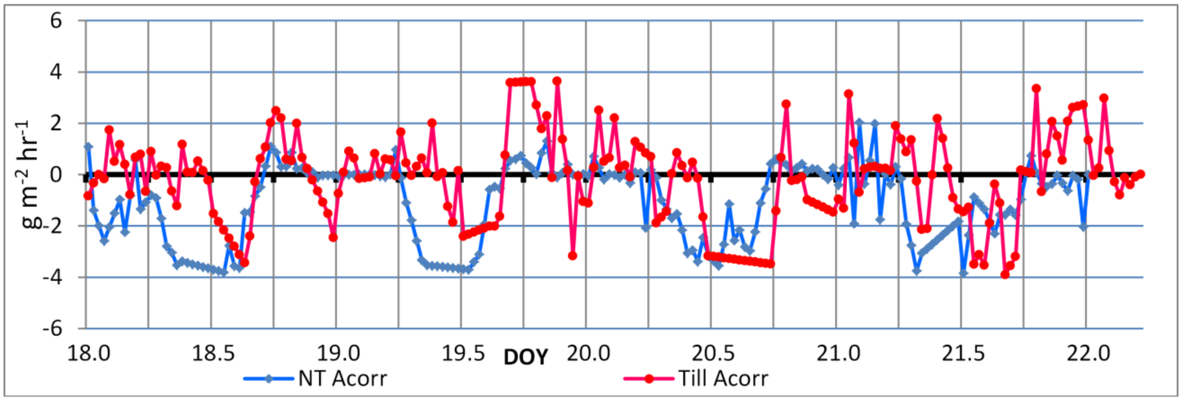

Figure 5 CO_2 Flux Density for NT and Till plots during growing season

During this period daytime temperatures reached 37°C with nighttime temperatures reaching a low of 12°C. Sensible heat fluxes were greater than in the non-growing (August and September) season represented in Figure 4. This difference and the presence of a rapidly growing crop explain in part the greater CO_2 fluxes during this later period (January). For the growing season data set, the mean difference in flux was statistically significant (alpha = 0.05).

It was postulated that the spikes that occurred with increased frequency in the growing season data likely resulted from the use of air temperature readings from the Rotronic humidity and temperature probe. Reliance on these sensors was necessitated by the failure of some of the thermistor sensors. Figure 6 is a graph of both the thermistor sensors (shown in purple) and Rotronic (shown in green) 5-min readings for both the Till and NT instruments, where the right (R) temperature (T) sensor exchanges positions every 5 minutes with the left (L) sensor between the upper and lower heights. Figure 6 does not indicate an obvious difference between the observed 5-min thermistor and Rotronic temperature readings of 8 sensors tracking in the same pattern within 1-4 °C of each other. However when subtracting the upper sensor reading from the lower to determine the gradient as shown in Figure 7 the thermistor sensors have a distinctly larger difference. Because the difference in potential temperature between the two measurement heights is used in the denominator when calculating the turbulent diffusivity, the smaller the difference, the larger the turbulent diffusivity, which directly affects the calculations of CO_2 flux. Near sunrise and sunset, in particular, the sensible heat flux changes sign while the evaporative flux typically reduces but does not reverse in sign (unless dewfall occurs). In these situations, small temperature differences can occur while turbulent exchange remains strong. However, the small gradients of temperature and humidity cause enhanced susceptibility to small errors of measurement, particularly in the Bowen ratio calculations.

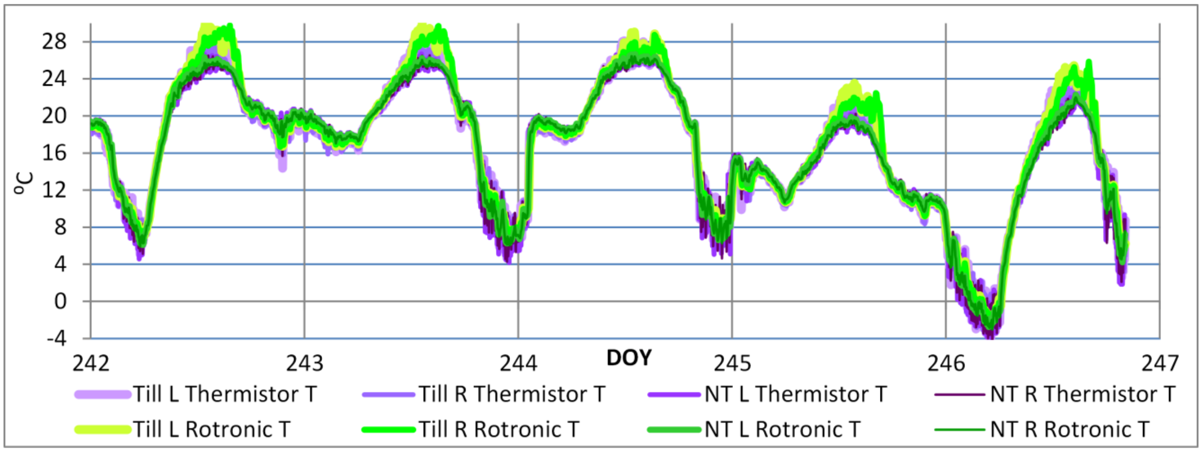

Figure 6 Five-min temperature readings for DOY 241-247 (August 29-September 3, 2011) (Thermistor and Rotronic)

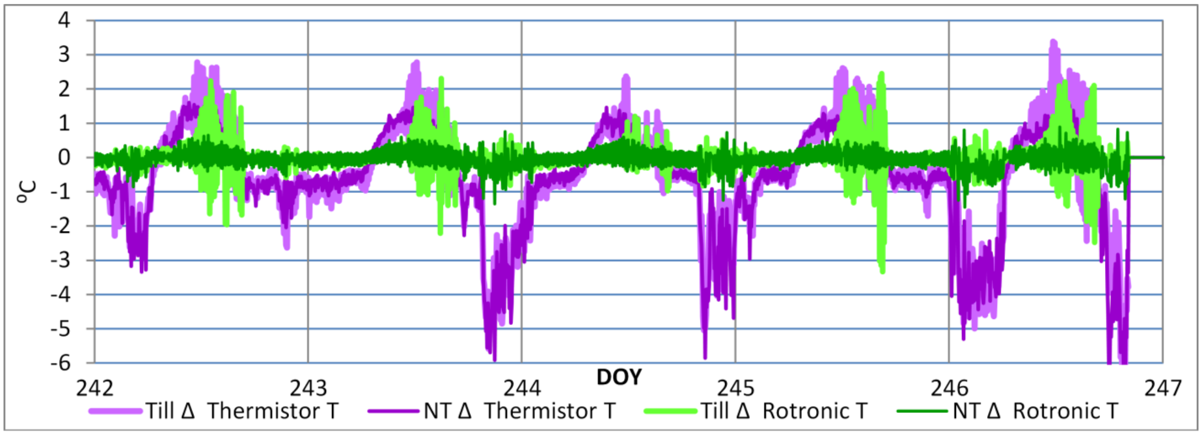

Figure 7 Temperature differences for DOY 241-247 (August 29-September 3, 2011) (Thermistor and Rotronic)

The consistent difference between the temperature gradients derived from the two systems (thermistor and Rotronic) is attributed to the substantial differences in the response time of the two sensor systems. To address this issue and to achieve a more accurate reading of temperature and other meteorological data at each sensor height, it has been proposed that after the arms rotate, a delay of one to two minutes be added before collecting five-second readings to allow for the sensors to equilibrate to the new sensor height and atmospheric conditions. This would eliminate vestiges of temperature and vapor pressure properties from the previous position and provide a more accurate and likely stronger difference between the two measurement heights increasing the signal associated with the gradient.

Soil samples were taken at the beginning of the study to provide input into the site characterization. Table 1 shows mean organic C concentrations in the 0-5 cm layer and 5-10 cm of soil for 16 samples with four samples taken in the top five cm and four between 5 and 10 cm in the NT and Till plots at the start of measurements.

Table 1 Organic C concentrations in top 5 cm and between 5-10 cm of soil measured at beginning of study

Depth below surface	Till Organic C (g/kg)	Till Std dev	NT Organic C mean (g/kg)	NT Std dev
0-5 cm depth	16	0.14	25	0.21
5-10 cm depth	17	0.36	23	0.21

Conclusions

Though the BREB system requires expertise and a careful balance of interrelated parts it was still viewed as a preferred choice for remote sites and small fields in Africa as it requires a smaller uniform measurement area and less sophisticated and expensive sensors as compared to eddy covariance. Rotation of sensor arm positions to overcome intrinsic sensor bias was determined to be critical for measuring the temperature and vapor pressure gradient for calculating the energy balance and CO_2 flux density for the BREB system.

Implementing the BREB system revealed many challenges in establishing robust instrumentation in a remote setting to satisfactorily capture relevant data. With the experience gained refining the instrument structure and resilience, and analysis of data and meteorological conditions, the BREB approach has a lot of potential in capturing real time exchange of CO_2, moisture and temperature, all important aspects for agriculture and climate interactions. More research is needed to determine which processes need finer tuning and which processes provide key information for measuring CO_2 flux. Due to the intricacies associated with this type of instrumentation it is mandatory that on-site personnel have significant interest in the project and in the details of data collection. While this research is difficult, time consuming, and meticulous it is important to understand soil C sequestration and emission issues that could become important if C trading and crediting policies are implemented.

Despite the limitations presented by operating micrometeorological instruments in a remote area of Africa, the data collected indicate that no-till management practices can sequester more carbon than conventional tillage on small-holder farms in Africa.

Acknowledgements

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CHAPTER II

MEASURING REAL-TIME CARBON SEQUESTRATION UNDER AFRICAN CONDITIONS

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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 program addressed here is an exploration of the efficacy of alternative agricultural practices in sequestering carbon (C) and in increasing soil fertility and crop yields. The study was conducted in Zimbabwe, with the intent to (a) demonstrate the utility of micrometeorological methods for measuring carbon dioxide (CO_2) exchange rates between the surface and the atmosphere, and (b) to quantify differences in such exchange rates for a variety of agricultural surfaces. Four Bowen ratio energy balance (BREB) systems were established on 0.64 ha sites at the International Maize and Wheat Improvement Center (CIMMYT) in Harare, Zimbabwe. The four tested agricultural management practices were: (1) no-till followed by planting of winter wheat (*Triticum aestivum*), (2) no-till followed by planting of blue lupin (*Lupinus angustifolios L.*), (3) maize crop (*Zea mays* L.) residue left on the surface, and (4) maize residue incorporated with tillage. Continuous micrometeorological and other environmental data were collected for the estimation of CO_2 flux density of the contrasting tillage and cover crop practices. Over a period of 139 days

from 15 June to 31 October 2013, the winter wheat cover crop produced a net sequestration of 257 g CO_2-C m^{-2}, while a tilled plot with no cover crop emitted 197 g CO_2-C m^{-2} and an untilled plot with no cover emitted 235 g CO_2-C m^{-2}. The blue lupin cover crop emitted 58 g CO_2-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 manuscript can detect significant differences between treatments, an outcome important to determine which smallholder soil management practices can contribute to mitigating climate change.

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 percent of total GHG emissions [1], 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 carbon in the carbon cycle. The oceans 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 [2, 3]. The oceans are already playing an important role in C sequestration. With about 12 percent of the global land surface under cultivation, agricultural C sequestration is an important low-cost mitigation strategy with substantial co-benefits [4].

The United Nations Food and Agricultural Organization (FAO) projects that food production must increase by 70 percent to feed over 9 billion people by 2050 [5]. Land degradation and land use change are estimated to produce between 6 percent and 20 percent of global GHG emissions, and hence if agriculture is the biggest driver of deforestation and degradation with its impact on land use change [6,7], then indirectly and directly 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 improving land use practices in Africa, where population growth is the fastest, in the most productive yet environmentally sustainable way.

Some agricultural practices already address the problems of food security and GHG emissions simultaneously; for example reduced tillage (especially no-till) maintains yields through improved soil fertility while also sequestering C [4,8,9]. Maintaining or improving soil fertility and crop yield reduces pressure to convert forests or marginal land into farmland as the conventional response to declining agricultural productivity. Thus, such agricultural practices have multiple benefits by increasing food security, soil fertility and sustainability, and soil carbon sequestration while forestalling the conversion of higher carbon-content forests and grassland soils to cropland [10]. Yet, the overall GHG mitigation potential of these practices is probably underestimated. Finally, several reviews raise the importance of related socio-economic factors – without increases in profitability through improved productivity, mitigation techniques are less likely to be adopted [4,11].

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 [12-14]. Conservation agriculture practices can reverse soil degradation and improve agricultural productivity by reducing erosion and enhancing soil fertility, water holding capacity, soil structure, biological activity and water infiltration [9,10,15].

The CA practice of using cover crops may play an important role in mitigating GHG emissions by promoting C sequestration [9,16]. Cover crops are also known to reduce erosion between periods of growing agricultural crops. Leguminous covers may 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 through crop nutrient uptake, making those nutrients available to future plant growth. The Intergovernmental Panel on Climate Change (IPCC) claims that there is no universally accepted list of best mitigation practices, since their effectiveness varies across climates and settings [4]. 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 need to measure small year-to-year changes in soil C; and previous land use practices [17].

Switching from tillage to a no-till (NT) agricultural management practice has the potential to reduce agricultural CO_2 emissions [18-22]. Tillage increases aeration within the upper soil horizons, fueling organic matter decomposition by microbes and producing soil microbial respiration and CO_2 emissions [23]. West and Post [20] 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 fertility and productivity [9, 24-26]. However, the potential of NT to increase soil C has been questioned [27-29], especially for moist, cool climates [30]. Some studies do not identify greater C concentrations under NT as compared to conventional tillage in soil layers deeper in the profile compared with shallow or surface soil layers [31]. 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 [32]. Methods for measuring C are often onerous, 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 combinations of agricultural practices and environmental conditions sequester C and the real time C sequestration rates. Carbon dioxide emissions from land can also be determined in real time by measuring the exchange between the surface and the atmosphere – the ‘flux’. There are two main approaches for measuring CO_2 exchange over agricultural ecosystems including the use of static or dynamic chambers and micrometeorological techniques [24]. Among the micrometeorological methods available for use, the Bowen ratio energy balance (BREB) system and eddy covariance have gained considerable popularity [24]. Dugas [33] compared three BREB systems with nine soil chambers and found good CO_2 flux agreement between the two methods. He also noted that the micrometeorological methods (of which there are several) integrate the soil-atmospheric boundary layer interactions over a much larger area than chamber methods and thus accommodates more of the spatial variability of CO_2 flux from soil, allowing high resolution measurements representative of larger expanses. 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 [34,35]. Due to the temporal and spatial issues and resulting maintenance challenges in using chamber systems, the BREB approach was selected for this research.

Materials and Methods

Site Description

Soil properties and micrometeorological variables were measured from 15 June 2013 to 31 October 2013 at Mt. Pleasant, Zimbabwe (17.7220 ºS, 31.0209 ºE, 1,494 m elevation) about 12 km north of the center of the capital city Harare. The study site is located at the International Maize and Wheat Improvement Center (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 percent of rainfall occurring from November to March.

The soils are classified as *Chromic Luvisols* [36] in the World Reference Base for Soil Resources international standard taxonomic soil classification system, equivalent to *rhodustalfs* in USDA Soil Taxonomy [37]. The soil texture is sandy clay loam from a metamorphosed sedimentary rock developed on granite parent material. The study site is level, with a slope of less than 2 percent. 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.

An area approximately 160 m by 160 m was divided into four square plots about 0.64 ha each. Two plots were seeded early in 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 25 cm for a target population density of 44,444 plants ha^{-1}. One 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 (NPK) 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. A description of the four plot treatments and abbreviations used is provided in Table 2.

Table 2 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
Crop residue left on the surface	Untilled
Crop residue incorporated with disc plow	Tilled

During germination and initial growth, 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.

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 [33] and implemented in a prior experiment [22]. 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. 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 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 8. 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 CO_2 intake tubes were housed in the horizontal air intakes for measurements at two heights (periodically adjusted to be 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 m^3/min. CO_2 concentrations were measured with a non-dispersive infrared (NDIR) 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).

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”

Figure 8 Micrometeorological station with rotating arms at the Mt. Pleasant, Zimbabwe study site

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 3 cm 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 6 cm to about 15 cm 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 seven-second time delay to allow for gas to be purged from the CO_2 analyzer tubing. The data logger calculated and recorded five-minute averages of the five-second readings. Following the storage of each five-minute 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.

Data analysis

The Bowen ratio and the CO_2 flux density were calculated using the following equations based on research refining the BREB approach [33] [38-44] and performed using the same method as reported by O’Dell et al. [22]. Five-min water vapor pressure and temperature differences were averaged at 30-min intervals to calculate the Bowen ratio (β):

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

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 (2.45x10^6 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) [33, 38-40, 43].

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

$$\theta = T(P_o / P)^{R/Cp} \tag{2}$$

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}) [43].

Latent heat flux density, LE (W m^{-2}) was calculated as:

$$LE = \left(R_n - G_0\right) / \left(1 + \beta\right) \tag{3}$$

where R_n is the measured net radiation (W m^{-2}) and G_0 is the soil heat flux at the soil surface (W m^{-2}) [33, 38, 39, 40, 43]. 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. $G_0 = G_{0.06m} + \Delta S$) via:

$$\Delta S = C\left(\Delta T / \Delta t\right) \times z \times 10^6 \tag{4}$$

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:

$$C = C_m(1 - \phi_f) + C_w \times \theta \tag{6}$$

where the volumetric heat capacity for soil particles 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 0.3 on the wheat and blue lupin plots. Soil porosity, ϕ_f, was calculated as:

$$\phi_f = 1 - (\rho_b / \rho_s) \tag{7}$$

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_b, was assumed to be 2.65 Mg m^{-3}. Sensible heat flux density, H (W m^{-2}) was calculated as [33] [39-41]:

$$H = R_n - G_0 - LE \tag{8}$$

Turbulent diffusivity for sensible heat, K_h (m^2 s^{-1}) was calculated as:

$$K_h = \left(H / \rho_a C_p\right) \times \left(\Delta z / \Delta \theta\right) \tag{9}$$

$\rho_a C_p$ is the volumetric heat capacity for air (1,200 J m^{-3} K^{-1}), Δz is the sensor separation distance (1.5 m) [41].

A, the CO_2 flux density (kg m^{-2} s^{-1}) was calculated as:

$$A = K_c\left(\Delta \rho_c / \Delta z\right) \tag{10}$$

where K_c is the turbulent diffusivity for CO_2 (m^2 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 CO_2 density between measurement heights converted from the LI-820 CO_2 concentration output of ppm to kg CO_2 m^{-3} [33, 40, 41].

The CO_2 flux was corrected (A_{corr}) for temperature and vapor density differences at the two measurement heights using the following equation:

$$A_{corr} = A + \left(\rho_c / \rho_a\right) \times \left(0.649 \times 10^{-6} \times LE + 3.358 \times 10^{-6} \times H\right) \tag{11}$$

where A_{corr} and A are in kg m^{-2} s^{-1}, ρ_c is the average CO_2 density at both measurement heights (g m^{-3}), ρ_a is the density of dry air (~1,200 g m^{-3}) [44].

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 is positive when moving down from the top of the soil surface [31, 39]. The sign convention for CO_2 flux is that an upward flux is positive, i.e., a positive A_{corr} number represents CO_2 emissions from the soil and a downward flux is negative, i.e., negative A_{corr} represents C sequestration [33].

Because the Bowen ratio definition uses measured vertical temperature and humidity differences, computed CO_2 fluxes are subject to error as the Bowen ratio approaches -1, which often occurs near sunrise, sunset or during rainfall [43, 45]. 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.

Bowen ratio energy balance measurement recordings began on 14 June 2013 and continued through November. To account for differences in the response times of some of the sensors, the data logger program was modified to wait for two minutes (after each arm rotation) to average five-second readings following the rotation of the arms. The program change to delay averaging of five-second readings was installed on 5-6 August 2013.

In the CO_2 flux calculations there were occasionally unexplained large spikes or periods of unusually large values. Some of the spikes in CO_2 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 CO_2 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 3 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 3 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	0.27 (± 0.077)	0.23 (± 0.084)

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.

A non-parametric bootstrap rolling procedure was developed to simulate 95 percent confidence intervals for the cumulative distribution of CO_2 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 (see for example Balcilar and Ozdemir [46]). In this application the *variance around the accumulation* of CO_2 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 $t = 1,\ldots 139$*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 $D = \{d_1, d_2, d_3\ldots, d_t\}$, 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 CO_2–C accumulated from D^*.

Repeat Steps 1 and 2 1,000 times.

Step 3: Determine and save the 2.5 percent and 97.5 percent 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; $D = \{d_1, d_2, d_3\ldots, d_t, d_{t+1}\}$.

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 CO_2 accumulations associated with each are compared graphically.

Results

There was a smaller range of CO_2 flux for all plots during June and July as would be expected for the nascent cover crops (Figure 9). From July to September the daily maximum rate of CO_2 uptake by the wheat cover crop increased to greater than ten times that of the other surfaces (Figures 9 and 10). Note that the scale of the wheat graph in Figure 10 is greater than the scale for the other treatments, so that differences among the months can be seen for all of the plots. The CO_2 flux reveals a strong diurnal signal for the wheat case during this period, and during September as the wheat flux diminishes, the diurnal signal of blue lupin CO_2 flux increases in strength as that crop reaches maturity (Figure 10). This relative magnitude of CO_2 flux is consistent with the extent of biomass production of the wheat and blue lupin crops (Figure 11). At this time the wheat averaged approximately 0.6 m tall, and the blue lupin averaged approximately 0.1 m. These photographs show the sparser growth and population density of the blue lupin treatment that is reflected in the CO_2 flux for that treatment. The CO_2 flux of both the wheat and the blue lupin treatments from August through October are consistent with observed vegetative growth, showing a peak of CO_2 flux from the wheat crop in September as the wheat reached maturity, while the blue lupin began flowering in mid-August and reached peak CO_2 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.

One noticeable feature of the data record is a consistent association of the CO_2 flux with the latent heat flux (Figures 12-15). This association is most evident in August and September for

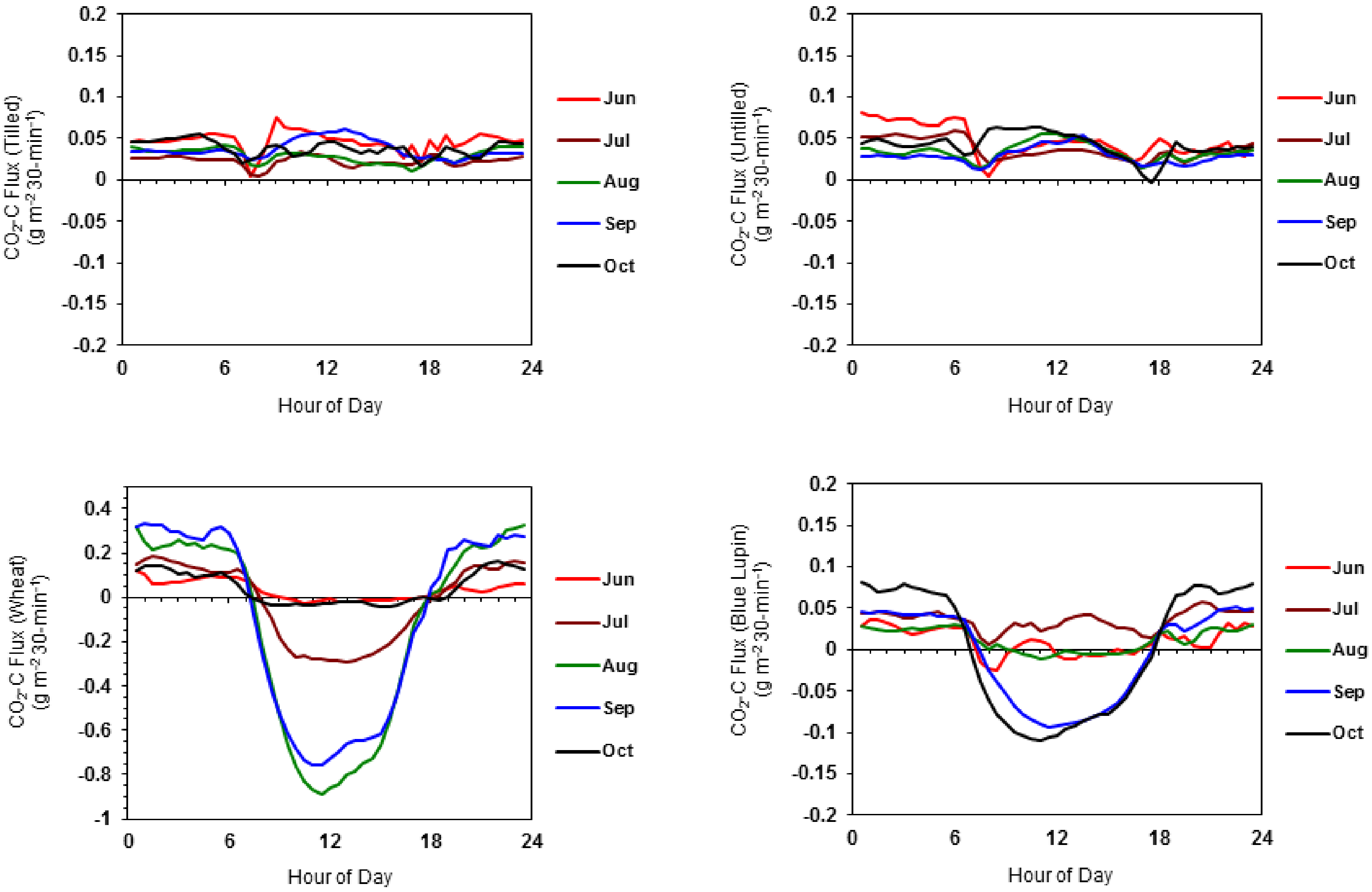

Figure 9 CO_2-C from CO_2 Flux Density for each plot by month from 15 June through 31 October(DOY 166-181), 2013, Mt. Pleasant, Zimbabwe (Note for clarity the figure for the Wheat plot is at a different scale to allow the smaller trends to be visually perceptible on the other plots)

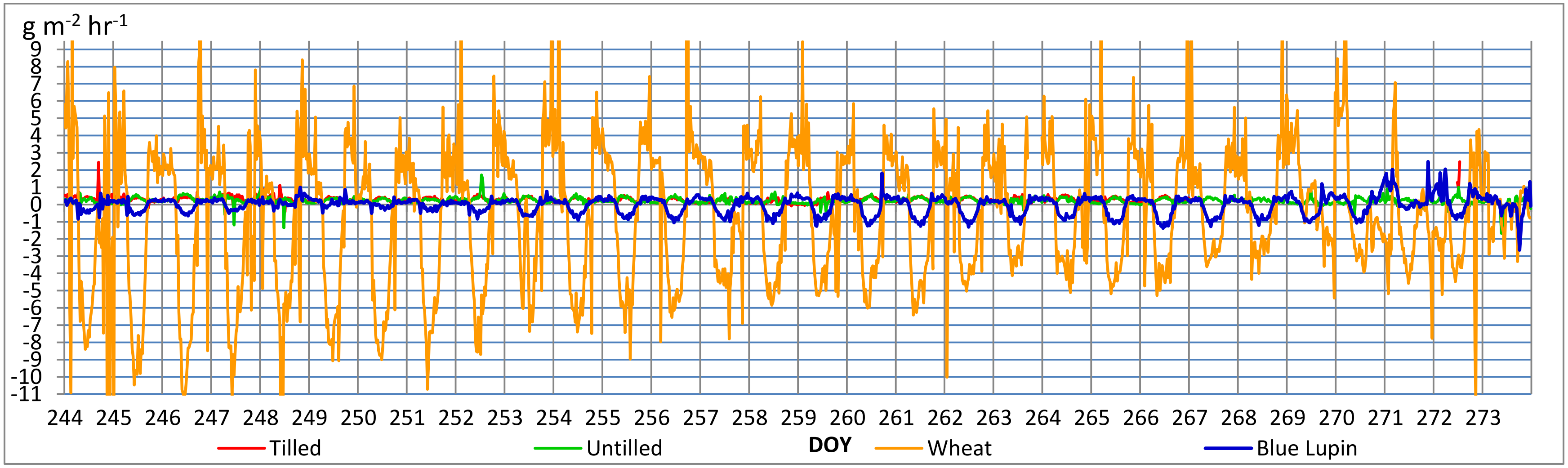

Figure 10 CO$_2$ Flux Density (A$_{corr}$) for all plots in September 2013, Mt. Pleasant, Zimbabwe

Figure 11 Photographs of 4 plots taken 9 August 2013, Mt. Pleasant, Zimbabwe

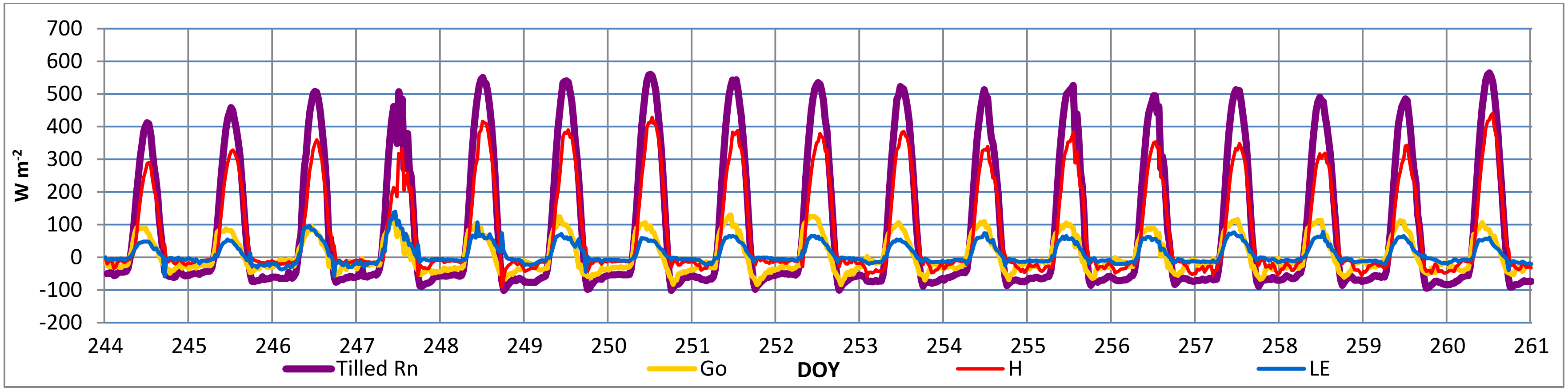

Figure 12 Energy balance for the tilled plot for September 1-18, 2013 (DOY 244-261), Mt. Pleasant, Zimbabwe

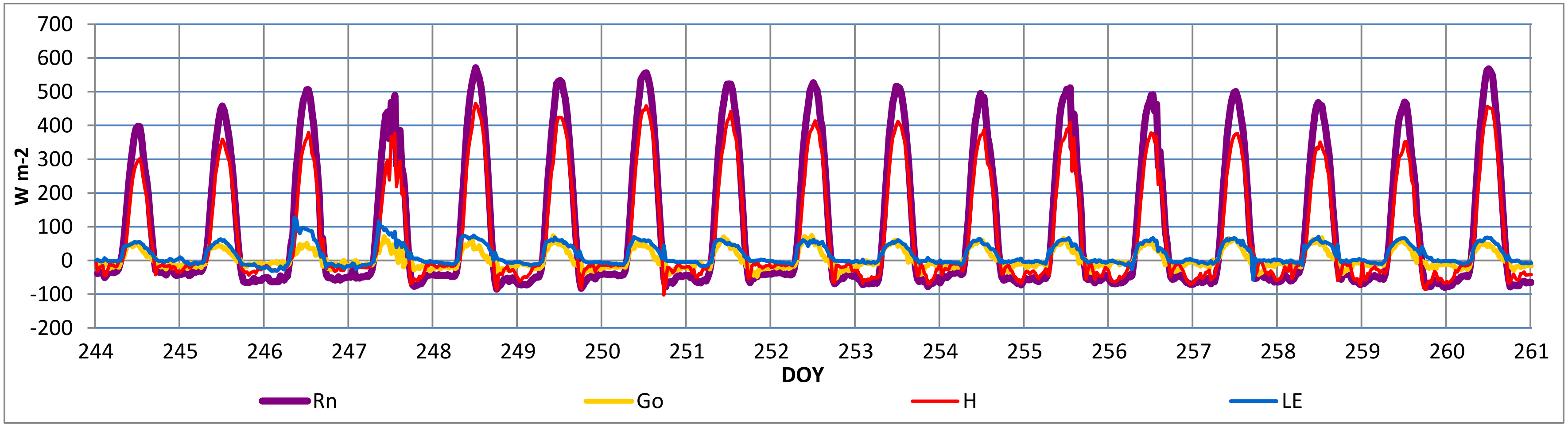

Figure 13 Energy Balance for Untilled Plot for September 1-18, 2013 (DOY 244-261), Mt. Pleasant, Zimbabwe

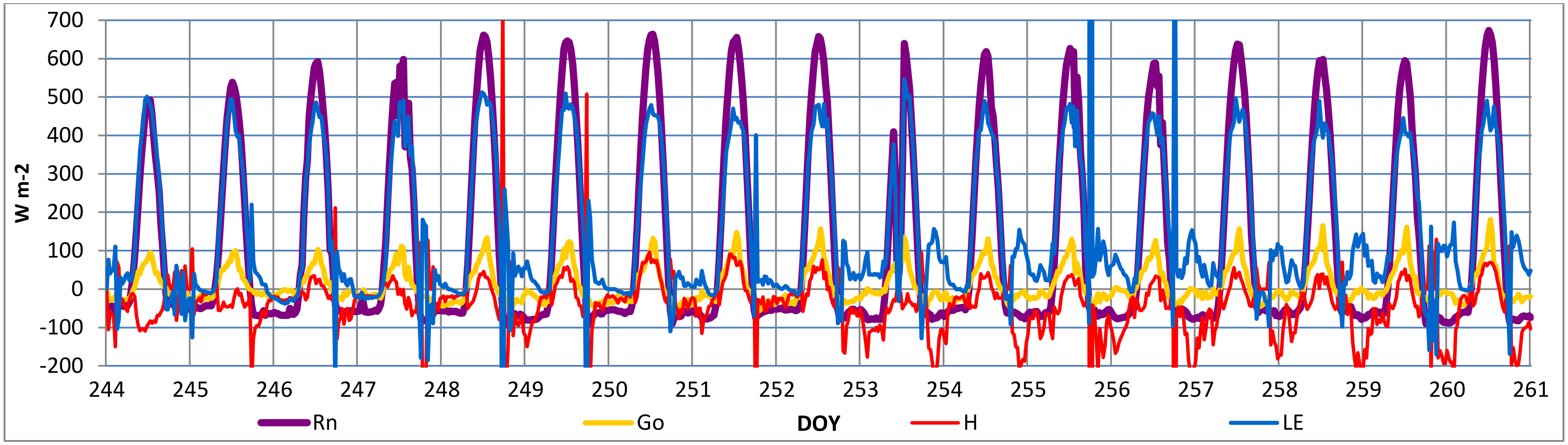

Figure 14 Energy balance for wheat plot for September 1-18 (DOY 244-261), 2013, Mt. Pleasant, Zimbabwe

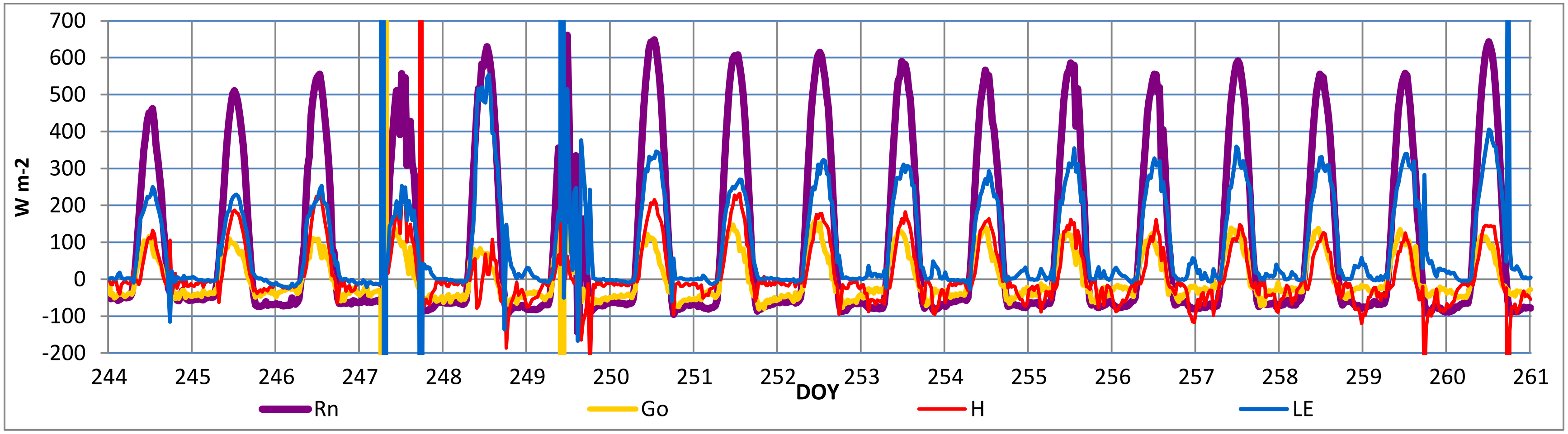

Figure 15 Energy balance for blue lupin plot for September 1-18 (DOY 244-261), 2013, Mt. Pleasant, Zimbabwe

the wheat plot and in September and October for the blue lupin plot. There is a strong partitioning of available energy to sensible heat in the energy balance in the tilled and untilled fields (Figures 12 and 13) with no vegetation and no irrigation. On the other hand the latent heat flux totally dominates the wheat plot (Figure 14) for this period consistent with the trend of CO_2 flux density. Likewise the latent energy flux on the blue lupin plot (Figure 15) begins to increase and dominate by the end of this period also consistent with increasing evapotranspiration and CO_2 sequestration of a growing crop.

The net radiation on the tilled and untilled plots (Figures 12 and 13) 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 14 and 15) (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 13) and highest albedo (Figure 11) and the tilled having the highest surface temperature. Notably the wheat plot has the greatest net radiation during September, 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 15) coincides with irrigation over that plot.

Carbon dioxide concentration data collected during this period were also analyzed for periodic fluctuations during nighttime hours and were found to have a pattern (unpublished observations) that could indicate meteorological conditions that could influence nighttime CO_2 flux.

Total and monthly averages of hourly CO_2 flux density for each treatment and a total for 139 days of the experiment from 15 June, the first full day of measurements and ending 31 October (Table 4) provide a summary of the data. 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 August 8 through September 19 where all instruments were working continuously; the hourly average CO_2 flux density for this period is shown for comparison purposes. While as much as 11 percent of data for the tilled treatment were missing, the total amount of missing observations across all measurement records was 7.4 percent, although for about 23 percent of the time at least one of the four systems was not operational. By comparison FluxNet sites reported an average of 35 percent of rejected or missing data [47].

This shows a degree of resilience and robustness in instrumentation, process, maintenance and technical support derived in part from prior experience in a remote setting [22].

Table 4 Hourly averages of CO_2 flux and percentage of missing values by month and other periods, 15 June to 31 October, 2013, Mt. Pleasant, Zimbabwe

Period	Tilled Average CO_2 A_{corr} (g m^{-2} hr^{-1})	Tilled Percent Missing Values for Period	Untilled Average CO_2 A_{corr} (g m^{-2} hr^{-1})	Untilled Percent Missing Values for Period	Wheat Average CO_2 A_{corr} (g m^{-2} hr^{-1})	Wheat Percent Missing Values for Period	Blue Lupin Average CO_2 A_{corr} (g m^{-2} hr^{-1})	Blue Lupin Percent Missing Values for Period
June 15-30	**0.373**	0.0%	**0.366**	1.2%	**0.355**	6.3%	**0.099**	6.2%
July 1-31	**0.215**	0.0%	**0.286**	11.9%	**-0.365**	20.6%	**0.282**	31.9%
August 1-31	**0.239**	0.0%	**0.260**	8.3%	**-1.858**	0.0%	**0.123**	1.7%
August 8 – September 19	**0.254**	0.0%	**0.258**	0.0%	**-1.766**	0.0%	**0.045**	0.0%
September 1-31	**0.277**	22.8%	**0.226**	0.0%	**-1.389**	1.0%	**-0.061**	0.0%
October 1-31	**0.315**	27.4%	**0.335**	0.9%	**0.483**	0.3%	**0.033**	0.1%
June 15 – October 31	**0.274**	11.0%	**0.287**	5%	**-0.535**	6%	**0.100**	8%

Accumulated sums of CO_2-C emitted or sequestered from available data for each month and the entire 139-day period with the percentage of missing values (Table 5) provide comparisons of sums for each treatment in each month.

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 ($P = 0.56$).

A graphic comparison of the accumulation of 30-minute fluxes of CO_2-C for the 4 treatments (Figure 16) 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 minute period that did not have a value for all four treatments, leaving 77 percent of original data for the analysis. The shaded areas are 95 percent bootstrap confidence intervals.

Table 5 Sum of CO_2-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 CO2-C (g m^{-2} period^{-1})	Tilled Percent Missing Values for Period	Untilled Sum of CO2-C (g m^{-2} period^{-1})	Untilled Percent Missing Values for Period	Wheat Sum of CO2-C (g m^{-2} period^{-1})	Wheat Percent Missing Values for Period	Blue Lupin Sum of CO2-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%

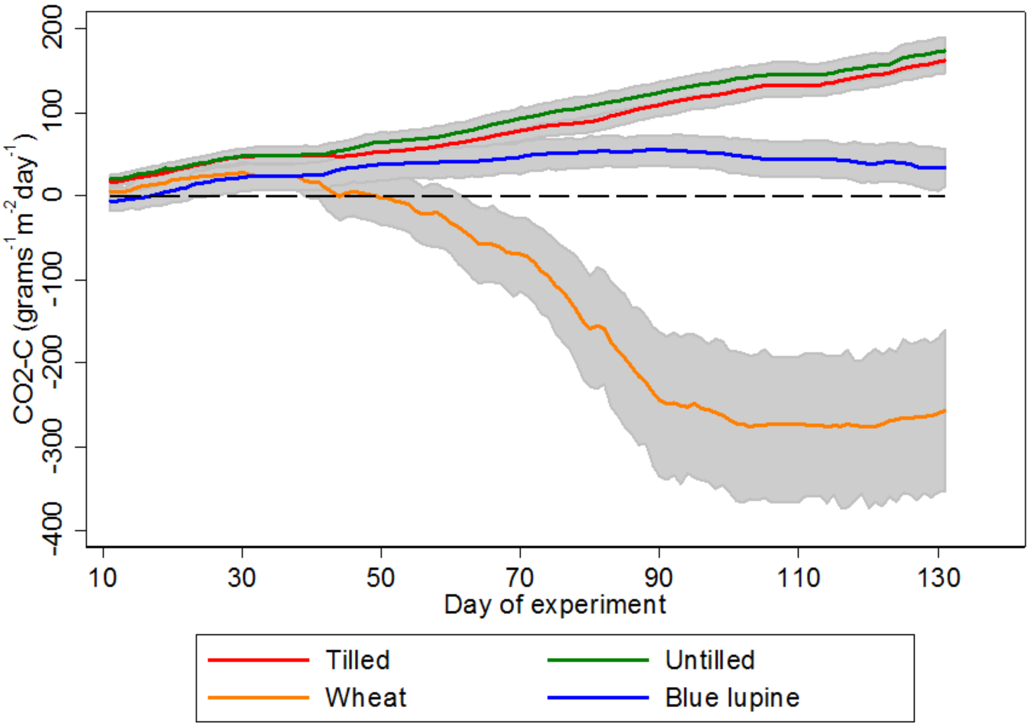

Figure 16 Comparison of accumulated sum of half-hour CO_2-C for all treatments (shaded areas are 95 percent bootstrapped confidence intervals)

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

Discussion

BREB techniques can detect differences in C sequestration among different agricultural practices and environmental conditions. Cover crops reduce CO_2 emissions over bare-fallow, and some cover crops (wheat was tested here) can have a net sequestration of C over the short term. These results are consistent with other studies found in the literature [9,10,16,48-50]. In particular Mapanda's measurements of CO_2 flux from soil of maize plots using chambers at the nearby University of Zimbabwe research farm from 2007 through 2008 were similar to CO_2 emissions of the blue lupin, tilled and untilled treatments, accounting for the possible underestimation of flux from chamber methods. The current study adds to Mapanda's work by including the CO_2 flux of the vegetative canopy and providing continuous measurements over a 4 month 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 tillage and land left untilled, and raises the value of cover crops during the non-growing season. In a dry winter climate growing a cover crop can be a challenge, but is worth examining for the smallholder.

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. Bowen ratio energy balance 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 CO_2 flux from agriculture, and in the last few decades instrument advances have created a global network of micrometeorology towers that are measuring CO_2, such as FLUXNET [51] and GRACEnet [52]. Most of these sites are in developed countries and integrated with university and government programs. Gilmanov et al. [47] 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. [47] 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, consider recent US estimates. According to the US EPA [53], 94 percent of US CO_2 emissions were from fossil fuel combustion. In contrast, Canadell et al. [54] report that from 1990 to 2005 48% of CO_2 emissions in Africa were from land use change, of which 89 percent was attributed to agricultural use (43 percent was from deforestation for permanent cropland, 48 percent was from deforestation due to shifting agriculture, and 11 percent 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 measuring the CO_2 flux from practices that sequester C deeper in soil layers and promote the incorporation of residues before decomposition and respiration between cropping cycles. Also there is value in validating the Bowen ratio data with alternative approaches like eddy covariance or canopy chambers, which has been planned for subsequent trials.

This data shows that differences can be discerned between management practices. It remains (a) to obtain more data to refine understanding of this difference, especially in regard to its seasonality, (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.

Summary and Conclusions

Bowen ratio energy balance measured differences in CO_2 flux at the field scale. Carbon dioxide flux was significantly less 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 CO_2 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 required 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 CO_2 flux for measuring the potential of agricultural practices to sequester carbon in real time over shorter periods. This approach shows considerable promise 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 emission and sequestration 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 defensible 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 CO_2 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.

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CHAPTER III

SOILS AND CIVILIZATIONS: USING A GENERAL EDUCATION COURSE TO TEACH AGRICULTURAL RELEVANCE

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This article was a result of research conducted in conjunction with the general education course, "Soils and Civilizations" taught at UT by Professor Eash. Deb O'Dell participated as a teaching assistant in the course, and was a co-author in analyzing and writing up results of data collected to study the course's effects on student attitudes.

Abstract

The enrollment of students to the major scientific disciplines related to agriculture has been on the decline over the past decades. While it is unclear why enrollments change, few would argue that these same disciplines have not been proactive in raising the awareness and importance of environmental disciplines towards sustainable development and the survival and stability of civilizations. Today, most students are unaware of current food production and food security issues and the career opportunities associated with our majors that are hidden inside the "College of Agriculture." We developed a general education course that addresses relevant food security issues and outlines the sciences contained within agriculture and future opportunities for feeding future generations. The objectives of this paper were to determine how our general education course changes student perception of population, food security and civilization stability and the relationship these concepts have with environmental sustainability. We evaluated student survey responses from two semesters (n=435) of our course. Fifty-two percent of students did not know a major in soil science existed, while 56% responded that they would like to take another course in that discipline. Ninety-nine percent indicated that knowledge of soil science was important in understanding food security, with 43% indicating that their opinion of these issues changed since

the beginning of the semester. The food security knowledge and expertise contained within the Agriculture College is seen by students as highly relevant to their future and suggests more forthright marketing through general education courses of our expertise and career opportunities related to these disciplines should be explored further.

Introduction

Climate change, population growth, food security and sustainable intensification are all examples of the buzz words that drive the public discourse shaping our perceptions about the role agriculture and the environment will play in future generations. While roughly 12% of the world's population does not get enough to eat, most health issues in developed countries revolve around obesity and overconsumption. Population growth is occurring in areas with less productive soils that are degraded or rapidly degrading due to unsustainable agricultural practices [1]. Agriculture can be a source or a sink in regards to greenhouse gases (GHG) and currently produces as much as 13% of GHG emissions [2-5].

Since 1960 when our population surpassed 3 billion people, more than 4 billion new faces have populated our planet with an increase of nearly 80 million each year. Malthus [6] warns us about how populations crash when food production does not grow at the same rate as population. By the time our current college graduates arrive at mid-career–in just 20 years–there will be another two billion persons to clothe and feed. This represents a range of problems that will require the best minds to research and solve these pressing issues. Unfortunately, most of the current young generation has a low awareness and inaccurate perceptions with regards to the importance of agriculture [7, 8]. This has mainly been attributed to urbanization and lack of exposure to food production activities. Farm and rural populations have declined, with less than 5% of the U.S. population now living on farms and less than 2% of the labor force working in agriculture [9], resulting in less contact by young people with agriculture. Gonzalez [8] found most high school students either have misconceptions about agriculture or lack knowledge about agricultural fields of study and employment opportunities.

While the National Academy of Sciences [10] reported significant increases in the number of U.S. college graduates in agricultural and natural resources disciplines from 1987 to 2007, most of the increases were in natural resources conservation, research and animal science fields of study. Several studies have also shown that the enrollment of students to disciplines related to soil and earth sciences has been on the decline since the early 1990's and 2000's [11, 12]. Unfortunately, agricultural scientists and Land Grant Universities have generally adopted a "Field of Dreams" approach to marketing our disciplines whereby we do little to entice students to explore the relevancy of our scientific disciplines to food security and civilization sustainability. In 2010, the Soil Science Society of America conducted a survey to further investigate the trends in soil science education and training (Havlin et al., 2010). One of the concerns that prompted the study was the fact that there was declining academic course offering and enrollment to soil science education programs at land grant universities, a concern also raised by Collins [12]. Havlin et al. [13] recommended promoting soil science during earlier stages of education and opening general soil science courses up to the wider college student population as part of "general education science credits."

The National Academy of Sciences book, "Transforming Agricultural Education for a Changing World," presented an imperative to change agricultural education [10]. The national research priority agenda for 2011-2015 put forth by the American Association for Agricultural Education supports this view [14]. While many approaches are needed, this paper addresses one ongoing development of a curriculum to increase knowledge of agriculture and soil science by changing fundamental perceptions about agriculture that would appeal to a broader student population. The "Soils and Civilizations" curriculum presented in this paper blends soil science and agriculture with respect to history and civilization and has success at the University of Tennessee (UT) by increasing the number of degrees pursued within the "College of Agriculture." This class is populated by a variety of students with undeclared majors to upperclassmen in engineering and nursing.

The course fills a general education requirement at UT and has evolved and grown over the nine years of its offering to over 200 students each semester. Several approaches are used in the course and data is being collected to begin to assess the impact this course has on attitudes about agriculture and soil science. Each semester several students change majors and become students in the College of Agriculture and Natural Resources as a result of taking this course.

The course addresses some of the most important intersections of agriculture and society, including:

1. Distribution of both population and food production and their impact on food security
2. Environmental degradation and its impact on food production
3. Historical analysis of the relationship between civilization success or failure and soil conservation
4. The potential impact of climate change on food production
5. An analysis of climate change as a contemporary example of the "tragedy of the commons" [15, 16]

These topics provide a dynamic and cross-disciplinary subject matter that draws students into the material with issues that they can relate to on a personal level. At the outset, few students think there are environmental issues that could impact their livelihood but by semester's end there has been some movement on the educational continuum. That combined with the tragic collapse of civilizations provides a dramatic background for learning about soil science, agriculture, history and geography. For example the disappearance of the Anasazi, Sumerians and Nubians provides a rich backdrop for learning about agricultural practices and the impacts of drought, deforestation and salinization.

The objective of this approach is to:

1. Educate the student populace about agriculture
2. Make knowledge of agriculture more accessible to non-agriculture students by juxtaposing contemporary food security issues with historical collapses
3. Show the importance of agriculture in addressing today's pressing issues, such as food security and climate change
4. Show the relationship between agriculture and natural resource conservation to the rise and fall of civilizations
5. Entice students to learn more about agriculture and soil science with follow-up courses and possible pursuit of a major or career in agriculture and soil science.

Materials and Methods

The course "Soils and Civilizations" was developed nine years ago at the University of Tennessee and has been taught 14 times. The class in spring 2013 had 188 students with 233 registered for Fall 2013. For the past five years enrollment has been capped by the seating capacity of the chosen classroom; in 2013 this course is held in the largest lecture hall on campus. The approach involves presenting interesting historical stories combined with science, problems and solutions and engaging and challenging students.

There is no way to precisely measure the impact of a curriculum on students, as ideas and concepts can be presented and discussed that students may not grasp until later in their academic career. However, this paper is an attempt to quantify more immediate change in perception and attitude. During the 2012 fall semester a survey was conducted at the end of the course to characterize attitudes towards agriculture, climate change and soil science and to determine if the course had an impact on their opinions. The survey response rate was 62% (84 of 135 students). Tables 6 and 7 list the survey questions given to students at the end of the fall 2012 semester and the overall response of the students to the questions based on a Likert scale of importance (Table 6) and scale of agreement to several statements (Table 7). For the spring 2013 semester, surveys were conducted at the beginning and end of the semester to capture the actual change in student perceptions to various topics within the period of the course and to gauge how significant this course is towards enhancing perceptions about the importance of soils and agriculture to development and food security. Questions were modified and student responses are compared between the beginning and end of the semester for scale of importance questions (Table 8) and scale of agreement statements (Table 9).

Results and Discussion

Thirteen percent of respondents in the fall 2012 survey indicated they were freshmen, 34% sophomores, 27% juniors and 26% seniors, with 56% male and 44% female. Based on the responses to the survey in Tables 6 and 7, we are able to make several noteworthy observations. Most of the students signified recognition of the connection between soils, agriculture and food security with 99% of respondents indicating that the class was somewhat or extremely important for understanding why soil is important to food security. Sixty-eight percent indicated it was extremely important for them to understand food security. Seventy-six percent indicated it was extremely important to understand soil resources to avoid environmental catastrophe. Forty percent of survey respondents agreed that their understanding of the topics covered in this course changed since the beginning of this class, while an additional 43% strongly agreed that their understanding of the topics covered in this course changed since the beginning of this class.

Response to the survey also suggests that this course could have an impact on students actually considering a career in soil science. While 52% indicated that soil science was an unknown discipline to them before the course, the survey shows a change in awareness with 56% agreeing or strongly agreeing that they would like to take another class in soil science. Interestingly, 13% agreed that if they had taken the course earlier in their academic career, they might have changed their major to soil science, while an additional 5% strongly agreed they might have changed their major.

The spring semester began with 193 students registered and 181 completed the course. During this session, 175 students took the survey at the beginning of the semester and 176 students completed the survey at the end. Twenty-nine percent of respondents taking

Table 6 Student responses at the end of 2012 Fall Semester using a Likert scale based are questions/statements asked with answers on a scale of importance

				Scale of Importance									
				Extremely		**Somewhat**		**No Opinion**		**Not Very**		**Not At All**	
#	**Questions/Statements**	**Mean**	**SD**	**# of 5's**	**% of 5's**	**# of 4's**	**% of 4's**	**# of 3's**	**% of 3's**	**# of 2's**	**% of 2's**	**# of 1's**	**% of 1's**
1	The topics covered in this course	**4.4**	**0.59**	40	**48%**	42	**50%**	1	**1%**	1	**1%**	0	**0%**
2	This class is important for understanding why soil is important to food security	**4.7**	**0.49**	60	**71%**	23	**27%**	1	**1%**	0	**0%**	0	**0%**
3	It is important to understand intrinsic soil productivity and its link to sustainability	**4.5**	**0.59**	44	**52%**	36	**43%**	4	**5%**	0	**0%**	0	**0%**
4	How important would it be for you to take a student travel course to further understand food security?	**3.4**	**1.10**	14	**17%**	30	**36%**	22	**26%**	14	**17%**	4	**5%**
5	How important is it to understand the downfall of the Maya	**4.0**	**0.75**	17	**20%**	51	**61%**	13	**15%**	2	**2%**	1	**1%**
6	How important is it to understand the downfall of the Greenland Norse?	**3.8**	**0.78**	14	**17%**	49	**58%**	15	**18%**	6	**7%**	0	**0%**
7	How important is it to understand the role of energy in our lifestyle?	**4.8**	**0.45**	66	**79%**	17	**20%**	1	**1%**	0	**0%**	0	**0%**
8	How important were the oral readings in lecture?	**3.4**	**1.02**	5	**6%**	45	**54%**	14	**17%**	16	**19%**	4	**5%**
9	How important is it to you to understand food security?	**4.6**	**0.70**	57	**68%**	20	**24%**	4	**5%**	2	**2%**	0	**0%**
10	If you were forced to emigrate, how important would it be to evaluate the soils before hand?	**4.3**	**0.82**	43	**51%**	26	**31%**	13	**15%**	2	**2%**	0	**0%**
11	Understanding soil resources to avoid environmental catastrophe?	**4.8**	**0.46**	64	**76%**	19	**23%**	1	**1%**	0	**0%**	0	**0%**

Table 7 Student responses at the end of 2012 Fall Semester using a Likert scale based are questions/statements asked with answers on a scale of agreement

				Scale of Agreement									
				Strongly Agree		Agree		No Opinion		Disagree		Strongly Disagree	
	Statements	**Mean**	**SD**	**# of 5's**	**% of 5's**	**# of 4's**	**% of 4's**	**# of 3's**	**% of 3's**	**# of 2's**	**% of 2's**	**# of 1's**	**% of 1's**
12	This class has changed my understanding of how we feed ourselves	4.0	**0.84**	22	**26%**	45	**54%**	12	**14%**	4	**5%**	1	**1%**
13	Climate Change is a fact	4.6	**0.60**	56	**67%**	23	**27%**	5	**6%**	0	**0%**	0	**0%**
14	We collectively need to understand the effects of humans on our changing climate	4.6	**0.60**	57	**68%**	24	**29%**	2	**2%**	1	**1%**	0	**0%**
15	The information provided in this course is important for all UT students	4.1	**0.96**	32	**38%**	39	**46%**	7	**8%**	3	**4%**	3	**4%**
16	My understanding of the topics covered in this course has changed since the beginning of this class	4.2	**0.85**	36	**43%**	34	**40%**	11	**13%**	2	**2%**	1	**1%**
17	This class has taught me that understanding population growth is important to understanding our future	4.4	**0.72**	46	**55%**	29	**35%**	8	**10%**	1	**1%**	0	**0%**
18	If I had taken this course earlier in my academic career, I might have changed my major to soil science	2.5	**1.09**	4	**5%**	11	**13%**	24	**29%**	29	**35%**	16	**19%**
19	I would like to take another course in soil science	3.6	**1.04**	17	**20%**	30	**36%**	25	**30%**	9	**11%**	3	**4%**
20	The oral readings in class wasted limited class time	2.5	**0.98**	2	**2%**	9	**11%**	32	**38%**	25	**30%**	14	**17%**
21	If I knew I could make a living as a soil scientist I would become one	2.7	**1.14**	5	**6%**	15	**18%**	27	**32%**	22	**26%**	15	**18%**
22	There is more fiction than fact in this course	1.8	**1.01**	3	**4%**	3	**4%**	8	**10%**	28	**33%**	42	**50%**
23	The Bushmen are an example of a sustainable civilization	3.5	**1.19**	19	**23%**	30	**36%**	14	**17%**	17	**20%**	4	**5%**
24	We—the Americans—are an example of a sustainable civilization	2.0	**1.11**	1	**1%**	11	**13%**	12	**14%**	23	**27%**	36	**43%**
25	Global Warming is a fact and due to human activity	3.7	**1.04**	20	**24%**	35	**42%**	20	**24%**	5	**6%**	4	**5%**
26	Soil science was an unknown discipline to me until I took this course!	3.2	**1.45**	22	**26%**	22	**26%**	6	**7%**	22	**26%**	12	**14%**

Table 8 Comparison of the mean responses to survey questions at the start and end of 2013 Spring Semester to questions based on the scale of importance shown in Table 6

#	Questions	Beginning Survey Mean	Ending Survey Mean	Difference
1	How important were the topics covered in this course to you?	4.0	4.2	0.21
2	How important is a course on soils for understanding food security?	4.5	4.8	0.28
3	How important is it to understand intrinsic soil productivity and its link to sustainability?	4.1	4.6	0.42
4	How important would it be for you to take a student travel course to further understand food security?	3.3	3.3	-0.02
5	How important is it to understand the downfall of the Maya?	3.6	3.7	0.10
6	How important is it to understand the downfall of the Greenland Norse?	3.5	3.6	0.11
7	How important is it to understand the role of energy in our lifestyle?	4.6	4.8	0.17
8	How important is it to understand the role of agriculture in climate change?	4.5	4.7	0.17
9	How important is it to you to understand food security?	4.2	4.6	0.42
10	If you were forced to emigrate, how important would it be to evaluate the soils beforehand?	3.8	4.4	0.59
11	Understanding soil resources to avoid environmental catastrophe?	4.5	4.8	0.32

the spring 2013 survey indicated they were freshmen, 21% sophomores, 26% juniors and 23% seniors, with 60% male and 40% female. Forty-six percent indicated they grew up in the suburbs, 16% in the city, 25% in rural areas and 13% on farm. The most significant change in responses by students to survey statements at the end of the course was an increase in the mean from 2.9, where 3 was "No opinion" to 4.1, with 4, being "Agree" in response to the statement, "I have a good understanding of sustainable agriculture." Another notable change was an increase in the mean from 3.2 to 3.8 in response to the statement, "I think that all students should be required to take a class in agriculture or soil science" and from 3.5 to 4.3 in response to the statement that "The information provided

Table 9 : Comparison of the mean responses to survey statements at the start and end of 2013 Spring Semester to statements based on the scale of agreement shown in Table 7

#	Statements	Beginning Survey Mean	Ending Survey Mean	Difference
12	I understand how we feed ourselves	**3.9**	**4.2**	**0.28**
13	Climate Change is a fact	**4.1**	**4.8**	**0.75**
14	We collectively need to understand the effects of humans on our changing climate	**4.6**	**4.6**	**-0.01**
15	The information provided in this course is important for all UT students	**3.6**	**4.3**	**0.78**
16	I have good understanding of sustainable agriculture.	**3.0**	**4.1**	**1.12**
17	I think population growth is important to understanding our future.	**4.2**	**4.5**	**0.35**
18	I would like to take another course in soil science	**3.3**	**3.6**	**0.34**
19	I would like to take more agriculture related classes.	**3.7**	**3.8**	**0.11**
20	If I knew I could make a living as a soil scientist I would become one	**2.7**	**2.8**	**0.06**
21	I believe technology can solve all of our problems	**2.5**	**2.6**	**0.10**
22	The Bushmen are an example of a sustainable civilization	**3.1**	**3.9**	**0.83**
23	We—the Americans—are an example of a sustainable civilization	**3.0**	**2.9**	**-0.09**
24	Global Warming is a fact and due to human activity	**3.4**	**3.8**	**0.32**
25	Soil science is an unknown discipline to me	**3.4**	**2.3**	**-1.10**
26	Today more countries have programs on fighting obesity than hunger	**3.1**	**3.4**	**0.22**
27	Climate change is a new phenomenon	**2.3**	**1.8**	**-0.45**
28	Sustainable energy use is an issue that should be addressed	**4.2**	**4.5**	**0.27**
29	Soils have little impact on food security	**1.7**	**1.6**	**-0.17**
30	"Civilizations" are "sustainable"	**3.0**	**2.8**	**-0.17**
31	I think that all students should be required to take a class in agriculture or soil science	**3.3**	**3.9**	**0.59**
32	I think that government has an important role in protecting natural resources	**3.8**	**4.3**	**0.47**

in this course is important for all UT students." By the end of the course students indicated that the !Kung Bushmen were an example of a sustainable civilization and our US civilization is similar to most civilizations studied that have disappeared. While the news politicizes climate change issues, students found climate change to be a fact.

But perhaps more importantly for those of us employed within the Land Grant University System, the survey results suggested that students gained a better understanding of food production and how population growth can cause civilization demise. Student perceptions moved toward the understanding that few of our current civilizations are truly sustainable with sustainable energy use as just one issue that needs to be addressed.

Summary

Based on the responses of this survey, there is a strong indication that this course has an influence/impact on the attitudes of students towards soil, agriculture and their relation to food security and sustainability. Registration for the fall 2013 semester increased 17% to a total of 233 students. Surveys will be used to continue measurements and other methods will be explored to quantify the impact of this course on enrollment to soil science courses.

We think an introductory class is necessary to explain agriculture's role in civilization, subsequent civilization stability and solving global agricultural and food security problems. Quite simply, this course outlines the mission of the Land Grant Universities, a mission that can only be completed if we strive to enlist the best minds to work in agricultural sciences. Our future may depend on our success at marketing our disciplines to future generations and this course is a tool to do so.

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CONCLUSION

Agriculture has a role to play in addressing both the need to feed a growing population and in mitigating climate change. Agriculture can be part of a sustainable solution to address food security and global warming or it can exacerbate both problems. Identifying and measuring sustainable agricultural practices that can address both problems is a worthwhile goal and the research described in this thesis adds to our knowledge of the role of agriculture and soil in mitigating GHG emissions. Refining approaches that show significant differences among agriculture practices to sequester or emit CO2 can address gaps in knowledge and provide evidence for the development of effective policies to mitigate GHG emissions. More research is needed to address the potential of various practices, the variability among soil and climatic regimes, measurement uncertainties and the lack of data in developing countries.

VITA

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