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Using Micrometeorology to Gauge Agriculture's Potential to Sequester Soil Carbon

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I am submitting herewith a dissertation written by Debra Blumberg O'Dell entitled "Using Micrometeorology to Gauge Agriculture's Potential to Sequester Soil Carbon." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Plant, Soil and Environmental Sciences.

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ABSTRACT

In addition to reducing carbon dioxide (CO_2) emissions from fossil fuel combustion, removing atmospheric CO_2 may be critical to limit global warming to less than two degrees Celsius above pre-industrial levels recommended by leading experts. Since cropland occupies 11% of the earth's land and is intensively managed, cropland agriculture provides one approach for removing CO_2 from the atmosphere to mitigate climate change. However, current assessments indicate agriculture is a net emitter of CO_2 and other greenhouse gases, and it is unclear how soil management can effect carbon sequestration.

In this work micrometeorological methods are used to measure the exchange (flux) of CO_2 between the surface and atmosphere and can assess whether an agricultural ecosystem is a source or sink for carbon. Three studies were performed using micrometeorology to understand agriculture's potential to sequester carbon.

Using Bowen Ratio Energy Balance (BREB) micrometeorological methods, the first study measured CO_2 flux from a maize crop grown on no-till and tilled soils to determine tillage effects on CO_2 emissions during 104 days of the 2015 maize growing season in north central Ohio. During this period, the no-till plot sequestered CO_2, while the tilled plot was a net emitter.

A second study determined if industrial biotechnology waste reutilization in agriculture could reduce CO_2 emissions and generate environmental benefits, while meeting farmer yield expectations. Using both BREB and eddy covariance (EC) micrometeorological methods, CO_2 flux was measured over maize where heat-inactivated, spent microbial biomass (SMB) amendment was land applied and compared with typical farmer practices from October 2016 to October 2017 in Loudon, Tennessee. While treatments with SMB emitted more CO_2 than farmer practices, the SMB applications produced yields similar to farmer practices.

Using BREB micrometeorology methods, the third study measured CO_2 emissions over conservation agriculture (CA) practices as compared to conventional tillage from June 2013 to May 2016 in central Zimbabwe. The CA practices of no-till and cover crops produced significantly fewer CO_2 emissions than conventional tillage.

These studies demonstrate that micrometeorology can detect short- and long-term differences in CO_2 flux between practices, providing data supporting agriculture's potential to reduce CO_2 emissions and sequester carbon.

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GLOSSARY OF TERMS

The following terms, concepts and expressions used in this dissertation may not be familiar outside their disciplinary use and may also be defined differently within the scientific literature.

Biomass is the mass of organic matter in an organism, population, given area or ecosystem (USDA, 2018) or the material produced from organisms (USGCRP, 2018). In this dissertation, “biomass” has multiple meanings including the organic matter in human and animal waste (e.g., manure), the organic matter used in and produced by biotechnology processes, and the above-ground mass of maize vegetation (including leaves, stalks, husks, cobs and grain) produced by an agroecosystem through photosynthesis,. A related term used in the dissertation, **biosolids** (also known as sewage sludge), is derived from municipal wastewater treatment plants (USDA, 2018). Biosolids and animal manure usually contain plant nutrients, such as N, P and K that are useful agricultural amendments. The major types of biomass referred to include the heat inactivated cellular waste product generated from the production of 1,3-propanediol, i.e., spent microbial biomass (SMB), the living and dead plant material above and below ground of the crop and/or weeds in the ecosystem (plant biomass), or the living crop plant material above the soil (above-ground biomass), which includes stems, foliage and seed grain. **Soil amendment** (or referred to simply as amendment) includes a range of materials from organic matter such as manure, biosolids or crop residue to inorganic material such as lime Such amendments may be applied to agricultural soil for the purpose of enhancing soil chemical or physical properties, as well as plant growth (SSSA, 2018). **Yield** is a term which can refer to the mass of the above-ground maize biomass or the mass of the harvested grain per unit area (SSSA, 2018).

The **Bowen ratio** is the ratio of heat lost by conduction to heat lost by evaporation at the surface (Bowen, 1926), which was later described as the ratio of sensible heat flux to latent heat flux and subsequently named by Sverdrup (1943) as the Bowen ratio. The Bowen ratio can be calculated from measurements of the gradients of temperature and vapor pressure above the surface. **Sensible heat flux** is defined as the conductive or turbulent flow of heat between the earth's surface and atmosphere (not associated with phase changes), while **latent heat flux**, also known as **latent energy flux**, is the turbulent flow associated with the condensation or evaporation of water vapor (Planton, 2013). The Bowen ratio can be used to calculate sensible and latent heat fluxes in the **Bowen ratio energy balance (BREB)** micrometeorological method by assuming that the sum of sensible and latent heat fluxes can be equated to the sum of incoming solar and longwave radiation minus reflected shortwave and outgoing longwave radiation, while also subtracting the heat that goes into the ground (Penman, 1948). This first-order approximation omits the small consequence of energy used in photosynthesis as well as the heat storage within the vegetated canopy that might be present. The latter is sometimes an important contribution to the surface energy budget, especially when the other terms are small (near dawn and dusk). The BREB method can calculate a vertical gradient transport coefficient, also known as **eddy diffusivity** (K), from the sensible or latent heat flux to estimate the vertical flux of a gas proportional to its time-averaged vertical concentration gradient, also known as K gradient/profile transport or K-theory. An alternative gradient/profile transport approach called the **aerodynamic method** calculates eddy diffusivity from wind speed, canopy aerodynamic characteristics, and atmospheric stability. Energy, momentum, and scalar flux at the surface atmosphere boundary layer are defined as positive when they are moving upward from the earth surface to the atmosphere and negative when they are moving down from the atmosphere to the surface. Soil heat flux (G) is positive when the soil is being heated.

Conservation Agriculture (CA) is a farming system based on the principles of (1) minimal soil disturbance (such as with no-till), (2) maintaining year-round soil cover with residue, mulch, and/or cover crops, and (3) crop rotation (Hobbs, 2007). Conservation Agriculture was established to address issues of soil erosion and degradation resulting from intensive agricultural practices such as tillage, while sustaining crop production and improving soil quality. Since 2002, the United Nations (UN) Food and Agricultural Organization (FAO) has promoted CA adoption worldwide—especially among smallholder farmers (FAO, 2019).

The **C:N ratio** is the ratio of the mass of carbon to nitrogen in a substance. When known for a crop residue or amendment, the C:N ratio can be an indicator of the potential decomposition rate in soil or on the soil surface (Linley and Newell, 1984). Because soil microbes must take in a balance of nutrients to meet their cellular and energy needs, C:N ratios greater than about 24:1 will induce microbes to scavenge for additional N in the soil to meet their requirements, resulting in N **immobilization** (USDA-NRCS, 2011). Residues or amendments with lower C:N ratios (e.g., legumes or manures) would have an excess of N that microbes release during decomposition to mineral forms of N such as ammonium and nitrate, in a process known as **mineralization** (Jansson and Persson, 1982). These mineralized forms of N are plant-available, while organic forms of N in microbes and soil organic matter are considered immobilized, and are thus not plant-available.

The **CO_2 fertilization effect** refers to enhanced photosynthesis due to increases in atmospheric CO_2 concentrations (Planton, 2013). This is a topic of interest in the context of climate change, but is also of relevance when concentrations of CO_2 are increased within the crop canopy due to soil and plant respiration, especially during periods of low atmospheric turbulence. This effect has been studied experimentally and is now known to lead to greater yield and biomass production as atmospheric concentrations increase with time.

An **eddy** is both a physical manifestation of air movement in the shape of a three-dimensional vortex or whirl ranging in size from 10^{-3} to 10^{3} m as well as an abstract concept used for describing turbulence (Arya, 2001). The atmosphere near the ground is characteristically turbulent, especially in daytime, and this turbulence serves to transport momentum, heat, and scalars through the atmosphere (Sutton, 1953).

Eddy covariance (EC) is considered the most direct method for measuring the vertical flux of mass, energy, and momentum and is calculated as the covariance of the vertical wind velocity and the other quantity of interest (Swinbank, 1951). Sonic anemometers provide precise 3D measurements of the wind velocity and its variance over time, permitting the eddy flux of CO_2, for example, to be quantified as the covariance between the vertical velocity wind component and the instantaneous CO_2 concentration at the same location.

A typical "**farmer practice**" generally refers to an accepted on-farm procedure. In Chapter 2, the commercial inorganic fertilizer NPK application rate, which a local farmer chose to produce his/her economically optimum yields is the "farmer practice" and was compared to the case of additional biomass treatment.

Flux for this dissertation refers to the flow of mass, energy, radiation, or momentum through a horizontal surface area per unit of time. In meteorology, fluxes are defined as the transport of energy or mass from the earth's surface to the atmosphere. This dissertation includes fluxes of mass such as CO_2, of momentum, and of energy, the last involving the sensible heat flux, *H*; the latent heat flux, *LE*, caused by the evaporation and condensation of water; the net radiation, R_n, which is incoming solar energy minus outgoing reflected and emitted energy; and soil heat flux, *G*, the energy used to heat the soil.

Friction velocity, u_*, is the velocity defined by the shearing stress exerted by the wind on the earth's surface. It depends on the magnitude of mean wind speed, the stability of the atmosphere, and the nature of the surface (Sutton, 1953). Friction velocity can be calculated as the covariance of the instantaneous horizontal and vertical wind velocities (Sutton, 1953). Friction velocity can also be estimated from horizontal wind speed, turbulent flow and surface roughness parameters (the roughness parameter and zero plane displacement) if such quantities are well enough determined (Rosenberg et al., 1983).

Industrial biotechnology is defined by the Belgian Academy Council of Applied Science as "the application of modern biotechnology for the industrial production of chemical substances and bio-energy, using inherently clean processes, with less waste generation and reduced energy consumption" (Vandamme et al., 2004). In 1992, the United Nations Environment Program (UNEP) defined biotechnology as "any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use" (UNEP, 1992). Industrial biotechnology is also known as "white biotechnology", which is symbolic of clean or sustainable technologies (Vandamme et al., 2004).

While **meteorology** is the study of the chemistry, physics, and dynamics of the earth's atmosphere, **micrometeorology** is the study of phenomena taking place between the surface (land, water and plants) and the lowest layers of the atmosphere (Sutton, 1953; American Meteorological Society, 2019). Micrometeorology uses methods such as EC, BREB and aerodynamic methods to measure the exchange of energy, gases, and momentum between the surface and atmosphere and can monitor the effects of human activities in the atmosphere (American Meteorological Society, 2019).

Net ecosystem exchange (NEE) refers to the net vertical flux of CO_2 between an ecosystem and the atmosphere (Bartlett et al., 1989) and is estimated through micrometeorological measurements of CO_2 flux above the canopy or soil surface. NEE is one component of the net ecosystem carbon balance, which is the total carbon accumulation or loss from an ecosystem and includes NEE and vertical and lateral movement of other organic and inorganic carbon (Chapin et al., 2006). NEE represents the sum of ecosystem CO_2 assimilation through photosynthesis and CO_2 loss through respiration by ecosystem plants, animals and other organisms. While the CO_2 exchange between the atmosphere and surface has been studied since the 1960's (Lemon, 1960) the first use of the term NEE was by Bartlett, et al. (1989). NEE is positive when CO_2 is added to the atmosphere (emission) and negative when CO_2 is removed from the atmosphere (sequestration). NEE is essentially the same as the CO_2 flux as measured and reported here, averaged or summed over a period of time. In this dissertation, the term CO_2 flux is used interchangeably with NEE.

The **gradient Richardson number, *Ri***, is a ratio that relates buoyant energy production to energy dissipation through mechanical turbulence and is used as a parameter to indicate atmospheric stability (Monteith and Unsworth, 2013). Negative *Ri* numbers correspond to unstable conditions, *Ri* numbers near zero are neutral, and positive *Ri* values indicate stable stratification. In unstable conditions there is upward heat transport, in neutral conditions there is no vertical exchange of heat energy, and in stable conditions the atmosphere resists vertical motion.

Sensor resolution and accuracy are identified by the manufacturer. Each sensor may have an accuracy prescribed within a range of measurements, e.g., temperature sensors being accurate within ± 0.1 °C over a range of -25 to +50°C. Perez et al. (1999) explain that to minimize errors in BREB flux estimation, data within the instrument uncertainty should be excluded for gradient measurements, i.e., since the difference between the lower and upper sensor can be small and less than the sensor accuracy.

A **scalar** is a physical quantity including energy (e.g., heat) or matter (e.g., water vapor, trace gases such as CO_2, or particulate matter such as pollutants) (Paw U et al., 2005).

Soil organic matter (SOM) is the organic fraction of soil, with larger flora or fauna removed that do not accompany soil across a 2-mm sieve (Vaughan and Ord, 1985; Nelson and Sommers, 1996). Soil organic matter has been identified as a key indicator of soil fertility (Kononova, 1966; Nannipieri and Sequi, 1982), because it serves as a plant nutrient reservoir in addition to its influence on soil chemical, biological and physical properties. Studies have shown a relationship between soil organic matter and **soil organic carbon (SOC)**, generally within the range of 1.72 to 2.0 parts SOM to SOC varying by soil (Davies, 1974; Nelson and Sommers, 1996). Since measuring SOM is difficult, Nelson and Sommers (1996) suggested that SOC content be measured and reported as an index of SOM. Soil organic carbon was measured and used as a gauge of both SOM and soil fertility.

The **specific surface** is defined as the soil or other porous media solid-particle surface area divided by its mass or volume (SSSA, 2018). Surface area increases as particle size decreases. Specific surface area has an important role in water retention for soil and other porous media. In this study the specific surface area of the spent microbial biomass is expected to have an important role in nutrient availability and also in decomposition. As the size of spent microbial biomass particles decreases and specific surface increases, nutrients become more available to roots and microbes, increasing decomposition, mineralization, and nutrient availability (Swift et al., 1979).

Turbulent diffusivity, *K*, (also known as the coefficient for turbulent diffusivity, turbulent transfer coefficient, eddy diffusivity, eddy viscosity, eddy exchange coefficient and eddy diffusion coefficient) is the turbulent diffusion transport coefficient that associates fluxes with gradients (Stull, 2012).

References

American Meteorological Society (2019) *American Meteorological Society Glossary*, *American Meteorological Society Glossary*. Available at: http://http//glossary.ametsoc.org/wiki/Meteorology (Accessed: 14 February 2019).

Arya, S. P. (2001) *Introduction to Micrometeorology*. 2nd edn. San Diego: Academic Press. doi: 10.1016/s0074-6142(01)x8014-5.

Bartlett, D. S., Whiting, G. J. and Hartman, J. M. (1989) 'Use of vegetation indices to estimate indices to estimate intercepted solar radiation and net carbon dioxide exchange of a grass canopy', *Remote Sensing of Environment*, 30(2), pp. 115–128. doi: 10.1016/0034-4257(89)90054-0.

Bowen, I. S. (1926) 'The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface', *Physical review*, 27(6), pp. 779–787. doi: https://doi.org/10.1103/PhysRev.27.779.

Chapin, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., Clark, D. A., Harmon, M. E., Schimel, D. S., Valentini, R., Wirth, C., Aber, J. D., Cole, J. J., Goulden, M. L., Harden, J. W., Heimann, M., Howarth, R. W., Matson, P. A., McGuire, A. D., Melillo, J. M., Mooney, H. A., Neff, J. C., Houghton, R. A., Pace, M. L., Ryan, M. G., Running, S. W., Sala, O. E., Schlesinger, W. H. and Schulze, E. D. (2006) 'Reconciling carbon-cycle concepts, terminology, and methods', *Ecosystems*, 9(7), pp. 1041–1050. doi: 10.1007/s10021-005-0105-7.

Davies, B. E. (1974) 'Loss-on-Ignition as an Estimate of Soil Organic Matter', *Soil Science Society of America Journal*, 38(1), pp. 150–151. doi: 10.2136/sssaj1974.03615995003800010046x.

FAO (2019) *Conservation Agriculture principles*. Available at: http://www.fao.org/conservation-agriculture/overview/principles-of-ca/en/ (Accessed: 25 January 2019).

Hobbs, P. R. (2007) 'Paper Presented at International Workshop on Increasing Wheat Yield Potential, CIMMYT, Obregon, Mexico, 20-24 March 2006: Conservation agriculture: What is it and why is it important for future sustainable food production?', *Journal of Agricultural Science*, 145(2), pp. 127–137. doi: 10.1017/S0021859607006892.

Jansson, S. L. and Persson, J. (1982) 'Mineralization and Immobilization of Soil Nitrogen', in Stevenson, F. J. (ed.) *Nitrogen in agricultural soils*. Madison, WI: ASA-CSSA-SSSA, pp. 229–252.

Kononova, M. M. (1966) 'The Importance of Organic Matter in Soil Formation and Soil Fertility', in. New York: Pergamon Press, pp. 183–228. doi: https://doi.org/10.1016/B978-0-08-011470-5.50007-1.

Lemon, E. R. (1960) ‘Photosynthesis Under Field Conditions. II. An Aerodynamic Method for Determining the Turbulent Carbon Dioxide Exchange Between the Atmosphere and a Corn Field1’, *Agronomy Journal*, 52(502), p. 697. doi: 10.2134/agronj1960.00021962005200120009x.

Linley, E. A. S. and Newell, R. C. (1984) ‘Estimates of Bacterial-Growth Yields Based on Plant Detritus’, *Bulletin of Marine Science*, 35(3), pp. 409–425.

Monteith, J. and Unsworth, M. (2013) *Principles of Environmental Physics: Plants, Animals, and the Atmosphere: Fourth Edition, Principles of Environmental Physics: Plants, Animals, and the Atmosphere: Fourth Edition*. doi: 10.1016/C2010-0-66393-0.

Nannipieri, P. and Sequi, P. (1982) ‘Soil Fertility - the determination and the turnover of soil organic matter’, in *Evolution du niveau de fertilite des sols dans differents systemes de culture. Criteres pour mesurer cette fertilite*, pp. 141–151.

Nelson, D. W. and Sommers, L. E. (1996) ‘Total Carbon, Organic Carbon, and Organic Matter’, in Sparks, D. L., Page, A. L., Helmke, P. A., and Loeppert, R. H. (eds) *Methods of soil analysis Part 3-Chemical Methoods*. Madison: Soil Science Society of America, Inc. American Society of Agronomy, Inc., pp. 961–1010. doi: 10.2136/sssabookser5.3.c34.

Paw U, K. T., Snyder, R. L., Spano, D. and Su, H. (2005) ‘Surface Renewal Estimates of Scalar Exchange’, in Hatfield, J. L. and Baker, J. M. (eds) *Micrometeorology in Agricultural Systems*. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, pp. 1–65. doi: 10.2134/agronmonogr47.c20.

Penman, H. L. (1948) ‘Natural Evaporation from Open Water, Bare Soil and Grass’, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 193(1032), pp. 120–145. doi: 10.1098/rspa.1948.0037.

Perez, P. J., Castellvi, F., Ibañez, M. and Rosell, J. I. (1999) ‘Assessment of reliability of Bowen ratio method for partitioning fluxes’, *Agricultural and Forest Meteorology*, 97(3), pp. 141–150. doi: 10.1016/S0168-1923(99)00080-5.

Planton, S. (2013) *Annex III: Glossary, In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom. doi: 10.1017/CBO9781107415324.031.

Rosenberg, N. J., Blad, B. L. and Verma, S. B. (1983) *Microclimate: The Biological Environment*. New York: John Wiley & Sons.

SSSA (2018) *Soil Science Society of America: Glossary of Soil Science Terms*. Madison, WI. Available at: https://www.soils.org/publications/soils-glossary (Accessed: 26 April 2018).

Stull, R. (2012) *An introduction to boundary layer meteorology*. Dordrecht: Kluwer Academic Publishers. doi: 10.1007/978·94-009-3027-8.

Sutton, O. G. (1953) *Micrometeorology*. New York: McGraw-Hill Book Company, Inc. doi: 10.1002/qj.49707934125.

Sverdrup, H. U. (1943) ‘On the Ratio Between Heat Conduction From the Sea Surface and Heat Used for Evaporation’, *Annals of the New York Academy of Sciences*, 44(1), pp. 81–88. doi: 10.1111/j.1749-6632.1943.tb31294.x.

Swift, M. J., Heal, O. W. and Anderson, J. M. (1979) *Decomposition in terrestrial ecosystems. Studies in Ecology, Vol. 5*. Oxford, UK: Blackwell Scientific.

Swinbank, W. C. (1951) ‘the Measurement of Vertical Transfer of Heat and Water Vapor By Eddies in the Lower Atmosphere’, *Journal of Meteorology*, 8(3), pp. 135–145. doi: 10.1175/1520-0469(1951)008<0135:TMOVTO>2.0.CO;2.

UNEP (1992) *Convention on Biological Diversity*. Nairobi. Available at: https://www.cbd.int/convention/text/.

USDA-NRCS (2011) *Carbon to Nitrogen Ratios in Cropping Systems, USDA Natural Resources Conservation Service*. Available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1166766.pdf (Accessed: 10 April 2018).

USDA (2018) *National Agricultural Library Glossary*. Available at: https://agclass.nal.usda.gov/glossary.shtml.

USGCRP (2018) *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report*. Edited by N. Cavallaro, G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, and Z. Zhu. Washington, D.C.: U.S. Global Change Research Program. doi: 10.7930/SOCCR2.2018.

Vandamme, E., Soetaert, W. and Bienfait, C. G. (2004) *Industrial Biotechnology and Sustainable Chemistry*. Brussels. Available at: www.sustentabilidad.uai.edu.ar/pdf/tec/bacas_report_en.pdf.

Vaughan, D. and Ord, B. G. (1985) *Soil Organic Matter and Biological Activity*. Dordrecht: Springer. doi: 10.1007/978-94-009-5105-1.

INTRODUCTION

Climate Change

The scientific community has reached a consensus that since the beginning of the industrial age, the primary cause of global warming is the emission of anthropogenic greenhouse gases (GHGs). Recent unprecedented increases in GHGs pose a threat to human populations through increases in hot temperature extremes, rising sea levels, and intensifying weather events (Clarke et al., 2014; IPCC-SR15, 2018; Cook et al., 2013; Seneviratne et al., 2014). Atmospheric GHGs contributing to global warming include carbon dioxide (CO_2) (76% of total anthropogenic GHG emissions with each gas estimated in CO_2 equivalent emissions per year in 2010), methane (16%), nitrous oxide (6%), and fluorinated gases (2%) (IPCC, 2014). Ice core records have shown that atmospheric concentrations remained under 300 ppm for the past 420,000 years (Petit et al., 1999) until 100 years ago. Current data shows that atmospheric CO_2 is at historically high levels with the recent global monthly average of CO_2 concentration for December 2018 estimated at 409 ppm, which is a 46% increase above a representative pre-industrial concentration of 280 ppm used by the National Oceanographic and Atmospheric Administration (NOAA) (Etheridge et al., 1996; NOAA, 2019).

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) generally focuses attention on the CO_2 emissions from fossil fuel and industrial processes because they currently represent the majority of GHG emissions (65% of total GHG emissions in 2010) as well as the greatest increase in emissions (6% increase between 1990 and 2010), and thus the largest problem to address (IPCC, 2014).

The Paris Agreement reached at the 2015 United Nations (UN) Climate Change Conference focuses on reducing GHG emissions, in order to keep the rise in global warming below 2°C (UNFCCC, 2015), especially fossil fuel emissions considering the magnitude of that source (Houghton, 2007; IPCC, 2013a). The Paris agreement also provides for the development of other climate change mitigation strategies that can show measurable, long-term benefits. Given the nature and importance of the problem of global warming as presented in the recent special report of the IPCC (2018), all manner of solutions and tools should be considered to reduce chances of potentially catastrophic events.

The Carbon Cycle

The global C cycle and budget provides some background and context for understanding the causes and effects of global warming. The C cycle can be divided into two timescales: the first being a fast or active cycle on the order of a few years to millennia, also called a biogeochemical cycle of C (Schlesinger, 1995), that is comprised of reservoirs and fluxes of C in and between the ocean, atmosphere, and terrestrial vegetation, soil, freshwater, and fossil fuel reserves. The second slower cycle, also known as a rock cycle or geochemical cycle, includes large C reserves in rocks and sediments that exchange C through erosion and chemical weathering of sediments, volcanic emissions of CO_2, and sediment formation on the ocean floor (Ciais et al., 2013; Schlesinger, 1995; Sundquist, 1986). While most volcanism occurs on shorter episodic timescales, volcanism's effect on and exchange with the faster biogeochemical cycle is roughly equivalent to the annual CO_2 released from volcanos, which is about 0.018 - 0.13 PgCa—range representing less than 1% of anthropogenic emissions—thus it is not consequential on the faster timescale (IPCC, 2013b; Schlesinger, 1995). The following C cycle description focuses on the faster biogeochemical cycle, which has the greatest impact on the phenomenon of current climate change.

AR5 estimated the size of the main reservoirs of the biogeochemical C cycle as 38,703 PgC in the ocean (not including ocean floor sediments), 828 PgC in the atmosphere, 450-650 PgC in terrestrial vegetation, 637-1,575 PgC in fossil fuel reserves, and 1,500-2,400 PgC in soil, with an additional ~1,700 PgC in permafrost soils (Ciais et al., 2013). Carbon moves within and between these reservoirs via many mechanisms, though the largest accumulative net fluxes are between the atmosphere and other reservoirs. For example, the flux of C between the atmosphere and ocean before the industrial age was approximately 90 PgC per year in both directions and the C flux between atmosphere and terrestrial ecosystems through respiration and photosynthesis was ~120 PgC in both directions (Houghton, 2007). An ecosystem is defined using the UN Environment Programme's definition of ecosystem as "a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit" (UNEP, 1992). Fluxes between these global reservoirs are measured through gas concentration gradients combined with kinetic and thermodynamic measurements and are also inferred through models of biogeochemical processes and circulation models (Wanninkhof et al., 2013).

Since 1750, 470-640 PgC have been released to the atmosphere from the combustion of fossil fuels and 230-250 PgC from land use change—such as deforestation— resulting in an increase in atmospheric concentrations of CO_2 of ~35% to 390 ppm in 2011 (IPCC, 2013b). As a sink, the oceans may have taken up as much as 48% of the anthropogenic emissions during this period (Sabine, 2004).

Over the last 300 years the transformation of forest to agricultural land reduced the total amount of terrestrial C released as CO_2 from this human activity—an estimated 156 PgC from 1850 to 2000 (Houghton, 2003). Atmospheric CO_2 was identified as one of the drivers of climate change because of measurements in radiative forcing (RF), a method that compares the influence of most radiative forcing agents, such as solar radiation, gases, aerosols and albedo that produce a net change in earth's energy balance and global mean surface temperature (IPCC, 2013a). IPCC's AR5 found that since the beginning of the Industrial Era, and especially from 1980-2011, CO_2 was the largest contributor to the increase in total RF (IPCC, 2013a).

Agriculture's Role in Climate Change

The U.S. Council for Agricultural Science and Technology (CAST) Task Force Report states that world-wide, agriculture produces 13.5% of GHG emissions (Follett et al., 2011). The U.S. Environmental Protection Agency (USEPA) inventory of GHG emissions reported that 9% of total U.S. GHG emissions in 2015 were produced from activities associated with agriculture (USEPA, 2017).

Agricultural activities that emit GHGs include soil and crop management, rice farming, livestock manure, livestock enteric fermentation, and burning of agricultural residue (Denef et al., 2011). Denef et al. (2011) also attributed most of the CO_2 emissions from agriculture to management practices that decrease soil organic carbon (SOC) stocks. While methane and nitrous oxide are potent GHGs that are related to agriculture such as with rice farming and livestock manure, this dissertation focuses on CO_2 emissions from cropland agriculture and soils.

Quantifying the contributions of agriculture to GHG emissions has evolved over the five IPCC assessment reports due to agriculture's interactions with other sectors such as energy, forestry and land use change, and also due to agriculture's role in food security given the growing human population (Porter et al., 2017). Agriculture's role in deforestation, including the transformation of forests into farmland and other land use change, accounted for a third of emissions since 1750, but represented 12% of emissions between 2000-2009 (Smith et al., 2014). The conversion of forests into farmland has been incorporated into the emissions category: land use, land-use change and forestry (LULUCF), by the United Nations Framework Convention on Climate Change (UNFCCC, 2019). Vermeulen et al. (2012) connected agricultural impacts on forestry more directly, noting that of the 18% of global GHG emissions due to land use change, 75% of those are from agriculture.

While agriculture is currently a net emitter of CO_2 and other GHGs, Lal (2004) estimated that agriculture could sequester up to 33% of annual atmospheric CO_2 increases. The term "terrestrial C sequestration" (hereafter referred to as C sequestration) is the conversion of atmospheric CO_2 into plant biomass (organic C) through photosynthesis (Lal, 2008). While some of the living and dead plant biomass can be respired back into the atmosphere through decomposition, some of the organic C can be converted over time into more stable forms of soil organic matter (SOM), a term which is often used interchangeably with SOC. Many factors such as climate, soil, plant type, and disturbance influence the rate of decomposition or sequestration.

The United Nations Food and Agriculture Organization (FAO) submission to the UNFCCC (FAO, 2009) and the CAST Task Force Report (Follett et al., 2011) both assert that agricultural management practices can reduce emissions and increase C sequestration into soils and plant biomass. Caldeira et al. (2004) suggested that changing agricultural management practices provides an important option for reducing GHGs and increasing C sequestration in the short term. Another consideration for agriculture's role in mitigating CO_2 emissions is that it does not require the generation of new technology to increase the pool of C in soil (Powlson et al., 2011).

Follett, et al. (2011) outlined agricultural management practices that have been shown to increase SOC stocks. These practices include: high residue crops and crop residue retention, changing from conventional tillage to no-till, utilizing cover crops, changing from annual crops to perennials, reducing fallow, adding manure applications, improved soil fertility, irrigation to support greater plant biomass, and planting trees on cropland. However, it is important to note that the CAST report referenced few experiments that determined which combination of agricultural practices would maximize soil C sequestration (Follett, et al., 2011). This gap in data is central to this dissertation.

To address issues of land degradation and decreasing soil fertility, a farming system called Conservation Agriculture (CA), which is based on the three principles of (1) minimal soil disturbance (such as with no-till), (2) maintaining permanent soil cover with residue, mulch and/or cover crops, and (3) crop rotation (Hobbs, 2007), was established to improve soil quality and to sustain crop production. While the three principles of CA do not address the entire set of practices mentioned in the CAST report, they provide a beginning core set of practices for improving agricultural sustainability (Hobbs et al., 2008). Since 2002, the UN FAO has promoted CA adoption worldwide—especially among smallholder farmers, and expanded the rotation principle to encourage species diversification (FAO, 2019). This dissertation examines CA practices in Chapter 3.

Many studies have investigated the differences between conventional tillage and no-till as an agricultural management practice to increase soil C (Ismail et al., 1994; West and Post, 2002). Conventional tillage disturbs soils and increases aeration within the top layer of the soil, which enhances microbial decomposition of organic matter, which increases soil respiration and CO_2 emissions (Schlesinger and Andrews, 2000).

West and Post (2002) found in their meta-analysis of 67 different studies that changing from conventional tillage to no-till produced significant increases in SOC in the top 15 cm of soil in all studies except under a wheat followed by fallow rotation (Halvorson et al., 2002). In their research, Kern and Johnson (1993) also found that conventional tillage caused a loss of SOC, while no-till increased SOC. They further distinguished the C sequestration potential of 'reduced' or 'minimum' tillage, finding that reduced tillage remained C neutral and did not produce a net C loss like conventional tillage. However, some research questions the potential of no-till to increase soil C (Manley et al., 2005; Baker et al., 2007; Powlson et al., 2011), especially deeper in the soil profile (Angers and Eriksen-Hamel, 2008). Others suggest that no-till has a compelling economic potential that justifies promoting its adoption (Derpsch et al., 2010).

In addition to reduced tillage, other practices that could increase SOC include the use of cover crops. In a meta-analysis of 37 sites, Poeplau and Don (2015) found that cover crop treatments had greater SOC stocks than reference crops. Other management practices may increase SOC, such as switching from monoculture to rotational cropping or crop intensification with intercropping or increased populations. However, West and Post (2002) found that changing from conventional tillage to no-till sequestered on average more SOC than intensifying crop rotation practices. Similarly, Govaerts et al. (2009) found that reduced tillage had the largest reduction in CO_2 emissions in Conservation Agriculture practices. This suggests that many different combinations of agricultural management practices may increase SOC, but the effect varies by practice and may also vary by crop, soil type, and climate.

The Challenge of Measuring Soil C

In order to recommend agricultural management practices that effectively sequester C, it is necessary to measure and quantify their impact on SOC. The FAO submission to the UNFCCC identifies the challenges in measuring the potential of agricultural practices and soil to sequester or emit C including that: (1) within a field, soil C can be highly variable, (2) annual changes in soil C are small and hard to measure, (3) factors such as previous land use, climate and soil type impact soil C and finally, (4) there is a lack of measurements for most combinations of soil, crop, management practice and climate (FAO, 2009).

One of the greatest challenges to determining the impact of any management practice is the amount of time it can take to detect changes in SOC. Smith (2004) found that it can take between 7 and 10 years to detect changes in SOC, even when extensive sampling is performed. Hungate et al. (1996) did not detect significant differences in SOC in an experiment lasting four growing seasons and Necpálová et al. (2014) found that it could take at least seven years to detect differences in SOC.

One reason that it can take so long to measure changes in SOC is that climate may interact with or have a confounding impact on an agricultural management practice's C sequestration or emission. Ogle, Breidt, and Paustian, (2005) found in a meta-analysis greater increases in SOC when converting to no-till in the following order of climates from smallest to largest gain in SOC: temperate dry, temperate moist, tropical dry, tropical moist. Other studies found that no-till did not increase soil C in cold moist temperate soils (VandenBygaart et al., 2003; Gregorich et al., 2005; Hermle et al., 2008).

CO_2 emissions also vary with soil temperature and soil respiration is expected to increase with increasing temperatures, potentially adding to greater GHG concentrations (Kirschbaum, 1995; Schlesinger, 1995). Several studies have shown that moisture and temperature are the primary factors affecting SOC respiration (Craine and Wedin, 2002; Guntiñas et al., 2013). Consequently higher temperatures and greater precipitation due to climate change may reduce or eliminate net C sequestration of some agricultural management practices.

There are other issues with understanding and measuring agriculture's potential to sequester soil C including the question of "non-permanence" or potential reversibility of C sequestered in the agricultural soil and ecosystem (Smith, 2005; Alexander et al., 2015). For example, soil organic C that has been sequestered can return to the atmosphere if agricultural management practices are not maintained (Follett, et al., 2011). After changing management practices from no-till to conventional cultivation, Pankhurst et al. (2002) found a significant reduction in SOC in the top 0–5 cm within 3 years. However, when going from conventional cultivation to no-till, there was a "negligible" effect on soil chemical properties (Pankhurst et al., 2002), indicating that it takes less time to emit sequestered C in agricultural soils than it takes to build up C within the soil. Therefore, understanding factors that cause emissions over the short term is critical to identifying the necessary conditions for C sequestration.

Methods of CO_2 Flux Measurement

Due to the challenges inherent in determining changes in SOC, other methods can be used to quantify the net change of C between the atmosphere and an ecosystem. The transfer of CO_2 mass per unit area per unit of time (e.g., g CO_2 m^{-2} hr^{-1}) between the ecosystem and the atmosphere is the CO_2 flux (also referred to as CO_2 flux density). By measuring CO_2, flux we can quantify the net C loss or gain by the ecosystem over a period of time. Chapin et al. (2006) refined carbon cycle terms for consistent measurements across systems and defined the net ecosystem exchange (NEE) as “the net CO_2 flux from the ecosystem to the atmosphere”. Therefore, a positive NEE indicates a net loss of CO_2 from the ecosystem to the atmosphere and a negative NEE indicates the ecosystem is sequestering C from the atmosphere.

There are two common types of systems for measuring CO_2 flux over agriculture and other ecosystems including accumulation techniques such as static chambers and micrometeorological techniques (Follett, et al., 2011). Chamber methods are limited in their ability to accurately capture the CO_2 flux due to various factors. Firstly, their size and ability to include plants within the chamber is limited, their spatial and temporal variation require extensive sampling, and they lastly are subject to error because they can alter the pressure differential and CO_2 concentration gradient between the chamber headspace and outside air (Davidson et al., 2002).

The main micrometeorological methods include the Bowen ratio energy balance (BREB) system and eddy covariance (EC). BREB is a flux-gradient technique that measures the differences in vapor pressure and ambient air temperature over two heights above the soil or canopy to calculate the Bowen ratio (Bowen, 1926; Sverdrup, 1943). Adding soil heat flux, net solar radiation, and the difference in CO_2 concentrations at the two heights provides the data needed to calculate CO_2 flux (Rosenberg et al., 1983; Dugas, 1993; Webb et al., 1980). EC measures the covariance (fluctuations) around the mean of both the vertical wind velocity and the magnitude of energy or mass (such as CO_2) (Kanemasu et al., 1979). Because EC and BREB provide independent and different measurement approaches, they have been used to compare observations and refine measurements of meteorological properties and fluxes (Brotzge and Crawford, 2003; Shi et al., 2008; Alfieri et al., 2009).

Micrometeorological methods can provide NEE for short periods as well as long-term. Short-term flux measurements on the order of days to months can provide information about diurnal cycles, or real time impact on CO_2 flux by agricultural management practices such as tillage or climate variables such as heat and moisture. Long-term NEE data provides opportunities to assess the impact of a sequence of practices for understanding the mitigation potential of agricultural management practices for sequestering C.

Knowledge Gaps in the Scientific Literature

While BREB micrometeorological methods are still being used to estimate evapotranspiration (Irmak et al., 2014; Vanomark et al., 2018), with the advent of lower cost sonic anemometers and infrared gas analyzers, EC methods are currently the dominant micrometeorological method for quantifying NEE. There are more than 900 EC micrometeorological measurement stations worldwide providing data increasing our knowledge and quantifying the role of terrestrial ecosystems for C sequestration (Baldocchi, 2014; Chu et al., 2017). Gilmanov et al. (2017) and Skinner and Wagner-Riddle (2012) identified the need for annual studies comparing EC and BREB to evaluate historical BREB data for integration with current EC network data. Chapter 2 provides a side by side comparison of EC and BREB micrometeorological methods and an exploration of nighttime questions to address this need.

While there is one AmeriFlux micrometeorological measurement station in Ohio, it is in the NW, measuring NEE, water, and energy fluxes over an oak woodland northwest Ohio. There are no micrometeorological measurement stations measuring over agriculture in Ohio. Chapter 1 provides data about the impacts of contrasting agricultural tillage practices on micrometeorological properties in north central Ohio, including abnormally wet and dry conditions during a growing season.

BREB can provide information more representative of the surface since it measures closer to the canopy and soil surface. Comparing BREB and EC provides an opportunity to explore the impact of the surface on CO_2 flux especially at night during stable periods (low turbulence) when fluxes are not consistent with, or are near the limits of, the flux-gradient theory.

While there are long-term studies comparing the use of biosolids applied as soil amendments to degraded crop soils (Tian et al., 2009), to our knowledge, there are few, if any studies that have compared the emissions of these amendments. No studies were found in the literature measuring CO_2 flux over cropland with industrial biotechnology waste applied as a soil amendment. Chapter 2 provides data to address this knowledge gap.

The FAO submission to the UNFCCC in 2009 identified the lack of measurements for most combinations of soil, crop, management practice, and climate in assessing the potential of agricultural practices and soil to sequester C (FAO, 2009). The CAST report also noted that field experiments involving only one or two agricultural management practices give an incomplete understanding of best practices to sequester C (Follett, et al., 2011). The study described in Chapter 3 investigated the CO_2 flux of a sequence of practices over three years to increase knowledge of the effects and differences of multiple crop sequences and combinations.

Ciais et al. (2011) reviewed the C balances of African ecosystems and reported a need for more observations of C fluxes and stocks, recommending a network of EC flux towers for agroecosystems as well as other terrestrial ecosystems. Few micrometeorological studies have measured CO_2 flux over agriculture in Africa and most experiment durations have lasted less than a year. Chapter 3 provides close to 3 years of data to address the need for more observations of C fluxes in Africa.

Research Goals

The goal of the research described in this dissertation was to further understand agriculture's potential to sequester C in climate change mitigation. Using micrometeorological instrumentation, this research measured CO_2 flux in real time over contrasting agricultural management practices to quantify the role of soil, climate, and management factors that contribute to C sequestration and CO_2 emissions from agriculture. This research measured and analyzed CO_2 flux of agricultural management practices including tillage, biomass application, fallow periods, cover crops, and crop type to provide data on the potential of these practices to sequester soil C or at a minimum to reduce CO_2 emissions to address climate change. This research included the setup of BREB and EC micrometeorological instrumentation in Ohio, Tennessee and Zimbabwe, and the collection and analysis of data to determine the NEE over contrasting agricultural practices.

Dissertation Organization

Chapter 1 summarizes a four-month study comparing contrasting tillage practices on CO_2 flux over maize (*Zea mays* L.) after tilling a long-term no-till field as compared with a no-till plot using BREB micrometeorology during the 2015 growing season in Ohio.

Chapter 2 describes the measurement of CO_2 flux between October 2016 to October 2017 over no-till maize with application of DuPont 1,3-Propanediol (PDO) manufacturing residue as compared to a conventional fertilizer management. This on-farm research used both BREB and EC micrometeorological instruments in East Tennessee.

In Chapter 3, BREB micrometeorology elucidated differences between CA and conventional tillage practices over 35 months in Zimbabwe, beginning in June 2013 through May of 2016. A sequence of agricultural management practices were measured over four plots.

Terms Used in this Dissertation

Note that this research is multidisciplinary, including the disciplines of soil science, micrometeorology, agronomy and including concepts from the biogeochemical C cycle to industrial biotechnology. Many terms will be defined as they are introduced, however there is also a glossary immediately preceding this introduction on page xi, that defines many of the terms associated with soil science and micrometeorology.

References

Alexander, P., Paustian, K., Smith, P. and Moran, D. (2015) 'The economics of soil c sequestration and agricultural emissions abatement', *Soil*, 1(1), pp. 331–339. doi: 10.5194/soil-1-331-2015.

Alfieri, J. G., Blanken, P. D., Smith, D. and Morgan, J. (2009) 'Concerning the measurement and magnitude of heat, water vapor, and carbon dioxide exchange from a semiarid grassland', *Journal of Applied Meteorology and Climatology*, 48(5), pp. 982–996. doi: 10.1175/2008JAMC1873.1.

Angers, D. A. and Eriksen-Hamel, N. S. (2008) 'Full-Inversion Tillage and Organic Carbon Distribution in Soil Profiles: A Meta-Analysis', *Soil Science Society of America Journal*, 72(5), p. 1370. doi: 10.2136/sssaj2007.0342.

Baker, J. M., Ochsner, T. E., Venterea, R. T. and Griffis, T. J. (2007) 'Tillage and soil carbon sequestration-What do we really know?', *Agriculture, Ecosystems and Environment*, 118(1–4), pp. 1–5. doi: 10.1016/j.agee.2006.05.014.

Baldocchi, D. (2014) 'Measuring fluxes of trace gases and energy between ecosystems and the atmosphere - the state and future of the eddy covariance method', *Global Change Biology*, 20(12), pp. 3600–3609. doi: 10.1111/gcb.12649.

Bowen, I. S. (1926) 'The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface', *Physical review*, 27(6), pp. 779–787. doi: https://doi.org/10.1103/PhysRev.27.779.

Brotzge, J. A. and Crawford, K. C. (2003) 'Examination of the Surface Energy Budget: A Comparison of Eddy Correlation and Bowen Ratio Measurement Systems', *Journal of Hydrometeorology*, 4(2), pp. 160–178. doi: 10.1175/1525-7541(2003)4<160:EOTSEB>2.0.CO;2.

Caldeira, K., Granger Morgan, M., Baldocchi, D., Brewer, P. G., Chen, C. T. A., Nabuurs, G. J., Nakicenovic, N. and Robertson, G. P. (2004) 'A Portfolio of Carbon Management Options', in Field, C. B. and Raupach, M. R. (eds) *The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World*, pp. 103–129. doi: 10.1243/09544119JEIM691.

Chapin, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., Clark, D. A., Harmon, M. E., Schimel, D. S., Valentini, R., Wirth, C., Aber, J. D., Cole, J. J., Goulden, M. L., Harden, J. W., Heimann, M., Howarth, R. W., Matson, P. A., McGuire, A. D., Melillo, J. M., Mooney, H. A., Neff, J. C., Houghton, R. A., Pace, M. L., Ryan, M. G., Running, S. W., Sala, O. E., Schlesinger, W. H. and Schulze, E. D. (2006) 'Reconciling carbon-cycle concepts, terminology, and methods', *Ecosystems*, 9(7), pp. 1041–1050. doi: 10.1007/s10021-005-0105-7.

Chu, H., Baldocchi, D. D., John, R., Wolf, S. and Reichstein, M. (2017) 'Fluxes all of the time? A primer on the temporal representativeness of FLUXNET', *Journal of Geophysical Research: Biogeosciences*, 122(2), pp. 289–307. doi: 10.1002/2016JG003576.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Quéré, C. Le, Myneni, R. B., Piao, S. and Thornton, P. (2013) 'Carbon and Other Biogeochemical Cycles', in Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. P. and P. T. (ed.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press, pp. 465–570. doi: 10.1017/CBO9781107415324.015.

Clarke, L. E., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., van der Zwaan, B. C. C. and van Vuuren, D. P. (2014) 'Assessing transformation pathways', *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 413–510. doi: DOI: 10.1017/CBO9781107415416.012.

Cook, J., Nuccitelli, D., Green, S. A., Richardson, M., Winkler, B., Painting, R., Way, R., Jacobs, P. and Skuce, A. (2013) 'Quantifying the consensus on anthropogenic global warming in the scientific literature', *Environmental Research Letters*, 8(2), p. 7. doi: 10.1088/1748-9326/11/4/048001.

Craine, J. M. and Wedin, D. A. (2002) 'Determinants of growing season soil CO 2 flux in a Minnesota grassland', *Biogeochemistry*, 59, pp. 303–313.

Davidson, E. A., Savage, K., Verchot, L. V. and Navarro, R. (2002) 'Minimizing artifacts and biases in chamber-based measurements of soil respiration', *Agricultural and Forest Meteorology*, 113(8), pp. 21–37. doi: 10.1016/s0168-1923(02)00100-4.

Denef, K., Archibeque, S. and Paustian, K. (2011) *Greenhouse Gas Emissions from U. S. Agriculture and Forestry: A Review of Emission Sources, Controlling Factors, and Mitigation Potential, Interim report to USDA under Contract #GS23F8182H*.

Derpsch, R., Friedrich, T., Kassam, A. and Hongwen, L. (2010) 'Current status of adoption of no-till farming in the world and some of its main benefits', *International Journal of Agricultural and Biological Engineering*, 3(1), pp. 1–25. doi: 10.3965/j.issn.1934-6344.2010.01.001-025.

Dugas, W. A. (1993) 'Micrometeorological and chamber measurements of CO2 flux from bare soil', *Agricultural and Forest Meteorology*, 67(1–2), pp. 115–128. doi: 10.1016/0168-1923(93)90053-K.

Etheridge, D. M., Steele, L. P., Langenfelds, R. L., Francey, R. J., Barnola, J. M. and Morgan, V. I. (1996) 'Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn', *Journal of Geophysical Research*, 101(D2), pp. 4115–4128. doi: https://doi.org/10.1029/95jd03410.

FAO (2009) *Enabling agriculture to contribute to climate change mitigation, Current*. Available at: https://unfccc.int/resource/docs/2008/smsn/igo/036.pdf.

FAO (2019) *Conservation Agriculture principles*. Available at: http://www.fao.org/conservation-agriculture/overview/principles-of-ca/en/ (Accessed: 25 January 2019).

Follett, R., Mooney, S., Morgan, J., Paustian, K., Allen Jr, L. H., Archibeque, S., Baker, J. M., Del Grosso, S. J., Derner, J., Dijkstra, F. and Franzluebbers, A. J. (2011) *Carbon sequestration and greenhouse gas fluxes in agriculture: challenges and opportunities*. Council for Agricultural Science and Technology (CAST).

Gilmanov, T. G., Morgan, J. A., Hanan, N. P., Wylie, B. K., Rajan, N., Smith, D. P. and Howard, D. M. (2017) 'Productivity and CO2 Exchange of Great Plains Ecoregions. I. Shortgrass Steppe: Flux Tower Estimates', *Rangeland Ecology and Management*. The Authors, 70(6), pp. 700–717. doi: 10.1016/j.rama.2017.06.007.

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K. D., Dixon, J. and Dendooven, L. (2009) 'Conservation agriculture and soil carbon sequestration: Between myth and farmer reality', *Critical Reviews in Plant Sciences*, 28(3), pp. 97–122. doi: 10.1080/07352680902776358.

Gregorich, E. G., Rochette, P., VandenBygaart, A. J. and Angers, D. A. (2005) 'Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada', *Soil and Tillage Research*, 83(1 SPEC. ISS.), pp. 53–72. doi: 10.1016/j.still.2005.02.009.

Guntiñas, M. E., Gil-Sotres, F., Leiros, M. C. and Trasar-Cepeda, C. (2013) 'Sensitivity of soil respiration to moisture and temperature', *Journal of Soil Science and Plant Nutrition*, 13(2), pp. 445–461. doi: 10.4067/S0718-95162013005000035.

Halvorson, A. D., Wienhold, B. J. and Black, A. L. (2002) 'Tillage, Nitrogen, and Cropping System Effects on Soil Carbon Sequestration', *Soil Science Society of America Journal*, 66(3), pp. 906–912. doi: 10.2136/sssaj2002.0906.

Hermle, S., Anken, T., Leifeld, J. and Weisskopf, P. (2008) 'The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions', *Soil and Tillage Research*, 98(1), pp. 94–105. doi: 10.1016/j.still.2007.10.010.

Hobbs, P. R. (2007) 'Paper Presented at International Workshop on Increasing Wheat Yield Potential, CIMMYT, Obregon, Mexico, 20-24 March 2006: Conservation agriculture: What is it and why is it important for future sustainable food production?', *Journal of Agricultural Science*, 145(2), pp. 127–137. doi: 10.1017/S0021859607006892.

Hobbs, P. R., Sayre, K. and Gupta, R. (2008) 'The role of conservation agriculture in sustainable agriculture', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491), pp. 543–555. doi: 10.1098/rstb.2007.2169.

Houghton, R. A. (2003) ‘Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850 – 2000’, *Tellus Series B – Chemical and Physical Meteorology*, 55, pp. 378–390. doi: https://doi.org/10.1034/j.1600-0889.2003.01450.x.

Houghton, R. A. (2007) ‘Balancing the Global Carbon Budget’, *Annual Review of Earth and Planetary Sciences*, 35(1), pp. 313–347. doi: 10.1146/annurev.earth.35.031306.140057.

Hungate, B. A., Jackson, R. B., Field, C. B. and Chapin III, F. S. (1996) ‘Detecting changes in soil carbon in CO2 enrichment experiments’, *Plan and Soil*, 187(2), pp. 135–145. doi: 10.1007/BF00017086.

IPCC-SR15 (2018) ‘IPCC, 2018: Summary for Policymakers.’, in Masson-Delmotte, V. Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C. Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (ed.) *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. Geneva, Switzerland, p. 32. Available at: http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf.

IPCC (2013a) ‘Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change’, in Stocker, T. ., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (eds) *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press, p. 1535. doi: 10.1017/cbo9781107415324.

IPCC (2013b) ‘Technical Summary. 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change’, in Stocker, T. F., Dahe, Q., Plattner, G.-K., Alexander, L. V., Allen, S. K., Bindoff, N. L., Bréon, F.-M., Church, J. A., Cubash, U., Emori, S., Forster, P., Friedlingstein, P., Talley, L. D., Vaughan, D. G., and Xie, S.-P. (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 33–115. doi: 10.1017/ CBO9781107415324.005.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), is published under the title Climate Change 2014.* Geneva, Switzerland. Available at: https://www.ipcc.ch/report/ar5/syr/.

IPCC (2018) *GLOBAL WARMING OF 1 . 5°C an IPCC special report Summary for Policymakers*. Available at: http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf.

Irmak, S., Skaggs, K. E. and Chatterjee, S. (2014) ‘A Review of the Bowen Ratio Surface Energy Balance Method for Quantifying Evapotranspiration and other Energy Fluxes’, *Transactions of the ASABE*, 57(6), pp. 1657–1674. doi: 10.13031/trans.57.10686.

Ismail, I., Blevins, R. L. and Frye, W. W. (1994) 'Long-Term No-tillage Effects on Soil Properties and Continuous Corn Yields', *Soil Science Society of America Journal*, 58(1), p. 193. doi: 10.2136/sssaj1994.03615995005800010028x.

Kanemasu, E. T., Wesely, M. L., Hicks, B. B. and Heilman, J. L. (1979) 'Techniques for calculating energy and mass fluxes', in Barfield, B. J. and Gerber, J. F. (eds) *Modification of the aerial environment of plants*. St. Joseph: American Society of Agricultural Engineers, pp. 156–182.

Kern, J. S. and Johnson, M. G. (1993) 'Conservation Tillage Impacts on National Soil and Atmospheric Carbon Levels', *Soil Science Society of America Journal*, 57(1), p. 200. doi: 10.2136/sssaj1993.03615995005700010036x.

Kirschbaum, M. U. F. (1995) 'The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage', *Soil Biology and Biochemistry*, 27(6), pp. 753–760. doi: 10.1016/0038-0717(94)00242-s.

Lal, R. (2004) 'Soil carbon sequestration impacts on global climate change and food security', *Science*, 304(5677), pp. 1623–1627. doi: 10.1126/science.1097396.

Lal, R. (2008) 'Carbon sequestration', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), pp. 815–830. doi: 10.1098/rstb.2007.2185.

Manley, J., Van Kooten, G. C., Moeltner, K. and Johnson, D. W. (2005) 'Creating carbon offsets in agriculture through no-till cultivation: A meta-analysis of costs and carbon benefits', *Climatic Change*, 68(1–2), pp. 41–65. doi: 10.1007/s10584-005-6010-4.

Necpálová, M., Anex, R. P., Kravchenko, A. N., Abendroth, L. J., Grosso, S. J. Del and Dick, W. A. (2014) 'What does it take to detect a change in soil carbon stock ? A regional comparison of minimum detectable difference and experiment duration in the north central United States', 69(6), pp. 517–531. doi: 10.2489/jswc.69.6.517.

NOAA (2019) *National Oceanic and Atmospheric Administration Earth System Research Laboratory Global Monitoring Division*. Available at: https://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html (Accessed: 1 January 2019).

Ogle, S. M., Breidt, F. J. and Paustian, K. (2005) 'Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions', *Biogeochemistry*, 72(1), pp. 87–121. doi: 10.1007/s10533-004-0360-2.

Pankhurst, C. E., Kirkby, C. A., Hawke, B. G. and Harch, B. D. (2002) 'Impact of a change in tillage and crop residue management practice on soil chemical and microbiological properties in a cereal-producing red duplex soil in NSW, Australia', *Biology and Fertility of Soils*, 35(3), pp. 189–196. doi: 10.1007/s00374-002-0459-3.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotiyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E. and Stievenard, M. (1999) 'Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica', *Nature*, 399(6735), pp. 429–436. doi: 10.1038/20859.

Poeplau, C. and Don, A. (2015) 'Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis', *Agriculture, Ecosystems and Environment*. Elsevier B.V., 200, pp. 33–41. doi: 10.1016/j.agee.2014.10.024.

Porter, J. R., Howden, M. and Smith, P. (2017) 'Considering agriculture in IPCC assessments', *Nature Climate Change*. Nature Publishing Group, 7(10), pp. 680–683. doi: 10.1038/nclimate3404.

Powlson, D. S., Whitmore, A. P. and Goulding, K. W. T. (2011) 'Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false', *European Journal of Soil Science*, 62(1), pp. 42–55. doi: 10.1111/j.1365-2389.2010.01342.x.

Rosenberg, N. J., Blad, B. L. and Verma, S. B. (1983) *Microclimate: The Biological Environment*. New York: John Wiley & Sons.

Sabine, C. L. (2004) 'The Oceanic Sink for Anthropogenic CO2', *Science*, 305(5682), pp. 367–371. doi: 10.1126/science.1097403.

Schlesinger, W. H. (1995) 'An overview of the C cycle', in Lal, R., Kimble, J., and Stewart, B. A. (eds) *Soils and Global Change*. Boca Raton: Lewis Publishers, pp. 9–26.

Schlesinger, W. W. H. and Andrews, J. (2000) 'Soil respiration and the global carbon cycle', *Biogeochemistry*, 48(1), pp. 7–20. doi: 10.1023/A:1006247623877.

Seneviratne, S. I., Donat, M. G., Mueller, B. and Alexander, L. V (2014) 'No pause in the increase of hot temperature extremes', *Nature Climate Change*, 4(March), pp. 161–164.

Shi, T. T., Guan, D. X., Wu, J. B., Wang, A. Z., Jin, C. J. and Han, S. J. (2008) 'Comparison of methods for estimating evapotranspiration rate of dry forest canopy: Eddy covariance, Bowen ratio energy balance, and Penman-Monteith equation', *Journal of Geophysical Research Atmospheres*, 113(19), pp. 1–15. doi: 10.1029/2008JD010174.

Skinner, R. H. and Wagner-Riddle, C. (2012) *Micrometeorological Methods for Assessing Greenhouse Gas Flux, Managing Agricultural Greenhouse Gases*. Elsevier Inc. doi: 10.1016/B978-0-12-386897-8.00021-8.

Smith, P. (2004) 'How long before a change in soil organic carbon can be detected?', *Global Change Biology*, 10(11), pp. 1878–1883. doi: 10.1111/j.1365-2486.2004.00854.x.

Smith, P. (2005) 'An overview of the permanence of soil organic carbon stocks: Influence of direct human-induced, indirect and natural effects', *European Journal of Soil Science*, 56(5), pp. 673–680. doi: 10.1111/j.1365-2389.2005.00708.x.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C. W., Abad, C. R., Romanovskaya, A., Sperling, F. and Tubiello, F. (2014) *Agriculture, forestry and other land use (AFOLU), In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA. doi: 10.1104/pp.900074.

Sundquist, E. T. (1986) ‘Geologic analogs: their value and limitations in carbon dioxide research’, in Trabalka, J. R. and Reichle, D. E. (eds) *The changing carbon cycle*. New York: Springer, pp. 371–402.

Sverdrup, H. U. (1943) ‘On the Ratio Between Heat Conduction From the Sea Surface and Heat Used for Evaporation’, *Annals of the New York Academy of Sciences*, 44(1), pp. 81–88. doi: 10.1111/j.1749-6632.1943.tb31294.x.

Tian, G., Granato, T. C., Cox, A. E., Pietz, R. I., Carlson, C. R. and Abedin, Z. (2009) ‘Soil Carbon Sequestration Resulting from Long-Term Application of Biosolids for Land Reclamation’, *Journal of Environment Quality*, 38(1), p. 61. doi: 10.2134/jeq2007.0471.

UNEP (1992) *Convention on Biological Diversity*. Nairobi. Available at: https://www.cbd.int/convention/text/.

UNFCCC (2015) *Convention on Climate Change: Climate Agreement of Paris.* Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (Accessed: 21 January 2019).

UNFCCC (2019) *Land Use, Land-Use Change and Forestry*. Available at: https://unfccc.int/topics/land-use/workstreams/land-use--land-use-change-and-forestry-lulucf/land-use--land-use-change-and-forestry (Accessed: 24 January 2019).

USEPA (2017) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015 Executive Summary*. Available at: https://www.epa.gov/sites/production/files/2017-02/documents/2017_executive_summary.pdf (Accessed: 1 February 2019).

VandenBygaart, A. J., Gregorich, E. G. and Angers, D. A. (2003) ‘Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies’, *Canadian Journal of Soil Science*, 83(4), pp. 363–380. doi: 10.4141/S03-009.

Vanomark, G. M. M. de S., Sobrinho, J. E., Bezerra, J. R. C., dos Santos, C. A. C., de Azevedo, P. V., da Silva, S. T. A. and Bezerra, B. G. (2018) ‘Energy balance partitioning and evapotranspiration from irrigated muskmelon under semi-arid conditions’, *Bragantia*, 77(1), pp. 168–180. doi: 10.1590/1678-4499.2016453.

Vermeulen, S. J., Campbell, B. M. and Ingram, J. S. (2012) ‘Climate Change and Food Systems’, *Annu. Rev. Environ. Resour.*, 37, pp. 195–222. doi: 10.1146/annurev-environ-020411-130608.

Wanninkhof, R., Park, G.-H., Takahashi, T., Sweeney, C., Feely, R., Nojiri, Y., Gruber, N., Doney, S. C., McKinley, G. A., Lenton, A., Le Quéré, C., Heinze, C., Schwinger, J., Graven,

H. and Khatiwala, S. (2013) ‘Global ocean carbon uptake: magnitude , variability and trends’, *Biogeosciences*, 10, pp. 1983–2000. doi: 10.5194/bg-10-1983-2013.

Webb, E. K., Pearman, G. I. and Leuning, R. (1980) ‘Correction of flux measurements for density effects due to heat and water vapour transfer’, *Q. J. Roy. Meteorol. Soc.*, 106(447), pp. 85–100. doi: http://dx.doi.org/10.1002/qj.49710644707.

West, T. O. and Post, W. M. (2002) ‘Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation : A Global Data Analysis’, *Soil Science Society of America Journal*, 66, pp. 1930–1946.

CHAPTER 1

REDUCING CO_2 FLUX BY DECREASING TILLAGE IN OHIO:

OVERCOMING CONJECTURE WITH DATA

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Abstract

While the literature is clear about excessive tillage decreasing soil carbon (C) content, there are few experimental studies that document the comparative effects of soil and crop management on C sequestration. Using micrometeorology we measured CO_2 flux from a maize crop grown on both no-till and tilled soils in north-central Ohio. We used Bowen Ratio Energy Balance (BREB) systems to quantify the flux between the atmosphere and either the soil surface (at crop planting) or 0.2 m above the canopy once the crop was established and growing. The no-

till plot sequestered 263 g CO_2 m^{-2} (90% confidence interval -432.1 to -99.9) while the tilled plot emitted 146 g CO_2 m^{-2} (90% confidence interval -53.3 to 332.2) during 104 days of the 2015 growing season; a net difference of 410 g CO_2 m^{-2}. The difference is statistically significant at the 90% confidence level (based on a bootstrap analysis). The results indicate that no-tillage practices can sequester C, maintain soil productivity, and ensure landscape sustainability.

Introduction

The principal sinks for removing CO_2 from the atmosphere are usually assumed to be oceans and forests; however, oceans will absorb less CO_2 as they warm (Morrison et al., 2015) and forest area is shrinking due to agriculture and other land use changes (FAO, 2016). It has been shown that soil could be a strong sink for atmospheric CO_2 (Paustian et al., 2016), partially offsetting increasing global greenhouse gas (GHG) emissions (Tubiello et al., 2015; EPA, 2014; Scripps Institution of Oceanography, 2016). Jenny's (1941) classic work provides the basis for the collective understanding of the processes by which soils emit and sequester C through soil-climate-vegetation interactions. These processes depend on many factors including soil type, climate, crop, and agricultural management practices.

While agriculture is a major contributor to increases in GHG emissions, careful implementation of agricultural practices to enhance C sequestration presents an opportunity to manage soils to mitigate climate change. In particular, the practice of reduced tillage, especially no-till, has been found to reduce CO_2 emissions from soils and potentially sequester C (Schlesinger, 1999; West and Post, 2002; O'Dell et al., 2014). Studies suggest that tillage can influence plant physiology including increased rooting depth from decreased moisture in surface layers of tilled soil (Dwyer et al., 1996) or decreased mechanical resistance (Cox et al., 1990).

Other studies indicate that tillage effects on plant physiology may interact with climate as Yu et al. (2016) found that no-till likely increased yield during drought periods by conserving soil moisture. Since arable land represents more than 10% of the global land base (FAO, 2011), arable soils could provide a C sink to offset fossil fuel emissions (Paustian et al., 2016; Lal, 2004).

Recent literature provides a conflicting story of the potential impact of different agricultural practices on soil C. While West and Post (2002) found significant increases in soil organic C (SOC) in the top 7-cm of soil in no-till practices compared to tillage across 67 long-term studies, Vanden Bygaart et al. (2003) and Angers et al. (1997) did not find any differences between no-till and conventional tillage when sampling to a deeper soil depth. Vanden Bygaart and Angers (2006) note the obstacles in comparing measured SOC values due to differences in equivalent soil sampling depth, bulk density, landscape, climate, soil type and experiment duration. Another confounding factor is the lack of a standardized description of tillage, and the variety of related practices used in many research reports. Measurement difficulties also complicate the issue—changes in soil C can take up to a decade to detect if trends are measured using destructive sampling (Smith, 2004). Recently, several publications have been critical of conservation agriculture and no-till because some studies concluded that no-till does not increase C sequestration or increase crop yields (Baudron et al., 2012) especially in low yield environs common in Sub-Saharan Africa (Cheesman et al., 2016). However, these results are not surprising; it is hypothetically difficult to increase SOC without substantial plant biomass.

Some older research papers and textbooks provide examples of results obtained in the USA showing that tilling enhances CO_2 emissions (e.g., Reicosky et al., 1995; Bear, 1953; West and Marland, 2002). Similarly, recent work found greater C sequestration with no-till during the crop growing season using BREB in Lesotho and greater no-till sequestration when comparing fallow treatments with cover crops in Zimbabwe (O'Dell et al., 2014; O'Dell et al., 2015). Baker and Griffis (2005) compared the net ecosystem exchange (NEE) of contrasting tillage regimes and cover crops in a maize (*Zea mays* L.)-soybean (*Glycine max* L.) rotation using eddy covariance (EC) but found no significant differences in the NEE of strip tillage with a cover crop compared to conventional tillage with no cover crop. Hollinger et al. (2005) reported that maize sequestered C, while soybean emitted C during two years of a six-year maize-soybean rotation EC study. Using EC, Taylor et al. (2013) found that oat (*Avena sativa* L.) crops grown on fields converted from perennial hay/pasture were net emitters for more than three years while a control hay/pasture field sequestered C.

Many researchers rely on SOC changes by soil depth as the means to determine if C is accumulated. Yet, without accurate surveying measurements from the bedrock to the soil surface, any total SOC estimates will be incomplete and the resulting determinations of changes in accumulated C will be questionable. An obvious example could be the subsidence post measuring soil depth from the bedrock at the Everglades Agricultural Area in Belle Glade, FL where oxidation of SOC in a histosol profile has resulted in dramatic soil loss as evidenced by the subsidence post markings (Stephens and Johnson, 1951; Shih et al., 1998).

Micrometeorological methods including BREB systems and EC provide alternative methodologies for investigating changes in crop and soil carbon inventories. These methods have been used to quantify the differences in CO_2 flux between agricultural practices (Dugas et al., 1993; Taylor et al., 2013; O'Dell et al., 2015). The exchange (flux) of CO_2 between the surface and the atmosphere can alternatively be measured using static or dynamic chambers. Chamber systems have spatial and temporal challenges somewhat similar to soil sampling (Norman et al., 1997; Davidson et al., 2002; Reicosky, 1997; Reicosky and Lindstrom, 1995), and are therefore less frequently used in contemporary studies. While the EC and BREB approaches are technically demanding, we believe them to be the optimal approach to evaluate how soil C sequestration can be manipulated to intensify management impacts. EC and BREB systems measure the flux of CO_2 between the atmosphere and the terrestrial system and by summing this flux, the NEE can be determined for a type of ecosystem over a period of time (Chapin et al., 2006). For the purposes of this paper, the term sequestration is used to reflect the capture of atmospheric CO_2 by the ecosystem or treatment, e.g., through photosynthesis, while CO_2 emissions refers to a release of CO_2 by the ecosystem to the atmosphere, such as through respiration. While the ecosystem includes soil, organic matter, plants and other biota, the NEE does not distinguish between the components of the ecosystem. The objective of the present study was to determine tillage effects on CO_2 emissions during the maize growing season using the BREB methodology.

Materials and Methods

Site Description

This study site was in north-central Ohio, USA (40.606° N, -82.674° W, 426 m asl). Micrometeorological and soil properties were measured from 6 May to 17 August 2015. The soil series on the 9-ha research site are classified as: Bennington (fine, illitic, mesic Aeric Epiaqualfs), Amanda (fine-loamy, mixed, active, mesic Typic Hapludalfs), Centerburg (fine-loamy, mixed, active, mesic Aquic Hapludalfs), and Condit (fine, illitic, mesic Typic Epiaqualfs) in USDA Soil Taxonomy (USDA Soil Survey Staff, 1999). The surface soil texture is a silt loam and the study site has a slope of 2-6%. The climate is classified as humid continental (Dfb) according to Köppen climate classification, with mean annual rainfall of 955 mm. The study site was managed as an annual row crop production system under no-till for seven years prior to the present study. The prior year's crop was maize.

The study site consisted of two adjacent square plots approximately 4.5 ha each; one plot managed as no-till and the other tilled. A BREB micrometeorological station was erected near the center of each plot. On the no-till plot, maize was planted directly without any tillage except for opening the seed slot (row cleaners were removed). The tilled plot was tandem disked (to manage crop residues), moldboard plowed to a depth of 15 cm, then tandem disked again followed by planting.

Both plots were planted with maize (*Zea mays* L.) on 8-10 May 2015 at a population density of 84,000 plants ha-1 using 0.76-m rows using a John Deere 7200 6-row Conservation planter. Nitrogen (N) fertilizer was applied to both plots on 3 June 2015 as granular urea (46-0-0) at the rate of 224 kg N ha-1, phosphorus (P) was applied as triple super phosphate (0-45-0) at 112 kg P ha-1 and potassium (K) was applied as potash (0-0-60) at 112 kg K ha-1 prior to planting.

Micrometeorological Measurements and Data Analysis

Air temperature, vapor pressure and CO_2 concentrations were measured before and after planting by the BREB systems, at 0.2- and 1.8-m height above the soil or canopy (note: the BREB units were raised incrementally as the maize crop grew, see below). The BREB units had shielded horizontal air intake tubes facing the direction of prevailing winds (west). Temperature was measured with negative temperature coefficient bead type thermistors, vapor pressure was measured with relative humidity probes (model HC2-S3-L, Rotronic, Switzerland supplied by Campbell Scientific, Inc, Logan, UT) and CO_2 concentrations were measured with non-dispersive infrared gas analyzers (model LI-820, LI-COR Inc., Lincoln, NE). Five-second sensor data were averaged and recorded every five minutes using a data logger (Model CR3000, Campbell Scientific Inc.). To overcome sensor bias at the two heights, the intake tubes housing the sensors were attached at the end of a centrally mounted rotating arm that swapped the position of the atmospheric sensors every five minutes. To allow for equilibration after sensor rotation, the data logger waited two minutes before collecting 5-s readings in estimating the 5-min average from three minutes of data. As the crop grew, the BREB temperature, humidity and CO_2 sensors were elevated so that the lowest sensor remained about 0.2 m above the crop canopy, with the height differential (1.6 m) between sensor intake points remaining constant.

The BREB stations also measured net radiation, soil heat flux, soil temperature, and wind speed. Net radiation was measured with a net radiometer (NR Lite2, Kipp and Zonen, Delft, The Netherlands), soil heat flux with soil heat flux plates (model HFT3-L, Radiation Energy Balance System (REBS), Seattle, WA) and soil temperatures with four Type "T" thermocouples, two buried at 1.5 cm and two at 4.5 cm below the surface. Volumetric soil moisture content was measured 3 cm below the surface with a water content reflectometer (model CS616, Campbell Scientific, Inc, Logan, UT). Wind direction and speed were measured at the till BREB station with a mechanical wind sensor (Model 05305-5, R. M. Young, Inc. Traverse City, MI), and wind speed was measured at the no-till BREB station with a 3-cup anemometer (model 014A, Met One Instruments, Inc., Grants Pass, OR). Rainfall was measured at the no-till BREB station with a tipping bucket rain gauge (model TE525, Texas Electronics, Dallas, TX). Atmospheric pressure was recorded with one silicon altimeter/barometer pressure sensor (model MPX4115, Freescale Semiconductor, Inc., Tempe, AZ). All sensors except thermistors and thermocouples were new and factory-calibrated. Thermistors were created and calibrated in the laboratory; thermocouples were created and calibrated in the field.

Five-second micrometeorological measurements were averaged to calculate 30-min CO_2 fluxes according to BREB system theory (Bowen, 1926; Kanemasu et al., 1979; Webb et al., 1980; Held et al., 1990; McGinn and King, 1990; Dugas, 1993; Perez et al., 1999; Rosenberg et al., 1983) using the following equations as reported by O'Dell et al. (2015). Values of the Bowen ratio (β) were derived as:

$$\beta = [P \times C_P(\Theta_L - \Theta_U)]/[\lambda \times \varepsilon \, (e_L - e_U)] \tag{1}$$

where, P is measured atmospheric pressure, C_P the specific heat capacity of air, Θ_L and Θ_U are the potential temperatures calculated from air temperatures measured at lower and upper positions, λ the latent heat of vaporization of water, ε the ratio of the molecular weights of air and water, and e_L and e_U are the vapor pressures at lower and upper positions.

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

$$LE = (R_n - G_0)/(1 + \beta) \tag{2}$$

where, R_n is the measured net radiation and G_0 is the soil heat flux at the soil surface. The correction of soil heat flux for heat storage above the depth of the soil heat flux measurement, ΔS, where, $G_0 = G_{0.06m} + \Delta S$ was calculated as:

$$\Delta S = C\,(\Delta T/\Delta t)\,z \tag{3}$$

where, ΔS is the change in heat storage above the soil heat flux plate, C the volumetric heat capacity of the soil, ΔT the change in temperature (current minus previous) of the soil above the heat flux plate taken from average soil temperature measurements at 1.5 and 4.5 cm depths,

Δt is the time step (s), z is the depth of the soil heat flux plate (6 cm). C was calculated (de Vries, 1963) as:

$$C = C_m\,(1 - \phi_f) + C_w \times \theta \quad (4)$$

where, the volumetric heat capacity for dry soil is C_m (2.35 MJ m^{-3} K^{-1} (Ochsner et al., 2001) the volumetric heat capacity of water is C_w (4.18 MJ m^{-3} K^{-1}), and soil volumetric water content, θ was based on measurements from soil moisture sensors in both the tilled and untilled plots. Soil porosity, ϕ_f, was calculated as:

$$\phi_f = 1 - (\rho_b/\rho_s) \quad (5)$$

where, ρ_b is soil bulk density, measured at 1.31 and 1.5 Mg m^{-3} for the till and no-till plots respectively. Soil particle density, ρ_s, was assumed to be 2.65 Mg m^{-3}.

In practice, two additional terms enter into consideration in the surface energy budget: (a) the storage of heat in the canopy biomass and its water content and (b) the energy used in photosynthesis. Meyers and Hollinger (2004) report a combined influence on the surface energy budget comprising about 15% of the net radiation for a fully developed maize canopy in daytime. For the Ohio study reported here, canopy biomass was estimated from yield and the harvest index factor for rainfed maize (Djaman et al., 2013). Heat storage in the canopy at the final stage of plant growth at the end of the experiment was found to rarely exceed 1% of net radiation. The photosynthetic energy used was also estimated to be small, and hence both terms have been omitted from the simple surface energy budget on which the analysis to follow rests. Sensible heat flux, H (W m^{-2}) was calculated as:

$$H = R_n - G_0 - LE \quad (6)$$

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

$$K_h = (H/\rho_b C_p) \times (\Delta z/\Delta\Theta) \quad (7)$$

where, $\rho_b C_p$ is the volumetric heat capacity for air, Δz is the sensor separation distance (1.6 m).

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

$$A = K_c\ (\Delta\rho_c/\Delta z) \qquad (8)$$

where, K_c is the turbulent diffusivity for CO_2 (m^2 s^{-1}), assumed to be equal to the turbulent diffusivity for sensible heat, and $\Delta\rho_c$ is the average difference in CO_2 density between measurement heights.

The CO_2 flux was corrected for temperature and vapor density differences in terms of latent and sensible heat flux using the following equation (Webb et al., 1980):

$$A_{corr} = A + (\rho_c/\rho_a) \times (0.649 \times 10^{-6} \times LE + 3.358 \times 10^{-6} \times H) \qquad (9)$$

where, A_{corr} and A are in kg m^{-2} s^{-1}, ρ_c is the average CO_2 density at both measurement heights, ρ_a is the density of dry air. In practice, the correction is sufficiently small that its consequences are within the error bounds associated with the measurements.

As expressed above, the purpose of the study was to explore the role of tillage within the context of CO_2 emissions and/or sequestration. In view of the experimental complexity, we limited the study to the crop growth period. Sensor data recording began on 6 May 2015 (before seedling emergence) and extended to 17 August 2015 (crop senescence); therefore the 104-day experimental period encompassed the entire period of crop growth. The sign conventions used in this analysis follow standard micrometeorological practice wherein CO_2 flux is positive when CO_2 is emitted from the surface and negative when sequestered/absorbed. Data recorded while rain was falling or when sensor failures resulted in incomplete datasets were omitted.

Flux calculations during the night and transition periods (sunrise and sunset, when temperature differences were close to zero) are problematic, resulting in many periods of large uncertainty that produced spikes in calculations of CO_2 flux, as also reported elsewhere (e.g., Gilmanov et al., 2003; Massman and Lee, 2002; Aubinet, 2008; Savage et al., 2009). We utilized an algorithm to remove data spikes in the half-hour CO_2 flux data using a median filter similar to that used with eddy covariance data (Papale et al., 2006). The strength in this approach lies with the median's resistance to local outliers. While a median filter can distort the flux signal, it is possible to adjust the window width and threshold value as a means to tune the median filter and limit this distortion. This limitation is solved with the use of a median filter extension called the Hampel identifier (Davies and Gather, 1993; Hampel, 1985). This filter depends on both the window width and an additional tuning parameter: a threshold. If the threshold value is reduced to zero, the Hampel identifier functions as a typical median filter, and if the threshold approaches infinity the filter effectively becomes an identity filter (Pearson, 1999). The parameters of the Hampel identifier for the two datasets were tuned by trial and error to best exclude outliers. The half width window was chosen to be 5 data points meaning that the window was in total 2.5 hours (five 30-min data points). The threshold value was chosen as 5. Spikes remaining after the application of the median filter may be a reflection of atmospheric phenomenon or artifacts of the BREB method, especially during night and transition periods.

Once the data spikes were identified they were removed and the data gaps were linearly interpolated. The maximum range of removed and/or missing values interpolated was limited to two hours or less (four 30-min data points). "Absent data" for periods longer than two hours were not interpolated. For consistent comparison, the total sum of CO_2 flux was calculated for the period when flux data was available for both till and no-till instruments.

A non-parametric bootstrap procedure (Efron, 1979) was used to determine the variance around the time evolving accumulation of CO_2, as described in O'Dell et al. (2015) and was performed with Stata version 14.1 (Stata Corporation, College Station, Texas, USA).

Results and Discussion

Figure 1.1 provides graphs showing continual 30-min CO_2 flux for each month. During May there were positive CO_2 fluxes (emissions) from both the till and no-till plots with greater emissions from the tilled treatment. The tilled plot was plowed on 6 May 2015 (Day of Year (DOY) 126) and planted 8-10 May 2015 (DOY 128-130) and Figure 1.1 shows positive CO_2 fluxes after plowing in May and during the period of emergence. For five days following tillage on DOY 126 the average daytime CO_2 flux (between 1000 and 1600 hrs) for till and no-till were similar in magnitude at 0.61 +/- 0.03 and 0.40 +/- 0.02 g CO_2 m^{-2} hr^{-1} respectively (plus or minus standard error of the mean). During the subsequent five-day period in May (DOY 132-137), 9.1 mm of rain fell. Whereas before the rainfall the soil temperatures were similar (19.4 +/- 0.22 and 19.3 +/- 0.22 ^{o}C for till and no-till respectively), during the nine-day period (DOY 138-146) following the rainfall soil temperatures averaged over 2 ^{o}C greater in the till than the no-till (17.4 +/- 0.29 and 15.2 +/- 0.20 ^{o}C respectively) due to collective effects of residue cover, albedo and greater evaporative cooling at the soil surface. The average daytime CO_2 flux over the tilled plot (0.73 +/- 0.02 g CO_2 m^{-2} hr^{-2}) during this nine-day period following rain was three times greater than over the no-till (0.21 +/- 0.01 g CO_2 m^{-2} hr^{-2}), consistent with expected rates of microbial decomposition (Swift et al., 1979). Greater emission of CO_2 is expected following intensive tillage due to aerobic and anaerobic decomposition of exposed organic matter that was occluded

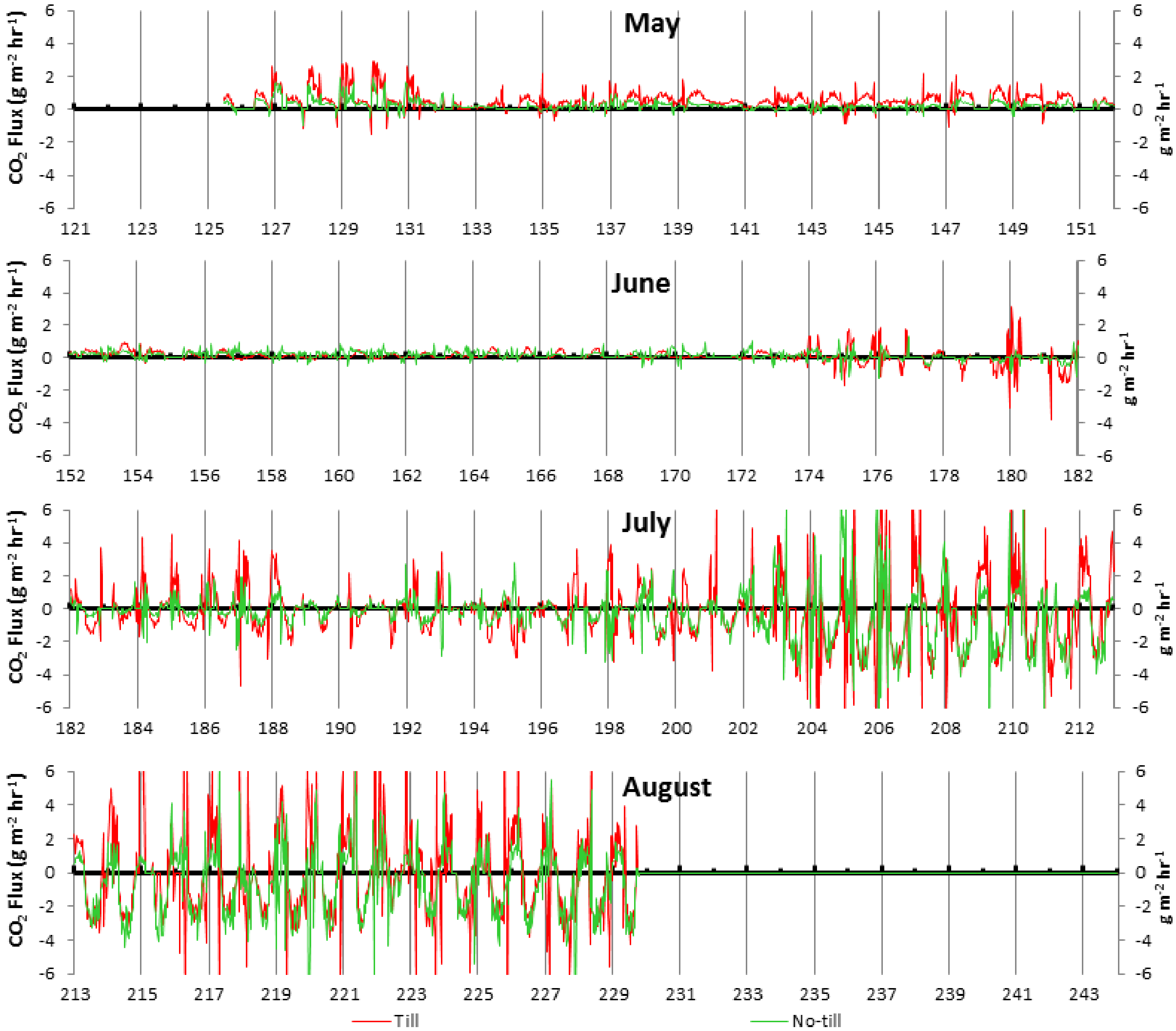

Figure 1.1. Plots of continual 30-min calculated CO_2 flux for each month of the experiment for the till treatment (red) and no-till treatment (green) beginning on 6 May to 17 August 2015 (DOY 126-229).

in aggregates and unavailable to degradation prior to tillage (Elliott and Coleman, 1988; Beare et al., 1994; Six et al., 2000).

Figure 1.2 shows the mean CO_2 flux during May by time of day for the till (in red) and no-till (in green) treatments. The mean 30-min CO_2 flux by time of day for the till and no-till treatments was then averaged and compared during four distinct periods: daytime between 0900 and 1800 hrs, nighttime between 2200 and 0500 hrs, the sunrise transition period between 0500 and 0900 and sunset transition period between 1800 and 2200 (Table 1.1). The mean CO_2 flux during each of these periods in May was significantly different when till was compared to no-till using the Student's t-test ($P<0.01$).

During June the maize plants were approaching exponential growth in biomass. The positive fluxes (emission) measured over both plots began to decrease (Figure 1.1) and negative fluxes began to appear near the end of June (roughly day 179-182). These trends are especially revealing because of the unusually heavy rainfall—nearly 200-mm above average rainfall (Table 1.2). Of the monthly total of 300 mm, 232 mm fell during a ten-day period between June 12-20 (DOY 162-171) (Figure 1.3). It seems likely that this period of heavy rain resulted in denitrification and subsequent N loss for the cropping season. June was followed by below average rainfall for the rest of the growing season (including periods of drought stress during R1 growth stage).

Table 1.1. Mean CO_2 flux (g CO_2 m^{-2} hr^{-1}) for each time of day period by month and treatment, when mean flux was significantly different between treatments according to a t-test ($p < 0.01$). Mean flux (when no significant difference found between treatments) are shaded in gray.

Month	Time Period	Till	No-till	Significant Difference	Net Sequestration	Net Emission
May	Daytime[a]	0.651	0.292	Y	N	Y
	Nighttime[b]	0.690	0.360	Y	N	Y
	Morning Transition[c]	0.542	0.284	Y	N	Y
	Evening Transition[d]	0.416	0.159	Y	N	Y
June	Daytime	0.128	0.161	N	N	Y
	Nighttime	0.0841	0.179	Y	N	Y
	Morning Transition	0.166	0.245	N	N	Y
	Evening Transition	0.216	0.0624	Y	N	Y
July	Daytime	-1.16	-1.33	N	Y	N
	Nighttime	1.04	0.412	Y	N	Y
	Morning Transition	0.451	-0.017	Y	Y	Y
	Evening Transition	0.171	-0.116	Y	Y	Y
August	Daytime	-2.17	-2.40	Y	Y	Y
	Nighttime	2.21	0.701	Y	N	Y
	Morning Transition	0.695	0.375	N	N	Y
	Evening Transition	-0.166	-0.341	N	Y	N

Note. [a]Daytime hours between 0900 and 1800; [b]Nighttime hours between 2200 and 0500; [c]Morning transition hours between 0500 and 0900; [d]Evening transition hours between 1800 and 2200.

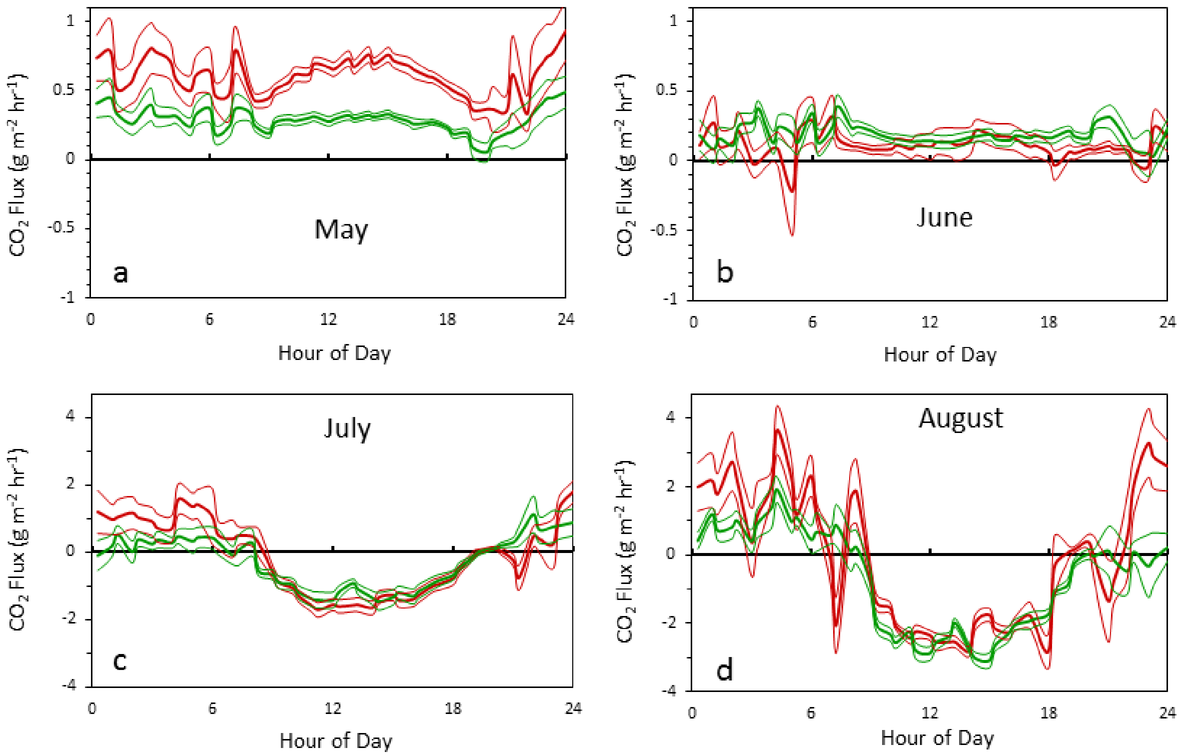

Figure 1.2. Mean CO_2 flux plus/minus one standard error for the till (red) and no-till (green) treatments by time of day for each month.

Table 1.2. Monthly precipitation measured at experiment site compared to monthly total and 30 year mean recorded at Mansfield Ohio weather station 21.2 km NE of experiment site (NOAA National Centers for Environmental Information, 2016).

	May	June	July	August
	------------------ mm ------------------			
Monthly precipitation measured at experiment site	83.1	300	93.0	27.4
Monthly precipitation at Mansfield, OH weather station	112	189	37.8	32.3
30-year mean monthly precipitation at Mansfield, OH weather station	115	121	111	111

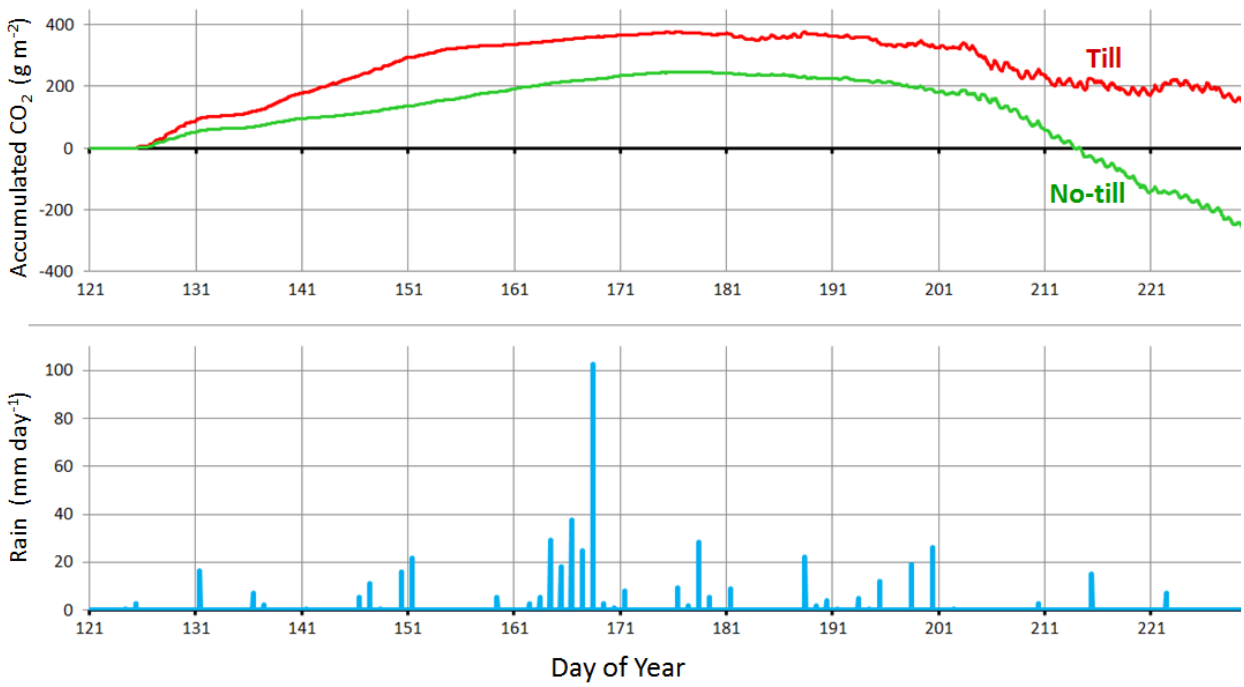

Figure 1.3. Upper graph is the accumulated sum of 30-min CO_2 flux for duration of experiment and lower graph is daily rainfall for the same period.

Towards the end of June (DOY 175-181) both plots began to sequester CO_2 during the day. The 30-min flux graph for June (Figure 1.1) shows greater sequestration by the tilled plot than the no-till plot, which corresponded with greener and taller plants. On the whole, during June the no-till plot emitted 98.7 g CO_2 m^{-2} while the till emitted 59.2 (Table 1.3). This was the only month during which the no-till plot emitted more CO_2 than the tilled. CO_2 flux data for June (Figure 1.2 and Table 1.1) show no significant differences between the tilled and no-till treatments, except during the nighttime and evening when the no-till plot emitted more than the tilled.

Rainfall during the experiment was erratic and excessive. June had near-record rainfall at the research site that continued into the first half of July (Table 1.2). As the soils drained and began to dry out there were some days of strong sequestration for both plot treatments, mainly occurring after 22 July 2015 (DOY 203) (see Figure 1.1). Precipitation measured in the field was 300 and 93.0 mm for June and July, respectively. The C accumulations during July (Figure 1.3) were flat until after the rains ceased. At that time, sequestration rates paralleled increased crop growth as the crop approached the near exponential growth period. July shows negative CO_2 fluxes (Figure 1.1) during the day with higher emissions at night for the tilled plot (Table 1.1). Abnormally high rainfall resulted in marginally chlorotic (lighter green color) and shorter maize plants in several rows of both tillage treatments. These observations effectively predicted lower than normal crop productivity. While no-till has many benefits to long-term soil health and environmental sustainability, no-till fields are greatly impacted by high rainfall because the soil surface cover prevents the soil from drying, which slows soil warming, retards crop growth and development, and enhances denitrification conditions. Linn and Doran (1984) found maximum production of CO_2 by soil microbes when the percentage of water-filled pores approached 60%,

Table 1.3. Summation of 30-min CO_2 flux by month and treatment between May 6 and August 17.

Treatment	May	June	July	August	Sum of period
	-------------------------- g CO_2 m^{-2} per period --------------------------------				
Till	300	59.2	-145	-68.1	146
No-till	141	98.7	-221	-282	-263

and they found on average greater percentages of water-filled pores in no-till compared to tilled soils. Greater precipitation during the first part of June likely contributed to greater microbial respiration on the no-till plot during that month.

The BREB stations continued measuring fluxes through August 17 (Figure 1.1). The mean 30-min CO_2 flux graph illustrates large negative daytime fluxes as well as large positive night time fluxes, with the net accumulation being negative for both plots during August (Table 1.3). Table 1.1 shows that the crop and soil managed under no-till had, on average, less emission at night in August and greater sequestration during the day than soils that had been intensively tilled.

Monthly evapotranspiration (ET) was estimated from the BREB latent heat fluxes, calculated as ET = LE/λ, and was compared with monthly precipitation rates in Table 1.4, expressed in units of mm per period. Comparison of monthly ET with rainfall can indicate water availability for crop growth (Díaz-Zorita, et al., 2002; FAO, 1985). During May and June, precipitation exceeded ET; from May through July—the period with the most rain—the tilled ET was greater than no-till ET. During August—when ET was more than double the precipitation—the no-till and tilled ET were similar, suggesting that most ET was from canopy transpiration and/or soil moisture conserved by the no-till residue that became available for the final period of crop growth during a dry period. Consistent with evapotranspiration, a comparison of sensible and latent heat flux showed greater latent heat flux for the till treatment and greater sensible heat flux for the no-till during May and June, while differences were not detected during July and August. A comparison of net radiation and soil heat flux did not show discernable differences between the two treatments.

Table 1.4. Monthly evapotranspiration computed from latent heat flux for each treatment compared with monthly measured precipitation.

Treatment	May	June	July	August	Sum of period
	---------------------------- mm ------------------------------				
Monthly precipitation	82.6	300	93.0	22.1	497
Till	71.3	89.4	109	58.9	329
No-till	49.1	62.8	97.3	58.1	267

Average CO_2 flux by time of day for each month (Figure 1.2) summarizes the diurnal flux patterns and their change over time. These graphs show a more consistent and smooth behavior for the daytime hours with greater variability at night, especially for the tilled treatment. During July and August, crop growth dominates the daytime flux resulting in smaller differences between treatments. However following the tillage in May, the tilled plot showed greater soil respiration (emission) than the no-till, a trend that continued through July and August at night. Calculated 30-min fluxes of CO_2 were totaled by month and for the period from May 6 through August 17 for the till and no-till plots (Table 1.3). These calculations show that no-till sequestered 263 g CO_2 m^{-2} while the tilled plot emitted 146 g CO_2 m^{-2} during the 104 days of measurement, a difference of 410 g CO_2 m^{-2}.

A rolling bootstrap simulation (Figure 1.4) was used to estimate the CO_2 accumulation variance for each treatment (at 90% confidence interval). Data for periods when either treatment did not have values for over two hours were removed leaving ca. 75% of the original data (we also removed the first 10 days to create the initial set for resampling data). The 90% confidence intervals of the bootstrap distribution are shown in grey (Figure 1.4). The bootstrap accumulation for this 104 day period was 146 g CO_2 m^{-2} (90% confidence interval -53.3 to 332) for the till plot and -263 g CO_2 m^{-2} for the no-till plot (90% confidence interval -432 to -99.9).

The difference in total CO_2 flux between the two plots was 410 g CO_2 m^{-2} for 104 days. Our results suggest that no-till soil management practices have the potential to sequester C compared to soil management practices that use intensive tillage. The results also suggest that the extreme rainfall that occurred the year of this study may have lessened the beneficial impact of no-till practices within the context of CO_2 sequestration. While there is no such thing as a "normal" year, 2015 was a very wet year at the study site. The major rainfall event (in June

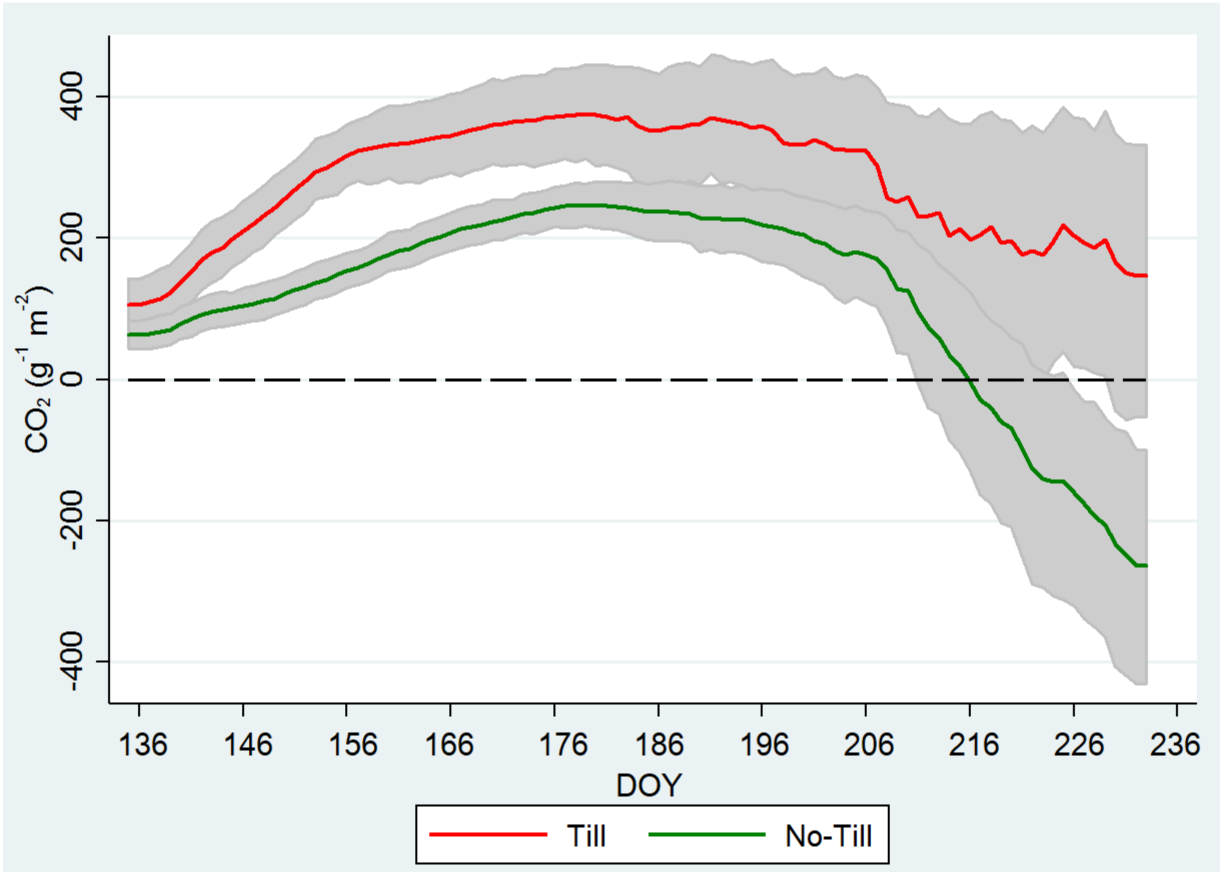

Figure 1.4. Comparison of accumulated sum of half-hour CO_2 for till and no-till plots (shaded areas are 90% bootstrapped confidence intervals).

(DOY 162-171), as indicated in Figure 1.3) was followed by a period of very dry weather during pollination that greatly impacted overall yields.

The crop produced below average yield—likely the lowest yields harvested in the recent history of the site—due to above average rainfall in June and below average rainfall in August during the pollination and grainfill periods. Denitrification stunted plants resulting in low ear placement (< 0.3 m above the soil surface) and excessively high combine header loss due to low ear placement on the maize stalk. An adjacent experiment comparing the combine harvest totals with two hand harvesting methods measured a significantly lower ($p < 0.0001$) combine harvest yield at 1.70 t ha^{-1} than both hand harvest methods at 2.75 t ha^{-1} for a ten-plant method and 2.72 t ha^{-1} for an in-the-row method (Sullivan, 2016). This adjacent experiment also measured a significantly lower yield ($p < 0.0002$) for the no-till at 2.17 t ha^{-1} compared to 3.26 t ha^{-1} for the till plot. Despite the lower yield for no-till, there was still some advantage by the no-till practice in sequestering C. In a typical year with greater crop yields and normal rainfall one could expect sequestration rates to be higher. The whole farm maize yield exceeded 14 t ha^{-1} the following year (2016) with a better rainfall—more *normal*—pattern.

Studies have shown that surface residue decomposes more slowly than residue incorporated with greater soil contact (Coppens et al., 2004; Noack et al., 2014). Surface residue can act as an insulating barrier reducing soil temperatures and the no-till treatment also may have protected soil C with lower soil temperatures consistent with studies that found greater CO_2 emissions from soil covered with crop residue than from bare soil (Corradi et al., 2013; Al-Kaisi and Yin, 2005; Fortin et al., 1996). Fortin et al. (1996) showed a correlation between lower soil temperatures and lower CO_2 flux for no-till treatment, but this was not found in the present study.

In general, the CO_2 fluxes reported here are measurements made above the maize canopy. They represent the consequence of exchange with the soil plus exchange with crop biomass above the surface. If it was assumed that the measured CO_2 BREB fluxes at night indicate exchange with the soil, with negligible involvement of the plants (whose stomata are then closed), then it is apparent that the tilled soil must lose CO_2 considerably more rapidly than the no-till. Further, if this increased rate of CO_2 loss from the tilled soil continues through the daytime, then the present data would indicate a substantial difference between the accumulation of CO_2 by the growing canopies. An estimate of the rate of CO_2 accumulation in the growing biomass can be derived by simply subtracting the mean nighttime CO_2 flux from the daytime as shown in Table 1.5. While no more than a first-order approximation, the results show that when the crop is growing most rapidly in July and August, the tilled plot accumulated more biomass than the untilled—a conclusion that is compatible with farming expectations that tilling is economically beneficial over the short term.

The present results indicate that no-till practices can reduce the loss of CO_2 from the crop surface during the growing season, when compared with soil tilled after seven years of no-till. When combined with cover crops, it is possible that no-till practices could produce a substantial net annual sequestration of CO_2. In the present study, tillage resulted in increased CO_2 loss from the soil that appears to have continued throughout the study period. Tillage exhumes buried C sources and provides a means for the soil organisms to mineralize previously occluded organic matter and accelerate decomposition of recently buried crop residue. This study shows that more CO_2 flux can be lost from the terrestrial system to the atmosphere during the first year of a transition from a no-till to a conventionally tilled management practice, confirming that tilling

Table 1.5. Accumulation rates of CO_2 by the canopy assuming that nighttime losses from the soil are representative of the daytime mean fluxes (g CO_2 m^{-2} hr^{-1}) as shown in Table 1.1.

Till	**May**	**June**	**July**	**August**
Daytime flux	0.651	0.128	-1.16	-2.17
Nightime flux	0.69	0.084	1.04	2.21
Excess daytime vs night	-0.039	0.044	-2.2	-4.38
No-Till	**May**	**June**	**July**	**August**
Daytime flux	0.292	0.161	-1.33	-2.4
Nighttime flux	0.36	0.179	0.412	0.701
Excess daytime vs night	-0.068	-0.018	-2.74	-3.10

increased the decomposition and respiration of crop residues during the growing season resulting in a net C loss from soils.

In addition to sequestering C, the retention of residues on the soil surface has many positive effects on soil by improving soil aggregation, reducing erosion, and the retention and transport of heat, water, and air in the soil (Larson et al., 1978). Though there were periods of high rainfall during the growing season, during drought conditions no-till surface residue can reduce soil moisture loss (Anderson, 2015). While it appears that climate patterns are becoming more erratic and extreme—as evidenced in this study—no-till can be an important management tool to enhance the role of soil in mitigating increased atmospheric CO_2 levels. While C can be sequestered in humid areas under intensive agriculture, sequestering C in areas with marginal soils and rainfall will likely require that winter cover crops be used to further produce biomass that will be needed if soil C levels are to be improved.

Conclusions

The present study found that the CO_2 flux for a growing season over an experimental tilled plot was 410 g CO_2 m^{-2} greater than over an adjacent untilled plot. It is recognized that our maize yields were likely affected by excessive precipitation resulting in water-logged soil conditions, N loss, denitrification, and retarded crop growth. Higher emissions under the tilled treatment were likely due to a release of organic matter built up during seven preceding years of no-till practice, as reported in other studies. Subsequent tillage could remove more stored organic matter but would result in lower emissions over time (less new previously occluded organic matter becoming available for mineralization). The ability of no-till to keep the soil cooler may reduce decomposition and preserve soil C, providing a co-benefit in adapting to rising global temperatures. While our maize yields were much less than average yields for this area, our results show that no-till can be an important practice that not only minimizes C loss from soil but can also be an important tool for sequestering C in an environment becoming more and more CO_2 enriched.

Although the results of this experiment add observational data in support of no-till as a practice to sequester C, more data are needed to understand and quantify these differences under varying climate regimes. To understand the potential magnitude of emissions, factors that impact those emissions, and the overall potential for agriculture to become a recognized climate change mitigant warrants further study. While no-till could reduce CO_2 emissions when considering agricultural practices to offset emissions from other sectors, it can only be one small part of an agricultural program that ensures annual net agricultural C sequestration in high yield environs. Comparative studies of a suite of practices such as the use of cover crops, reduced tillage, and reduced fallow periods are likely necessary to reveal the extent of net soil C sequestration across a greater range of arable soils.

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References

Al-Kaisi, M., and Yin, X. (2005) 'Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soybean rotations', *Journal of Environmental Quality, 34*(2), 437-445. https://doi.org/10.2134/ jeq2005.0437

Anderson, R. L. (2016) 'Increasing corn yield with no-till cropping systems: a case study in South Dakota', *Renewable Agriculture and Food Systems, 31*(6), 568-573. https://doi.org/10.1017/s1742170515000435

Angers, D., Bolinder, M., Carter, M., Gregorich, E., Drury, C., Liang, B., … Martel, J. (1997) 'Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada', *Soil and Tillage Research, 41*(3), 191-201. https://doi.org/10.1016/s0167-1987(96)01100-2

Aubinet, M. (2008) 'Eddy covariance CO_2 flux measurements in nocturnal conditions: An analysis of the problem', *Ecological Applications*, *18*(6), 1368-1378. https://doi.org/10.1890/06-1336.1

Baker, J., and Griffis, T. (2005) 'Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques', *Agricultural and Forest Meteorology, 128*(3), 163-177. https://doi.org/10.1016/j.agrformet.2004.11.005

Baudron, F., Tittonell, P., Corbeels, M., Letourmy, P., and Giller, K. (2012) 'Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe', *Field Crops Research*, *132*, 117-128. https://doi.org/10.1016/j.fcr.2011.09.008

Bear, F. E. (1953) *Soils and fertilizers*. 4th ed. New York: John Wiley and Sons, Inc.

Beare, M., Hendrix, P., Cabrera, M., and Coleman, D. (1994) 'Aggregate-protected and unprotected organic matter pools in conventional-and no-tillage soils', *Soil Science Society of America Journal, 58*(3), 787-795. https://doi.org/10.2136/sssaj1994.03615995005800030021x

Bowen, I. (1926) 'The ratio of heat losses by conduction and by evaporation from any water surface', *Physical Review, 27*(6), 779. https://doi.org/10.1103/physrev.27.779

Chapin, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., ... Wirth, C. (2006) 'Reconciling Carbon-cycle Concepts, Terminology, and Methods', *Ecosystems, 9*(7), 1041-1050. https://doi.org/10.1007/s10021-005-0105-7

Cheesman, S., Thierfelder, C., Eash, N.S., Kassie, G. T., and Frossard, E. (2016) 'Soil carbon stocks in conservation agriculture systems of Southern Africa', *Soil and Tillage Research, 156*, 99-109. https://doi.org/10.1016/j.still.2015.09.018

Coppens, F., Garnier, P. F., Merckx, R., and Recous, S. (2004) ‘Decomposition of mulched versus incorporated crop residues: modelling with PASTIS clarifies interactions between residue quality and location’, *Soil Biology and Biochemistry, 39*(9), 2339-2350. https://doi.org/10.1016/j.soilbio.2007.04.005

Corradi, M., Panosso, A., Martins Filho, M., and La Scala Junior, N. (2013) ‘Crop residues on short-term CO_2 emissions in sugarcane production areas’, *Engenharia Agrícola, 33*(4), 699-708. https://doi.org/10.1590/ S0100-69162013000400009

Cox, W., Zobel, R., Van Es, H., & Otis, D. (1990) ‘Tillage effects on some soil physical and corn physiological characteristics’, *Agron. J., 82*, 806-812. https://doi.org/10.2134/agronj1990.00021962008200040030x

Davidson, E., Savage, K., Verchot, L., and Navarro, R. (2002) ‘Minimizing artifacts and biases in chamber-based measurements of soil respiration’, *Agricultural and Forest Meteorology, 113*(1), 21-37. https://doi.org/ 10.1016/s0168-1923(02)00100-4

Davies, L., and Gather, U. (1993) ‘The identification of multiple outliers’, *Journal of the American Statistical Association, 88*(423), 782-792. https://doi.org/10.2307/2290763

de Vries, D. (1963) ‘Thermal properties of soils’, In W. R. van. Wijk (Ed.) *Physics of plant environment.* Amsterdam: North-Holland Publ. Co.m (pp. 210-235).

Díaz-Zorita, M., Duarte, G., and Grove, J. (2002) ‘A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina’, *Soil and Tillage Research, 65*(1), 1-18. https://doi.org/10.1016/s0167-1987(01)00274-4

Djaman, K., Irmak, S., Rathje, W., Martin, D., and Eisenhauer, D. (2013) ‘Maize evapotranspiration, yield production functions, biomass, grain yield, harvest index, and yield response factors under full and limited irrigation’, *Transactions of the ASABE, 56*(2), 373-393. https://doi.org/10.13031/2013.42676

Dugas, W. A. (1993) ‘Micrometeorological and chamber measurements of CO_2 flux from bare soil’, *Agricultural and Forest Meteorology, 67*, 115-128. https://doi.org/10.1016/0168-1923(93)90053-K

Dwyer, L., Ma, B., Stewart, D., Hayhoe, H., Balchin, D., Culley, J., and McGovem, M. (1996) ‘Root mass distribution under conventional and conservation tillage’, *Canadian Journal of Soil Science, 76*, 23-28. https://doi.org/10.4141/cjss96-004

Efron, B. (1979) ‘Bootstrap methods: Another look at the jackknife’, *Annals of Statistics, 7*, 1-26. https://doi.org/10.1214/aos/1176344552

Elliott, E., and Coleman, D. (1988) ‘Let the soil work for us’, *Ecological Bulletins, 39*, 23-32.

EPA. (2014) ‘*Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012’,* Washington, D.C.: U.S. Environmental Protection Agency.

FAO. (1985) ‘*Agroclimatological data for Latin America and the Caribbean’,* (FAO Production and Protection Series ed.) Rome: FAO.

FAO. (2011) ‘*FAOSTAT % of Agricultural area/land area’*, Retrieved May 14, 2016, from http://faostat3.fao.org/ download/E/EL/E

FAO. (2016) ‘*Global Forest Resources Assessments*’, Retrieved May 13, 2016, from http://www.fao.org/forest- resources-assessment/en

Fortin, M., Rochette, P., and Pattey, E. (1996) ‘Soil carbon dioxide fluxes from conventional and no-tillage small-grain cropping systems’. *Soil Science Society of America Journal, 60*(5), 1541-1547. https://doi.org/ 10.2136/sssaj1996.03615995006000050036x

Gilmanov, T. G., Johnson, D. A. and Saliendra, N. Z. (2003) ‘Growing season CO2fluxes in a sagebrush-steppe ecosystem in Idaho: Bowen ratio/energy balance measurements and modeling’, *Basic and Applied Ecology*, 4(2), pp. 167–183. https://doi.org/10.1078/1439-1791-00144.

Hampel, F. (1985) ‘The Breakdown Points of the Mean Combined With Some Rejection Rules’, *Technometrics, 27*, 95-107. https://doi.org/10.1080/00401706.1985.10488027

Held, A. A., Steduto, P., Orgaz, F., Matista, A., and Hsiao, T. C. (1990) ‘Bowen ratio/energy balance technique for estimating crop net CO_2 assimilation, and comparison with a canopy chamber’, *Theor. Appl. Climatol., 42*, 203-213. https://doi.org/10.1007/bf00865980

Hollinger, S., Bernacchi, C., and Meyers, T. (2005) ‘Carbon budget of mature no-till ecosystem in North Central Region of the United States’, *Agricultural and Forest Meteorology, 130*(1), 59-69. https://doi.org/10.1016/ j.agrformet.2005.01.005

Jenny, H. (1941) ‘*Factors of soil formation: a system of quantitative pedology’,* New York: McGraw-Hill.

Kanemasu, E. T., Wesely, M. L., Hicks, B. B., and Heilman, J. L. (1979) ‘Techniques for calculating energy and mass fluxes’, In B. J. Barfield and J. F. Gerber (Eds.), *Modification of the Aerial Environment of Crops* (pp. 156-182) ‘St. Joseph, MI: American Society of Agricultural and Biological Engineers.

Lal, R. (2004) ‘Soil carbon sequestration impacts on global climate change and food security’, *Science, 304*(5677), 1623-1627. https://doi.org/10.1126/science.1097396

Larson, W., Holt, R., and Carlson, C. (1978) ‘Residues for soil conservation. Crop residue management systems’, In W. R. Oschwald (Ed.), *Crop Residue Management Systems* (pp. 1-15) ‘Madison: ASA, CSSA, and SSSA. https://doi.org/10.2134/asaspecpub31.c1

Linn, D., and Doran, J. (1984) ‘Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils’, *Soil Science Society of America Journal, 48*(6), 1267-1272. https://doi.org/ 10.2136/sssaj1984.03615995004800060013x

Massman, W. J. and Lee, X. (2002) ‘Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges’, *Agricultural and Forest Meteorology*, 113(1–4), pp. 121–144. https://doi.org/10.1016/S0168-1923(02)00105-3.

McGinn, S. M., and King, K. M. (1990) ‘Simultaneous measurements of heat, water vapour and CO_2 fluxes above alfalfa and maize’, *Agricultural and Forest Meteorology*,49, 331-349. https://doi.org/10.1016/0168-1923(90)90005-q

Meyers, T., and Hollinger, S. (2004) ‘An assessment of storage terms in the surface energy balance of maize and soybean’, *Agricultural and Forest Meteorology,* 125(1), 105-115. https://doi.org/10.1016/j.agrformet. 2004.03.001

Morrison, A., Frölicher, T., and Sarmiento, J. (2015) ‘Upwelling in the Southern Ocean’, *Physics Today, 68*(1), 27. https://doi.org/10.1063/PT.3.2654

Noack, S., McBeath, T., McLaughlin, M., Smernik, R., and Armstrong, R. (2014) ‘Management of crop residues affects the transfer of phosphorus to plant and soil pools: Results from a dual-labelling experiment’, *Soil Biology and Biochemistry, 71*, 31-39. https://doi.org/10.1016/j.soilbio.2013.12.022

Norman, J., Kucharik, C., Gower, S., Baldocchi, D., Crill, P., Rayment, M., … Strieglfi, R. (1997) ‘A comparison of six methods for measuring soil-surface carbon dioxide fluxes’, *Journal of Geophysical Research, 103*(D24), 28-771. https://doi.org/10.1029/97jd01440

O’Dell, D., Sauer, T. J., Hicks, B. B., Thierfelder, C., Lambert, D. M., Logan, J., and Eash, N. S. (2015) ‘A short-term assessment of carbon dioxide fluxes under contrasting agricultural and soil management practices in Zimbabwe’, *Journal of Agricultural Science, 7*(3), 32-48. https://doi.org/10.5539/jas.v7n3p32

O’Dell, D., Sauer, T., Hicks, B., Lambert, D., Smith, D., Bruns, W., … Eash, N. (2014) ‘Bowen Ratio Energy Balance Measurement of Carbon Dioxide (CO_2) Fluxes of No-Till and Conventional Tillage Agriculture in Lesotho’, *Open Journal of Soil Science, 4*(3), Article ID: 43617. https://doi.org/10.4236/ojss.2014.43012

Ochsner, T., Horton, R., and Ren, T. (2001) ‘A new perspective on soil thermal properties’, *Soil science society of America Journal, 65*(6), 1641-1647. https://doi.org/10.2136/sssaj2001.1641

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., … Yakir, D. (2006) ‘Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: Algorithms and uncertainty estimation’, *Biogeosciences, 3*(4), 571-583. https://doi.org/10.5194/bg-3-571-2006

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

Pearson, R. (1999) ‘*Data cleaning for dynamic modeling and control*’, Karlsruhe: European Control Conference.

Perez, P. J., Castellvi, F., Ibanez, M., and Rosell, J. I. (1999) 'Assessment of reliability of Bowen ratio method for partitioning fluxes', *Agric. For. Meteorol., 97*, 141-150. https://doi.org/10.1016/s0168-1923(99)00080-5

Reicosky, D. (1997) 'Tillage-induced CO_2 emission from soil', *Nutrient Cycling in Agroecosystems, 1*(3), 273-285. https://doi.org/10.1023/A:1009766510274

Reicosky, D., and Lindstrom, M. (1995) 'Impact of fall tillage on short-term carbon dioxide flux', In L. Rattan, J. Kimble, E. Levine, and B. Stewart (Eds.), *Soil and Global Change* (pp. 177-187) Chelsea, Michigan: Lewis Publishers.

Reicosky, D., Kemper, W., Langdale, G., Douglas, C., and Rasmussen, P. (1995) 'Soil organic matter changes resulting from tillage and biomass production', *Journal of Soil and Water Conservation, 50*(3), 253-261.

Rosenberg, N.J., Blad, B., and Verma, S. (1983) '*Microclimate: The Biological Environment*', New York: John Wiley and Sons.

Savage, M., Everson, C., and Metelerkamp, B. (2009) 'Bowen ratio evaporation measurement in a remote montane grassland: Data integrity and fluxes', *Journal of Hydrology, 376*(1), 249-260. https://doi.org/10.1016/ j.jhydrol.2009.07.038

Schlesinger, W. H. (1999) 'Carbon sequestration in soils', *Science, 284*, 2095. https://doi.org/10.1126/ science.284.5423.2095

Scripps Institution of Oceanography. (2016) *Scripps CO2 Program: The Keeling Curve*', Retrieved August 10, 2016, from https://scripps.ucsd.edu/programs/keelingcurve

Shih, S., Glaz, B., and Barnes Jr., R. (1998) 'Subsidence of organic soils in the Everglades Agricultural Area during the past 19 years', *Soil Crop Sci. Soc., 57*, 20-29.

Six, J., Elliott, E., and Paustian, K. (2000) 'Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture', *Soil Biology and Biochemistry, 32*(14), 2099-2103. https://doi.org/10.1016/s0038-0717(00)00179-6

Smith, P. (2004) 'How long before a change in soil organic carbon can be detected? *Global Change Biology, 10*(11), 1878-1883', https://doi.org/10.1111/j.1365-2486.2004.00854.x

Stephens, J., and Johnson, L. (1951) 'Subsidence of organic soils in the upper Everglades region of Florida', *Soil Sci. Soc., 11*, 191-237. https://doi.org/10.2136/sssaj1956.03615995002000010019x

Sullivan, C. (2016) '*Contrasting Soil Management Practice, Nitrogen Source, and Harvest Method Effects on Corn Production in Ohio and Tennessee*', Knoxville: University of Tennessee.

Swift, M., Heal, O., and Anderson, J. (1979) '*Decomposition in terrestrial ecosystems*', London: Blackwell.

Taylor, A., Amiro, B., and Fraser, T. (2013) 'Net CO_2 exchange and carbon budgets of a three-year crop rotation following conversion of perennial lands to annual cropping in Manitoba, Canada', *Agricultural and Forest Meteorology, 182*, 67-75. https://doi.org/10.1016/j.agrformet.2013.07.008

Tubiello, F., Salvatore, M., Ferrara, A., House, J., Federici, S., Rossi, S., … Prosperi, P. (2015) 'The contribution of agriculture, forestry and other land use activities to global warming', *Global Change Biology, 21*(7), 2655-2660. https://doi.org/10.1111/gcb.12865

USDA Soil Survey Staff. (1999) 'Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys', *Soil Taxonomy* (2nd ed.) Retrieved May 31, 2014, from http://www.nrcs.usda.gov/ wps/portal/nrcs/main/soils/survey/class/taxonomy/

Vanden Bygaart, A., and Angers, D. (2006) 'Towards accurate measurements of soil organic carbon stock change in agroecosystems', *Canadian Journal of Soil Science, 86*(3), 465-471. https://doi.org/10.4141/s05-106

Vanden Bygaart, A., Gregorich, E., and Angers, D. (2003) 'Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies', *Canadian Journal of Soil Science, 83*(4), 363-380. https://doi.org/10.4141/s03-009

Webb, E. K., Pearman, G. I., and Leuning, R. (1980) 'Correction of flux measurements for density effects due to heat and water vapour transfer', *Quart. J. R. Met. Soc., 106*, 85-100. https://doi.org/10.1002/qj.49710644707

West, T. O., and Marland, G. (2002) 'A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States', *Agriculture, Ecosystems and Environment, 91*(1), 217-232. https://doi.org/10.1016/s0167-8809(01)00233-x

West, T. O., and Post, W. M. (2002) 'Soil organic carbon sequestration rates', *Soil Science Society of America Journal, 66*(6), 1930-1946. https://doi.org/10.2136/sssaj2002.1930

Yu, C., Hui, D., Deng, Q., Wang, J., Reddy, K., and Dennis, S. (2016) 'Responses of corn physiology and yield to six agricultural practices over three years in middle Tennessee', *Scientific Reports, 6*, 27504. https://doi.org/10.1038/srep27504

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Appendix

Abbreviations

Excluding SI units and US States

asl	above sea level
BREB	Bowen ratio energy balance
C	carbon
C	volumetric heat capacity of the soil
CO_2	carbon dioxide
C_m	volumetric heat capacity for dry soil
C_p	specific heat capacity of air
C_w	volumetric heat capacity of water
e	vapor pressure
DOY	day of year
EC	eddy covariance
ET	evapotranspiration
et al.	et alia (and others)
G_0	soil heat flux at the surface
$G_{0.06m}$	soil heat flux measured 0.06m below the surface
GHG	greenhouse gas

H	sensible heat flux
hr	hour
K	potassium
K	turbulent diffusivity
K_c	turbulent diffusivity for CO_2
K_h	turbulent diffusivity for sensible heat
LE	latent heat flux
N	nitrogen
NEE	net ecosystem exchange
NOAA	National Oceanic and Atmospheric Administration
P	phosphorus
p	probability
P	atmospheric pressure
R1	reproductive stage of maize with R1 where silk becomes visible outside the husk leaves
R_n	net radiation
SOC	soil organic carbon
T	temperature of the soil
t	time

USDA	United States Department of Agriculture
z	depth of soil heat flux plate
β	Bowen ratio
ΔS	change in heat storage above the soil heat flux plate
Δt	change in time
Δz	sensor separation distance difference
$\Delta \rho_c$	average difference in CO_2 density between measurement heights
ε	ratio of the molecular weight of air and water
Θ	potential temperature
θ	soil volumetric water content
λ	latent heat of vaporization
ρ_a	density of dry air
ρ_b	soil bulk density
ρ_c	average CO_2 density at both measurement heights
ρ_s	soil particle density
ϕ_f	soil porosity

CHAPTER 2

TILLAGE AND NUTRIENT SOURCE EFFECTS ON SOIL CARBON DIOXIDE EMISSIONS AND MAIZE YIELD

This article has been submitted for publication to a peer-reviewed journal. The co-authors on this article included: Neal S. Eash, James A. Zahn, Bruce B. Hicks, Joel N. Oetting, Thomas J. Sauer, Dayton M. Lambert, Joanne Logan, and John J. Goddard. The role of collaborators included research design and execution, data analysis, as well as review and co-authorship of the manuscript. I worked with my major advisor, Professor Neal Eash, to plan and execute the research and I provided the first draft of the manuscript and incorporated co-author input into the manuscript.

Abstract

Re-use of the by-products from industrial biotechnology processes has become an important component of circular bio-economies whereby nutrient-rich wastes are returned to agricultural land to improve soil fertility and crop productivity. Heat-inactivated spent microbial biomass (SMB) from the production of 1,3-propanediol is an industrial fermentation by-product with nutrients that could replace conventional fertilizers. Our objectives were to evaluate methods for measuring carbon dioxide (CO_2) emissions over agriculture and determine if SMB utilization as a soil amendment in agriculture could reduce CO_2 emissions and generate environmental benefits, while meeting farmer yield expectations. This study examined the replacement of typical farmer fertilizer practices with SMB, generated from a bio-manufacturing facility as applied to a local farm in East Tennessee, USA. In addition to yellow dent corn (*Zea mays* var. *indentata*) grain yield, above-ground biomass, and soil organic carbon (SOC) were measured. CO_2 flux was measured using both Bowen Ratio Energy Balance (BREB) and eddy covariance (EC) micrometeorological methods. This study also investigated the use of an aerodynamic method to replace BREB CO_2 flux calculations when conditions were near the

limits of the BREB flux-gradient theory. The SMB applications provided yields typical of applications of low C:N products, with yields positively correlated with increasing application rates of SMB. Treatments with SMB applications indicated greater increases in SOC and also emitted more CO_2 (794 g CO_2 m^{-2} yr^{-1}) compared to a treatment with typical farmer practices (274 g CO_2 m^{-2} yr^{-1}) as measured by eddy covariance (EC). In general, total CO_2 emissions were greater, as detected by the Bowen Ratio Energy Balance (BREB) and aerodynamic methods than the EC method. Comparing the CO_2 emissions of spent microbial biomass with typical fertilizer treatments provides information about nutrient cycling in the soil/plant ecosystem for improving productivity and increasing SOC.

Introduction

Climate change from unabated greenhouse gas (GHG) emissions presents an existential threat to humanity (Hansen et al., 2016; Xu and Ramanathan, 2017; Figueres et al., 2017) making the quantification of CO_2 emissions from agriculture and industry important to understand. Acknowledged goals of the biotechnology industry are to be environmentally friendly and to be perceived as being such. As pointed out by the Ellen MacArthur Foundation (2013), when the waste of industrial biotechnology can be recycled into other industrial processes, then those materials promote the conservation of resources and reduction of waste. Using industrial waste as a resource elsewhere addresses sustainability goals and is a key element in the circular economy (Romero-Hernández and Romero, 2018). Industrial biotechnologies applied to the production of bioenergy and chemicals use cleaner methods, require less energy, and produce less waste (OECD, 2011). Moreover, recent industrial biotechnologies comply with a recently proposed definition of sustainability that "resources, including energy, should be used at a rate at which they can be replaced naturally, and the generation of wastes cannot be faster than the rate of their remediation" (Cséfalvay, Akien, Qi, and Horváth, 2015; Horváth, 2018).

An example of recovering resource value from recycled industrial waste is the use of industrial fermentation bioresidual waste as animal feed or nutrient input for crops (Westendorf and Wohlt, 2002; Moore, 2011; Tuck et al., 2012; Sullivan et al., 2017). The use of waste as an input has been researched in agriculture with the use of manures since the 1800's (Lawes, 1845; Lawes and Gilbert, 1863), but the use of industrial waste as a resource is a more recent phenomenon. Bioresiduals generated by industrial biotechnologies tend to be rich in organic matter, containing macro- and micronutrients essential for plant growth, and therefore have agricultural value. However, there remain technical, logistical, and social challenges and costs in value recovery as demonstrated by the municipal waste management industry (Rhyner et al., 1995; Gregson et al., 2015), as highlighted by a negative reaction to dry biosolids being blown by high winds onto an adjacent property when New York City biosolids were applied to winter wheat (*Triticum aestivum* L.) farms in southern CO (Stulp, 1995).

An additional criterion for assessing the sustainability of industrial biotechnology processes is the measurement of environmental impacts, such as the reduction of GHG emissions (Hermann et al., 2007; Adom et al., 2014). Comprehensive life cycle assessments (LCAs) can assess a spectrum of environmental impacts such as human and ecosystem toxicity (Jolliet et al., 2003). Guinée *et al.* (2011) state that a considerable portion of the total imposed environmental burden of product development is associated with the transport of the product itself as well as the eventual disposal of its waste or co-products. Some LCAs that evaluate the sustainability of bioenergy utilize GHG emissions as one proxy to assess the environmental impact of a process

(Hermann et al., 2007; Chiaramonti and Recchia, 2010). Measuring CO_2 emissions from recovered wastes from one industry subsequently used as a valued input for another industry is one method to quantify the environmental sustainability of waste recovery.

This study evaluates the use of an industrial fermentation waste product as a fertilizer replacement for agriculture. Industrial fermentation uses biocatalysts such as micro-organisms to convert grain sugars and oils to produce bio-energy, food, pharmaceuticals, fibers, and chemical products. The spent microbes are separated from the product. If these materials cannot be reused or recycled, they are disposed of in landfills (Halter and Zahn, 2017). The present analysis examines the alternative strategy of using heat-inactivated spent microbial biomass generated from the production of 1,3-propanediol as a nutrient rich soil amendment. The research focuses on two aspects: (1) yield benefits to farmers, and (2) environmental benefits in terms of soil fertility and CO_2 emissions. The specific research goals were to understand the C pathway (CO_2 flux rates and accumulation) of the spent microbial biomass into the soil-maize (*Zea mays* L.) ecosystem and atmosphere. In particular, the study compares CO_2 emissions from a plot treated with the spent microbial biomass with emissions from a plot treated with a typical farmer fertilizer practice. The study was also designed to measure the extent to which applied spent biomass decomposes and is emitted as CO_2.

Micrometeorological methods, such as the BREB and EC systems, can be used to measure the exchange of heat, water vapor, and CO_2 between the surface (soil and/or plant canopy) and the atmosphere (Dugas, 1993; Taylor et al., 2013; O'Dell et al., 2015). Net ecosystem exchange (NEE) of CO_2 is the net vertical CO_2 flux between the soil/plant environment and the atmosphere (Chapin et al., 2006). NEE provides estimates of the CO_2 flux rate and accumulation of the spent biomass and farmer practice (FP) treated fields of the present study, thereby allowing quantification of the beneficial aspects of the land application treatment. It is important to understand C sequestration pathways once a nutrient rich waste product is land applied and quantify CO_2 emissions.

The specific objectives of the present study were to (1) determine if there were differences in the NEE of CO_2 over the course of one year, and (2) measure the maize yield following spent biomass application as compared to FP.

Materials and Methods

Site Description

The study was conducted on a 19.1 ha farm in Loudon, TN (35.708° N, -84.373° W, 274 m asl) with a slope of 2-12%. The mapped soil series at the site were dominated by Decatur (fine, kaolinitic, thermic Rhodic Paleudults) and Emory series (fine-silty, siliceous, active, thermic Fluventic Humic Dystrudepts), with minor areas of Hermitage (fine-loamy, siliceous, semiactive, thermic Typic Paleudults) and Linside series (fine-silty, mixed, active, mesic Fluvaquentic Eutrudepts) (Soil Survey Staff, 2017). The climate is classified as humid subtropical (Cfa) according to Köppen's climate classification with mean annual rainfall of 1245 mm (NOAA, 2019).

The study site was managed as an annual row crop production system of maize under no-till for three years prior to micrometeorological measurements and cropped to hay for five years prior to that.

Treatment Applications

The field site was divided between the SMB application and FP treatments. The spent biomass was applied in March 2016. In 2017 the site was subsequently divided into four treatments to allow for incorporation of the SMB through a tillage operation, retaining no-till sections for both the FP and SMB.

The present study reports one year of CO_2 fluxes from October 2016 to October 2017, so as to accommodate a complete growing season and to follow the convention of summarizing net annual CO_2 fluxes. Flux calculations are presented for one year. Accompanying factors such as farmer yield benefits or ecosystem impacts (e.g., changes in soil organic matter) are presented for two years.

The study site was divided so that the north 8.4 ha area was set aside for the SMB application and the southern 10.3 ha received the FP treatment. During the period 10-28 March 2016, 9.34 t ha^{-1} of spent microbial biomass was spread on the SMB plot at a dry mass rate of 6.6 t ha^{-1} (729 g kg^{-1}dry matter as applied). The SMB provided a potential loading that contributed 592 kg N ha^{-1}, 55 kg P ha^{-1}, 22 kg K ha^{-1} of slow release mineralizable nutrients.

Initial SMB application rates were based on chemical and historical values of organic soil amendments (Eghball et al., 2002; Gutser et al., 2005), assuming that approximately 50% of the N (296 kg N ha^{-1}) was plant available the first year. With the SMB applied using a side discharge manure spreader (Gehl model 1312 Scavenger, Gehl Company, West Bend, WI), many large clumps of SMB (> 100 cm^3 in size) were found in the field. These clumps persisted throughout the growing season and reduced SMB nutrient mineralization and availability. Chemical analyses of the SMB indicated that approximately 25% of the N (148 kg N ha^{-1}) was inorganic and immediately available to plants while the remainder was a slow-release organic form of N that was not available that cropping season. Increased quantities of SMB application were applied the following growing season.

On 8 May 2016, 1.44 kg active ingredient (ai) ha^{-1} of glyphosate were applied to the entire field to kill weeds as a systemic burndown. On 17 May, 2.2 kg ha^{-1} 2, 4-dichlorophenoxyacetic acid (2, 4-D) were applied for longer term control of broadleaf weeds. On 10 May, 20 kg P ha^{-1} as triple superphosphate and 74 kg K ha^{-1} were applied on both the FP and SMB plots and 179 kg N ha^{-1} were applied on the FP plot. On 25-26 May 2016, maize (P1319HR, DuPont Pioneer, Johnston, IA) was no-till planted with an average population of 63,600 plants ha^{-1}. Five 183-meter adjacent transects were harvested on the SMB and FP treatment plots on 7 October 2016 and grain weighed for yield calculations with a weigh wagon (Par-Kan model GW150, Par-Kan Company, LLC, Silver Lake, IN) with subsamples tested for moisture content. The following year, the plots were harvested and grain yield samples weighed with the same weigh wagon on 14 November with three replicates harvested on the SMB no-till and four replicates on the remaining three treatment plots. All grain yields were adjusted to 15.5% moisture.

On 30 May 2017, 1.44 kg ai ha^{-1} of glyphosate and 2.2 kg ha^{-1} 2, 4-D were applied to the entire field. From 12-15 June 2017, 19.5 t ha^{-1} of spent microbial biomass (dry mass rate of 13.1 t ha^{-1} (with an average of 31% moisture) were spread on the SMB plot with a vertical beater manure spreader (Kuhn Krause Knight model 2044 ProPush, Kuhn Krause, Inc., Hutchinson, KS). The biomass application was assayed as 1415 kg N ha^{-1}, 104 kg P ha^{-1}, 54.2 kg K ha^{-1}, with approximately 354 kg N ha^{-1} expected to be plant-available within the first year of application. On 16 June 2017, a surface tillage operation was performed with a vertical tillage system (Kuhn Krause Excelerator model 8000-14, Kuhn Krause, Inc., Hutchinson, KS) to incorporate the SMB into the soil with the intent to reduce the size of persisting clumps, thereby increasing the SMB surface area and nutrient availability. To compare the effects of tillage, the FP plot was also tilled with a strip of approximately 18 m wide left untilled on each side of the line separating the SMB treatment from the FP.

On 16 June, 112 kg N, 20 kg P and 74 kg K ha^{-1} were applied to the FP plot. On 16-17 June 2017, maize (Beck's 6127A3 and XL®6575RR™ registered trademark of DuPont Pioneer and distributed by Beck's Superior Hybrids, Atlanta, IN) was planted to both plots at a target population of 74,100 plants ha^{-1}. Seedling emergence rate was 63,000 plants ha^{-1}, measured on 27 June 2017. A surface sidedress application of 67 kg N ha^{-1} was applied on 20 July 2017 to the FP plot.

Soil bulk density and organic matter were sampled and measured to determine SOC content of the surface soil (0-15 cm depth). Four discrete soil samples were collected before the biomass application in March 2016. Twenty-seven discrete soil samples were collected in March 2017 and 45 composite samples were collected in November 2017. SOC concentration was measured on air-dried samples using automated thermal combustion instrumentation (model Flash EA 1112, Thermo Finnigan, Hemel Hempsted, UK). Bulk density samples were taken for each of the composite samples in November 2017 and a subset of samples were averaged across similar treatment areas for March 2016 and 2017. Bulk density was estimated from the soil core volume and rock-free oven-dried mass of soil. SOC for each sample was then determined using an equivalent mass basis adjusting for bulk density by multiplying the SOC concentration by the bulk density and depth of the sample to arrive at total SOC per unit area (Mg SOC ha^{-1}) for the 0-15 cm depth (Ellert and Bettany, 1995; Nelson et al., 2008).

Above-ground biomass of the maize including grain was randomly sampled for each of the four treatments on 20 September 2017. Maize shoots with leaves and grain were cut off at ground level from four 2.03 m^2 areas per treatment. Samples were oven dried at 105°C and weighed.

CO_2 Flux Measurements

EC and BREB systems were used to measure micrometeorological and soil properties between 1 October 2016 and 30 September 2017. Eddy covariance is the most commonly used method for measuring surface fluxes and NEE of CO_2. Prior to the development of inexpensive 3D sonic anemometers and fast-response open-path IRGA's, BREB systems were commonly used to estimate NEE, especially for grassland and agricultural ecosystems with short canopies (Angell et al., 2001), thus minimizing the need to include biomass heat storage terms in the energy balance relationship. Some comparisons between EC and BREB methodologies yielded similar results (Frank and Dugas, 2001; Wolf et al., 2008), while Alfieri *et al.*, (2009) found considerable differences between the methods for measurement of surface fluxes. BREB systems are still being used to estimate evapotranspiration (Irmak et al., 2014; Vanomark et al., 2018). Gilmanov *et al.*, (2017) and Skinner and Wagner-Riddle (2012) identified the need for annual studies comparing EC and BREB to evaluate historical BREB data for integration with current EC network data.

Both the BREB and EC methods are based on the turbulent flow of air that transports heat, moisture, and trace gases such as CO_2 between the surface and lower atmosphere. The EC method estimates the vertical fluxes of energy and mass as the covariance of the vertical wind velocity and the energy or mass quantity; e.g., the product of the mean fluctuation of CO_2 concentration and vertical wind (Webb et al., 1980; Lee and Massman, 2011). BREB is a flux-gradient method that estimates the vertical flux of a gas from the time-averaged concentration gradient of the gas over a vertical profile by applying a turbulent transport coefficient known as the turbulent diffusivity, *K*. Turbulent diffusivity coefficients for momentum, sensible heat, or latent energy are calculated from measurements of wind speed, temperature, and humidity; the last two made at two heights above the surface of interest. The turbulent diffusivity for CO_2 is assumed to be the same as that calculated for sensible heat (Monin and Obukhov, 1954; Dyer, 1967; Brutsaert, 1982; Hicks, 1985).

During daytime hours, mechanically-generated turbulence at the surface (due to the wind and friction) is augmented by convection resulting from solar heating of the ground and all its components, such as vegetation. At night, and in the absence of this radiative heating, the lower atmosphere relaxes—with less turbulence—and becomes stratified and stable. During the day, the stratification is usually unstable, i.e., turbulent. At night, stratification can be such that air can decouple into layers within and above the plant canopy. Concentrations of CO_2 from respiration can then build up or pool near the surface. Since both the EC and BREB micrometeorological methods are based on an assumption that the air is well mixed, strongly stable periods pose challenges for both techniques. EC systems measure at one fixed height above the canopy, and therefore may not be able to detect the buildup of CO_2 near the surface but below the fixed measurement height, which could explain why EC tends to underestimate nighttime fluxes during stable conditions (Baldocchi, 2003; Lindroth et al., 1998; Wofsy et al., 1993). A practical solution to this problem used by the FLUXNET community is to apply a correction factor to adjust nighttime respiration measurements made when friction velocities, u_*, are low (Gu et al., 2005; Barr et al., 2013). This approach was applied to the EC flux calculations as described below.

BREB calculations are also vulnerable to error in strongly stable conditions. To make a first-order correction for the errors that may arise, an aerodynamic flux-gradient method was used when conditions of strong stratification prevailed (described below).

A BREB and an EC station were located near the center of each plot, in each case with the EC instrument placed 12 m NE of the BREB instrument. The BREB and EC instruments on the FP plot were positioned 155 m from the southern edge of the field and 60 m SW of the edge of the SMB plot. The BREB and EC instruments on the SMB plot were located 68 m north of the southern edge of the SMB plot. The EC instruments were oriented toward the prevailing wind direction of 225° SW and mounted at a 1.75 m height above the canopy or soil surface, adjusted throughout the growing season. The mean flux footprint area using the Korman and Meixner model (Kormann and Meixner, 2001) showed that at least 80% of the EC flux measurements reflected atmospheric properties within the plot area.

Eddy fluxes were measured using IRGASONs (Campbell Scientific Inc., Logan, UT) that include sonic anemometers for the measurement of the three-dimensional wind velocity. Coupling the derived vertical velocity signal with temperature data from the same sonic instruments yielded sensible heat fluxes. Similarly, open-path infrared gas analyzers (IRGAs) measured water vapor and CO_2 concentrations, yielding direct measurement of corresponding eddy fluxes as covariances according to the sonic anemometer vertical velocity data. IRGASON data were collected at a frequency of 10 Hz.

Despite technological advancements in sensor robustness, EC systems also experience system failures and data loss in addition to the issues associated with nighttime stability. A FLUXNET survey reported a range of missing or rejected data between 9 and 65% with an average site loss of 35% of observations (Falge et al., 2001). Gaps in data can result from power or equipment failures, maintenance, sensor obstruction from precipitation, dew, or even bird droppings. Erroneous CO_2 flux calculations can also result from internal heating of open-path IRGAs especially during colder temperatures (Bonneville et al., 2008). Several gap-filling strategies have been developed for addressing data loss. REddyProc software (Reichstein et al., 2005; Wutzler et al., 2018) provides quality-checks and filtering for EC based on relationships between measured flux and friction velocity, u_*, and was used for this study. REddyProc estimates u_* thresholds and fills gaps in data based upon environmental conditions, including recalculation of nighttime fluxes. The first application of REddyProc gap-filling and nocturnal recalculation showed low and negative nighttime fluxes, which were considered to be an effect of the sloping terrain. The planar fit tilt correction (Wilczak et al., 2001) was applied using EddyPro software (LI-COR Biosciences, Lincoln, NE, USA) recalculating most of the raw EC data, followed by the REddyProc marginal distribution sampling (MDS) gap-filling method (Reichstein et al., 2005). For this study, 26% of 30-min EC flux calculations for the FP and 27% for the SMB treatment were gap-filled and or recalculated by the REddyProc MDS gap-filling method.

BREB flux calculations used 5-s average air temperature values, vapor pressure and CO_2 concentrations measured at two heights, 0.2 m and 1.8 m, above the vegetation or soil surface. Measurements were made within aspirated and shielded horizontal air intake tubes facing the direction of prevailing winds (from the SW) with fans drawing ambient air over the sensors. The BREB systems were built by an in-house team following designs developed for similar applications elsewhere (Irmak et al., 2014; Sauer et al., 1998). Vapor pressure and temperature were measured using relative humidity probes coupled with platinum-resistance thermometers (model HC2-S3-L, Rotronic, Switzerland supplied by Campbell Scientific, Inc, Logan, UT). CO_2

concentrations were measured with non-dispersive infrared gas analyzers (IRGA) (model LI-820, LI-COR Inc., Lincoln, NE). To overcome sensor bias at the two heights, the intake tubes housing the sensors were attached at the end of a rotating arm centrally mounted on a frame that exchanged the position of the atmospheric sensors every 5 minutes. As the crop grew, the rotating arms were elevated so that the lower sensors were always approximately 0.2 m above the crop canopy with the differential between the upper and lower sensors remaining constant. The first 2 min of measurements following each arm rotation were discarded to ensure sample gases were purged from the lines before measuring at the new sample height.

Precipitation was measured, as well as wind speed and direction, net radiation, soil heat flux, and soil temperature. Rainfall was measured with a tipping bucket rain gauge (model TE525, Texas Electronics, Dallas, TX); wind direction and speed were measured with a wind monitor (Model 05305-5, R. M. Young, Inc. Traverse City, MI); wind speed was measured with a three-cup anemometer (model 014A, Met One Instruments, Inc., Grants Pass, OR); net radiation was measured with a net radiometer (NR Lite2, Kipp & Zonen, Delft, The Netherlands); soil heat flux was measured with soil heat flux plates (model HFT3-L, Radiation Energy Balance System (REBS), Seattle, WA); and soil temperatures with Type "T" (copper constantan) thermocouples buried at 0.015 m and 0.045 m below the surface.

Five-second micrometeorological measurements were averaged over successive 5-min intervals by the BREB systems and used to calculate 30-min mean CO_2 flux according to BREB system theory (Bowen, 1926; Tanner, 1960; Kanemasu et al., 1979; Webb et al., 1980; Dugas, 1993) using the approach as reported by O'Dell et al. (2018). Five-minute water vapor pressure and temperature differences were averaged over 30-min intervals to calculate the Bowen ratio, which was then used to calculate latent energy and sensible heat fluxes. Sensible heat was used to calculate turbulent diffusivity for sensible heat, K_H, which was assumed to be the same as turbulent diffusivity for CO_2 flux. CO_2 flux was then calculated as the product of the average difference of CO_2 density between the two measurement heights. Thirty-minute CO_2 fluxes were calculated for 365 days between 1 October 2016 and 30 September 2017, after installation and configuration of the BREB and EC stations.

The BREB method for calculating fluxes is limited by sensor, mechanical and analytical issues: (1) when the arms fail to change positions every five minutes; (2) when a problem occurs with one or more of the sensors used to calculate the Bowen ratio energy balance or CO_2 concentration; (3) when the difference between the upper and lower temperature and vapor pressure measurements are less than the measurement accuracy of the sensors (Perez et al., 1999); (4) when the Bowen ratio is near -1 (Ohmura, 1982); (5) or when the sensible heat flux direction was not the same as the temperature gradient (Ohmura, 1982). Because the BREB method uses turbulent diffusivity to calculate flux, the fluxes calculated during stable periods (low turbulence) are not consistent with, or are near the limits of, the flux-gradient theory. Several studies used the aerodynamic method for calculating turbulent diffusivity and CO_2 flux during stable periods and the other conditions when BREB calculations are called into question as described above (Dugas et al., 1999; Frank and Dugas, 2001; Emmerich, 2003; Mielnick *et al.*, 2005).

Payero *et al*., (2003) developed the following inequality relationship to detect the conditions that Ohmura (1982) identified as being inconsistent with the flux-gradient relationship:

$$\lambda(\Delta e + \gamma\Delta T)\ (R_n - G) > 0 \quad (1)$$

where λ is the latent heat of vaporization (J kg^{-1}), Δe is the vapor pressure difference and ΔT is the difference in air temperature (°C) between the lower and upper position, R_n is the net radiation (W m^{-2}), and G is the soil heat flux (W m^{-2}). The psychrometric constant, $\gamma = (C_p P/\varepsilon\ \lambda)$, where C_p is the specific heat of air (J kg^{-1} °C^{-1}), P is atmospheric pressure and ε is the ratio of the molecular weight of water to that of dry air (0.622).

The following aerodynamic method described by Dugas et al. (1999) was used to calculate turbulent diffusivity when the Payero et al. (2003) test and other tests identified conditions when the BREB method was in question as described above.

The zero plane displacement, *d* (m), a measure of momentum transfer between surface roughness elements and horizontal flow associated with the flux used in the aerodynamic method was calculated as a function of crop height, *h* (m) (Stanhill, 1969):

$$\log_{10} d = 0.979 \log_{10} h - 0.154 \quad (2)$$

The roughness parameter, z_0 (m), a measure of surface roughness, was also calculated as a function of crop height (Tanner and Pelton, 1960):

$$\log_{10} z_0 = 0.997 \log_{10} h - 0.883 \quad (3)$$

The friction velocity, u_* (m s^{-1}), a measure of eddy velocities, was calculated from wind speed, u (m s^{-1}) at height z (m), roughness parameter z_0, and zero plane displacement, d, and the von Kármán constant, k, using a value of 0.41 (Dugas et al., 1999) with the following equation (Rosenberg et al., 1983):

$$u_* = u(z)\, k / \ln((z - d) / z_0) \quad (4)$$

The change in wind speed to the change in height, $\partial u/\partial z$, was calculated as (Monteith and Unsworth, 2013):

$$\partial u/\partial z = u_*/[k\,(z - d)] \quad (5)$$

Eqs (4) and (5) are correct only for neutral conditions. In other situations allowance must be made for the role of atmospheric stability. In the present case, measurements were made sufficiently close to the surface that stability effects were generally small. To examine this further, values of the gradient Richardson number, *Ri*, were computed from gradients of potential temperature, $\partial\theta$ (K) and wind speed ∂u (m s^{-1}) as (Monteith and Unsworth, 2013):

$$Ri = (gT^{-1}\ \partial\theta/\partial z) \,/\, (\partial u/\partial z)^2 \qquad (6)$$

where g (m s^{-2}) is the acceleration due to gravity, and T is the absolute temperature (K). Negative *Ri* numbers < -0.1 correspond to unstable conditions (Dyer and Hicks, 1970) and positive to stable conditions. In stable stratification (mostly at night) the atmosphere resists vertical motion (Webb, 1970). With increasing stability, turbulence is dampened and the relationships underlying the similarity theory (Monin and Obukhov, 1954) of flux-gradient methods are not valid (Mahrt, 2010). Following Dugas et al. (1999), when *Ri* was greater than 0.2, the turbulent diffusivity coefficient for sensible heat, K_H, was set to 0.005 $m^2\ s^{-1}$.

In unstable conditions when *Ri* < -0.1 and there is a greater upward rather than horizontal transport of heat, the stability functions for momentum, sensible heat and water vapor, ϕ_M, ϕ_H, ϕ_W, respectively, were calculated from *Ri* by the following equation (Dyer and Hicks, 1970) after the conversion of the Monin-Obukhov length L to the *Ri* number via the relationship $(z - d)/L = (\phi_M^2/\ \phi_H)$ (Monteith and Unsworth, 2013):

$$\phi_M^2 = \phi_H = \phi_W = (1 - 16Ri)^{-0.5} \qquad (7)$$

In conditions when *Ri* was greater than −0.1 and less than 0.2, the stability functions for momentum, sensible heat, and water vapor were equal and were calculated from results found by Webb, (1970) under stable conditions:

$$\phi_M = \phi_H = \phi_W = (1 - 5Ri)^{-1} \qquad (8)$$

Turbulent diffusivity for sensible heat, K_H, was then calculated using the stability function in Eqs. 7 and 8 depending on the *Ri* number with the following equation in an iterative fashion (Campbell, 1985):

$$K_H = k\, u_* \,(z - d)\, \phi_H^{-1} \quad (9)$$

CO_2 flux was then calculated according to methods described in O'Dell et al. (2018) as the product of the turbulent diffusivity for CO_2 flux (assumed to be equal to K_H) and the average difference of CO_2 density between the two measurement heights. The flux was then corrected for vapor pressure and temperature differences at the two measurement heights according to Webb et al. (1980).

To evaluate the use of this aerodynamic method, we also applied a recent method for calculating the zero plane displacement and the roughness parameter (Graf et al., 2014). Since the EC systems provided direct measurements of friction velocity, one aerodynamic method was developed using the EC u_* measurements for comparison with calculations of u_* and CO_2 flux from BREB station wind speed measurements.

In recognition of the distinctions among the alternative methodologies described above, and of the differences of their results in (primarily) nighttime conditions, several comparisons were conducted. The results of these tests are presented below.

Data Analysis

Missing data resulting from power loss, or the failure of one or more critical sensors for periods greater than eight hours, resulted in approximately 6% data loss for the BREB and aerodynamic methods. During periods of less than eight hours, fluxes were linearly interpolated, which occurred for less than 1% of observations. While no power losses or sensor issues occurred for the EC stations, approximately 3% data loss occurred due to rain events and were gap-filled using REddyProc.

We created five analytical methods to compare 30-min fluxes and to evaluate the effect of different aerodynamic inputs such as canopy height estimation and wind speed on the calculated flux. A description of each follows:

(1) "BREB-Aero" is a combined method using BREB when it satisfied the conditions as described above and using the aerodynamic method when it did not. The aerodynamic method included the zero plane displacement (d) and the roughness parameter (z_0) as a function of crop height as described by Dugas et al. (1999) and in lieu of wind measurements at the BREB stations, friction velocity, u_*, from the EC stations was used in the aerodynamic calculations.

(2) "Aero-Stanhill" is an aerodynamic-only method using the results of Stanhill (1969) to calculate d, the zero plane displacement (Eq 2). Tanner and Pelton's (1960) method was used to calculate z_0 (Eq 3). This method used the wind speed measured at each BREB station.

(3) "Aero-Graf" refers to an aerodynamic-only method, which uses the method described by Graf et al. (2014) to calculate d and z_0. This method used the wind measured at each BREB station.

(4) "Aero-EC u_*" is an aerodynamic-only method that uses the u_* derived from EC measurements to calculate the change in wind speed to the change in height in Eq. 5 as described above.

(5) "EC" are the flux calculations produced by the EC instruments after planar fit tilt correction, gap-filling and flux recalculation.

The first year's maize grain yield treatment means were analyzed using F tests and the Student's t-test with Microsoft Excel (Microsoft Corporation, Redmond, WA). Regression analysis was performed using Excel. The second year's grain yield and above-ground biomass were analyzed using a two-way analysis of variance (ANOVA) mixed procedure of SAS (SAS V9.4, SAS Institute, Cary, NC) to account for the tillage sub-factor within the nutrient treatment. Mean SOC was analyzed using SAS's one-way ANOVA and two-way ANOVA for the final November 2017 set of measurements. Yield, biomass, and SOC means were separated using the GLIMMIX procedure of SAS, which included the Fisher's Least Significant Difference (LSD) test, Tukey's Honest Significant Difference (HSD) and Bonferroni correction methods for mean separation. Least squares mean separation output was converted to letter groupings with the PDMIX macro (Saxton, 1998).

Results and Discussion

The first harvest of maize occurred on 7 October 2016, 177 to 210 days after the SMB was applied. The mean yield on the SMB plot was 7.73 Mg ha^{-1}, which was significantly different than the mean yield of 8.64 Mg ha^{-1} on the FP plot (Student's one-tail *t*-test, $n = 5$, $p = 0.000186$) (Table 2.1). The plant available N of 148 kg N ha^{-1} from the first SMB application at the estimated rate of 25% plant available was less than the 202 kg N ha^{-1} inorganic fertilizer that the farmer applied and is considered the major contributing factor to the yield difference. The first year SMB application had irregular distribution due to issues with the spreader that may have influenced the available N. The spreader was unable to adequately pulverize the SMB such that the larger clumps would not readily undergo mineralization, which limited nutrient release.

For the following year, the harvested yield on 14 November 2017 was analyzed using a two-way ANOVA to account for the tillage factor within the nutrient application treatment (Table 2.2). The yield data was transformed using rank transformation to meet ANOVA

Table 2.1. Mean 2016 maize grain yield (Mg ha^{-1}) by nutrient effect.

Treatment	Grain yield (Mg ha^{-1})	Standard Error (Mg ha^{-1})
SMB	7.73 b †	0.114
FP	8.64 a	0.106

† Grain yield values followed by different letters indicate significant differences between treatments.

Table 2.2. Mean 2017 maize grain yield (Mg ha^{-1}) by nutrient, tillage, and tillage within nutrient effects.

Effect	Treatment	Mean yield (Mg ha^{-1})	Standard Error (Mg ha^{-1})	*n*
Nutrient	SMB	3.72 a †	0.045	7
	FP	2.86 b	0.306	8
Tillage	Tilled	2.95 a	0.319	8
	No-till	3.63 a	0.127	7
Tillage within Nutrient	SMB Tilled	3.78 a	0.0609	4
	SMB No-till	3.65 ab	0.0399	3
	FP Tilled	2.11 b	0.0807	4
	FP No-till	3.61 a	0.236	4

†Grain yield means followed by different letters indicate significant differences between treatments (Bonferroni adjusted mean separation, $p \leq 0.05$).

assumptions of normality and equal variance. ANOVA type III tests for fixed effects indicated the nutrient effect was a significant factor of the yield ($F(1,11) = 5.07$, $p = 0.0457$), while the tillage effect was not ($F(1,11) = 2.12$, $p = 0.173$). The interaction term between the nutrient and tillage effect was significant, indicating the nutrient effect varied by tillage ($F(1,11) = 11.0$, $p = 0.0069$). The mean differences were compared for the nutrient application effect, as shown in Table 2.2, which includes the yield for each of the nutrient treatments. The least-squares mean separation for the nutrient application effect signifies that the SMB application grain yield was significantly different than the FP yield ($p < 0.05$).

The yield was further split into the tillage sub-factor (the tilled vs. the untilled section) in each of the nutrient application plots (Table 2.2). When comparing the means of just the tillage effect, no significant differences were evident. When comparing the means of the combined treatment factors (the tillage sub-factor within the nutrient treatment) there is a difference between the SMB tilled and the FP no-till vs. the FP tilled, though otherwise no significant differences were found between the other treatments.

All 2017 yields were less than half of 2016 yields, likely a result of the later planting date and reduced rainfall following emergence in 2017. These results suggest that the FP tilled treatment produced lower yields, which can be explained in part by a combination of two factors: (1) the farmer fertilizer application of 179 kg N and 20 kg P ha^{-1} was much lower than the estimated SMB N available at 354 kg N ha^{-1} and P applied at 104 kg ha^{-1}, and (2) during the first 21 days following planting (vegetative growth stages VE through V4) 98 mm of rain fell, followed by a period of 24 days with a total of 25 mm of rainfall during the final stages of vegetative growth (stages V5 through VT). This might explain the higher maize grain yield in the no-till area due to no-till moisture retention providing an advantage during this dry period and may indicate greater water holding capacity of the SMB within the tilled area of the SMB plot (Table 2.2).

We evaluated five methods to determine the NEE for the nutrient treatments. Table 2.3 provides a summary of annual totals of NEE in g CO_2 m^{-2} yr^{-1} for each of the five methods for both FP and SMB treatment, with aerodynamic-only methods (2, 3 and 4) being the greatest for both treatments. From an initial assessment of the five flux calculation methods, it was found that the aerodynamic-only methods (2, 3, and 4) underestimated daytime fluxes during the growing season as compared to EC (method 5). However the combined BREB-Aerodynamic method (1) more closely resembled the EC method daytime fluxes, which is consistent with other studies (Dugas, 1993; Angell et al., 2001).

NEE evaluations calculated by the three aerodynamic-only methods (2, 3 and 4) were similar during the daytime when averaged over two-week periods sorted by time of day and atmospheric stability (data not shown). While these methods could be used when the BREB method does not effectively calculate flux during stable periods at night or when the differences in the temperature or vapor pressure gradient is close to zero, the aerodynamic-only methods produced total accumulated NEE that exceeded both the EC method and the combined BREB-aerodynamic method (Table 2.3). The aerodynamic method that used the EC u_* produced the lowest flux of the three aerodynamic-only methods (Table 2.3). This may be due, in part, to greater accuracy of wind speed measurements at lower wind speeds by the EC system sonic anemometers as compared to the BREB systems' mechanical anemometers that had higher starting thresholds for wind speed detection.

The combined BREB-Aero method calculated 34% of the CO_2 flux using the BREB method for the FP treatment and 36% of CO_2 flux was calculated using the BREB method for the

Table 2.3. Total NEE (g CO_2 m^{-2} yr^{-1}) for each method from 1 October 2016 to 30 September 2017.

Treatment	Method 1 BREB-Aero	Method 2 Aero-Stanhill	Method 3 Aero-Graf	Method 4 Aero-EC u_*	Method 5 EC
SMB	1699	3498	3789	2460	794
FP	232	1016	1174	685	274

SMB treatment, gap-filling the remaining periods with flux calculated using the aerodynamic method. Much of the BREB calculated flux excluded was a factor of atmospheric stability as 41% of atmospheric conditions over the FP and 38% of SMB field conditions were identified as stable. Other studies substituted the aerodynamic method for the BREB method less often, with Dugas, et al. (1999) estimating its use at 10%, Frank and Dugas (2001) about 10%, Emmerich (2003) about 12%, Gilmanov et al. (2003) about 14%, Gilmanov *et al.*, (2006) 16 and 21% depending on the site, and during a six-year study Mielnick *et al.*, (2005) estimated that 23% of their flux data was gap-filled due to BREB issues. Despite reducing the turbulent diffusivity for calculating CO_2 to a constant of 0.005 m^2 s^{-1} for a large portion of night and transition periods, the total NEE for the combined BREB-Aero method was still greater than that of the EC systems, indicating a greater accounting of nighttime respiration (Table 2.3).

The aerodynamic-only methods (2, 3, and 4) showed less negative daytime flux (less sequestration) during the growing season than both the combined BREB-Aero (Method 1) and EC (Method 5) and greater negative flux (greater sequestration) during the non-growing season (data not shown). With the wide use and substantiation of the EC method, which is considered accurate during the daytime, the drift of the daytime aerodynamic estimates raises questions about using the aerodynamic method during daytime conditions. The BREB method has been shown to compare well with EC during the daytime; therefore, the combined BREB-Aero method appears to be more representative of atmospheric conditions. Subsequent analysis to discern the differences between the methods used one aerodynamic-only data (method 4) that used the EC u_*, which had greater accuracy in windspeed especially during periods of low turbulence than the other two aerodynamic-only methods. The biggest question for EC flux measurements and all of these methods, concern nighttime conditions when the EC method has been known to underestimate flux (Sun et al., 2007; Aubinet, 2008).

The accumulated annual CO_2 flux for the two nutrient treatments were compared and plotted for three methods in Figure 2.1: the combined BREB-Aero method 1, the aerodynamic-only method 4 that uses the EC u_*, and the EC method 5. Amounts greater than zero represent net transfer of CO_2 to the atmosphere, and less than zero represent net transfer from the atmosphere to the soil and plant canopy. A visual comparison of accumulation shows a small buildup of CO_2 during the non-growing season from October 2016 through February, where respiration exceeded photosynthesis with a net transfer of CO_2 from the soil and canopy to the atmosphere. The greatest increases in emissions followed herbicide application on 31 May 2017 and conclusion of biomass application and tillage on 16 June 2017. Positive fluxes continued to increase until the maize canopy reached the V5 vegetative state around 10 July 2017, when photosynthesis from the growing canopy exceeded both day and night respiration.

A comparison of CO_2 flux (g m^{-2} hr^{-1}) by time of day for the beginning of the non-growing season from 1 October 2016 through 31 January 2017 combined is shown in Figure 2.2 for the BREB-Aero method 1, the Aero-EC u_* method 4 and the EC method 5 when fluxes were small and similar by time of day. The EC method generally showed greater daytime sequestration by weed growth during this period, while the combined BREB-Aero and Aero-only methods generally showed net positive CO_2 emissions during the day. The SMB treatment showed greater night emissions than the FP for all three methods.

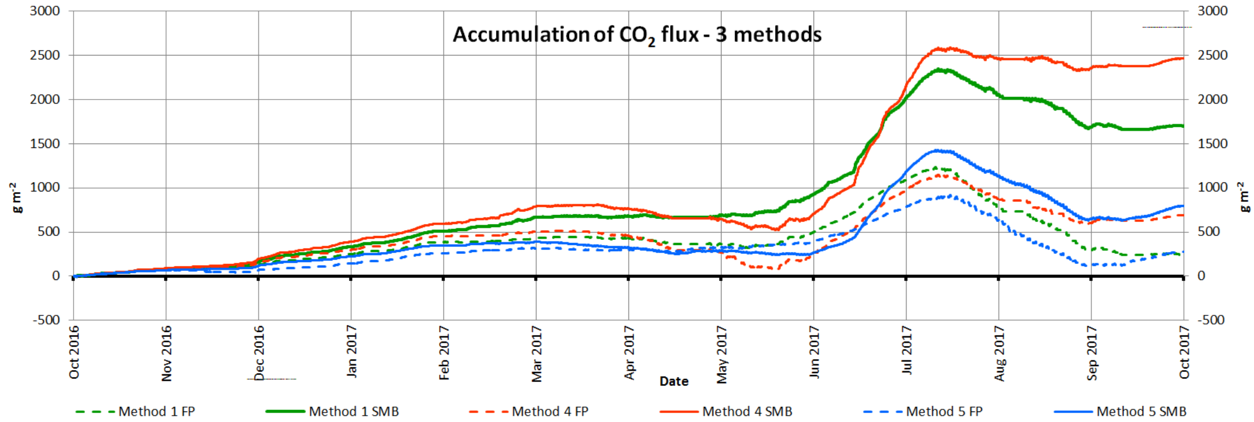

Figure 2.1. CO_2 flux accumulation shown for the BREB-Aero (1), Aero-EC u_* (4), and EC (5) methods for both treatments with the FP treatment shown with dashed lines and the SMB treatment solid lines.

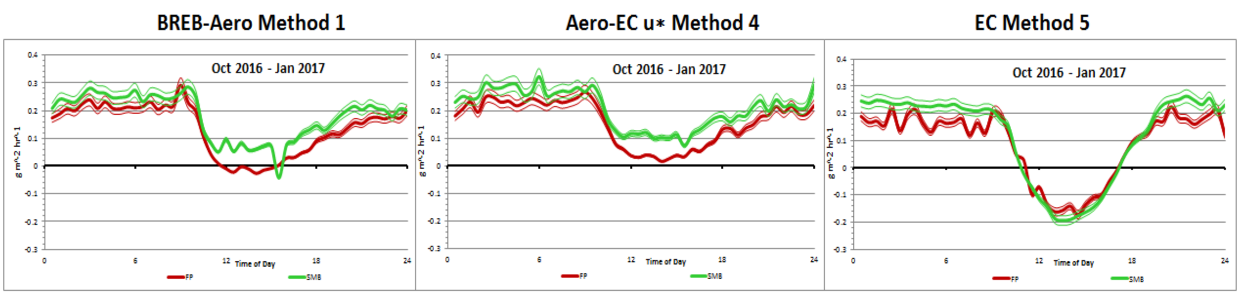

Figure 2.2. CO_2 flux by time of day for the first four months for BREB-Aero method 1, Aero-EC u_* method 4, and EC method 5 for FP (red) and SMB (green) treatments ± one standard error.

Figure 2.3 shows a comparison of flux by time of day and month from February to October 2017 for methods 1, 4 and 5 at a scale more than 10 times greater than Figure 2.2 to account for greater fluxes. Generally, the combined BREB-Aero method is more similar to the EC method during the daytime hours of the growing season, July through September 2017, when the greatest photosynthesis is taking place. The Aero-EC u_* method shows greater negative daytime CO_2 fluxes than the EC and combined BREB-Aero method in the spring during April and May 2017. In general, during the spring and growing season, the BREB-Aero and Aero-EC u_* methods show greater emissions for the SMB treatment than the FP treatment at night than the EC method.

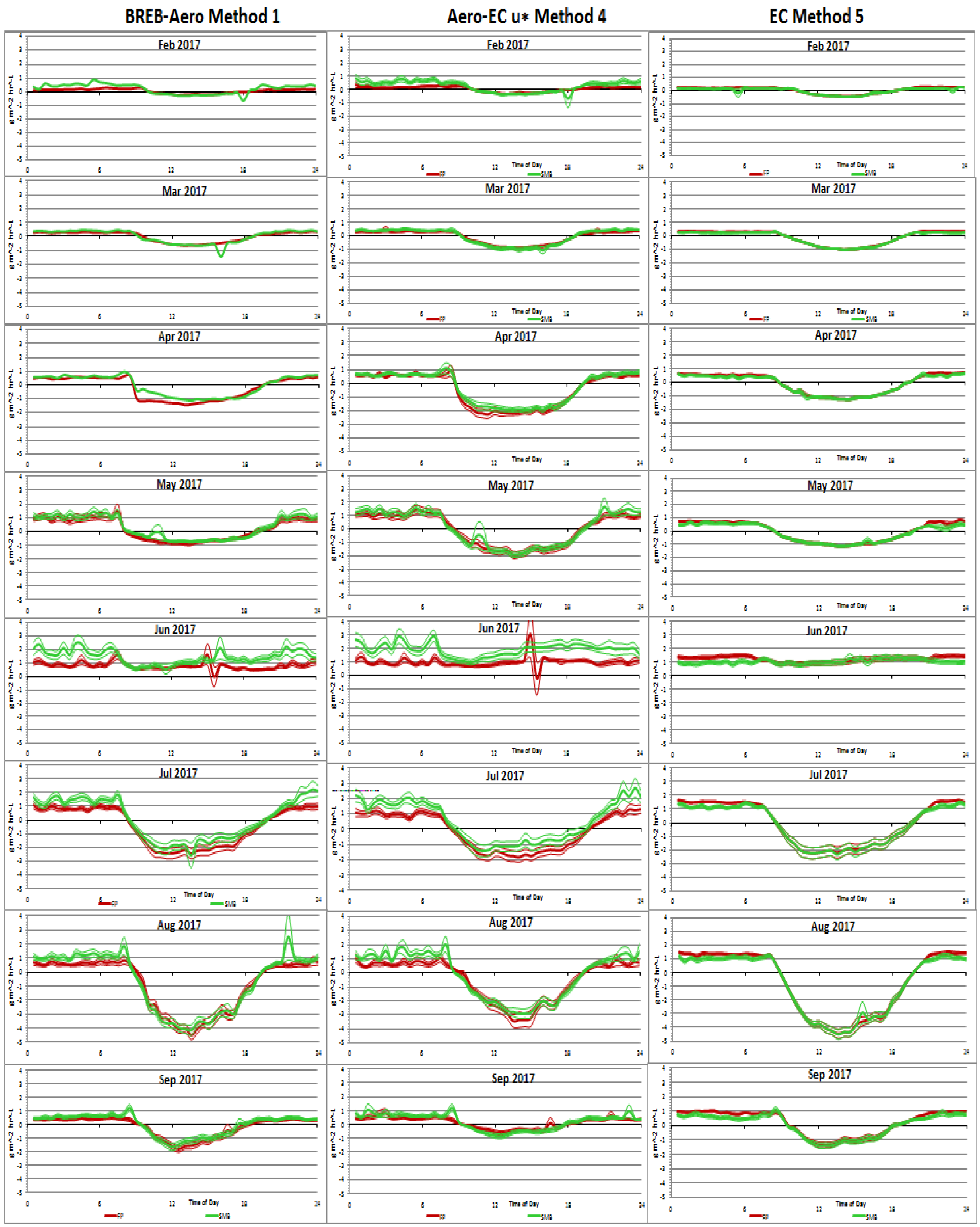

Figure 2.3. CO_2 flux by time of day and month for BREB-Aero method 1, Aero-EC $u*$ method 4, and the EC method 5 for FP (red) and SMB (green) treatments ± one standard error. Negative values below the bold line indicate a negative NEE or C sequestration into the soil ecosystem.

There is considerable agreement between BREB and EC during the day, providing evidence that these two methods more accurately estimate CO_2 flux (Figure 2.3). The aerodynamic method often overestimated daytime flux during cool temperatures and underestimated daytime flux during the growing season. Nighttime BREB fluxes are most often replaced with the aerodynamic method, but this approach generally disagrees with the EC method. It is not clear whether the EC or the Aerodynamic method is a better estimate of CO_2 flux at night. The following example explores some of the nighttime variable interactions.

Because of frequent stable conditions at night with low wind speed and thermal stratification of the lower atmosphere, CO_2 concentrations can build up at the surface and are not detected by the EC system. During these periods the BREB system detects differences in CO_2 concentrations where the lower sensor reads as much as 117 ppm higher than the upper sensor (the purple circle) shown in Figure 2.4 at 2 am on 17 June 2017 following biomass application and planting. Figure 2.4 shows the difference in CO_2 concentrations between the lower and upper sensors measured by the SMB BREB station during a five-hour period on 17 June, along with the calculation of CO_2 flux for the combined BREB-Aero and Aero-EC u_* (methods 1 and 4). All fluxes are the same for these two methods (method 4 in red on top of method 1 in green) signifying that during this stable period, the aerodynamic method was used to calculate CO_2 flux in place of the BREB method because conditions were consistent with Ohmura's criteria for rejecting Bowen ratio flux calculations (Ohmura, 1982). For this period, the CO_2 flux follows the increases and decreases of the CO_2 concentration difference between the two heights, increasing as concentration increases and decreasing as the concentration decreases (Figure 2.4).

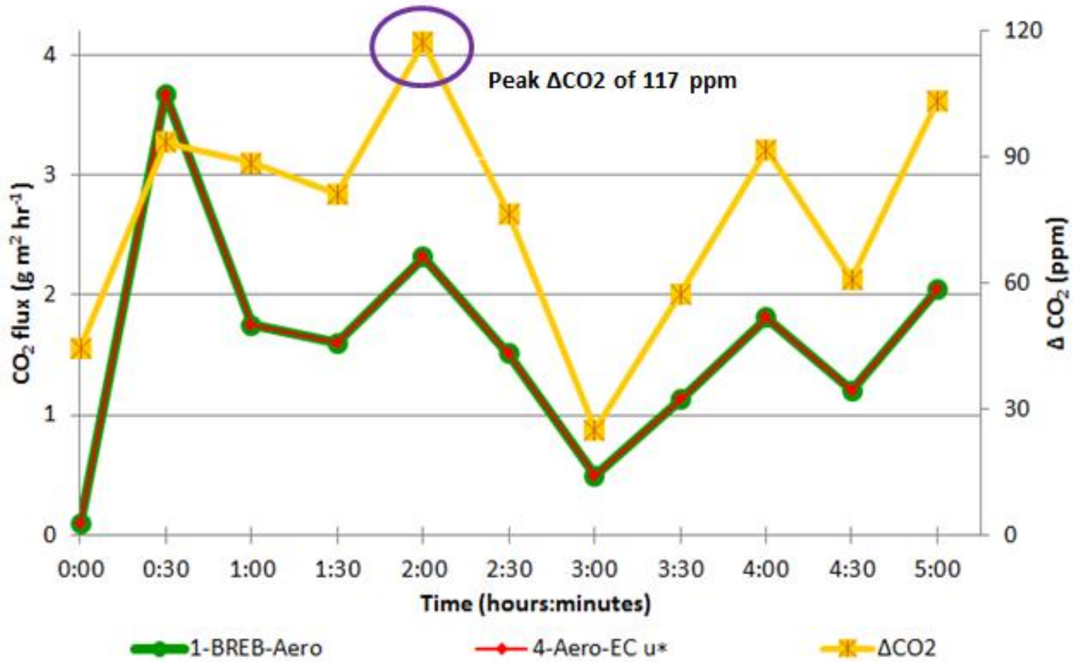

Figure 2.4. Half hour CO_2 flux for the BREB-Aero method 1 (green) and Aero-EC u_* method 4 (red) from midnight to 5:00 am on June 17, 2017 with 30-min average CO_2 differences (orange) between upper and lower sensor at the SMB BREB station.

Adding data from the EC method (Figure 2.5) for the raw 30-min average CO_2 flux data from the IRGASON instrument (5-EC-raw, blue), the planar fit tilt correction (turquoise), and the REddyProc recalculation of nighttime flux (5-EC-gap-filled, purple) indicates the EC raw data does not sense the buildup of CO_2 at the surface. Unlike the raw data, the planar fit tilt correction does not show negative fluxes during this period, and the REddyProc gap-filled recalculation estimated a higher mean CO_2 flux than the other methods for this five-hour period. REddyProc removes raw flux data below a $u*$ threshold and then fills gaps with average values under similar meteorological conditions, smoothing the data for this period as shown by the 5-EC gap-filled data (Figure 2.5).

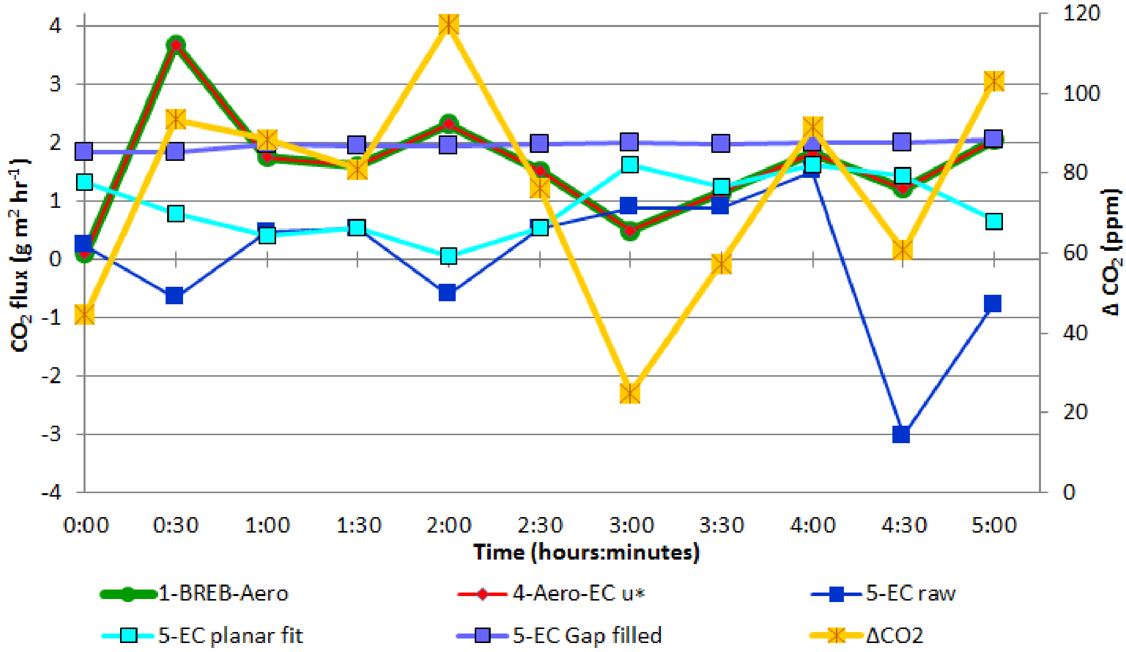

Figure 2.5. Half hour CO_2 flux for methods 1, 4 and 5 from midnight to 5:00 am on June 17, 2017 with 30-min average CO_2 differences between upper and lower sensor measured at the SMB BREB station.

The rise in CO_2 concentration between 0000 and 0200 hrs does not appear to be detected by the raw EC data. During the period between 0200 and 0300, the average wind speed (pink) increases (Figure 2.6) and the raw EC flux (5-EC-raw, blue) and the planar fit tilt correction flux (5-EC-planar-fit, turquoise) also increase, reflecting a mixing of the pooled CO_2 to heights that are detected by the EC system. As the windspeed decreases following the peak at 0300 hrs, the raw EC flux (blue) also decreases suggesting intermittent gusts of wind that provide for atmospheric mixing. During this five-hour period, the REddyProc recalculation (5-EC-gap-filled, purple) does not respond to windspeed or changes in CO_2 concentration. During this example of a stable nighttime period, the aerodynamic method estimates flux based more on the concentrations, while the post-processing of EC data with gap-filling produced a higher NEE for the period.

During this nighttime example, CO_2 concentration generally increased as wind speed decreased or averaged below 0.6 m s^{-1} (Figure 2.7) and concentrations decreased as wind speed increased illustrating a negative relationship between pooling concentrations at the surface and wind speed. The axis for wind speed in Figure 2.7 is inverted to show the negative relationship between CO_2 concentration and wind speed.

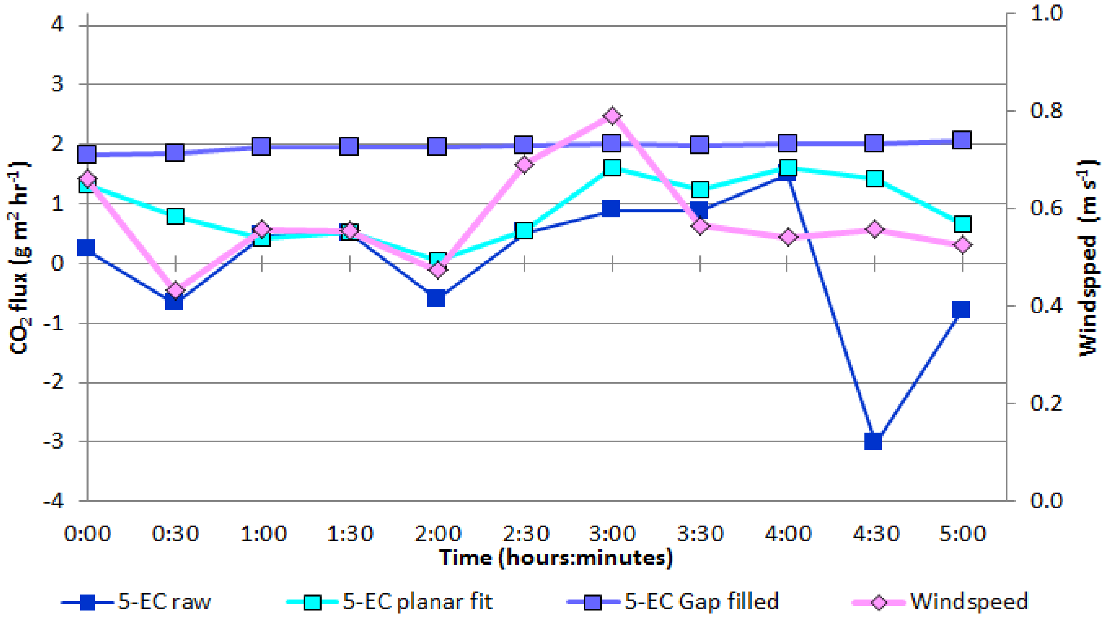

Figure 2.6. Half hour CO_2 flux for method 5, EC raw data (blue), EC raw planar tilt correction fit (turquoise), EC Gap-filled (purple), and wind speed measurements (pink) at the SMB EC station from midnight to 5:00 am on June 17, 2017.

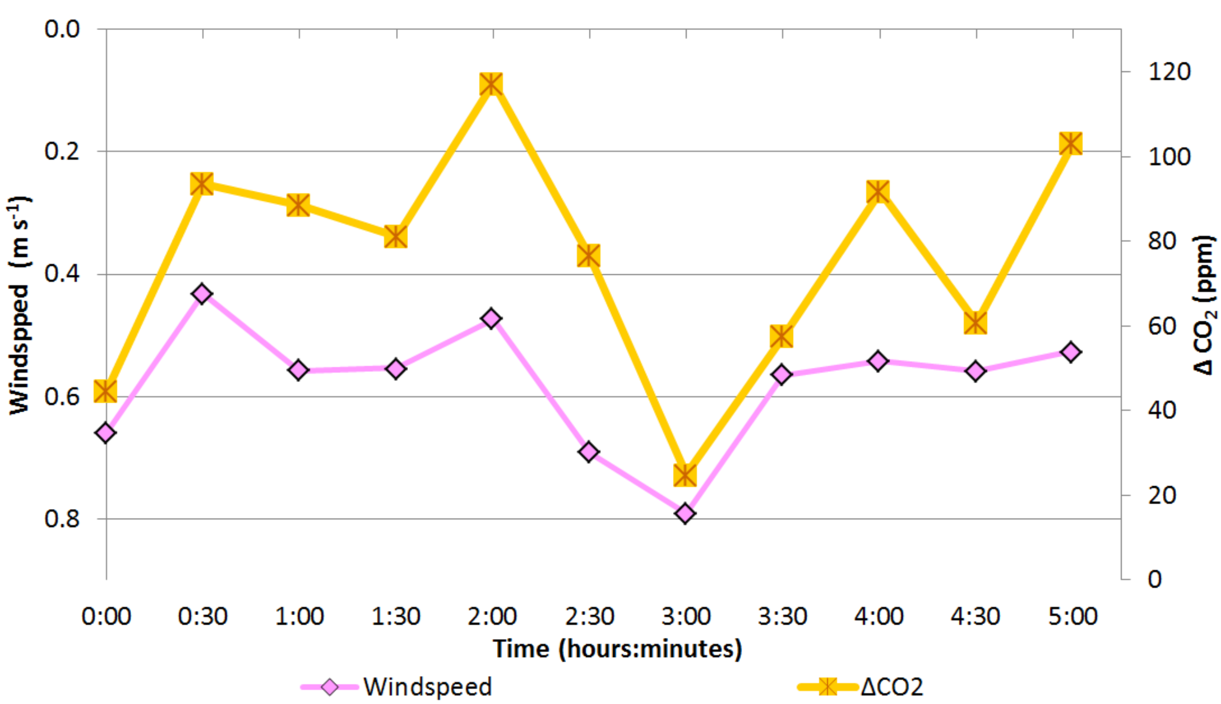

Figure 2.7. Wind speed (pink) at the SMB EC station with inverted y-axis and CO_2 differences at the SMB BREB station from midnight to 5:00 am on June 17, 2017.

This buildup of concentration near the surface is identified as a storage term in the quantification of CO_2 flux (Finnigan, 2006; Yang et al., 2007; McHugh et al., 2017). During stable periods at night (1-3 hour length), CO_2 concentrations will increase at the soil or canopy surface until disbursed by downward turbulence described as nocturnal intermittency (Hicks et al., 2015). While both EC and BREB systems detect the turbulent dispersion of CO_2 often with a spike in flux, only the concentration profile provided by the BREB station can detect the surface buildup of CO_2 before the intermittent turbulence. Using the aerodynamic method, this concentration difference can be accounted for in the NEE using a very conservative constant for the turbulent diffusivity coefficient (0.005 $m^2 s^{-1}$) (Dugas et al., 1999). By using this constant, the combined BREB-aerodynamic method system can more effectively estimate nighttime respiration that may be underestimated by EC.

While the sum of CO_2 flux over the SMB application is greater than the FP (indicating greater emissions of CO_2) during the measurement period (Table 2.3 and Figure 2.1), the comparison of nighttime emissions with daytime emissions may provide an indication of the canopy CO_2 accumulation rates. The CO_2 flux measurements represent the exchange of CO_2 between the soil and crop biomass above the soil surface with the atmosphere. If it was assumed that CO_2 flux measured at night is an indication of respiration by the soil, the SMB application and the canopy, then it is apparent that the SMB treatment is losing more CO_2 than the FP at night.

If it is assumed that a greater rate of CO_2 loss continues during the day from the SMB treatment, then the data presented indicates that the accumulation of CO_2 by the growing canopy during the day is also greater for the SMB treatment. The rate of CO_2 accumulation by the growing canopies can be compared between the two treatments by subtracting the mean nighttime CO_2 flux from the daytime as shown in Table 2.4 and as described by O'Dell et al. (2018). This approach averages the flux during the day between 1000 and 1600 hrs and night between 2200 and 0400 hrs for each month, omitting the morning and evening transition periods when changes to incoming and outgoing energy result in a change in direction of energy and flux. Though NEE shows respiration occurring for more than half the day for most of the year, by subtracting the average nighttime respiration during similar conditions from the period of daytime photosynthetic activity, we derived a first-order measure of how much more the canopy compensates for greater nighttime respiration. Table 2.4 shows day and nighttime means for the EC method with the daytime minus the nighttime means. Highlighted cells indicate the treatment with the greater canopy accumulation.

Data that supports this effect of greater canopy accumulation comes from above-ground biomass maize measurements (above-ground vegetation including maize grain) taken on 20 September 2017. Table 2.5 shows that the above-ground biomass of the SMB treatment canopy was significantly different than the FP treatment canopy when analyzed using a two-way ANOVA focused on the nutrient effect using the least-squares mean separation ($p < 0.05$). ANOVA type III tests for fixed effects indicated the nutrient effect was a significant factor of the above-ground biomass ($F(1,12) = 5.46$, $p = 0.0376$), while the tillage and the nutrient by tillage interaction effects were not significant.

Table 2.4. Monthly mean day and night CO_2 flux using EC data (g CO_2 m^{-2} hr^{-1}), with day minus night means denoting excess nighttime respiration.

	FP			SMB		
Month	**Day†**	**Night‡**	**Day – Night§**	**Day**	**Night**	**Day - Night**
Oct 2016	-0.239	0.267	-0.506	-0.305	0.299	**-0.604**
Nov 2016	-0.174	0.059	-0.234	-0.165	0.186	**-0.351**
Dec 2016	-0.005	0.157	-0.162	0.012	0.205	**-0.193**
Jan 2017	0.012	0.227	-0.215	-0.035	0.256	**-0.290**
Feb 2017	-0.240	0.238	-0.478	-0.328	0.236	**-0.564**
Mar 2017	-0.561	0.261	-0.822	-0.818	0.339	**-1.156**
Apr 2017	-0.919	0.673	-1.591	-1.080	0.653	**-1.733**
May 2017	-0.729	0.721	-1.450	-0.982	0.710	**-1.692**
Jun 2017	0.224	0.730	**-0.506**	1.016	1.400	-0.383
Jul 2017	-2.391	1.559	**-3.950**	-2.046	1.538	-3.584
Aug 2017	-3.728	1.315	-5.042	-3.841	1.406	**-5.248**
Sep 2017	-1.026	0.881	-1.907	-1.067	0.952	**-2.019**

†Day values are mean flux between 1000 and 1600 hrs by month.
‡Night values are mean flux between 2200 and 0400 hrs.
§Day minus night in bold indicate treatment with greater accumulation rates for a particular month.

Table 2.5. Nutrient effect for above-ground maize biomass 2017.

Nutrient Treatment	**Mean ($Mg\ ha^{-1}$)**	**Standard error ($Mg\ ha^{-1}$)**	***n***
SMB	1.95 a†	0.154	8
FP	1.47 b	0.126	8

†Biomass means followed by different letters indicate significant differences between treatments (Fisher's LSD test, $p \leq 0.05$).

When comparing the tillage effect within the nutrient application treatment for the above-ground maize biomass measurements using the two-way ANOVA, there was a significant difference between the no-till SMB and the FP tilled (Table 2.6). There was otherwise no significant difference between the other treatments.

The greater CO_2 uptake by the canopy on the SMB plot could also indicate recycling of respired CO_2. Others have shown photosynthetic overcompensation by the canopy (i.e., a fertilization effect) that occurs with greater nighttime respiration (Wan et al., 2009) or greater concentrations of CO_2 (Haworth et al., 2016). It is possible that availability of greater concentrations of CO_2 from nighttime respiration provides a photosynthetic boost in the morning. Decomposition of the SMB during the day may also contribute to this CO_2 fertilization affect. While some C_4 species like maize do not necessarily show an increase in net assimilation of CO_2 with higher concentrations (Long et al., 2005; Abebe et al., 2016), C_3 weed species may take advantage of greater CO_2 concentrations (Patterson and Flint, 1980). Other studies found that greater CO_2 concentrations benefited maize growth under restricted water conditions (Leakey, 2009; Manderscheid et al., 2014), which may have enhanced the SMB treatment since two dry periods occurred during the 2017 growing season.

A regression comparing the CO_2 flux between the FP and SMP treatments during the daytime hours of 1000 to 1600 for the growing season (July-September 2017) suggests increasing biomass production by the SMB plot (Figure 2.8) by the end of the period. The black lines in Figure 2.8 represent the linear regression while the red lines designate lines of equality (1:1 slopes). The July regression indicates that the FP treatment sequestered more than the SMB, especially during the peak photosynthetic period, while the SMB treatment had greater positive

Table 2.6. Above-ground maize biomass for 2017 growing season by tillage within nutrient effect.

Treatment	Mean (Mg ha^{-1})	Standard Error (Mg ha^{-1})	*n*
SMB Tilled	1.86 ab†	0.283	4
SMB No-Till	2.03 a	0.162	4
FP Tilled	1.33 b	0.207	4
FP No-Till	1.62 ab	0.128	4

†Biomass means followed by different letters indicate significant differences between treatments (Fisher's LSD test, $p \leq 0.05$).

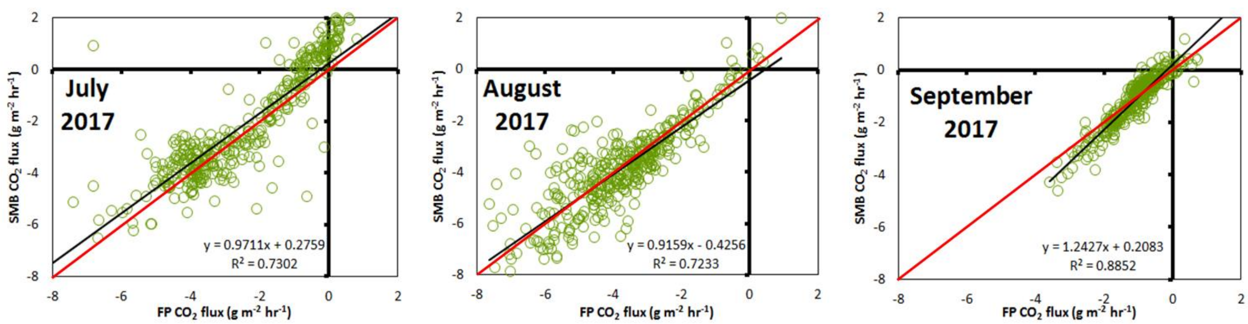

Figure 2.8. Linear regression equations and trendlines in black and lines of equality in red comparing the EC method CO_2 flux (g m^{-2} hr^{-1}) between the SMB (y-axis) and the FP (x-axis) treatments for July through September between 1000 to 1600 hrs.

emissions compared to the FP. However, by the end of the growing season in September, the SMB treatment exhibited greater negative daytime fluxes.

Mean SOC mass (the top 0-15 cm below the soil surface) was 31.3 Mg SOC ha^{-1} sampled before the first SMB application (March 2016) (Table 2.7). The mean SOC for the SMB plot measured in March 2017 one year after the application was not significantly different than the mean FP plot, which were both still under no-till management. Mean SOC, measured in November 2017 after the second SMB application, showed no significant differences between the SMB tilled plot (45.4 Mg SOC ha^{-1}) and the SMB no-till (45.6 Mg SOC ha^{-1}), while both SMB plots were significantly different than the FP tilled (35.8 Mg SOC ha^{-1}) (Table 2.7). These measurements indicate a 45% increase in SOC for the tilled SMB plot and 14% SOC increase for the tilled FP plot between March 2016 and November 2017, indicating a much greater increase in SOC on the SMB plots with a smaller increase on the FP practice plot. Increases in SOC on the tilled plots may be due in part to residue incorporation.

A two-way ANOVA examined the effects of the tillage factor within the nutrient application treatment for the November 2017 SOC measurements (Table 2.8) similar to the analysis of the November 2017 grain yield (Table 2.2) and used the same Bonferroni mean separation adjustment. Similar to the grain yield, ANOVA type III tests for fixed effects showed the nutrient effect was a significant factor of SOC ($F(1,41) = 13.2$, $p = 0.0008$), while the tillage effect was not ($F(1,41) = 2.34$, $p = 0.134$). Unlike grain yield, the interaction between the nutrient and tillage effect was not significant, indicating the nutrient effect did not vary by tillage ($F(1,41) = 1.93$, $p = 0.173$) for SOC. Similar to the grain yield, the least-squares mean separation for the nutrient application effect shows that the SOC for the SMB application was

Table 2.7. Mean soil organic carbon (SOC) mass and standard error mass for the 0-15 cm depth below the soil surface before biomass application in March 2016, and for the FP and SMB treatments in March and November 2017.

Treatment	**Month-Year of Measurement**	**Mean SOC (Mg SOC ha^{-1})**	**Standard Error (Mg SOC ha^{-1})**	***n***
Field Before Treatment	March 2016	31.3 c †	1.52	4
FP No-Till	March 2017	34.4 bc	0.650	13
SMB No-Till	March 2017	37.0 bc	0.937	14
FP No-Till	November 2017	41.4 ab	2.28	6
FP Tilled	November 2017	35.8 bc	1.16	16
SMB No-Till	November 2017	45.6 a	2.11	9
SMB Tilled	November 2017	45.4 a	1.88	14

†SOC means followed by different letters indicate significant differences between treatments (Tukey's Honest Significant Difference test, $p \leq 0.05$).

Table 2.8. Mean 2017 SOC mass and standard error for the 0-15 cm depth by nutrient, tillage, and tillage within nutrient effects for November 2017 SOC measurements.

Effect	**Treatment**	**Mean SOC (Mg SOC ha^{-1})**	**Standard Error (Mg SOC ha^{-1})**	***n***
Nutrient	SMB	45.5 a †	1.38	23
	FP	37.3 b	1.16	22
Tillage	Tilled	40.3 a	1.38	30
	No-till	43.9 a	1.61	15
Tillage within Nutrient	SMB Tilled	45.4 a	1.88	14
	SMB No-till	45.6 a	2.11	9
	FP Tilled	35.8 b	1.16	16
	FP No-till	41.4 ab	2.28	6

†SOC mass means followed by different letters indicate significant differences between treatments (Bonferroni adjusted mean separation, $p \leq 0.05$).

significantly different than the FP SOC ($p < 0.05$), while the mean SOC was not significantly different for the tilled than the no-till treatments (Table 2.8).

Both SMB tilled and SMB no-till showed significantly greater mean SOC than the mean FP tilled SOC (Table 2.8). This was different than the mean grain yield which showed significant differences between both no-till treatments and the mean FP tilled grain yield. The differences between mean SOC nutrient factor and the grain yield tillage factor between the treatments could be explained in part by the greater water use efficiency that no-till can provide in improving yield during dry periods.

The SMB application before the start of CO_2 flux data collection in October 2016 and toward the end of the experiment totaled 166 Mg dry biomass for 8.4 ha or a total of 87.6 Mg C. The difference in emissions between the SMB plot area and an equivalent FP area totaled 68.2 Mg of CO_2 for the field or 18.6 Mg of C, when using EC NEE calculations extrapolated for the 569 days from the first SMB application. The higher CO_2 emissions from the SMB treatment is believed to be due to the breakdown of organic carbon, which represents approximately 53% of the SMB based on dry matter (Sullivan, et al., 2017).

Given concerns about the underestimate of nighttime EC flux, the combined BREB-aerodynamic method may provide a more conservative estimate of the total emissions for use in quantifying environmental impact and the potential to sequester carbon. Combining the increase in soil organic matter with overall NEE could provide supporting evidence to assess the value of SMB applications.

Over time, more of the SMB C may be respired through decomposition and respiration, however this experiment shows that along with greater emissions there is also potential to increase biomass and soil organic matter accumulation and fertility. Tian *et al.* (2009) reviewed the impact of biosolids-amended fields in Illinois and found increases in soil organic C that was greater than fertilizer controls over 34 years of land reclamation, even suggesting that biosolids could turn degraded crop soils into C sinks. While our flux measurements showed that SMB applications have greater emissions than typical farmer fertilizer practices, as Tian (2009) indicates, there is value and many co-benefits to the soil and ecosystem biomass C cycling from the beneficial reuse of waste. Given that the costs of waste incineration or landfilling far outweigh the benefits (Golueke and Diaz, 1996), measuring the agronomic, soil and atmospheric effects of industrial fermentation waste recycling can provide greater understanding of the life cycle impacts for greater environmental sustainability.

When conditions are “favorable” (i.e., “turbulent”) during the day, the EC and BREB methods agree. The nature of nighttime turbulence poses challenges for measuring NEE using turbulence-based methods, such as EC, BREB, and aerodynamic methods. The data presented in this study showed that during the night, the EC and aerodynamic method generally did not agree. New scientific investigation should focus on the pooling and drainage of CO_2 at the surface during stable conditions at night. While the network of EC stations grows to increase understanding of the carbon cycle in agriculture and other ecosystems, profiles of meteorological measurements as provided by BREB and other approaches can be used to understand the nighttime buildup of CO_2 and other atmospheric characteristics near the surface. This complexity needs to be addressed using both spatial differences and turbulent exchanges.

Conclusions

The application of spent microbial biomass from industrial fermentation can achieve yields that are similar to typical farmer practices, though further study is required to determine application rates and timing that would be economically competitive and provide optimum value to the farmer. While multiple instruments and five methods were used to calculate CO_2 flux, all methods showed greater CO_2 emissions over the spent microbial biomass treatment than the farmer practice. Of particular interest was investigating the nighttime flux that can be underestimated by the EC method. Alternate flux-gradient micrometeorological approaches including BREB and aerodynamic methods, showed greater total NEE for both treatments and can be used to estimate nighttime flux especially during periods of low turbulence when micrometeorological techniques are challenged. This study found that while annual NEE for the spent microbial biomass application was greater than for the farmer practice, some of the excess emissions are apparently recycled back into the ecosystem through enhanced photosynthesis to produce more plant biomass and soil C. The additions of the spent microbial biomass provided yields on par with typical farmer practices when applied at greater rates and have the potential to enrich ecosystem productivity and environmental sustainability through conversion of waste nutrients into plant biomass and soil organic matter.

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References

Abebe, A., Pathak, H., Singh, S. D., Bhatia, A., Harit, R. C. and Kumar, V. (2016) 'Growth, yield and quality of maize with elevated atmospheric carbon dioxide and temperature in north-west India', *Agriculture, Ecosystems and Environment*. Elsevier B.V., 218, pp. 66–72. doi: 10.1016/j.agee.2015.11.014.

Adom, F., Dunn, J. B., Han, J. and Sather, N. (2014) 'Life-cycle fossil energy consumption and greenhouse gas emissions of bioderived chemicals and their conventional counterparts', *Environmental Science and Technology*, 48(24), pp. 14624–14631. doi: 10.1021/es503766e.

Alfieri, J. G., Blanken, P. D., Smith, D. and Morgan, J. (2009) 'Concerning the measurement and magnitude of heat, water vapor, and carbon dioxide exchange from a semiarid grassland', *Journal of Applied Meteorology and Climatology*, 48(5), pp. 982–996. doi: 10.1175/2008JAMC1873.1.

Angell, R. F., Svejcar, T., Bates, J., Saliendra, N. Z., and Johnson, D. A. (2001) 'Bowen ratio and closed chamber carbon dioxide flux measurements over sagebrush steppe vegetation', *Agricultural and Forest Meteorology*, 108(2), pp. 153–161. doi: 10.1016/S0168-1923(01)00227-1.

Aubinet, M. (2008) 'Eddy covariance CO2 flux measurements in nocturnal conditions: an analysis of the problem.', *Ecological applications : a publication of the Ecological Society of America*, 18(6), pp. 1368–78. doi: 10.1890/06-1336.1.

Baldocchi, D. D. (2003) 'Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future', *Global Change Biology*, 9(4), pp. 479–492. doi: 10.1046/j.1365-2486.2003.00629.x.

Barr, A. G., Richardson, A. D., Hollinger, D. Y., Papale, D., Arain, M. A., Black, T. A., Bohrer, G., Dragoni, D., Fischer, M. L., Gu, L., Law, B. E., Margolis, H. A., Mccaughey, J. H., Munger, J. W., Oechel, W. and Schaeffer, K. (2013) 'Use of change-point detection for friction-velocity threshold evaluation in eddy-covariance studies', *Agricultural and Forest Meteorology*, 171–172, pp. 31–45. doi: 10.1016/j.agrformet.2012.11.023.

Bonneville, M. C., Strachan, I. B., Humphreys, E. R. and Roulet, N. T. (2008) 'Net ecosystem CO2 exchange in a temperate cattail marsh in relation to biophysical properties', *Agricultural and Forest Meteorology*, 148(1), pp. 69–81. doi: 10.1016/j.agrformet.2007.09.004.

Bowen, I. S. (1926) 'The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface', *Physical review*, 27(6), pp. 779–787. doi: https://doi.org/10.1103/PhysRev.27.779.

Brutsaert, W. (1982) *Evaporation into the Atmosphere*. Dordrecht: D. Reidel Publishing Companyt. doi: 10.1007/978-94-017-1497-6.

Campbell, G. S. (1985) *Soil Physics with BASIC: Transport Models for Soil-Plant Systems, Elsevier Science*. Perth: Elsevier. doi: 10.1016/S0166-2481(08)70144-2.

Chapin, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., Clark, D. A., Harmon, M. E., Schimel, D. S., Valentini, R., Wirth, C., Aber, J. D., Cole, J. J., Goulden, M. L., Harden, J. W., Heimann, M., Howarth, R. W., Matson, P. A., McGuire, A. D., Melillo, J. M., Mooney, H. A., Neff, J. C., Houghton, R. A., Pace, M. L., Ryan, M. G., Running, S. W., Sala, O. E., Schlesinger, W. H. and Schulze, E. D. (2006) 'Reconciling carbon-cycle concepts, terminology, and methods', *Ecosystems*, 9(7), pp. 1041–1050. doi: 10.1007/s10021-005-0105-7.

Chiaramonti, D. and Recchia, L. (2010) 'Is life cycle assessment (LCA) a suitable method for quantitative CO2 saving estimations? the impact of field input on the LCA results for a pure vegetable oil chain', *Biomass and Bioenergy*. Elsevier Ltd, 34(5), pp. 787–797. doi: 10.1016/j.biombioe.2010.01.022.

Caéfalvay, E., Akien, G. R., Qi, L. and Horváth, I. T. (2015) 'Definition and application of ethanol equivalent: Sustainability performance metrics for biomass conversion to carbon-based fuels and chemicals', *Catalysis Today*. Elsevier B.V., 239, pp. 50–55. doi: 10.1016/j.cattod.2014.02.006.

Dugas, W. A. (1993) 'Micrometeorological and chamber measurements of CO2 flux from bare soil', *Agricultural and Forest Meteorology*, 67(1–2), pp. 115–128. doi: 10.1016/0168-1923(93)90053-K.

Dugas, W. A., Heuer, M. L. and Mayeux, H. S. (1999) 'Carbon dioxide fluxes over bermudagrass, native prairie, and sorghum', *Agricultural and Forest Meteorology*, 93(2), pp. 121–139. doi: 10.1016/S0168-1923(98)00118-X.

Dyer, A. J. (1967) 'The turbulent transport of heat and water vapour in an unstable atmosphere', *Quarterly Journal of the Royal Meteorological Society*, 93(398), pp. 501–508. doi: 10.1002/qj.49709339809.

Dyer, A. J. and Hicks, B. B. (1970) 'Flux- gradient relationships in the constant flux layer', *Quarterly Journal of the Royal Meteorological Society*, 96(410), pp. 715–721. doi: 10.1002/qj.49709641012.

Eghball, B., Wienhold, B. J., Gilley, J. E. and Eigenberg, R. A. (2002) 'Mineralization of manure nutrients', *Journal of Soil and Water Conservation*, 57(6), pp. 470–473. doi: 10.1006/meth.2001.1262.

Ellen MacArthur Foundation (2013) *Towards the Circular Economy Vol. 1: an economic and business rationale for an accelerated transition, Ellen MacArthur Foundation*. Available at: https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition.

Ellert, B. H. and Bettany, J. R. (1995) 'Calculation of organic matter and nutrients stored in soils under contrasting management regimes', *Canadian Journal of Soil Science*, 75(4), pp.

529–538. doi: 10.4141/cjss95-075.

Emmerich, W. E. (2003) 'Carbon dioxide fluxes in a semiarid environment with high carbonate soils', *Agricultural and Forest Meteorology*, 116(1–2), pp. 91–102. doi: http://dx.doi.org/10.1016/S0168-1923(02)00231-9.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N. O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, J., Moors, E., Munger, J. W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K. and Wofsy, S. (2001) 'Gap filling strategies for defensible annual sums of net ecosystem exchange', *Agricultural and Forest Meteorology*, 107(1), pp. 43–69. doi: 10.1016/S0168-1923(00)00225-2.

Figueres, C., Schellnhuber, H. J., Whiteman, G., Rockström, J., Hobley, A. and Rahmstorf, S. (2017) 'Three years to safeguard our climate', *Nature*, 546(7660), pp. 593–595. doi: 10.1038/546593a.

Finnigan, J. (2006) 'The storage term in eddy flux calculations', *Agricultural and Forest Meteorology*, 136(3–4), pp. 108–113. doi: 10.1016/j.agrformet.2004.12.010.

Frank, A. B. and Dugas, W. A. (2001) 'Carbon dioxide fluxes over a northern, semiarid, mixed-grass prairie', *Agricultural and Forest Meteorology*, 108(4), pp. 317–326. doi: 10.1016/S0168-1923(01)00238-6.

Gilmanov, T. G., Johnson, D. A. and Saliendra, N. Z. (2003) 'Growing season CO2 fluxes in a sagebrush-steppe ecosystem in Idaho: Bowen ratio/energy balance measurements and modeling', *Basic and Applied Ecology*, 4(2), pp. 167–183. doi: 10.1078/1439-1791-00144.

Gilmanov, T. G., Morgan, J. A., Hanan, N. P., Wylie, B. K., Rajan, N., Smith, D. P. and Howard, D. M. (2017) 'Productivity and CO2 Exchange of Great Plains Ecoregions. I. Shortgrass Steppe: Flux Tower Estimates', *Rangeland Ecology and Management*. The Authors, 70(6), pp. 700–717. doi: 10.1016/j.rama.2017.06.007.

Gilmanov, T. G., Svejcar, T. J., Johnson, D. A., Angell, R. F., Saliendra, N. Z. and Wylie, B. K. (2006) 'Long-Term Dynamics of Production , Respiration , and Net CO 2 Exchange in Two Sagebrush-Steppe Ecosystems', *Rangeland Ecology & Management*, 59(6), pp. 585–599. doi: 10.2111/05-198R1.1.

Golueke, C. G. and Diaz, L. F. (1996) 'Historical Review of Composting and its Role in Municipal Waste Management', *The Science of Composting*, pp. 3–14. doi: 10.1007/978-94-009-1569-5_1.

Graf, A., van de Boer, A., Moene, A. and Vereecken, H. (2014) 'Intercomparison of Methods for the Simultaneous Estimation of Zero-Plane Displacement and Aerodynamic Roughness Length from Single-Level Eddy-Covariance Data', *Boundary-Layer Meteorology*, 151(2), pp. 373–387. doi: 10.1007/s10546-013-9905-z.

Gregson, N., Crang, M., Fuller, S. and Holmes, H. (2015) ‘Interrogating the circular economy: the moral economy of resource recovery in the EU’, *Economy and Society*. Taylor & Francis, 44(2), pp. 218–243. doi: 10.1080/03085147.2015.1013353.

Gu, L., Falge, E. M., Boden, T., Baldocchi, D. D., Black, T. A., Saleska, S. R., Suni, T., Verma, S. B., Vesala, T., Wofsy, S. C. and Xu, L. (2005) ‘Objective threshold determination for nighttime eddy flux filtering’, *Agricultural and Forest Meteorology*, 128(3–4), pp. 179–197. doi: 10.1016/j.agrformet.2004.11.006.

Guinée, J., Heijungs, R., Huppes, G., Zamagni, A. and Masoni, P. (2011) ‘Life Cycle Assessment : Past, present and future’, *Environmental Science and Technology*, 45(1), pp. 90–96. doi: 10.1021/es101316v.

Gutser, R., Ebertseder, T., Weber, A., Schraml, M. and Schmidhalter, U. (2005) ‘Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land’, *Journal of Plant Nutrition and Soil Science*, 168, pp. 439–446. doi: 10.1002/jpln.200520510.

Halter, M. C. and Zahn, J. A. (2017) ‘Degradation and half-life of DNA present in biomass from a genetically-modified organism during land application’, *Journal of Industrial Microbiology and Biotechnology*. Springer Berlin Heidelberg, 44(2), pp. 213–220. doi: 10.1007/s10295-016-1876-x.

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Tormey, B., Donovan, B., Kandiano, E., Von Schuckmann, K., Kharecha, P., Legrande, A. N. and Bauer, M. (2016) ‘Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2 °c global warming could be dangerous’, *Atmospheric Chemistry and Physics*, 16(6), pp. 3761–3812. doi: 10.5194/acp-16-3761-2016.

Haworth, M., Moser, G., Raschi, A., Kammann, C., Grünhage, L. and Müller, C. (2016) ‘Carbon dioxide fertilisation and supressed respiration induce enhanced spring biomass production in a mixed species temperate meadow exposed to moderate carbon dioxide enrichment’, *Functional Plant Biology*, 43(1), pp. 26–39. doi: 10.1071/FP15232.

Hermann, B. G., Blok, K. and Patel, M. K. (2007) ‘Producing bio-based bulk chemicals using industrial biotechnology saves energy and combats climate change’, *Environmental Science and Technology*, 41(22), pp. 7915–7921. doi: 10.1021/es062559q.

Hicks, B. B. (1985) ‘Application of Forest Canopy—Atmosphere Turbulent Exchange Information’, in Hutchinson, B. A. and Hicks, B. B. (eds) *The Forest-Atmosphere Interaction*. Dordrecht: Springer, pp. 631–644. doi: 10.1007/978-94-009-5305-5.

Hicks, B. B., O’Dell, D. L., Eash, N. S. and Sauer, T. J. (2015) ‘Nocturnal intermittency in surface CO2 concentrations in sub-Saharan Africa’, *Agricultural and Forest Meteorology*. Elsevier B.V., 200, pp. 129–134. doi: 10.1016/j.agrformet.2014.09.007.

Horváth, I. T. (2018) ‘Introduction: Sustainable Chemistry’, *Chemical Reviews*, 118(2), pp. 369–371. doi: 10.1021/acs.chemrev.7b00721.

Irmak, S., Skaggs, K. E. and Chatterjee, S. (2014) 'A Review of the Bowen Ratio Surface Energy Balance Method for Quantifying Evapotranspiration and other Energy Fluxes', *Transactions of the ASABE*, 57(6), pp. 1657–1674. doi: 10.13031/trans.57.10686.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G. and Robenbaum, R. K. (2003) 'IMPACT 2002+: A New Life Cycle Impact Assessment Methodology', *The International Journal of Life Cycle Assessment*, 8(6), pp. 324–330. doi: 10.1007/BF02978505.

Kanemasu, E. T., Wesely, M. L., Hicks, B. B. and Heilman, J. L. (1979) 'Techniques for calculating energy and mass fluxes', in Barfield, B. J. and Gerber, J. F. (eds) *Modification of the aerial environment of plants*. St. Joseph: American Society of Agricultural Engineers, pp. 156–182.

Kormann, R. and Meixner, F. X. (2001) 'An analytical footprint model for non-neutral stratification', *Boundary-Layer Meteorology*, 99(2), pp. 207–224. doi: 10.1023/A:1018991015119.

Lawes, J. B. (1845) *Experiments with manures on wheat, in the year 1844*.

Lawes, J. B. and Gilbert, J. H. (1863) 'The effect of different manures on the mixed herbage of grassland', *Journal of the Royal Agricultural Society of England*, 24, p. 131–164.

Leakey, A. D. B. (2009) 'Rising atmospheric carbon dioxide concentration and the future of C4 crops for food and fuel', *Proceedings of the Royal Society B: Biological Sciences*, 276(1666), pp. 2333–2343. doi: 10.1098/rspb.2008.1517.

Lee, X. and Massman, W. J. (2011) 'A Perspective on Thirty Years of the Webb, Pearman and Leuning Density Corrections', *Boundary-Layer Meteorology*, 139(1), pp. 37–59. doi: 10.1007/s10546-010-9575-z.

Lindroth, A., Grelle, A. and More, A. (1998) 'Long-term measurements of boreal forest carbon balance', *Global Change Biology*, pp. 443–450. doi: 10.1046/j.1365-2486.1998.00165.x.

Long, S. P., Ainsworth, E. A., Leakey, A. D. B. and Morgan, P. B. (2005) 'Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360(1463), pp. 2011–2020. doi: 10.1098/rstb.2005.1749.

Mahrt, L. (2010) 'Computing turbulent fluxes near the surface: Needed improvements', *Agricultural and Forest Meteorology*. Elsevier B.V., 150(4), pp. 501–509. doi: 10.1016/j.agrformet.2010.01.015.

Manderscheid, R., Erbs, M. and Weigel, H. J. (2014) 'Interactive effects of free-air CO2 enrichment and drought stress on maize growth', *European Journal of Agronomy*. Elsevier B.V., 52, pp. 11–21. doi: 10.1016/j.eja.2011.12.007.

McHugh, I. D., Beringer, J., Cunningham, S. C., Baker, P. J., Cavagnaro, T. R., MacNally, R. and Thompson, R. M. (2017) ‘Interactions between nocturnal turbulent flux, storage and advection at an “ideal” eucalypt woodland site’, *Biogeosciences*, 14(12), pp. 3027–3050. doi: 10.5194/bg-14-3027-2017.

Mielnick, P., Dugas, W. A., Mitchell, K. and Havstad, K. (2005) ‘Long-term measurements of CO2flux and evapotranspiration in a Chihuahuan desert grassland’, *Journal of Arid Environments*, 60(3), pp. 423–436. doi: 10.1016/j.jaridenv.2004.06.001.

Monin, A. S. and Obukhov, A. M. (1954) ‘Basic laws of turbulent mixing in the surface layer of the atmosphere’, *Contrib. Geophys. Inst. Acad. Sci. USSR*, 24(151), pp. 163–187.

Monteith, J. and Unsworth, M. (2013) *Principles of Environmental Physics: Plants, Animals, and the Atmosphere: Fourth Edition, Principles of Environmental Physics: Plants, Animals, and the Atmosphere: Fourth Edition*. doi: 10.1016/C2010-0-66393-0.

Moore, A. (2011) ‘Fertilizer potential of biofuel byproducts’, in Bernardes, D. M. A. D. S. (ed.) *Biofuel Production-Recent Developments and Prospects*. InTechOpen. doi: 10.5772/16394.

Nelson, J. D. J., Schoenau, J. J. and Malhi, S. S. (2008) ‘Soil organic carbon changes and distribution in cultivated and restored grassland soils in Saskatchewan’, *Nutrient Cycling in Agroecosystems*, 82(2), pp. 137–148. doi: 10.1007/s10705-008-9175-1.

NOAA (2019) *National Oceanic and Atmospheric Administration Earth System Research Laboratory Global Monitoring Division*. Available at: https://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html (Accessed: 1 January 2019).

O’Dell, D., Eash, N. S., Hicks, B. B., Oetting, J. N., Sauer, T. J., Lambert, D. M., Logan, J., Wright, W. C. and Zahn, J. A. (2018) ‘Reducing CO2 Flux by Decreasing Tillage in Ohio: Overcoming Conjecture with Data’, *Journal of Agricultural Science*, 10(3), p. 1. doi: 10.5539/jas.v10n3p1.

O’Dell, D., Sauer, T. J., Hicks, B. B., Thierfelder, C., Lambert, D. M., Logan, J. and Eash, N. S. (2015) ‘A Short-Term Assessment of Carbon Dioxide Fluxes under Contrasting Agricultural and Soil Management Practices in Zimbabwe’, *Journal of Agricultural Science*, 7(3), pp. 32–48. doi: 10.5539/jas.v7n3p32.

OECD (2011) *Industrial Biotechnology and Climate Change: Opportunities and Challenges*. Paris, France.

Ohmura, A. (1982) ‘Objective Criteria for Rejecting Data for Bowen Ratio Flux Calculations’, *Journal of Applied Meteorology*, 21(4), pp. 595–598. doi: 10.1175/1520-0450(1982)021<0595:OCFRDF>2.0.CO;2.

Patterson, D. . and Flint, E. P. (1980) ‘Potential Effects of Global Atmospheric CO2 Enrichment on the Growth and Competitiveness of C3 and C4 Weed and Crop Plants’, *Weed Science*, 28(1), pp. 71–75.

Payero, J. O., Neale, C. M. U., Wright, J. L. and Allen, R. G. (2003) 'Guidelines for validating Bowen ratio data', *Transactions of the ASAE*, 46(4), pp. 1051–1060. doi: 10.13031/2013.13967.

Perez, P. J., Castellvi, F., Ibañez, M. and Rosell, J. I. (1999) 'Assessment of reliability of Bowen ratio method for partitioning fluxes', *Agricultural and Forest Meteorology*, 97(3), pp. 141–150. doi: 10.1016/S0168-1923(99)00080-5.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J. M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D. and Valentini, R. (2005) 'On the separation of net ecosystem exchange into assimilation and ecosystem respiration: Review and improved algorithm', *Global Change Biology*, 11(9), pp. 1424–1439. doi: 10.1111/j.1365-2486.2005.001002.x.

Rhyner, C. R., Schwartz, L. J., Wenger, R. B. and Kohrell, M. G. (1995) *Waste Management and Resource Recovery*. Boca Raton: CRC Press. doi: 10.1201/9780203734278.

Romero-Hernández, O. and Romero, S. (2018) 'Maximizing the value of waste: From waste management to the circular economy', *Thunderbird International Business Review*. Wiley Periodicals, Inc. doi: 10.1002/tie.21968.

Rosenberg, N. J., Blad, B. L. and Verma, S. B. (1983) *Microclimate: The Biological Environment*. New York: John Wiley & Sons.

Sauer, T. J., Hatfield, J. L., Prueger, J. H. and Norman, J. M. (1998) 'Surface energy balance of a corn residue-covered field', *Agricultural and Forest Meteorology*, 89(3–4), pp. 155–168. doi: 10.1016/S0168-1923(97)00090-7.

Saxton, A. M. (1998) 'A macro for converting mean separation output to letter groupings in Proc Mixed', in *Proc. 23rd SAS Users Group Intl*. Nashville: SAS Institute, pp. 1243–1246.

Skinner, R. H. and Wagner-Riddle, C. (2012) *Micrometeorological Methods for Assessing Greenhouse Gas Flux, Managing Agricultural Greenhouse Gases*. Elsevier Inc. doi: 10.1016/B978-0-12-386897-8.00021-8.

Soil Survey Staff (2017) *Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey*. Available at: https://websoilsurvey.sc.egov.usda.gov/ (Accessed: 10 May 2016).

Stanhill, G. (1969) 'A Simple Instrument for the Field Measurement of Turbulent Diffusion Flux', *Journal of Applied Meteorology*, pp. 509–513. doi: 10.1175/1520-0450(1969)008<0509:ASIFTF>2.0.CO;2.

Stulp, J. R. (1995) 'Social, Political, and Educational Factors Involved in Facilitating Municipal Waste Utilization', in *Agricultural Utilization of Urban and Industrial By-Products*.

Madison, WI: ASA Special Publication 58, pp. 1–9. doi: 10.2134/asaspecpub58.c1.

Sullivan, C. T., Harman, R. M., Eash, N. S., Zahn, J. A., Goddard, J. J., Walker, F. R., Saxton, A. M., Lambert, D. M., McIntosh, D. W., Hart, W. E., Freeland, R. S. and Morrison, J. E. (2017) 'Utilization of spent microbial biomass as an alternative crop nitrogen source', *Agronomy Journal*, 109(5), pp. 1870–1879. doi: 10.2134/agronj2016.12.0742.

Sun, J., Burns, S. P., Delany, A. C., Oncley, S. P., Turnipseed, A. A., Stephens, B. B., Lenschow, D. H., LeMone, M. A., Monson, R. K. and Anderson, D. E. (2007) 'CO2 transport over complex terrain', *Agricultural and Forest Meteorology*, 145(1–2), pp. 1–21. doi: 10.1016/j.agrformet.2007.02.007.

Tanner, C. B. (1960) 'Energy Balance Approach to Evapotranspiration from Crops', *Soil Science Society of America Journal*, 24(1), p. 1. doi: 10.2136/sssaj1960.03615995002400010012x.

Tanner, C. B. and Pelton, W. L. (1960) 'Potential evapotranspiration estimates by the approximate energy balance method of Penman', *Journal of Geophysical Research*, 65(10), pp. 3391–3413. doi: 10.1029/JZ065i010p03391.

Taylor, A. M., Amiro, B. D. and Fraser, T. J. (2013) 'Net CO2 exchange and carbon budgets of a three-year crop rotation following conversion of perennial lands to annual cropping in Manitoba, Canada', *Agricultural and Forest Meteorology*. Elsevier B.V., 182–183, pp. 67–75. doi: 10.1016/j.agrformet.2013.07.008.

Tian, G., Granato, T. C., Cox, A. E., Pietz, R. I., Carlson, C. R. and Abedin, Z. (2009) 'Soil Carbon Sequestration Resulting from Long-Term Application of Biosolids for Land Reclamation', *Journal of Environment Quality*, 38(1), p. 61. doi: 10.2134/jeq2007.0471.

Tuck, C. O., Pérez, E., Horváth, I. T., Sheldon, R. A. and Poliakoff, M. (2012) 'Valorization of biomass: Deriving more value from waste', *Science*, 337(6095), pp. 695–699. doi: 10.1126/science.1218930.

Vanomark, G. M. M. de S., Sobrinho, J. E., Bezerra, J. R. C., dos Santos, C. A. C., de Azevedo, P. V., da Silva, S. T. A. and Bezerra, B. G. (2018) 'Energy balance partitioning and evapotranspiration from irrigated muskmelon under semi-arid conditions', *Bragantia*, 77(1), pp. 168–180. doi: 10.1590/1678-4499.2016453.

Wan, S., Xia, J., Liu, W. and Niu, S. (2009) 'Photosynthetic Overcompensation under Nocturnal Warming Enhances Grassland Carbon Sequestration', *Ecology*, 90(10), pp. 2700–2710. doi: 10.1890/08-2026.1.

Webb, E. K. (1970) 'Profile relationships: The log- linear range, and extension to strong stability', *Quarterly Journal of the Royal Meteorological Society*, 96(407), pp. 67–90. doi: 10.1002/qj.49709640708.

Webb, E. K., Pearman, G. I. and Leuning, R. (1980) 'Correction of flux measurements for density effects due to heat and water vapour transfer', *Q. J. Roy. Meteorol. Soc.*, 106(447), pp. 85–100. doi: http://dx.doi.org/10.1002/qj.49710644707.

Westendorf, M. L. and Wohlt, J. E. (2002) *Brewing by-products: Their use as animal feeds*. Veterinary Clinics of North America: Food Animal Practice. doi: 10.1016/S0749-0720(02)00016-6.

Wilczak, J. M., Oncley, S. P. and Stage, S. A. (2001) 'Sonic anemometer tilt correction algorithms', *Boundary-Layer Meteorology*, 99(1), pp. 127–150. doi: 10.1023/A:1018966204465.

Wofsy, S. C., Goulden, M. L., Munger, J. W., Fan, S. M., Bakwin, P. S., Daube, B. C., Bassow, S. L. and Bazzaz, F. A. (1993) 'Net exchange of CO2 in a mid-latitude forest', *Science*, 260(5112), pp. 1314–1317. doi: 10.1126/science.260.5112.1314.

Wolf, A., Saliendra, N., Akshalov, K., Johnson, D. A. and Laca, E. (2008) 'Effects of different eddy covariance correction schemes on energy balance closure and comparisons with the modified Bowen ratio system', *Agricultural and Forest Meteorology*, 148(6–7), pp. 942–952. doi: 10.1016/j.agrformet.2008.01.005.

Wutzler, T., Lucas-Moffat, A., Migliavacca, M., Knauer, J., Sickel, K., Šigut, L., Menzer, O. and Reichstein, M. (2018) 'Basic and extensible post-processing of eddy covariance flux data with REddyProc', *Biogeosciences*, (February), pp. 1–39. doi: 10.5194/bg-2018-56.

Xu, Y. and Ramanathan, V. (2017) 'Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes', *Proceedings of the National Academy of Sciences*, pp. 1–9. doi: 10.1073/pnas.1618481114.

Yang, B., Hanson, P. J., Riggs, J. S., Pallardy, S. G., Heuer, M., Hosman, K. P., Meyers, T. P., Wullschleger, S. D. and Gu, L. H. (2007) 'Biases of CO2 storage in eddy flux measurements in a forest pertinent to vertical configurations of a profile system and CO2 density averaging', *Journal of Geophysical Research Atmospheres*, 112(20), pp. 1–15. doi: 10.1029/2006JD008243.

Appendix

Abbreviations

Excluding SI units and US States

ai	active ingredient
ANOVA	analysis of variance
asl	above sea level
BREB	Bowen ratio energy balance
C	carbon
C_3	C_3 photosynthesis
C_4	C_4 photosynthesis
CO_2	carbon dioxide
°C	degrees Celsius
C_p	specific heat of air
d	zero plane displacement
EC	eddy covariance
et al.	et alia (and others)
Eq.	equation
F	F-test statistic
FP	farmer practice

G	soil heat flux
GHG	greenhouse gas
h	crop height
H	heat
H	sensible heat flux
hr	hour
IRGA	infrared gas analyzer
k	von Kármán constant
K	potassium
K	turbulent diffusivity
K_h	turbulent diffusivity for sensible heat
LCA	life cycle assessment
LE	latent heat flux
M	momentum
MDS	marginal distribution sampling
n	the number of replications or observations in a statistical sample
N	nitrogen
NEE	net ecosystem exchange
OECD	Organization for Economic Co-operation and Development

p	probability value
P	phosphorus
P	atmospheric pressure
PDO	1,3-propanediol
R	reproductive stage
Ri	gradient Richardson number
R_n	net radiation
SMB	spent microbial biomass
SOC	soil organic carbon
SOM	soil organic matter
T	temperature
U	wind speed
u_*	friction velocity
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTK	University of Tennessee, Knoxville
V	vegetative growth stage of plants
VE	vegetative stage: emergence
V1-Vn	vegetative stages from appearance of leaf 1 to the total number of leaves (n)

VT	vegetative stage: tasseling
W	water vapor
yr	year
z	wind speed height
z_0	roughness parameter
Δ	difference
∂	change
γ	psychrometric constant
ε	ratio of the molecular weight of water to dry air
λ	latent heat of vaporization
ϕ	stability function

CHAPTER 3

CONSERVATION AGRICULTURE AS A CLIMATE CHANGE MITIGATION STRATEGY IN ZIMBABWE

This chapter is expected to be submitted for publication in a peer-reviewed journal upon final review by co-authors. The co-authors on this article included: Neal S. Eash, Bruce B. Hicks, Joel N. Oetting, Thomas J. Sauer, Dayton M. Lambert, Joanne Logan, John J. Goddard, and James A. Zahn. I worked with my major advisor, Professor Neal Eash to plan and execute the research, and I performed data and statistical analysis, provided the first draft of the manuscript, and incorporated co-author input. The role of co-authors included data processing and analysis as well as manuscript co-authorship.

Abstract

Quantifying agriculture's potential to sequester carbon (C) can inform global approaches aimed at mitigating climate change effects. Many factors including climate, crop, soil management practices, and soil type can influence the contribution of agriculture to the global carbon cycle. The objective of this study was to investigate the potential C sequestration potential of conservation agriculture (CA), which includes minimal soil disturbance, maintaining permanent soil cover and crop rotations. The study described here used micrometeorological methods to measure carbon dioxide (CO_2) flux from several alternative CA practices in central Zimbabwe. The study found that micrometeorological methods can detect differences in total CO_2 emissions of agricultural management practices and that CA practices produce less CO_2 emissions. Over three years of measurement, the mean and standard error (SE) of CO_2 emissions for the plot with the most consistent CA practices was 0.705 ± 0.0323 g CO_2 m^{-2} hr^{-1}, significantly less than 0.963 ± 0.0321 g CO_2 m^{-2} hr^{-1} for the plot treated with conventional agricultural management practices. Micrometeorological measurements revealed that the CA

practices of no-till and cover crops produced fewer CO_2 emissions than conventional tillage and fallow.

Introduction

Reducing CO_2 emissions from fossil fuel combustion is a critical step towards averting catastrophic changes to the climate if global temperature change exceeds the 2°C threshold above pre-industrial levels (Clarke et al., 2014; IPCC-SR15, 2018). The role of agriculture in the global context of climate change cannot be ignored. Smith (2016) concluded that agriculture offers several strategies that could help moderate the expected increases in atmospheric CO_2 concentrations. He proposed employing wide-scale changes in soil management that would promote soil C sequestration, such as changes that include restoration, reduced tillage, crop residue retention, cover crops, more diverse crop rotations, better utilization of organic amendments, deeper rooting plant varieties, optimal population densities, and optimal nutrient management (Smith; 2016). However, it is necessary to account for site-specific factors such as climate, soil type, and previous land use.

Following atmospheric convention, a flux is deemed to be positive when CO_2 is emitted from plants or soil to the atmosphere. This flux corresponds to the net ecosystem exchange (NEE) of the ecological community, although care must be taken about the sign convention (Chapin et al., 2006). The rate of exchange is considered to be negative when CO_2 is extracted from the atmosphere and “sequestered” into ecosystem plants (Baldocchi et al., 2001). Soil C reserves are accumulated over millennia, from the decay and assimilation of the organic matter deposited on and within the soil as plants die and decay, such as in prairie/grassland soils, wetlands, peatlands, marshes and the topsoil under forests. The organic C that plants produce from the sequestration of atmospheric CO_2 is transferred to the soil after plant necrosis with both root and plant residue mineralization being fundamental to soil C formation (Kirschbaum, 2000). From the soil ecosystem perspective, the C cycle continues with CO_2 released (emitted) back into the atmosphere through decomposition of both soil and plant organic matter by microorganisms (respiration) and can be accelerated by tillage.

Modifying agricultural practices would appear to be an obvious choice for climate change mitigation, since cropland occupies 11% of the earth's land surface (FAO, 2011) and is intensively managed. Like forests, crop production produces plants that remove CO_2 from the atmosphere.

The three principles of Conservation Agriculture (CA)—minimal soil disturbance, maintaining soil cover with residue and/or mulch, and crop rotation (Hobbs, 2007)—are among the crop management practices described by Smith (2016) that sequester soil C. However, field studies have not always confirmed that these practices sequester soil C (Alvarez and Alvarez, 2005; Gregorich et al., 2005; Ogle et al., 2005; Cheesman et al., 2016). Soil C sequestration depends on the site management, crop, yield, climate, soil type, and agro-ecologies involved.

The current assessment of agriculture is that it is generally a net emitter of CO_2 and other greenhouse gases because of the dominant contribution of CO_2 emissions from soils (Clarke et al., 2014). Many of the relevant soil C sequestration uncertainties result from challenges in measuring soil C stocks, which is made especially difficult considering soil spatial and temporal variability as well as the time needed to measure changes on a mass or volume basis (Eswaran et al., 1993; Paustian et al., 2016). Considering the temporal and spatial variability of soil C, small annual changes in soil C can take greater than five years to detect (Smith, 2004; Necpálová et al., 2014). Taking into account the impact of both climate and management practice on soil organic

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

Micrometeorological methods allow measurement of the exchanges of physical quantities—such as heat and mass—in the atmospheric boundary layer and can be used to estimate the movement of CO_2 and other trace gases between the surface (vegetation canopy, soil or soil cover) and the atmosphere at the field scale (Arya, 2001). By measuring CO_2 flux using micrometeorological methods (e.g., eddy covariance (EC) or Bowen ratio energy balance (BREB)) (Kanemasu et al., 1979), we can estimate the NEE of CO_2 between a surface and the atmosphere for a given agricultural management practice over a given period of time. The NEE summarizes whether an ecosystem is a CO_2 source or sink for a season or a year. Measuring CO_2 flux over several years can provide information about climate and agricultural management impacts on NEE not available from other experimental methods. Negative NEE (net removal of CO_2 from the atmosphere to the ecosystem for a time period) does not always translate into soil C sequestered. However, NEE can be used to show both the short- and long-term CO_2 sink and source potential of an ecosystem and the comparative benefits of factors such as climate and management practice that contribute to the overall CO_2 exchange. For example, the global and regional networks of more than 900 EC measurement stations distributed around the world have produced more than 7000 site-years of data, all of which shed light on factors such as the disturbance of vegetation or soil, plant phenology and climate, which contribute to NEE (Baldocchi, 2014; Chu et al., 2017).

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

Several chamber studies have examined CO_2 emissions over agriculture in Africa (Mapanda et al., 2010, 2011; Kim et al., 2016; Kimaro et al., 2016; Rosenstock et al., 2016). Studies using chambers confront many challenges, including spatial and temporal variability and cumbersome sample processing (Kimaro et al., 2016; Rosenstock et al., 2016). Hence, several studies in Africa have used micrometeorological methods to measure CO_2 exchange rates, though most have been over savanna ecosystems (Kutsch et al., 2008; Williams et al., 2009; Tagesson et al., 2015). Ciais et al. (2011) reviewed the C balances of African ecosystems and reported a need for more observations of C fluxes and stocks, recommending a network of EC flux towers for agroecosystems as well as other terrestrial ecosystems. There are also fewer micrometeorological stations measuring CO_2 flux in subtropical climates as opposed to temperate climates.

Few micrometeorological studies have measured NEE over CA in Africa and most experiment durations have been for less than a year (e.g., O'Dell et al., 2014; 2015). This three year study evaluates cross-seasonal micrometeorological data near Harare, Zimbabwe. The objective was to compare the CO_2 exchange consequences of CA practices with conventionally tilled controls to investigate their potential for soil C sequestration. Measurements used the BREB method due to its ability to enable relevant data to be obtained close to the surface and because of its demonstrated utility for measuring trace gas exchange (Gilmanov et al., 2017).

Materials and Methods

Site Description

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

The site's climate is classified as temperate highland tropical, with a unimodal rainfall pattern of dry winters and rainfall between 700–1000 mm during the six-month growing season. The soils are classified as Chromic Luvisols (Nyamapfene, 1992; IUSS Working Group WRB, 2015), which correspond to Rhodustalfs in the USDA soil taxonomic classification system (Soil Survey Staff, 2014). The soil texture is a sandy clay loam and the study site has a slope of less than 2%. The study site was fallow for two years prior to the beginning of micrometeorological measurements in June 2013.

The study site included four square plots approximately 0.64 ha in size upon which different tillage and crop treatments were applied. Plots were identified by number and treatment sequence summary as is shown in Figure 3.1. BREB stations were established a few meters downwind of the center of each plot; the predominant wind direction from the southeast.

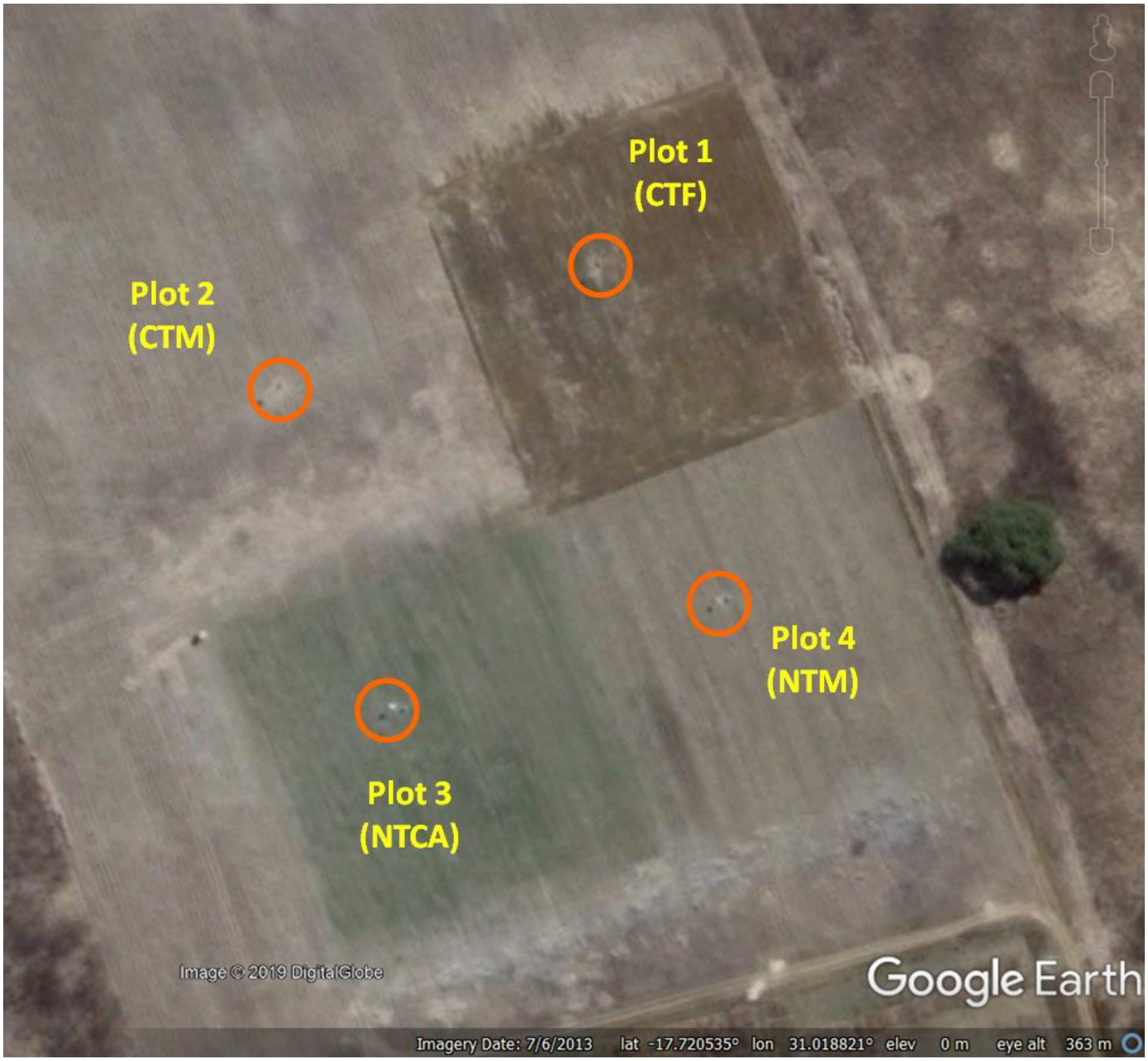

Figure 3.1. Plot layout image (imagery date 6 July 2013) about 2 months following initial planting in 2013, showing BREB station locations in orange circles (Google Earth Pro v7.3.2.5491; data provider DigitalGlobe 2018).

Treatment applications

The analysis that follows distinguishes between wet and dry seasons by year (Figure 3.2). The wet season is considered the same as the cropping season described by Mhlanga et al. (2015). For the purposes of this experiment, the wet season is assumed to start on 1 November and end 30 April of the following year and the dry season is assumed to start on 1 May and end 31 October. An exception is that the dry season experimentation for 2013 was delayed until 15 June when micrometeorological measurements began and was the only season that included irrigation of plots 3 and 4 that were planted with cover crops. Otherwise, the wet and dry season rainfall pattern was similar across years providing comparable environmental conditions by season and year.

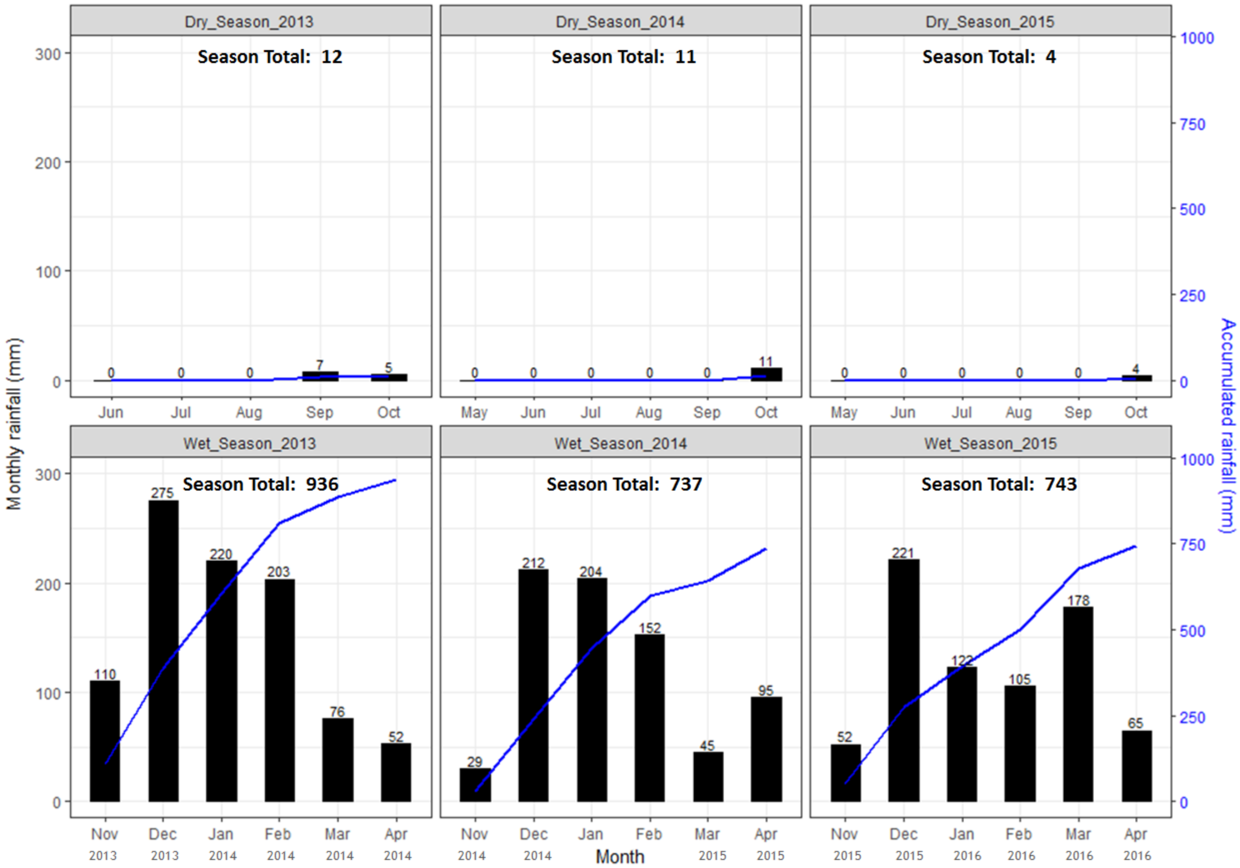

Figure 3.2. Total rainfall by month for each season-year with rainfall amounts (mm) displayed above each bar. The blue curves show the accumulation of rainfall during each of the seasons.

Table 3.1 provides a description of the treatments over the experiment period. CA treatments were selected to compare the net CO_2 flux between CA practices such as no-till and conventional tillage and the effect of additions to CA practices such as intercropping. For example, during the first wet season in 2013, plot 2 (2-CTMaize) was plowed and planted with maize in a conventional approach, while plots 3 (3-NTMaize) and 4 (4-NTMaizeVBI) were planted maize using no-till with a velvet bean (*Mucuna pruriens*) intercrop added (4-NTMaizeVBI) to determine if additional CO_2 would be sequestered through rotation/cropping system intensification. During the second and third wet seasons in 2014 and 2015, a maize trial was conducted on plot 4, which staggered the planting of maize.

To improve comparisons between treatments across years, planting dates would best be scheduled for similar calendar dates on each year. However, scheduling presented logistical issues due to labor availability and resource demand from competing experimental programs. Optimal planting dates also vary based on climate conditions. Simba and Chayangira (2017) describe how small holder farmers in Zimbabwe schedule planting based on the mean start of the growing season, which varies by month depending on the district and is usually dictated solely by the onset of effective planting rains, determined as rainfall of 30-50 mm falling after 15 November.

Table 3.1. Plot treatment operations and dates by season-year.

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

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

BREB methodology was selected for use because of its relative simplicity and its advantage for application over small plots. To obtain in-air measurements that are indeed relevant for studying the characteristics of the surface underneath, it is clearly best to make the measurements as close to the surface as experience and theory permit. In this regard, the BREB approach is better than alternative EC because BREB measures meteorological properties closer to the surface (frequently less than 0.5 m) while EC instruments typically measure at heights generally many meters above the surface. Due to the fact that BREB measurements are closer to the surface, they are more likely to be representative of it. The BREB analysis procedure does not impose a need for determination of an eddy viscosity with which to derive fluxes from measured gradients. Instead, it assumes equality of these eddy diffusivities and apportions heat fluxes according to the gradients based on the assumption that the contributing diffusivities are the same. Hence, the conventional micrometeorological requirement for extensive fetch (of the order of 100 times the height of measurement, see Rosenberg et al. (1983)) is not relevant and measurements can therefore be made closer to the surface than would be required if the analytical (or measurement) methodology were different. Whereas a fetch/height ratio of 100 might well be appropriate for the use of eddy correlation methods, studies elsewhere confirm that consistent flux estimates can be obtained using the Bowen ratio method at fetch to height ratios as low as 20:1 (Heilman et al., 1989).

CO_2 Flux Measurements

Micrometeorological sensor outputs were recorded at five-second intervals. To eliminate sensor biases, the present BREB measurements were made with a rotating arm system designed to switch the level of measurement by temperature, humidity, and CO_2 sensors every five minutes, yielding five-minute averages of differences in temperature, humidity and CO_2 concentration between the levels accessed by the arms (O'Dell et al., 2015). The resulting five-minute averages were then combined to produce 30-min averages, used as input for the BREB analysis routine (Bowen, 1926; Kanemasu et al., 1979; Dugas, 1993; Perez et al., 1999; McGinn and King, 1990; Webb et al., 1980). CO_2 fluxes were then derived as described by O'Dell et al. (2015). Data have been excluded for which the apparent 30-min turbulent diffusivity was negative (Savage et al., 2009). Occasions in which spikes in the flux results exceeded four times the standard deviation of the running average, flux data were removed and linearly interpolated (Vickers and Mahrt, 1997).

Statistical Analysis

Graphical representations of data were developed using the R programming language and environment (The R Foundation, 2018). Statistical analysis of variance (ANOVA) was conducted with the GLIMMIX procedure (SAS V9.4, SAS Institute, Cary, NC). The above-ground maize biomass and grain yield data were available for the 2013 wet season and a one-way ANOVA was used to analyze treatment effects with mean separation analysis performed using Fisher's least significant difference (LSD) test with mean separations converted to letter groupings using the PDMIX800 macro (Saxton, 1998). Maize grain yield was adjusted to 12.5% moisture content.

The mean CO_2 flux by season and for the entire experiment period was analyzed using a repeated measures ANOVA with Tukey's honest significant difference (HSD) mean separation test. Data are presented as mean or sum ± SE.

Results and Discussion

Table 3.2 provides the treatment sequence for each plot over the six seasons of the experiment, using abbreviated plot-treatment names for subsequent reference, with the following acronyms used: conventional tillage (CT), no-till (NT), velvet bean intercrop (VBI), staggered planting for maize trial (SP), pigeonpea (PP), jackbean (JB), fallow (F), and maize (M). In addition to tillage type, the total period sequence label includes all three growing season crop treatments. Note that plot 4 had staggered maize planting during the 2014 and 2015 growing seasons.

Table 3.3 provides a summary of CO_2 fluxes by season-year and treatment. The NEE for all seasons are positive, indicating net emissions for all of the study periods. Results during the 2013 dry season are greater than the estimates previously reported by O'Dell et al. (2015) due to the present rejection of flux evaluations when the indicated turbulent diffusivity was negative. Thus, negative nighttime fluxes were rejected—making total nighttime emissions greater. Table 3.3 shows plot 3 (3-NTJackBean) produced significantly fewer emissions than all of the other plots during the wet season 2015. For four of the six seasons (dry seasons 2014 and 2015 and wet seasons 2013 and 2015), plot 1 (1-CTFallow) produced significantly greater emissions than all the other plots.

Table 3.2. Sequence of treatments for each plot by season-year using abbreviated plot-treatment labels.

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

Table 3.3. NEE, SE, number (N) of 30-min measurements, and mean CO_2 flux followed by Tukey's HSD letter group for each treatment by season-year as compared with repeated measures ANOVA.

Season	**Year**	**Plot-Treatment Abbreviation**	**NEE (kg CO_2 m^{-2} $season^{-1}$)**	**SE of the NEE**	**N**	**Mean NEE (g CO_2 m^{-2} $season^{-1}$)**
Dry	2013	1-CTFallow	3.05	0.0451	6120	0.987 a
		2-NTFallow	2.72	0.0443	6200	0.860 a
		3-NTWheat	1.41	0.112	5587	0.427 b
		4-NTBlueLupin	1.02	0.0258	5672	0.375 b
	2014	1-NTFallow	4.47	0.0465	8277	1.096 a
		2-NTFallow	3.66	0.0485	8347	0.874 b
		3-NTFallow	3.15	0.0363	8431	0.737 c
		4-NTFallow	2.01	0.0384	5153	0.814 bc
	2015	1-CTFallow	2.16	0.0376	5042	0.833 a
		2-NTFallow	2.52	0.0345	7077	0.707 b
		3-NTFallow	2.55	0.0587	8347	0.610 c
		4-NTFallow	2.23	0.0443	6418	0.629 c
Wet	2013	1-TFallow	4.65	0.0764	5776	1.80 a
		2-CTMaize	2.15	0.113	6160	0.941 b
		3-NTMaize	1.67	0.136	6170	0.908 b
		4-NTMaizeVBI	2.12	0.0999	6372	0.915 b
	2014	1-TFallow	3.61	0.0731	6476	1.30 ab
		2-CTMaize	2.54	0.0507	3769	1.42 a
		3-NTMaize	1.27	0.0601	3111	1.01 b
		4-NTMaizeSP	4.19	0.0637	6658	1.38 a
	2015	1-TFallow	3.69	0.0625	5027	1.60 a
		2-NTPigeonpea	3.32	0.0736	6513	1.42 b
		3-NTJackBean	1.85	0.115	6021	1.00 c
		4-NTMaizeSP	3.02	0.0601	5272	1.40 b

The values listed in Table 3.3 lead to the conclusion that there were indeed differences among the plots, as they were affected individually by different treatments and crops. To examine the cause of emission disparity, a closer examination of the data is needed.

Comparisons of the CO_2 flux plotted by time of day for each season-year and each treatment are shown in Figure 3.3. CO_2 flux differences are most clearly observed during the daytime, while nighttime emissions rates often overlap. All plots yielded emissions during the night. For the wet growing seasons, only 2013 shows net sequestration during the day for all three plots planted to maize, while during the 2014 and 2015 wet seasons, only 3-NTMaize and 3-NTJackBean show net daytime sequestration.

The 2013 dry season was different from the other dry seasons; cover crops were planted on plots 3 and 4 (3-NTWheat and 4-NTBlueLupin) and those plots were irrigated. For the 2013 dry season, only 3-NTWheat had net C sequestration during the day. The other three plots had net daytime emissions. The 2014 and 2015 dry seasons show very little difference in emissions between treatments, except for lower daytime (during the hours of 0800 to 1600) emissions for 3-NTFallow during the final 2015 dry season.

All wet seasons (Figure 3.3) show the greatest daytime C sequestration (negative values) for plot 3 (3-NTCA), which had the most consistent application of CA. During the 2013 dry season, 3-NTWheat showed the greatest daytime sequestration and 3-NTFallow showed the lowest daytime emissions during the 2014 and 2015 dry seasons.

Harvest data was available during the 2013 wet season for the total grain yield and above-ground biomass (Table 3.4). The above-ground biomass for 3-NTMaize was significantly greater than both 2-CTMaize and 4-NTMaizeVBI (maize with velvet bean intercrop), while the grain yield for 3-NTMaize was only significantly greater than the grain yield for 2-CTMaize.

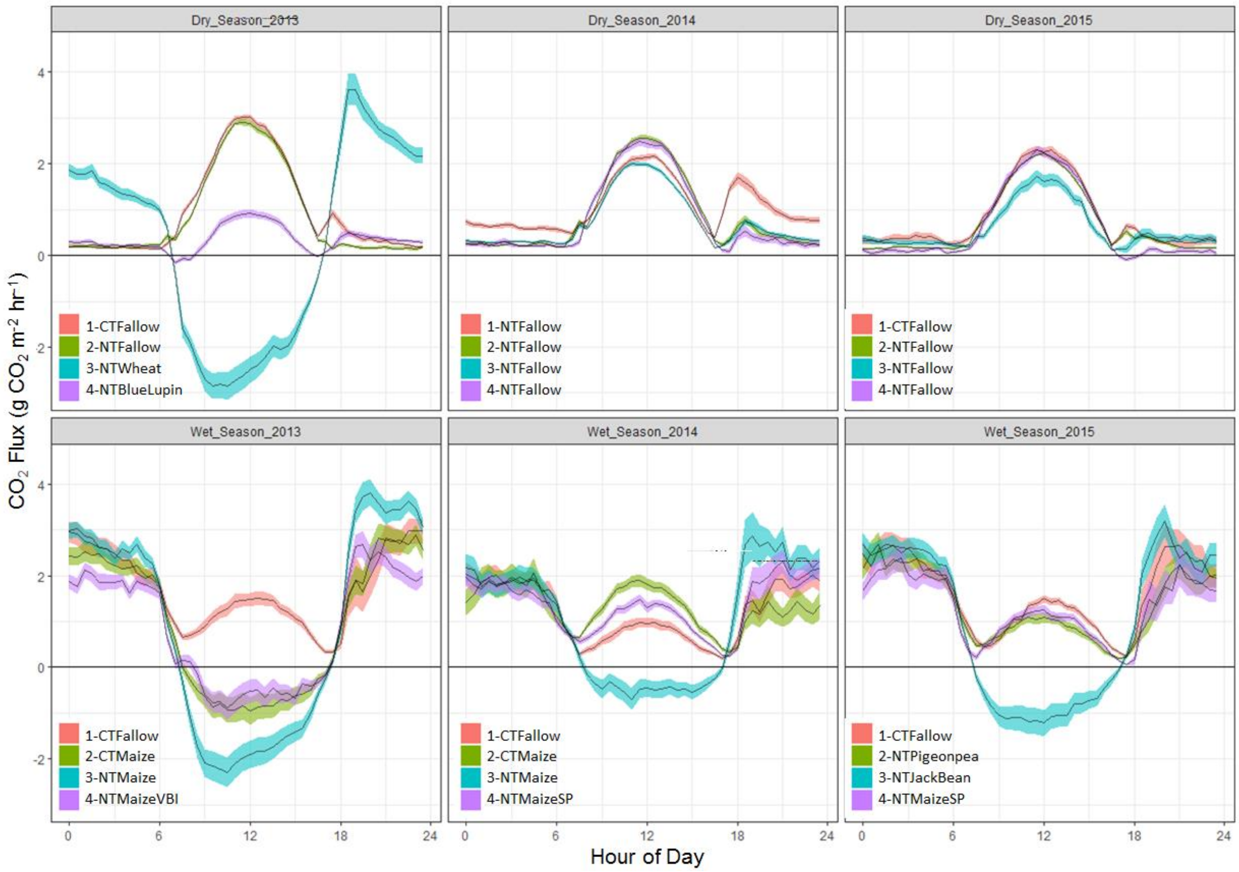

Figure 3.3. Mean CO_2 flux by time of day and season-year for each treatment ± one SE shown in translucent colors. Negative values represent uptake of CO_2 by the canopy and positive values represent emissions from the surface to the atmosphere.

Table 3.4. Mean and SE (Mg ha^{-1}) for grain yield (at 12.5% moisture content) and above-ground biomass for the 2013 wet season harvest for three maize treatments (plots 2-4). Means with different letters were significantly different (P<0.05, ANOVA Fisher LSD, N = 10).

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

The results for grain yield are consistent with the mean CO_2 flux for this season, which shows significantly greater emissions from 2-CTMaize than 3-NTMaize, and no significant difference between and mean CO_2 flux for 3-NTMaize and 4NTMaizeVBI.

Figure 3.4 shows the latent heat flux (LE) by time of day and season-year. Daytime LE was considerably greater during the 2013 dry season due to irrigation for the two cover crops (3-NTWheat and 4-NTBlueLupin) than during the 2014 and 2015 dry seasons.

The nighttime data illustrated in Figures 3.3 and 3.4 are particularly informative, since the high exchange rates evident for the CO_2 results are not mirrored in the LE data. The negligible nighttime LE in the wet season, when water was plentiful, is as expected. The ability of the BREB methodology to reproduce this expected LE can be interpreted as an indication that the approach is working. The high CO_2 flux at night, especially during wet seasons (Figure 3.3), can be attributed primarily to sub-surface biotic factors (soil microbes and root respiration). However, given that available heat energy becomes very small at night, the magnitude of positive nighttime CO_2 flux can be uncertain when quantified by turbulence-based micrometeorological methods, such as BREB (Dugas et al., 1999).

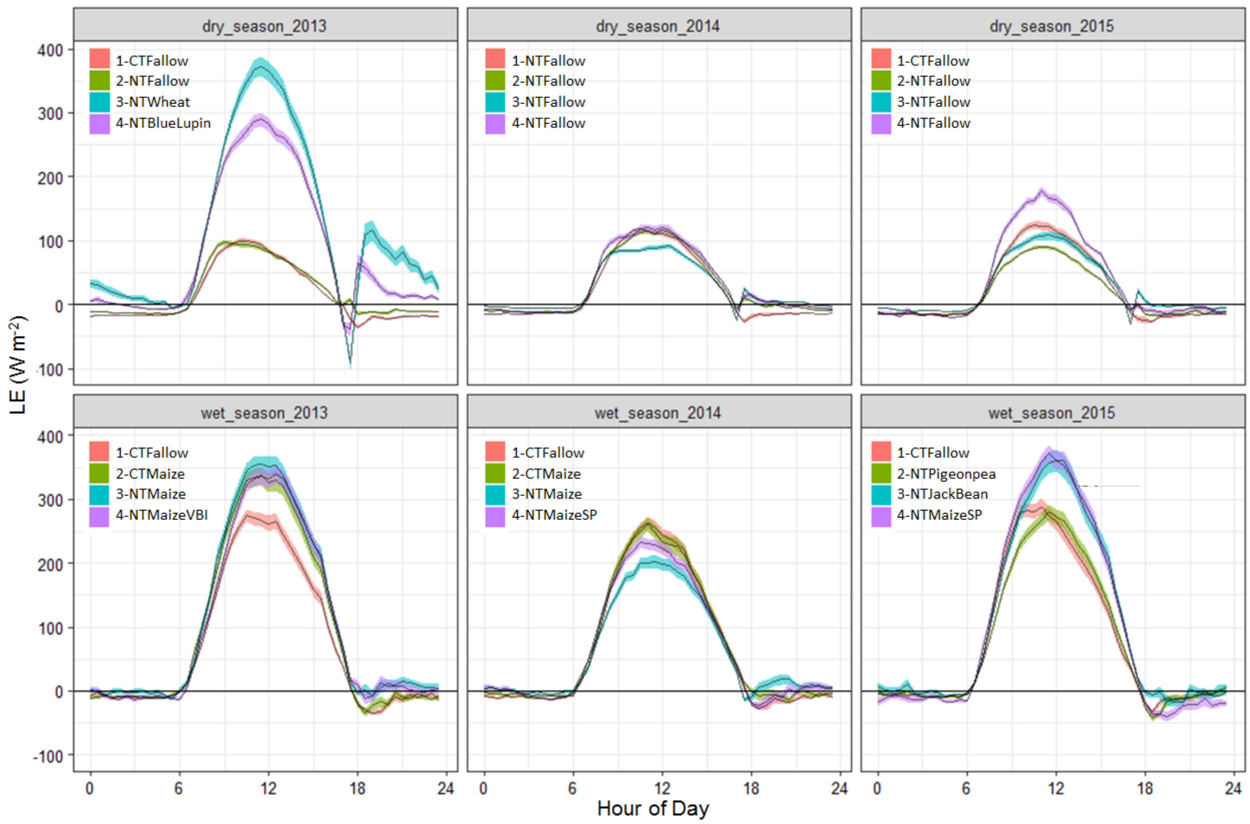

Figure 3.4. Mean latent heat flux (LE) (W m^{-2}) by time of day and season-year for each treatment ± one SE shown in translucent colors.

In the dry seasons, the outstanding feature that highlights the association between water and CO_2 flux is exemplified by the irrigated wheat crop of 2013 (Figure 3.3). It is evident, therefore, that the high CO_2 emission rates at night are associated with the presence of water. The origin of this nocturnal CO_2 emission was indisputably associated with both plant respiration and soil microbial activity. Irrigation not only provides for cover crop growth during the dry season, but also enhances microbial activity as shown during nighttime hours in Figure 3.3 (Orchard and Cook, 1983; Liu et al., 2010). Inspection of Figure 3.4 shows, however, that it is only for the irrigated plots in 2013 that the LE at night indicates respiration. Elsewhere, the nighttime LE rates are low, as expected, and indicative of the conventional curtailment of plant transpiration at night.

Examples of distinctive LE and CO_2 flux relationships include the greatest daytime sequestration found in 3-NTMaize (blue) along with the greatest daytime LE during the 2013 wet season (Figure 3.5). Another relationship that can be seen when comparing LE with CO_2 flux is apparent during the 2013 wet season where the greatest daytime CO_2 emissions occurs over the 1-TFallow (red) with the smallest daytime LE during that period showing that total evapotranspiration is decreased without plant transpiration, while daytime respiration rates contribute to total evaporation from the soil (Figure 3.5).

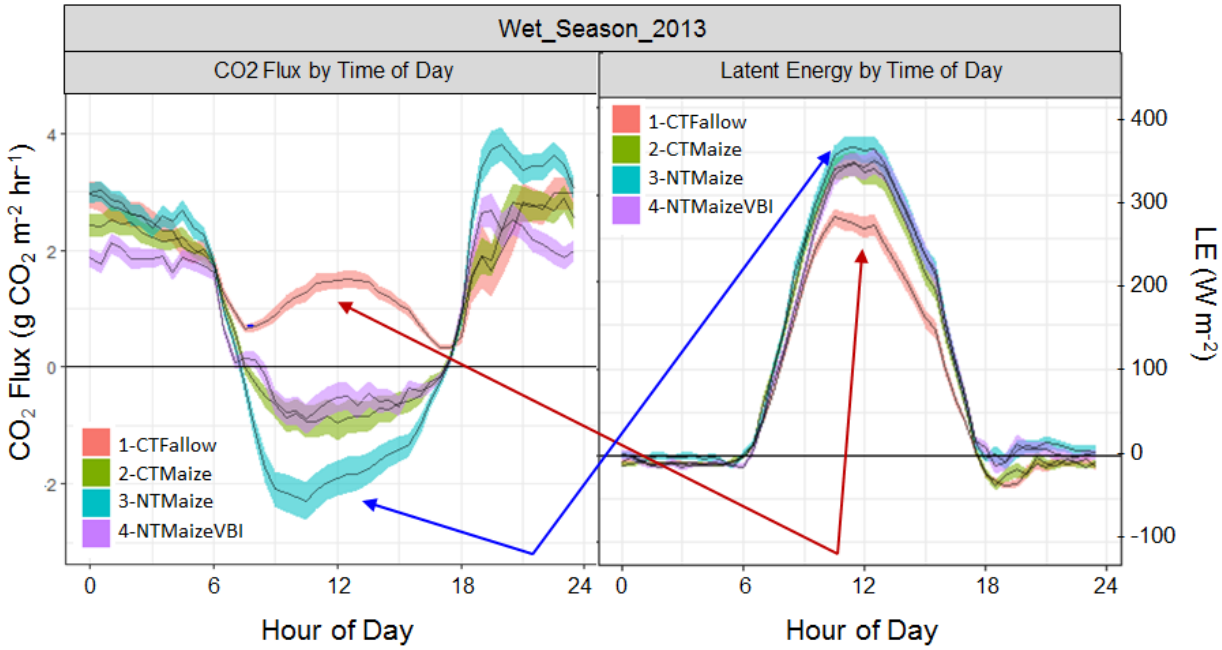

Figure 3.5. CO_2 flux and latent heat flux (LE) by time of day for wet season 2013 with blue arrows showing the relationship between CO_2 flux and LE for 3-NTMaize and red arrows showing the relationship between CO_2 flux and LE for 1-CTFallow.

During the first dry season in 2013, the total NEE for the two cover crops, 3-NTWheat (1.41 ± 0.113 kg m^{-2}) and 4-NTBlueLupin (1.02 ± 0.0258 kg m^{-2}) were significantly less than the two fallow plots and not significantly different from zero (at the 90% probability level), i.e., the cover crops were essentially in carbon-cycle equilibrium. The negative mean daytime fluxes (Figure 3.3) indicate strong photosynthesis by 3-NTWheat, while the greater nighttime flux indicates greater respiration for the wheat cover crop at night.

Several micrometeorological studies reported that winter wheat sequestered C (Moureaux et al., 2008; Gebremedhin et al., 2012), while Gilmanov et al. (2014) found that many legume crops, such as soybean, peanut (*Arachis hypogaea* L.) and pea (*Pisum sativum* L.), were net sources of C—though the perennial legume, alfalfa (*Medicago sativa* L.), sequestered more C than wheat. In a seven-year experiment comparing the effects of N fertilization with leguminous and non-leguminous cover crops, Sainju et al. (2002) found that the non-legume, rye (*Secale cereale* L.), produced greater SOC concentrations than two legumes, hairy vetch (*Vicia villosa* Roth.) and crimson clover (*Trifolium incarnatum* L.), supporting greater C sequestration shown for wheat in this experiment as compared to blue lupin.

During the first wet season in 2013, the total NEE was less in 3-NTMaize treatment (1.67 ± 0.136 kg m^{-2}) than 4-NTMaizeVBI (2.12 ± 0.0999 kg m^{-2}) though the velvet bean intercrop was expected to increase total sequestration (Table 3.3). This is counter-intuitive and may be a result of the greater residue cover left by the preceding wheat cover crop (on plot 3), which may have provided a catch crop releasing nutrients for the following maize crop. It is also possible that the preceding blue lupin cover crop (on plot 4) provided a more labile substrate for greater decomposition and respiration during the 2013 wet season. Interestingly, it appears that 3-NTMaize had greater daytime C sequestration, while 4-NTMaize-VBI had lower nighttime emissions (Figure 3.3). The 2-CTMaize treatment, which had the advantage of nutrient mineralization from tillage (Reicosky et al., 1995; Lupwayi et al., 2004), did not produce significantly greater total CO_2 emissions (2.15 ± 0.0113 kg m^{-2}) for the 2013 wet season than both CA no-till maize plots (3-NTMaize at 1.67 ± 0.0136 kg m^{-2} and 4-NTMaizeVBI at 2.12 ± 0.0999 kg m^{-2}). Though the daytime mean flux for the 2-CTMaize (Figure 3.3) was within one SE of the 4-NTMaizeVBI, both 2-CTMaize and 4-NTMaizeVBI show more than 2 SEs greater daytime flux than the 3-NTMaize treatment.

The dry seasons in 2014 and 2015 are comparable in environmental conditions representing a typical cool non-growing dry season; all treatments were no-till fallow with no cover crops or irrigation, except for plot 1 which was tilled in 2015. CO_2 flux by time of day for these seasons were very similar (Figure 3.3). The final 2015 wet/growing season showed differences in daytime CO_2 flux with the 3-NTJackBean treatment sequestering CO_2 while all the other plots emitted CO_2 (Figure 3.3). The total NEE for 3-NTJackBean of 1.85 ± 0.115 kg m^{-2} for the season was more than 3 SEs and significantly less than 4-NTMaizeSP at 3.02 ± 0.0601 kg m^{-2} (Table 3.3). While 3-NTJackBean produced the lowest NEE for this season, there was still a net CO_2 emission on this plot, suggesting that even with CA practices, it is possible that many crops will still be a net source of C.

It is important to note that precipitation was close to 200 mm less during the 2014 and 2015 growing seasons than the 2013 growing season. While some crops like jack bean and maize are known for rapid growth, it is also possible that the buildup of plant residues from the previous CA treatments also contributed to reduced evaporation at the soil surface and greater water use efficiency during a growing season with less rainfall (Greb, 1966; Mupangwa et al., 2007). This example provides evidence that CA may help farmers adapt to climate change under reduced rainfall conditions.

Table 3.5 provides the CO_2 flux sum (NEE) and mean for each plot for the total 34.5-month period of measurement. Consistent with individual seasons, the plot with the greatest NEE (1-CTF, 21.6 ± 0.341 kg CO_2 m^{-2} $period^{-1}$) was fallow and received more conventional tillage than all other plots, while the plot with the least total emissions (3-NTCA, 10.6 ± 0. 518 kg CO_2 m^{-2} $period^{-1}$) had the most systematic applications of CA treatments.

Plot 3 (NTCA) had the most consistent CA practices and the lowest mean CO_2 flux (0.705 ±0.0323 g CO_2 m^{-2}) for the three-year period, which was significantly different than all other plots (Figure 3.6, Table 3.5). Plot 4 (NTM) also included CA practices, however, its mean CO_2 flux (0.899 ± 0. 0325 g CO_2 m^{-2}) was lower and significantly different than 3-NTCA (Figure 3.6). Several possible explanations may account for this difference, including that 4-NTM had staggered planting, which may have contributed to increased emissions. Additionally, 4-NTM was planted with maize for three consecutive years, and continuous maize deviates from CA's third principle of crop rotation. Plot 1 (CTF), which was fallow and received the most tillage, had a greater mean CO_2 flux and was significantly different than the other three plots for the experiment period.

Table 3.5. Total NEE and SE (kg CO_2 m^{-2} $period^{-1}$), number of 30-min measurements, mean NEE (g CO_2 m^{-2} hr^{-1}) followed by Tukey's Honest Significant Difference (HSD) letter group and SE of the mean (g CO_2 m^{-2} hr^{-1}) for each plot over the 34.5-month experiment period.

Plot # - Treatment Sequence Name	Accumulated NEE (kg CO_2 m^{-2} $period^{-1}$)	SE of the NEE	N	Least Squares Mean NEE (g CO_2 m^{-2} hr^{-1})	Least Squares SE of the mean
1-CTF	21.6	0.341	36718	1.24 a	0.0323
2-CTM	17.7	0.365	38066	0.963 b	0.0321
3-NTCA	10.6	0.518	37667	0.705 c	0.0323
4-NTM	14.6	0.332	35545	0.899 b	0.0325

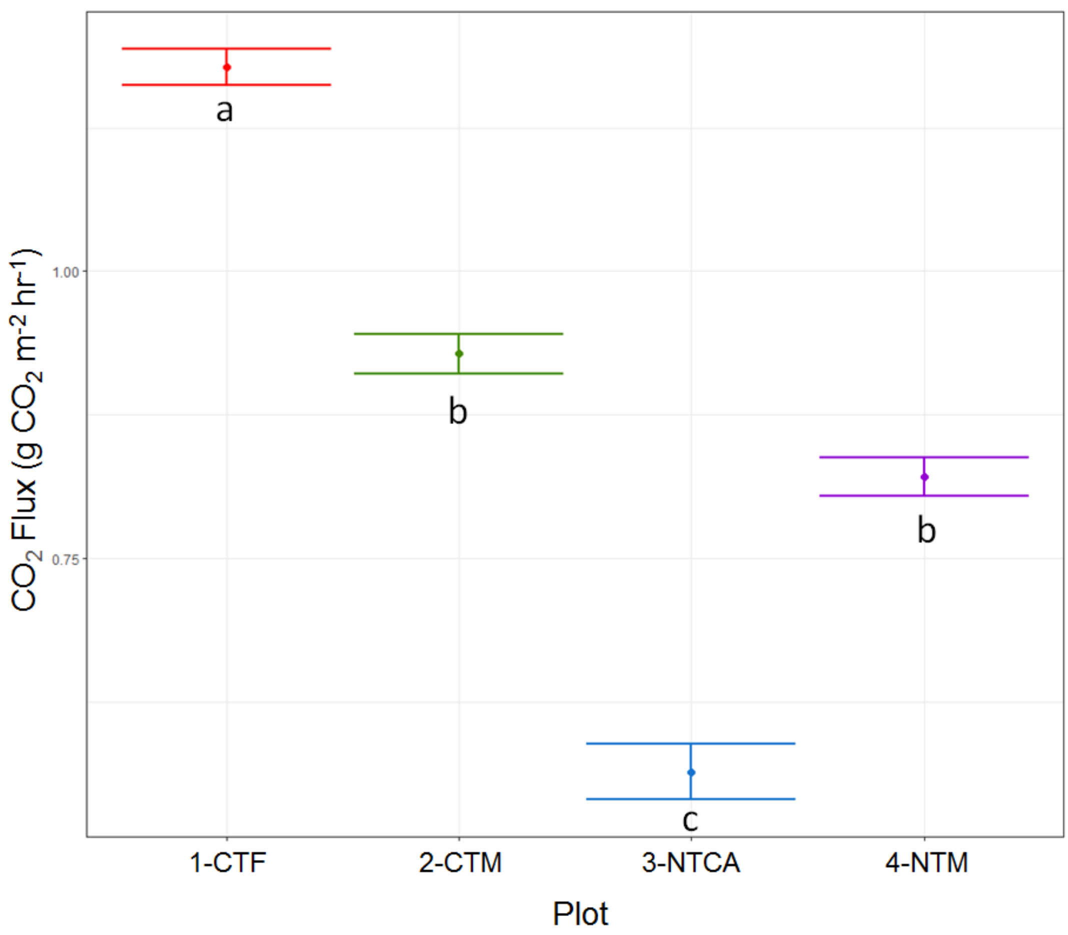

Figure 3.6. Mean CO_2 flux (g CO_2 m^{-2} hr^{-1}) with 95% confidence intervals for the 34.5-month experiment period and the ANOVA least squares mean separation output converted to letter grouping using Tukey's HSD.

Our results with micrometeorological methods show differences in net CO_2 flux between contrasting agricultural management practices. Further, effective rainfall utilization—as is common with CA practices—can be used to reduce total CO_2 emissions as evidenced by results from plot 3 (NTCA). The most consistent application of CA principles was on plot 3, and this plot produced significantly fewer CO_2 emissions than all the other treatment combinations as well as almost half the total emissions as compared to the tilled fallow treatment (1-CTF). This can be viewed in Figure 3.3 for all blue shaded daytime CO_2 flux, which showed the lowest (positive) emissions during dry seasons 2014 and 2015 and the greatest (negative) sequestration during the remaining seasons.

Of interest is plot 4 (NTM), which also had CA treatments, though its total emissions were not much lower than plot 2 (CTM) with conventional tillage. This result implies that CA may not sequester more C over time than conventional practices when CA principles are not fully implemented such as with crop rotation and sufficient soil cover. This experiment suggests that CA enhanced with a dense cover crop and its subsequent thick residue cover may reduce evaporation losses and trap nutrients, which will promote greater productivity in the following crops.

Conclusions

While there are intense constraints imposed on agriculture in a unimodal wet season/dry season climate, there is potential to reduce emissions using CA practices. Micrometeorology—as with BREB methods used here—can detect differences between soil and cropping practices both in the short term (by season) and over longer terms (multiple years). This study found that basic no-till CA practices coupled with cover crops produced healthy crop stands that emitted less CO_2 than tilled treatments. CA may be able to improve water use efficiency and crop yields in semi-arid climates in Africa. Furthermore, this research provides data regarding CA's potential to reduce C emissions (Thierfelder et al., 2017). The data show CO_2 emissions that appear related to the effects of reduced soil organic matter from tillage and surface residue that can impact evaporation, respiration, and crop productivity. These results indicate that CA may help to mitigate the consequences of climate change and adapt to climate change impacts such as reduced rainfall in tropical and/or semi-arid regions like southern Africa.

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References

Alvarez, R. and Alvarez, R. (2005) ‘A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage’, *Soil Use and Management*, 21(1), pp. 38–52. doi: 10.1079/SUM2005291.

Arya, S. P. (2001) *Introduction to Micrometeorology*. 2nd edn. San Diego: Academic Press. doi: 10.1016/s0074-6142(01)x8014-5.

Baker, J. M. and Griffis, T. J. (2005) ‘Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques’, *Agricultural and Forest Meteorology*, 128(3–4), pp. 163–177. doi: 10.1016/j.agrformet.2004.11.005.

Baldocchi, D. (2014) ‘Measuring fluxes of trace gases and energy between ecosystems and the atmosphere - the state and future of the eddy covariance method’, *Global Change Biology*, 20(12), pp. 3600–3609. doi: 10.1111/gcb.12649.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw U, K. T., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K. and Wofsy, S. (2001) ‘FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities.’, *Bull. Amer. Meteor. Soc.*, 82(11), pp. 2415–2434. doi: 10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2.

Bowen, I. S. (1926) ‘The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface’, *Physical review*, 27(6), pp. 779–787. doi: https://doi.org/10.1103/PhysRev.27.779.

Chapin, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., Clark, D. A., Harmon, M. E., Schimel, D. S., Valentini, R., Wirth, C., Aber, J. D., Cole, J. J., Goulden, M. L., Harden, J. W., Heimann, M., Howarth, R. W., Matson, P. A., McGuire, A. D., Melillo, J. M., Mooney, H. A., Neff, J. C., Houghton, R. A., Pace, M. L., Ryan, M. G., Running, S. W., Sala, O. E., Schlesinger, W. H. and Schulze, E. D. (2006) ‘Reconciling carbon-cycle concepts, terminology, and methods’, *Ecosystems*, 9(7), pp. 1041–1050. doi: 10.1007/s10021-005-0105-7.

Cheesman, S., Thierfelder, C., Eash, N. S., Kassie, G. T. and Frossard, E. (2016) ‘Soil carbon stocks in conservation agriculture systems of Southern Africa’, *Soil and Tillage Research*. Elsevier B.V., 156, pp. 99–109. doi: 10.1016/j.still.2015.09.018.

Chu, H., Baldocchi, D. D., John, R., Wolf, S. and Reichstein, M. (2017) ‘Fluxes all of the time? A primer on the temporal representativeness of FLUXNET’, *Journal of Geophysical Research: Biogeosciences*, 122(2), pp. 289–307. doi: 10.1002/2016JG003576.

Ciais, B. P., Bombelli, A., Williams, M., Piao, S. L., Chave, J., Ryan, C. M., Henry, M., Brender, P. and Valentini, R. (2011) ‘The carbon balance of Africa: Synthesis of recent research studies’, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1943), pp. 2038–2057. doi: 10.1098/rsta.2010.0328.

Clarke, L. E., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., van der Zwaan, B. C. C. and van Vuuren, D. P. (2014) ‘Assessing transformation pathways’, *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 413–510. doi: DOI: 10.1017/CBO9781107415416.012.

Dugas, W. A. (1993) ‘Micrometeorological and chamber measurements of CO2 flux from bare soil’, *Agricultural and Forest Meteorology*, 67(1–2), pp. 115–128. doi: 10.1016/0168-1923(93)90053-K.

Dugas, W. A., Heuer, M. L. and Mayeux, H. S. (1999) ‘Carbon dioxide fluxes over bermudagrass, native prairie, and sorghum’, *Agricultural and Forest Meteorology*, 93(2), pp. 121–139. doi: 10.1016/S0168-1923(98)00118-X.

Eswaran, H., Van Den Berg, E. and Reich, P. (1993) ‘Organic carbon in soils of the world’, *Soil sciensce society of America journal*, 57(1), pp. 192–194.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N. O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, J., Moors, E., Munger, J. W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K. and Wofsy, S. (2001) ‘Gap filling strategies for defensible annual sums of net ecosystem exchange’, *Agricultural and Forest Meteorology*, 107(1), pp. 43–69. doi: 10.1016/S0168-1923(00)00225-2.

FAO (2011) *The state of the world’s land and water resources for food and agriculture (SOLAW) – Managing systems at risk*. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London.

Gebremedhin, M. T., Loescher, H. W. and Tsegaye, T. D. (2012) ‘Carbon balance of no-till soybean with winter wheat cover crop in the Southeastern United States’, *Agronomy Journal*, 104(5), pp. 1321–1335. doi: 10.2134/agronj2012.0072.

Gilmanov, T. G., Baker, J. M., Bernacchi, C. J., Billesbach, D. P., Burba, G. G., Castro, S., Chen, J., Eugster, W., Fischer, M. L., Gamon, J. A., Gebremedhin, M. T., Glenn, A. J., Griffis, T. J., Hatfield, J. L., Prueger, J. H., Heuer, M. W., Howard, D. M., Leclerc, M. Y., Loescher, H. W., Marloie, O., Meyers, T. P., Olioso, A., Phillips, R. L., Skinner, R. H., Suyker, A. E., Tenuta, M. and Wylie, B. K. (2014) ‘Productivity and carbon dioxide exchange of leguminous crops: Estimates from flux tower measurements’, *Agronomy Journal*, 106(2), pp. 545–559. doi: 10.2134/agronj2013.0270.

Gilmanov, T. G., Morgan, J. A., Hanan, N. P., Wylie, B. K., Rajan, N., Smith, D. P. and Howard, D. M. (2017) ‘Productivity and CO2 Exchange of Great Plains Ecoregions. I.

Shortgrass Steppe: Flux Tower Estimates’, *Rangeland Ecology and Management*. The Authors, 70(6), pp. 700–717. doi: 10.1016/j.rama.2017.06.007.

Gilmanov, T. G., Svejcar, T. J., Johnson, D. A., Angell, R. F., Saliendra, N. Z. and Wylie, B. K. (2006) ‘Long-Term Dynamics of Production , Respiration , and Net CO 2 Exchange in Two Sagebrush-Steppe Ecosystems’, *Rangeland Ecology & Management*, 59(6), pp. 585–599. doi: 10.2111/05-198R1.1.

Greb, B. W. (1966) ‘Effect of Surface-Applied Wheat Straw on Soil Water Losses by Solar Distillation’, *Soil Sci Soc Am Proc*, 30, pp. 786–788.

Gregorich, E. G., Rochette, P., VandenBygaart, A. J. and Angers, D. A. (2005) ‘Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada’, *Soil and Tillage Research*, 83(1 SPEC. ISS.), pp. 53–72. doi: 10.1016/j.still.2005.02.009.

Heilman, J. L., Brittin, C. L. and Neale, C. M. U. (1989) ‘Fetch requirements for bowen ratio measurements of latent and sensible heat fluxes’, *Agricultural and Forest Meteorology*, 44(3–4), pp. 261–273. doi: 10.1016/0168-1923(89)90021-X.

Hernandez-Ramirez, G., Hatfield, J. L., Parkin, T. B., Sauer, T. J. and Prueger, J. H. (2011) ‘Carbon dioxide fluxes in corn-soybean rotation in the midwestern U.S.: Inter- and intra-annual variations, and biophysical controls’, *Agricultural and Forest Meteorology*, 151(12), pp. 1831–1842. doi: 10.1016/j.agrformet.2011.07.017.

Hobbs, P. R. (2007) ‘Paper Presented at International Workshop on Increasing Wheat Yield Potential, CIMMYT, Obregon, Mexico, 20-24 March 2006: Conservation agriculture: What is it and why is it important for future sustainable food production?’, *Journal of Agricultural Science*, 145(2), pp. 127–137. doi: 10.1017/S0021859607006892.

Hollinger, S. E., Bernacchi, C. J. and Meyers, T. P. (2005) ‘Carbon budget of mature no-till ecosystem in North Central Region of the United States’, *Agricultural and Forest Meteorology*, 130(1–2), pp. 59–69. doi: 10.1016/j.agrformet.2005.01.005.

IPCC-SR15 (2018) ‘IPCC, 2018: Summary for Policymakers.’, in Masson-Delmotte, V. Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C. Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (ed.) *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. Geneva, Switzerland, p. 32. Available at: http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf.

IUSS Working Group WRB (2015) *World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps., World Soil Resources Reports No. 106*. Rome. doi: 10.1017/S0014479706394902.

Kanemasu, E. T., Wesely, M. L., Hicks, B. B. and Heilman, J. L. (1979) ‘Techniques for calculating energy and mass fluxes', in Barfield, B. J. and Gerber, J. F. (eds) *Modification of the aerial environment of plants*. St. Joseph: American Society of Agricultural Engineers, pp. 156–182.

Kim, D. G., Thomas, A. D., Pelster, D., Rosenstock, T. S. and Sanz-Cobena, A. (2016) 'Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: Synthesis of available data and suggestions for further research', *Biogeosciences*, 13(16), pp. 4789–4809. doi: 10.5194/bg-13-4789-2016.

Kimaro, A. A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., Mutuo, P., Abwanda, S., Shepherd, K., Neufeldt, H. and Rosenstock, T. S. (2016) 'Is conservation agriculture "climate-smart" for maize farmers in the highlands of Tanzania?', *Nutrient Cycling in Agroecosystems*. Springer Netherlands, 105(3), pp. 217–228. doi: 10.1007/s10705-015-9711-8.

Kirschbaum, M. U. F. (2000) 'Will changes in soil organic carbon act as a positive or negative feedback on global warming?', *Biogeochemistry*, 48(Batjes 1996), pp. 21–51. doi: 10.1023/A:1006238902976.

Kutsch, W. L., Hanan, N., Scholes, R. J., Mchugh, I. and Kubheka, W. (2008) 'Response of carbon fluxes to water relations in a savanna ecosystem in South Africa', pp. 2197–2235.

Liu, Y., Li, S. Q., Yang, S. J., Hu, W. and Chen, X. P. (2010) 'Diurnal and seasonal soil CO2 flux patterns in spring maize fields on the Loess Plateau, China', *Acta Agriculturae Scandinavica Section B–Soil and Plant Science*, 60, pp. 245–255. doi: 10.1080/09064710902878121.

Lupwayi, N. Z., Clayton, G. W., Donovan, J. T. O., Harker, K. N., Turkington, T. K. and Rice, W. A. (2004) 'Decomposition of crop residues under conventional and zero tillage', *Canadian Journal of Soil Science*, 84(4), pp. 403–410.

Mapanda, F., Mupini, J., Wuta, M., Nyamangara, J. and Rees, R. M. (2010) 'A cross-ecosystem assessment of the effects of land cover and land use on soil emission of selected greenhouse gases and related soil properties in Zimbabwe', *European Journal of Soil Science*, 61(5), pp. 721–733. doi: 10.1111/j.1365-2389.2010.01266.x.

Mapanda, F., Wuta, M., Nyamangara, J. and Rees, R. M. (2011) 'Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe', *Plant and Soil*, 343(1–2), pp. 67–81. doi: 10.1007/s11104-011-0753-7.

McGinn, S. M. and King, K. M. (1990) 'Simultaneous measurements of heat, water vapour and CO2 fluxes above alfalfa and maize', *Agricultural and Forest Meteorology*, 49(4), pp. 331–349. doi: 10.1016/0168-1923(90)90005-Q.

Mhlanga, B., Cheesman, S., Maasdorp, B., Mupangwa, W. and Thierfelder, C. (2015) 'Contribution of cover crops to the productivity of maize-based conservation agriculture systems in zimbabwe', *Crop Science*, 55(4), pp. 1791–1805. doi: 10.2135/cropsci2014.11.0796.

Moureaux, C., Debacq, A., Hoyaux, J., Suleau, M., Tourneur, D., Vancutsem, F., Bodson, B. and Aubinet, M. (2008) ‘Carbon balance assessment of a Belgian winter wheat crop (Triticum aestivum L.)’, *Global Change Biology*, 14(6), pp. 1353–1366. doi: 10.1111/j.1365-2486.2008.01560.x.

Mupangwa, W., Twomlow, S., Walker, S. and Hove, L. (2007) ‘Effect of minimum tillage and mulching on maize (Zea mays L.) yield and water content of clayey and sandy soils’, 32, pp. 1127–1134. doi: 10.1016/j.pce.2007.07.030.

Necpálová, M., Anex, R. P., Kravchenko, A. N., Abendroth, L. J., Grosso, S. J. Del and Dick, W. A. (2014) ‘What does it take to detect a change in soil carbon stock ? A regional comparison of minimum detectable difference and experiment duration in the north central United States’, 69(6), pp. 517–531. doi: 10.2489/jswc.69.6.517.

Nyamapfene, K. (1992) ‘A GEOGRAPHICAL OVERVIEW OF THE SOILS OF ZIMBABWE AND THEIR AGRICULTURAL POTENTIAL’, 15(1), pp. 1–74.

O’Dell, D., Sauer, T. J., Hicks, B. B., Lambert, D. M., Smith, D. R., Bruns, W., Basson, A., Marake, M. V., Walker, F., Wilcox, M. D. and Eash, N. S. (2014) ‘Bowen Ratio Energy Balance Measurement of Carbon Dioxide (CO2) Fluxes of No-Till and Conventional Tillage Agriculture in Lesotho’, *Open Journal of Soil Science*, 04(03), pp. 87–97. doi: 10.4236/ojss.2014.43012.

O’Dell, D., Sauer, T. J., Hicks, B. B., Thierfelder, C., Lambert, D. M., Logan, J. and Eash, N. S. (2015) ‘A Short-Term Assessment of Carbon Dioxide Fluxes under Contrasting Agricultural and Soil Management Practices in Zimbabwe’, *Journal of Agricultural Science*, 7(3), pp. 32–48. doi: 10.5539/jas.v7n3p32.

Ogle, S. M., Breidt, F. J. and Paustian, K. (2005) ‘Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions’, *Biogeochemistry*, 72(1), pp. 87–121. doi: 10.1007/s10533-004-0360-2.

Orchard, V. A. and Cook, F. J. (1983) ‘Relationship between soil respiration and soil moisture’, *Soil Biology and Biochemistry*, 15(4), pp. 447–453.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P. and Smith, P. (2016) ‘Climate-smart soils’, *Nature*. Nature Publishing Group, 532(7597), pp. 49–57. doi: 10.1038/nature17174.

Perez, P. J., Castellvi, F., Ibañez, M. and Rosell, J. I. (1999) ‘Assessment of reliability of Bowen ratio method for partitioning fluxes’, *Agricultural and Forest Meteorology*, 97(3), pp. 141–150. doi: 10.1016/S0168-1923(99)00080-5.

Powlson, D. S., Stirling, C. M., Thierfelder, C., White, R. P. and Jat, M. L. (2016) ‘Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems ?’, *‘Agriculture, Ecosystems and Environment’*. Elsevier B.V., 220, pp. 164–174. doi: 10.1016/j.agee.2016.01.005.

Reicosky, D. C., Kemper, W. D., Langdale, G., Douglas, C. L. and Rasmussen, P. E.

(1995) ‘Soil organic matter changes resulting from tillage and biomass production’, *Journal of soil and water conservation*, 50(3), pp. 253–261.

Rosenberg, N. J., Blad, B. L. and Verma, S. B. (1983) *Microclimate: The Biological Environment*. New York: John Wiley & Sons.

Rosenstock, T. ., Mpanda, M., Pelster, D. ., Butterbach-Bahl, K., Rufino, M. ., Thiong’o, M., Mutuo, P., Abwanda, S., Rioux, J., Kimaro, A. . and Neufeldt, H. (2016) ‘Greenhouse gas fluxes from agricultural soils of Kenya and Tanzania’, *Journal of Geophysical Research: Biogeosciences*, 121(6), pp. 707–723. doi: 10.1002/2016JG003341.

Sainju, U. M., Singh, B. P. and Whitehead, W. F. (2002) ‘Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA’, *Soil and Tillage Research*, 63(3–4), pp. 167–179. doi: 10.1016/S0167-1987(01)00244-6.

Savage, M. J., Everson, C. S. and Metelerkamp, B. R. (2009) ‘Bowen ratio evaporation measurement in a remote montane grassland: Data integrity and fluxes’, *Journal of Hydrology*. Elsevier B.V., 376(1–2), pp. 249–260. doi: 10.1016/j.jhydrol.2009.07.038.

Saxton, A. M. (1998) ‘A macro for converting mean separation output to letter groupings in Proc Mixed’, in *Proc. 23rd SAS Users Group Intl*. Nashville: SAS Institute, pp. 1243–1246.

Simba, F. M. and Chayangira, J. (2017) ‘Rainfall Seasons Analysis as a Guiding Tool to Small Holder Farmers in The Face of Climate Change in Midlands in Zimbabwe’, *Journal of Earth Science & Climatic Change*, 8(3). doi: 10.4172/2157-7617.1000392.

Smith, P. (2004) ‘How long before a change in soil organic carbon can be detected?’, *Global Change Biology*, 10(11), pp. 1878–1883. doi: 10.1111/j.1365-2486.2004.00854.x.

Smith, P. (2016) ‘Soil carbon sequestration and biochar as negative emission technologies’, *Global Change Biology*, 22(3), pp. 1315–1324. doi: 10.1111/gcb.13178.

Soil Survey Staff (2014) ‘Keys to soil taxonomy’, *Soil Conservation Service*, 12, p. 410. doi: 10.1109/TIP.2005.854494.

Suyker, A. E. and Verma, S. B. (2012) ‘Gross primary production and ecosystem respiration of irrigated and rainfed maize-soybean cropping systems over 8 years’, *Agricultural and Forest Meteorology*. Elsevier B.V., 165, pp. 12–24. doi: 10.1016/j.agrformet.2012.05.021.

Tagesson, T., Fensholt, R., Cropley, F., Guiro, I., Horion, S., Ehammer, A. and Ardö, J. (2015) ‘Dynamics in carbon exchange fluxes for a grazed semi-arid savanna ecosystem in West Africa’, *Agriculture, Ecosystems and Environment*. Elsevier B.V., 205, pp. 15–24. doi: 10.1016/j.agee.2015.02.017.

The R Foundation (2018) *The R Project for Statistical Computing*. Available at: https://www.r-project.org/ (Accessed: 8 January 2018).

Thierfelder, C., Chivenge, P., Mupangwa, W., Rosenstock, T. S., Lamanna, C. and Eyre, J. X. (2017) 'How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa', *Food Security*. Food Security, 9(3), pp. 537–560. doi: 10.1007/s12571-017-0665-3.

Verma, S. B., Dobermann, A., Cassman, K. G., Walters, D. T., Knops, J. M., Arkebauer, T. J., Suyker, A. E., Burba, G. G., Amos, B., Yang, H., Ginting, D., Hubbard, K. G., Gitelson, A. A. and Walter-Shea, E. A. (2005) 'Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems', *Agricultural and Forest Meteorology*, 131(1–2), pp. 77–96. doi: 10.1016/j.agrformet.2005.05.003.

Vickers, D. and Mahrt, L. (1997) 'Quality control and flux sampling problems for tower and aircraft data', *Journal of Atmospheric and Oceanic Technology*, 14(3), pp. 512–526. doi: 10.1175/1520-0426(1997)014<0512:QCAFSP>2.0.CO;2.

Webb, E. K., Pearman, G. I. and Leuning, R. (1980) 'Correction of flux measurements for density effects due to heat and water vapour transfer', *Q. J. Roy. Meteorol. Soc.*, 106(447), pp. 85–100. doi: http://dx.doi.org/10.1002/qj.49710644707.

West, T. O. and Post, W. M. (2002) 'Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation : A Global Data Analysis', *Soil Science Society of America Journal*, 66, pp. 1930–1946.

Williams, C. A., Hanan, N., Scholes, R. J. and Kutsch, W. (2009) 'Complexity in water and carbon dioxide fluxes following rain pulses in an African savanna', *Oecologia*, 161(3), pp. 469–480. doi: 10.1007/s00442-009-1405-y.

Appendix

Abbreviations

Excluding SI units and US States

ANOVA	analysis of variance
asl	above sea level
BREB	Bowen ratio energy balance
C	carbon
CA	conservation agriculture
CT	conventional tillage
CTM	conventional tillage followed by maize crop
CO_2	carbon dioxide
°C	degrees Celsius
EC	eddy covariance
et al.	et alia (and others)
F	fallow
FAO	Food and Agriculture Organization of the United Nations
hr	hour
HSD	honest significant difference
IPCC	Intergovernmental Panel on Climate Change

JB	jackbean
LE	latent heat flux
LSD	least significant difference
M	maize
N	number of measurements
NEE	net ecosystem exchange
NT	no-till
NTCA	no-till with conservation agriculture practices
NTM	no-till with maize crop
PP	pigeonpeastandard error
SE	standard error
SP	staggered planting
VBI	velvet bean intercrop
USDA	United States Department of Agriculture

CONCLUSIONS

Research Results

The research presented in this dissertation measured net ecosystem exchange (NEE) of CO_2 over agricultural management practices using micrometeorological methods to understand the potential for agriculture to sequester atmospheric CO_2 to support climate change mitigation. These studies employed micrometeorology, including Bowen Ratio Energy Balance (BREB) and Eddy Covariance (EC) systems, to measure the exchange of CO_2 between the agricultural surface and the atmosphere over the short-term (by season) and over longer terms (one to three years) to determine whether agricultural practices can sequester CO_2.

The first study measured CO_2 flux using BREB micrometeorological methods from a maize crop grown on no-till and tilled soils to determine tillage effects on CO_2 emissions during a growing season in north central Ohio in 2015. The study found that the no-till plot sequestered 263 g CO_2 m^{-2} (90% confidence interval -432.1 to -99.9) while the tilled plot emitted 146 g CO_2 m^{-2} (90% confidence interval -53.3 to 332.2) during 104 days of the 2015 growing season; a net difference of 410 g CO_2 m^{-2}.

The second study also explored agriculture's role in recycling industrial biotechnology waste to reduce CO_2 emissions while generating environmental benefits and meeting farmer yield expectations. Using both BREB and EC micrometeorological methods, CO_2 flux was measured over maize where heat-inactivated, spent microbial biomass soil amendment was land applied and compared with typical farmer practices from October 2016 to October 2017. Findings indicate that annual NEE for the industrial biotechnology waste application was greater than for the farmer practice, however, excess emissions may be recycled back into the ecosystem through enhanced photosynthesis to produce more plant biomass and soil C. The additions of the biotechnology waste provided maize yields on par with typical farmer practices when applied at greater rates. Using industrial biotechnology by-products as a soil amendment has the potential to enrich ecosystem productivity and environmental sustainability through conversion of waste nutrients into plant biomass and soil organic matter.

This study also investigated the challenge of measuring nighttime emissions using turbulence-based methods, such as EC, BREB, and other aerodynamic methods. When conditions were turbulent during the day, the EC and BREB methods agreed, however, the study found that during the night, the EC and aerodynamic methods generally did not agree.

The third study measured CO_2 emissions over conservation agriculture (CA) practices including no-till and cover crops as compared to conventional tillage from June 2013 to May 2016 in central Zimbabwe. The CA practices of no-till and cover crops produced significantly fewer CO_2 emissions than conventional tillage.

Notable results of the first and third studies demonstrated that, in general, the CA practice of no-till produces significantly fewer emissions than tilled plots. Tillage disinters buried organic matter and provides a means for the soil organisms to mineralize previously occluded C sources and accelerates decomposition of recently tilled and buried crop residue.

These studies found that no-till practices may sequester C for a growing season, but did not sequester C over a year or longer, even when combined with cover crops. Several possibilities may explain these results, including fallow periods during non-growing seasons or between crops. These fallow periods emit CO_2 through ecosystem respiration, with little to no photosynthetic removal of atmospheric CO_2, producing a net gain to the atmosphere. Another explanation is the uncertainty of nighttime CO_2 flux using turbulence-based methods, such as

EC, BREB and other aerodynamic methods, resulting in a possible over-estimate of nighttime emissions—especially with the BREB calculations as used for most of these studies.

One unexpected result was that one CA implementation over a three-year period produced a significantly lower mean CO_2 emission rate than a plot with conventional tillage, while another plot that also used CA practices was not significantly lower. One possible explanation is that at the beginning of the experiment, one CA plot was planted with a wheat cover crop, which produced a dense surface residue cover that may have contributed to reduced emissions over subsequent seasons. The other CA plot was planted with a leguminous cover crop that took time to establish and produced labile residue that quickly decomposed, providing sparse soil cover. Also, the CA plot with greater emissions included staggered planting with no crop rotation. This suggests that when CA practices are not effectively applied—such as insufficient soil cover and/or not including crop rotation—CA practices may produce greater CO_2 emissions.

These results indicate that micrometeorology can detect differences between management practices over the short-term by season, the longer term by year, and with a sequence of management practices and crops over several years. These findings provide valuable information about NEE of a combination of crops, crop practices, and climate over time. These findings also provide data about management practices and crops that have greater potential to sequester C, and also provides data support for modifications to practices, such as earlier planting to reduce fallow periods and cropping during non-growing seasons.

Implications for Policy

There are several implications of this research that can inform agricultural policies for climate change mitigation. The evidence provided supports the ability of the CA practices of no-till, cover crops, and the retention of residue to reduce CO_2 emissions, which has implications for climate change mitigation. Data provided by this research illustrates that reduced evaporation at the soil surface and greater water use efficiency from the buildup of plant residues from CA practices may support crops in climates with reduced rainfall and rising temperatures, which has implications for policies supporting adaptation to climate change.

The CO_2 emissions, maize grain and biomass yield, and soil organic carbon data of the study that applied industrial waste as an amendment and replacement for mineral fertilizers has implications for sustainable resource and waste management, because nutrient rich industrial wastes can enrich soil, fortify agricultural production and reduce use of mineral fertilizers. Applying the waste output from one industry as a resource input into another industry reduces waste and conserves resources, which are essential principles of sustainability. By reducing greenhouse gas (GHG) emissions from both the manufacturing industry and agriculture through recycling of waste, industry and agriculture become more sustainable and contribute to climate change mitigation.

The greatest implication of this research is the potential for micrometeorology to identify the capacity of agricultural management practices to reduce CO_2 emissions and in quantifying the impact of other factors on emissions including climate, soil type, crop and sequence of practices over time. This data can be used to inform policies that identify agricultural management practices for carbon offsets.

This research provided data to address the need for more observations of C fluxes in Africa especially over agriculture and support for the use of CA for small-holder farming, especially to address adaptation to rising temperatures and drought. This research can provide lessons for future agro-meteorology measurement programs in Africa, especially with the use of BREB systems, which enable measurements closer to the soil and crop surface.

Future Areas of Research

These studies point to several avenues for future research, such as the identification of optimal crops, practices, and conditions for year round production that has the potential to be a roadmap for sustainable agriculture that sequesters C for consideration as a negative CO_2 emissions technology. Questions to be explored include how much residue and what kinds of residue reduce the ephemeral nature of plant and soil carbon. Can emissions be reduced, while value to the farmer is increased, through various combinations and timing of management practices such as using winter season or between season cover crops, as well as intercropping and intensification? Micrometeorology is one of the best tools for measuring the sequestration potential of agricultural management practices, especially when it can measure not only CO_2 but also the other important agricultural greenhouse gases including methane and nitrous oxide.

Future research should also investigate the agricultural application of industrial biotechnology waste, such as determining amendment rates, timing and material composition to identify best management practices in achieving optimal value for the farmer. Also, to identify the sustainability of both agriculture and industrial processes, research could quantify the total life cycle costs and emissions of landfill disposal of industrial biotechnology waste as compared to the cost and benefit of using those wastes as agricultural inputs that enrich ecosystem productivity and environmental sustainability through conversion of waste nutrients into plant biomass and soil organic matter. Bioresiduals generated by industrial biotechnologies tend to be rich in organic matter, containing macro- and micronutrients essential for plant growth, and therefore have agricultural value. However, there remain technical, logistical, and social challenges and costs in value recovery.

The network of more than 900 EC measurement stations distributed around the world provides valuable empirical observational data on meteorological properties and GHG fluxes near the surface, which is critical for models of the C cycle for use in climate change predictions. The research presented in this dissertation shows that BREB systems can produce data more representative of the surface, which is important in quantifying the role of agroecosystems in these models, considering that cropland occupies 11% of the earth's terrestrial surface. Undoubtedly, there is a need for models to consider incorporation of more surface data as collected by BREB and other systems.

Finally, an important subject for future research is the exploration of nighttime CO_2 flux given the issues that turbulence-based micrometeorological methods have under low turbulence conditions. New scientific investigation should focus on the pooling and drainage of CO_2 at the surface during stable conditions at night. While the network of EC stations grows to increase understanding of the carbon cycle in agriculture and other ecosystems, profiles of meteorological measurements as provided by BREB and other approaches can be used to understand the nighttime buildup of CO_2 and other atmospheric characteristics near the surface. This complexity needs to be addressed using both spatial differences and turbulent exchanges.

VITA

Deb O'Dell was born in Oak Ridge, TN and got her bachelor's degree in information systems management from the University of Maryland. After a career in information technology, Deb took a class in Conservation taught at UT by Professor Emeritus Richard Strange in the Department of Forestry, Wildlife and Fisheries who introduced Deb to the challenges of soil erosion. Deb was encouraged to take Professor Neal Eash's Introduction to Soil Science class where she discovered that soil also has a role in climate change through its ability to sequester or emit carbon. Professor Eash offered Deb the opportunity to study soil C sequestration by measuring CO_2 emissions over agriculture using micrometeorology. Working under Professor Eash's guidance, Deb received her Master of Science degree in Environmental and Soil Sciences at UT in 2014 after performing experiments measuring CO_2 flux over contrasting agriculture practices in Africa. Through Professor's Eash's passion for research, science, education and farming, Deb not only participated in agricultural research, but also assisted with classes, presented research at four national and international science meetings and contributed as a co-author on three peer reviewed scientific articles during her Master's education. Deb then began her doctoral studies at UT, continuing with her research under Professor Eash and her committee, presenting at four scientific conferences and co-authoring four publications including a new edition of the book, *Soil Science Simplified*.