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IMPACT OF TILLAGE AND INTEGRATED SOIL FERTILITY MANAGEMENT PRACTICES ON CARBON BALANCE IN MAIZE-BASED SYSTEM IN NORTHERN GHANA

A thesis, in the Rural Polytechnic Institute of Training and Applied Research (IPR/IFRA) in partnership with the West African Science Service Centre on Climate Change and Adapted Land use (WASCAL), submitted in partial fulfilment of the requirements for the Doctor of Philosophy in Climate Change and Agriculture of the University of Sciences, Techniques and Technologies of Bamako (USTTB)

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IMPACT OF TILLAGE AND INTEGRATED SOIL FERTILITY MANAGEMENT PRACTICES ON CARBON BALANCE IN MAIZE-BASED SYSTEM IN NORTHERN GHANA

BY

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Certification page

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Dedication

I dedicate this work to my lovely wife Ellen Owusuah White, children (Ingrid Koramah Asante, Ephraim Konadu Asante and Ivanna Asieduah Asante) and my parents (Jonas Agyei Kumi and Grace Konadu).

Table of Contents

List of tables

List of figures

List of abbreviations and acronyms

CSIR	Council for Scientific and Industrial Research
GENSTAT	General Statistical Programme
MoFA	Ministry of Food and Agriculture
N	Nitrogen
pH	Negative logarithm of hydrogen ion concentration
ppm	Parts per million
RCBD	Randomized Complete Block Design
SARI	Savannah Agricultural Research Institute
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SRID	Statistics, Research and Information Directorate
A	Basal area
cm	Centimeter
CO_2	Carbon dioxide
GHG	Greenhouse gas
GPP	Gross primary production
IRGA	Infrared gas analyzer
NECB	Net ecosystem carbon balance
NEE	Net ecosystem exchange
PAR	Photosynthetic active radiation
PVC	Polyvinyl chloride
Ra	Autotrophic respiration
Reco	Ecosystem respiration
Rh	Heterotrophic respiration
NPP	Net primary product
NDIR	Non dispersive infrared
NFT-NSS	Non-flow through non-steady state
DHT 22	Digital-output relative humidity and temperature
SHT31	Digital temperature & humidity sensor
UART	Universal Asynchronous Receiver Transmitter

V	Volume
C	Carbon
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
DOM	Day of the measurement
DOY	Day of the year
GPmax	Maximum rate of carbon fixation at PAR infinite
ISFM	Integrated soil fertility management
IPCC	Intergovernmental panel on climate change
^{o}K	Degree Kelvin
M	Molar mass [g C, N mol^{-1}]
N_2O	**N**itrous oxide
$Ra_{(root)}$	Below-ground autotrophic (root) respiration
$Ra_{(shoot)}$	Aboveground autotrophic (shoot) respiration
R_{Ref}	Ecosystem respiration at reference temperature
Rsoil	Soil respiration (Ra (root) + Rh)

List of symbols

σ standard deviation

α alpha (probability of making a type I error)

μg microgramme

E0 activation energy [K]

T0 temperature constant for start of biological process

μmol micromole

Abstract

An increasing world population necessitate the need to increase food production to meet the demand of a changing world. Intensified agriculture and accelerated climate crisis with increasing weather extremes threaten the resource base needed to improve crop production. Maize is an important staple food in Ghana. However, yield obtained by farmers in the guinea savannah zone of Ghana is generally low due to low soil fertility status resulting from continuous cropping coupled with low use of external inputs. Integrated Soil Fertility Management (ISFM) strategies have proven to sustainably increase maize yield. However, majority of the farmers practicing ISFM till their land conventionally, potentially resulting in substantial CO_2 emissions that contribute to global climate change. Determining carbon dynamics and net ecosystem carbon balances (NECB) on ISFM practices in combination with different tillage practices might play a key role in finding new ways to mitigate the global climate crises. This has even become necessary as there is dearth of information on net carbon emissions regarding crop production systems in sub-Saharan Africa in general and Ghana in particular. One important reason for this is the fact that commercially available system to measure CO_2 are highly capital-intensive. To overcome this financial limitation, recent trends within the field of low-cost microcontrollers and of NDIR CO_2 sensors where used to develop an affordable, manual closed chamber based CO_2 and ET flux measurement device. It uses K30FR (NDIR-CO_2 sensor) and DHT22 (RH sensor) and was tested at both, laboratory and field level. Being successfully validated, the device was further used within a field trial environment in Ghana to investigate the impact of different tillage practices and ISFM technologies under maize cultivation on seasonal CO_2 and ET emissions, NECB and water use efficiency (WUE) as well as grain yield. A split plot design was used with the main plot treatments being conventional tillage and reduced tillage and the subplot treatments being a factorial combination of organic and inorganic fertilizers at three levels each. Results presented here not only show that the developed low cost system was able to reliably measure CO_2 and ET fluxes from which NECB and WUE could be estimated, respectively, but also that the conventional tillage system emitted right after tillage operation 65% more CO_2 into the atmosphere than the reduced tillage. Furthermore, combined application of organic fertilizer (fertisoil/farmyard manure) at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} enhanced maize grain yield, reduced net CO_2 emission, sequestered more carbon and utilized applied nutrients and available water more efficiently. To safeguard the environment and enhanced soil health combined

application of organic and inorganic fertilizers on reduced tillage system should hence be practiced in the study area.

Résumé

L'augmentation de la population mondiale et l'évolution des préférences des consommateurs nécessitent d'accroître la production alimentaire pour répondre à la demande d'un monde en mutation. L'intensification de l'agriculture et l'accélération de la crise climatique avec l'augmentation des conditions météorologiques extrêmes menacent la base de ressources nécessaire pour améliorer la production agricole. Le maïs est un aliment de base important au Ghana. Cependant, le rendement obtenu par les agriculteurs dans la zone de savane guinéenne du Ghana est généralement faible en raison du faible état de fertilité des sols résultant d'une culture continue associée à une faible utilisation d'intrants externes. Les stratégies de gestion intégrée de la fertilité des sols (GIFS) se sont avérées efficaces pour augmenter durablement le rendement du maïs. Cependant, la majorité des agriculteurs pratiquant la GIFS cultivent leurs terres de manière conventionnelle, ce qui peut entraîner des émissions de CO_2 substantielles qui contribuent au changement climatique mondial. La détermination de la dynamique du carbone et des bilans nets de carbone de l'écosystème (BNCE) des pratiques de GIFS, combinée à différentes pratiques de travail du sol, pourrait jouer un rôle clé dans la recherche de nouvelles façons d'atténuer les crises climatiques mondiales ou de s'y adapter. Cela est même devenu nécessaire car il y a peu d'informations sur les émissions nettes de carbon concernant les systèmes de production agricole en Afrique subsaharienne en général et au Ghana en particulier. Une raison importante à cela est le fait que les systèmes de mesure du CO_2 disponibles dans le commerce sont très capitalistiques. Pour surmonter cette limitation financière, les tendances récentes dans le domaine des microcontrôleurs à faible coût et des capteurs de Infrarouge non dispersif CO_2 ont été utilisées pour développer un dispositif de mesure de flux de CO_2 et d'ET abordable à chambre fermée. Il utilise K30FR (capteur Infrarouge non dispersif-CO_2) et humidité relative et température de sortie numérique (capteur HR) et a été testé à la fois en laboratoire et sur le terrain. Une fois validé avec succès, le dispositif a ensuite été utilisé dans un environnement d'essai sur le terrain au Ghana pour étudier l'impact de différentes pratiques de travail du sol et technologies GIFS sous culture de maïs sur les émissions saisonnières de CO_2 et d'ET, le BNCE et l'efficacité de l'utilisation de l'eau ainsi que le rendement en grains. Le design expérimental est un split plot où les principaux traitements sont le labour conventionnel et le labour réduit. Les sous traitements sont obtenus à travers la combinaison factorielle à trois niveaux chacun des fertilisant organiques et inorganiques.. Les résultats présentés ici montrent non seulement que le système à faible coût développé était capable de mesurer de manière fiable les flux de CO_2 et d'ET à partir desquels

le BNCE et l'efficience de l'utilisation de l'eau pouvaient être respectivement estimés. Aussi, le système de labour conventionnel émettait juste après le travail du sol 65% de CO_2 de plus dans l'atmosphère que le labour réduit du sol. En outre l'application combinée d'engrais organiques (fertisol/fumier de ferme) à 5 t ha^{-1} et 90-60-60 kg NPK ha^{-1} a permis d'améliorer le rendement en grains de maïs, de réduire les émissions nettes de CO_2, de séquestrer davantage de C et d'utiliser plus efficacement les nutriments appliqués et l'eau disponible. Pour protéger l'environnement et améliorer la santé des sols, l'application combinée d'engrais organiques et inorganiques sur un système de travail réduit du sol devrait donc être pratiquée dans la zone d'étude.

CHAPTER ONE

1.0 Introduction

1.1 Justification of the study

The world's population is predicted to increase to 11.2 billion by the end of the century (United Nation, 2017). An increasing world population necessitate the need to increase food production to meet the demand of the changing world. Intensified agriculture and an accelerated climate crisis with increasing weather extremes threaten the resource base needed to improve crop production (Schauberger et al, 2017). Water and Heat stresses have great impact on crop production (Ngoune and Shelton , 2020). Water stress limits plant CO_2 assimilation rate due to reduced stomatal conductance and significantly affect leaf size, stem elongation, root proliferation and thus decreases water use efficiency (Keyvan, 2010). It also damage photosynthetic pigments and limit the exchange of gases by plants leading to retarded plant growth and poor yield (Jain et al, 2019). Extreme air temperature accelerate crop respiration and reduce the interception of radiation by crops resulting in less biomass production (Hillel and Rosenzweig, 2015). Strategies to enhance crop resilience to weather extremes are required to increase and sustain food production to feed the still growing world population.

Maize is one of the most widely consumed staple food and accounts for about 50% – 60% of the total cereal production in Ghana (MoFA/SRID, 2018). Beside being used as food for humans and feed for animals, it is also used for industrial products such as starch, sweeteners, oil, industrial alcohol and fuel ethanol (Olaniyan, 2015). However, maize yield obtained by farmers in Ghana especially the northern part is usually low (1 t ha^{-1}) and significantly below the national average of 3 t ha^{-1} (FAO, 2021) as well as the potential possible yields of up to 6 t ha^{-1} (Adu et al, 2018). Several factors such as varieties, plant density, pest and disease have impact on the yield of maize. However, low soil fertility coupled with limited use of external inputs are the main cause of the yields obtained in the study area (Mangnus and van Westen, 2018).

1.2 State of knowledge

Several technologies aimed to increase maize productivity in Ghana had been employed (Adu-Gyamfi et al, 2019; Kugbe et al, 2019). However, integrated soil fertility management (ISFM) technology has proven to increase and sustain maize yield as well as the general wellbeing of the soil (Bationo et al, 2018). ISFM entails the use of improved varieties, application of inorganic and organic fertilizers, and adaptation of the practices to local condition (Ruganzu et al., 2015). Majority of farmers in the Guinea Savannah zone of Ghana practicing ISFM usually till their land conventionally (ploughing with tractor), leading to accelerated organic matter decomposition potentially resulting in enhanced heterotrophic respiration contributing potentially to global climate change (Bilandžija et al, 2016). According to Krauss et al, (2017) reduced tillage might be an option, when compared to conventional tillage, in helping to reduce CO_2 emission and increasing carbon sequestration in the soil. Hence, determining carbon dynamics and net ecosystem carbon balances (NECB) on ISFM practices in combination with different tillage practices might play a key role in finding new ways to mitigate the global climate crises. This is even more the case, as there is lack of information regarding the effects of tillage and ISFM practices on carbon dynamics especially in the Guinea Savannah Zone of Ghana. However, commercially available system to measure greenhouse gas (GHG) in general and CO_2 in particular are capital-intensive making GHG research in Sub-Sahara Africa especially Ghana limited. Only few studies have estimated GHG emissions from Ghanaian agricultural production systems (Atakora et al, 2019; Maccarthy et al, 2018) and most of the adaptation strategies (Xia et al, 2016; Zhang et al, 2016) being promoted to combat climate change in Ghana are mainly based on findings generated in other parts of the world. Therefore, it is imperative that additional studies are done especially in the agriculture sector to generate reliable data that reflect the actual carbon dynamics from the agricultural production systems and the mitigation strategies adoptable to the local conditions.

1.3 Research hypothesis

It is hypothesized that:

i. The developed low-cost CO_2 measurement system could detect carbon exchange similar to the capital-intensive CO_2 measurement system.

ii. More CO_2 will be emitted and less C sequestrated on tractor ploughed field than bullock ploughed field.

iii. Combined application of organic and inorganic fertilizers will reduce CO_2 emissions more than the sole application of inorganic fertilizer irrespective of the tillage system.

iv. the NECB , water use efficiency (WUE) and the nitrogen use efficiency (NUE) would be higher in the combined fertilizer application than the sole application of inorganic fertilizer under different tillage systems.

1.4 Objectives

1.4.1 Overall objective

To determine the impact of tillage and ISFM practices on carbon dynamics in the guinea savannah zone of Ghana.

1.4.2 Specific objectives

i. develop an adaptive low-cost system to measure CO_2 emissions

ii. determine CO_2 emissions from different tillage practices.

iii. examine the influence of tillage systems and combined application of organic and inorganic fertilizers on CO_2 emissions, WUE and NECB

iv. investigate the effects of tillage systems and combined use of organic and inorganic fertilizers on nitrogen use efficiency and yield of maize.

CHAPTER TWO

2.0 Literature Review

2.1 Long term climatic conditions in Nyankpala-Ghana

A thirty-year rainfall and temperature data recorded at the CSIR-Savanna Agricultural Research Institute in Nyankpala, in the Northern region of Ghana is presented in (Figure 1). The data were taken from 1991 to 2020 and gave the long-term annual rainfall to be 1100 mm. The mean long-term minimum temperature was 19 °C with the mean long-term maximum temperature been 36 °C (Figure 1).

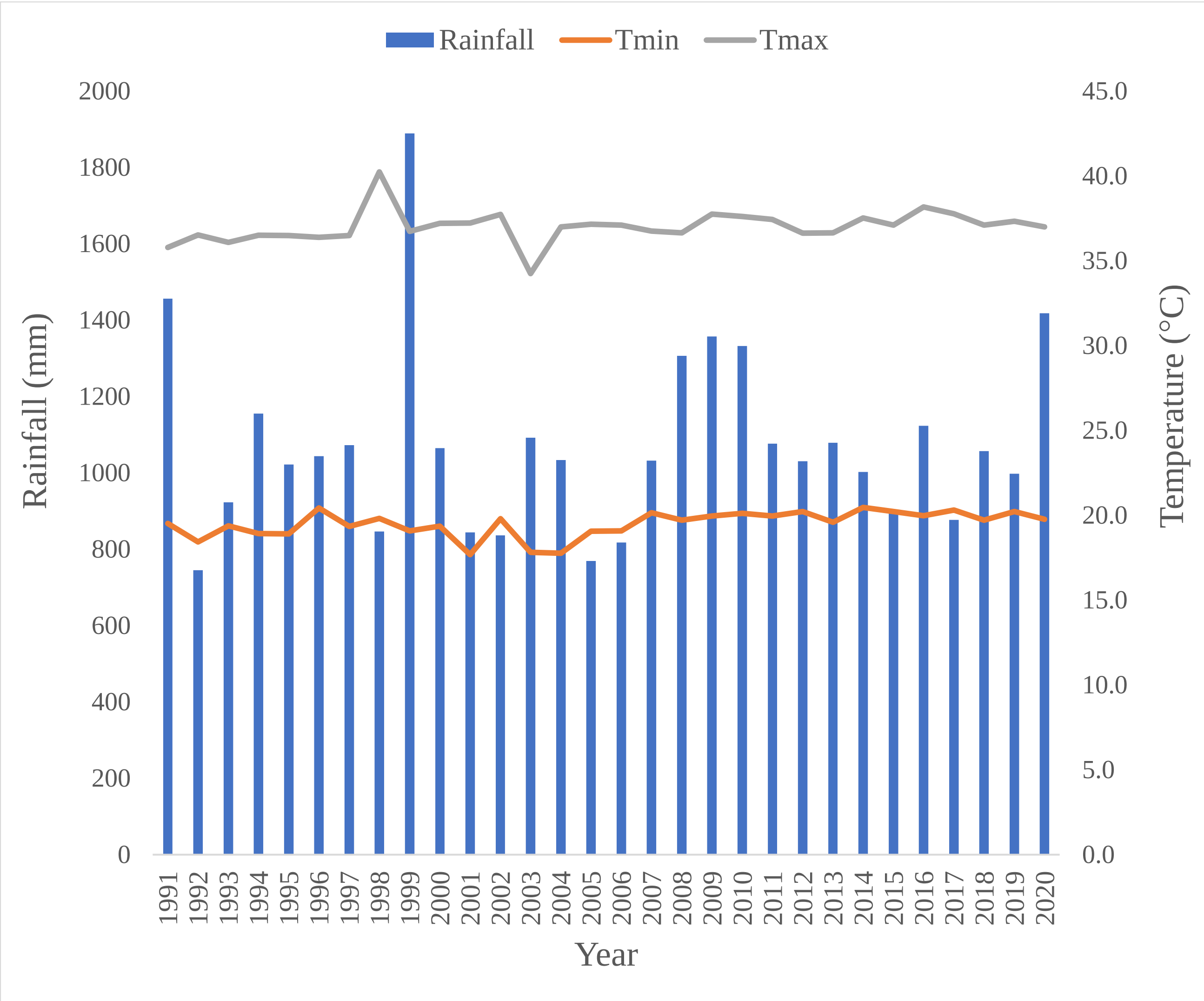

Figure 1: long-term rainfall and temperature in the study area (CSIR-SARI weather station, 1991-2020).

2.2 The carbon cycle

Carbon a vital element used by organisms to store and expand energy circulate between four main reservoirs on earth including, atmosphere, ocean, land (biosphere and pedosphere) and sediments and rocks (lithosphere) (Figure 2). Carbon dioxide (inorganic carbon) form small component of the atmosphere, though smallest in the atmosphere it plays a key role in the cycle by acting as a conduit between the other reservoirs. The lithosphere stored a substantial amount of carbon in the range of over 50,000,000 Gt C with slower carbon turn over time. However, the atmosphere had the fastest carbon turn over time among all the reservoirs storing approximately 760 Gt C (Alley et al, 2007). Between the lithosphere and the atmosphere are the ocean (storing about 38,000 Gt C) and biosphere (storing about 2000 Gt C) in terms of C storage capacity. Carbon is exchanged only in an inorganic form (CO_2) between the reservoirs. The movement of CO_2 is from the atmosphere to the biosphere, ocean and pedosphere via photosynthesis, physicochemical processes and weathering of rocks. The reverse (movement to the atmosphere) is mainly through biochemical (respiration, biomass decomposition) and chemical processes (Lal et al, 2013).

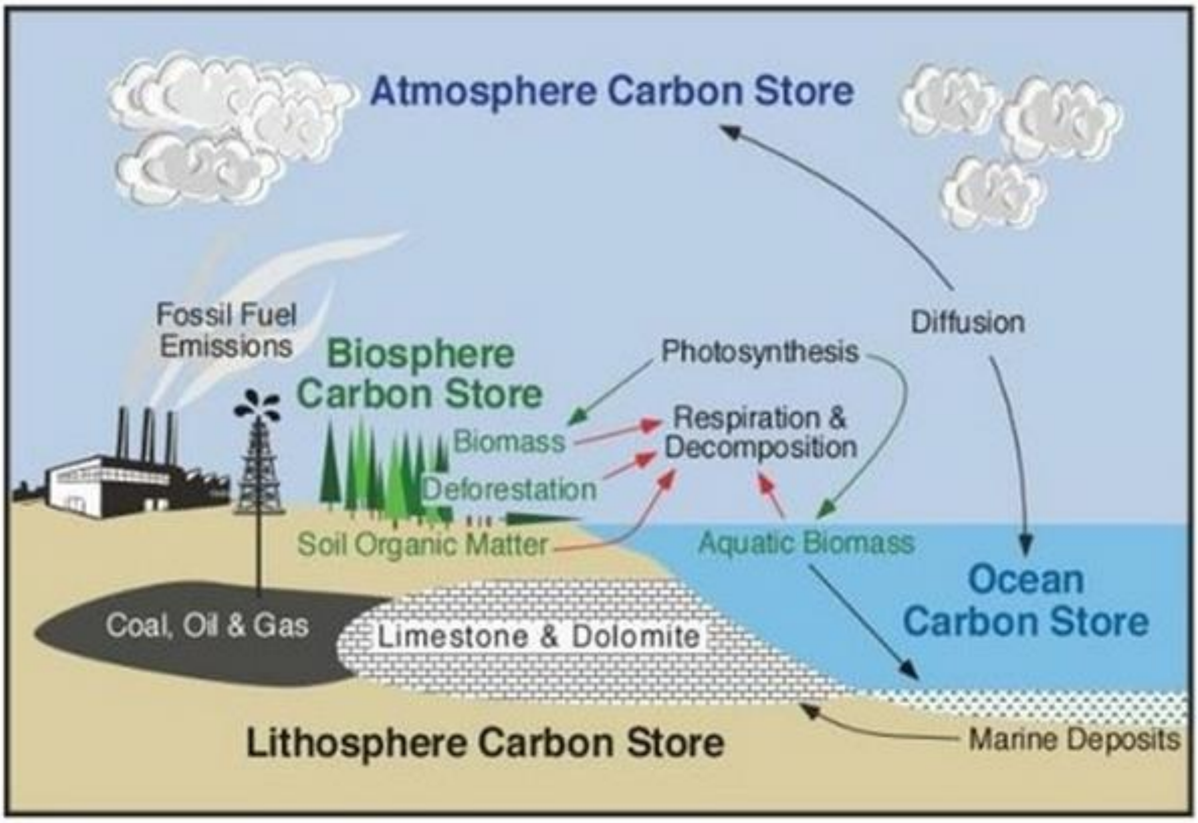

Figure 2: the different carbon reservoirs on earth (source: https://www.slideserve.com)

The CO_2 concentration in the atmosphere keeps increasing as a result of anthropogenic activities. Atmospheric CO_2 concentration of 280 ppm was found in late 1700s (prehistoric to industrial revolution). The increment was at a steady state after the industrial revolution between 1870 to 1970, a constant rise of about 0.28 ppm per year was observed (Hashimoto, 2019). The atmospheric CO_2 concentration is increasing at much faster rate due to the economic development of developing countries coupled with high industrial activities of developed countries. The atmospheric CO_2 concentration as at January 2018 stands at 415 ppm (Hashimoto, 2019).

2.3 Carbon exchange in terrestrial ecosystems

The main element controlling the amount of carbon input into ecosystems is the availability of water and nutrients (Chapin et al, 2012). Most carbon and chemical energy enter ecosystems through the process of photosynthesis (Chapin et al, 2006). The proximity of reactants such as solar energy and CO_2, temperature, which regulates reaction rates, and nitrogen which is needed to generate photosynthetic enzymes, are the main factors influencing photosynthesis in a single leaf (Chapin et al, 2012). Gross primary production (GPP) refers to photosynthesis at the level of ecosystems. GPP varies during the day and throughout the year in response to variations in light, temperature, and nitrogen availability, much like photosynthesis by individual leaves (Novick et al, 2015). The amount of leaf area and the amount of time that this leaf area is photosynthetically active, however, are what essentially determine differences in yearly GPP between ecosystems. The amount of water and nutrients in the soil, the climate, and the amount of time since a disturbance all affect leaf area and the photosynthetic season (Chapin et al, 2012). By fixing energy through photosynthesis, plants are able to grow and produce organic matter that is consumed by soil microorganisms and animals. Almost half of the organic matter on earth is made of carbon, which is produced from photosynthetic processes; the majority of the remaining portion is made of hydrogen and oxygen (Grace 2004). By altering the majority of the mechanisms that govern this process, human activities have significantly changed the rate at which carbon enters the terrestrial biosphere. The amount of atmospheric CO_2 to which all terrestrial plants are exposed has increased by 30% as a result of human activities (Niu et al, 2017). On a regional level, the activities of human had changed the water and nutrient availability, which are the two main factors affecting how well plants can absorb CO_2 from the atmosphere. The spatial distribution of the terrestrial biosphere's capacity to fix carbon has also changed as a result of changes in land use and the introduction and extinction of species (Wang, 2019). It is crucial that we comprehend the variables that control how carbon is cycled through vegetation and ecosystems because of the key function that carbon plays in the climate system and the biosphere. Since the same processes govern their input into ecosystems through photosynthesis, carbon and energy are linked as they travel through ecosystems. Light energy is used by photosynthesis to reduce CO_2 and organic compounds containing carbon are produced. Following a series of interactions among ecosystem elements, this organic carbon and the energy it contains are then emitted to space via combustion or respiration. While the energy content of various carbon compounds varies, it is generally constant for complete tissues at around 20 kJ g^{-1} of ash-free dry mass (Golley, 1961; Larcher, 1995). Although it varies, the carbon content of organic matter averages around 45% in herbaceous tissues and 50% in wood (Gower et al, 1999). Terrestrial ecosystems acquire carbon through photosynthesis and release it primarily as CO_2 through respiration in autotrophs (plants and photosynthetic bacteria) and heterotrophs (fungi, animals, and some bacteria), though losses of carbon as volatile organic compounds, methane, or dissolved carbon (i.e., non-CO_2 losses) could also be significant.

2.3.1 Factors influencing ecosystem carbon exchange

More than half of the world's ecosystems primary productivity is significantly limited by the availability of water as a result, changes in precipitation will have an immediate impact on the dynamics of ecosystem carbon (Baldocchi et al, 2018). A stronger negative water balance is predicted in a warmer planet due to increased evaporation, although this effect will likely be mitigated by lower water loss through stomata in a CO_2-richer environment. The net impact (production minus respiration) of a more negative overall water balance is likely dependent on the soil's ability to retain water, the soil's vertical carbon and root distribution, and the vegetation's overall sensitivity to drought. if soil water-holding capacity is low, as in shallow soils, vegetation productivity will be strongly affected by a negative water balance. Hence, under drier conditions, there are predictions of increased sequestration by suppression of respiration and of net loss of carbon through decreased productivity (Heimann M and Reichstein M, 2008). Nitrogen availability is another important interacting factor, which often determines the magnitude of the CO_2 fertilization effect and may suppress it completely if nitrogen is limiting (Reich et al, 2014). Moreover, there are signs of significant interactions between water and nitrogen, with nitrogen becoming more limited in drier environments. Additional elements to take into account include variations in light quantity and quality (direct or diffuse), which might affect vegetation productivity Ullah et al, (2019), and rising levels of ozone and air pollution, which have a negative impact on primary production (Ainsworth et al, 2020).

Ecosystems and the carbon cycle are intimately related because plants and animals are a crucial component of the carbon cycle. The carbon cycle will alter along with ecosystems as a result of a changing climate. Growing more plants will reduce carbon emissions from the atmosphere and lower temperatures. In contrast, if warming inhibits plant growth, habitats will change and more carbon will enter the atmosphere, where it might contribute to further warming. It is estimated that 20% of the world's net primary productivity (NPP) and 20% of the land use CO_2 emissions from deforestation and forest degradation come from African ecosystems. (Ciais et al, 2011). African ecosystems also contribute 40 per cent of fire emissions, mostly from savannah burning. The terrestrial biosphere now binds around one-fourth of the carbon dioxide released into the atmosphere by human fossil fuel combustion and cement production Quéré et al, (2016), thereby slowing down the rise of atmospheric CO_2 levels and thus mitigating climate change.

2.4 Tillage system influence on edaphic environment and carbon dioxide emission.

Tillage is a fundamental practice in agricultural management. It can be defined as a method of ‘working’ the soil either physically, chemically, mechanically or biologically to create suitable conditions for seedling germination, establishment and growth (Abdalla et al, 2013). Primary tillage implements loosen, granulate and crush soil particles (Mehra et al, 2018) and increases porosity (Mondal and Chakraborty, 2022). Although often regarded as an essential part of agricultural management, inappropriate tillage practices can have negative impacts on the sustainable use of land resources and result in environmental damage (Van Lynden and Lane, 2004). Conventional tillage (CT) embraces not only primary cultivation practices, based on ploughing or soil inversion, but also secondary operations directed at land preparation and sowing or planting. CT typically involves inversion tillage which disturbs the soil to a depth of 20–30 cm, redistributes soil layers and exposes subsurface horizons to oxidation (Shepherd et al, 2001). It involves ploughing (soil inversion), followed by one or two harrowing events to produce a suitable layer for plant establishment, as well as the removal of most of the plant residues derived from the previous crop. Conservation tillage (ConT) systems, in contrast, are primarily based on reducing soil disturbance by restricting any land preparation activities to a shallow depth and eliminating soil inversion, while conserving and managing crop residues (Cunningham et al, 2004). Traditional soil tillage plays a great role in influencing the balance between GHG emissions and soil health via decreasing SOM and altering soil structure (Milne et al, 2015). Al-Kaisi and Yin, (2005) showed that tillage disrupts the soil edaphic environment, because it accelerates soil carbon loss through exposure of SOC in inter- and intra-aggregate zones for rapid oxidation by aerobic microorganisms, a process generating CO_2. The consequences of the soil interacting with equipment used for tillage and the timing of operations may result in localized compaction of a particular soil zone and smearing (Batey, 2009). Particle-to-particle or aggregate-to-aggregate contact affects the physical status of the soil matrix and its associated water, air, and temperature properties (Six et al, 2002). The physical parameters (such as soil moisture content, aeration, temperature, and penetration resistance) are affected by tillage and can have a direct effect on the process of seedling emergence and root growth. Tillage has been used to optimize edaphological conditions, such as soil–water and soil–temperature regimes, soil aeration, seed–soil contact, nutrient availability, porosity, pore size distribution, and pest activity. All forms of soil disturbance (even in discrete rows), however, allow the soil pore–space water vapor to escape, even though most seeds germinate in an atmosphere of 90%–100% relative humidity (Baker et al, 2007). Baker et al, (2006) demonstrated that retention of soil pore–space humidity by avoiding tillage had a greater positive effect on seed germination and seedling emergence than maximizing seed to soil contact. Soil structure and SOM are two dynamic properties, which are sensitive to both crop and soil management and are found to impact soil-related properties such as fertility, erosion, tilth and water retention (Celik et al, 2017; Koehn et al, 2014; Lal, 2003; Salem et al, 2015).

Tillage has a major influence on soil carbon emissions and is one of the principal agronomic activities thought to reduce SOC stocks. The tillage practices modify the physical, chemical and biological properties of the soil and thus have great influence on CO_2 emissions. Physical factors that regulate GHG emissions during tillage are aeration, temperature, soil water content, and the degree of mixing of crop residues within the soil matrix (Ussiri et al, 2009). Chemically, the soil pH and the quantity and quality of soil organic carbon are the key players influencing CO_2 emission and carbon sequestration (Gulde et al, 2008). Reicosky et al, (2008) reported that the CO_2 released immediately following tillage increased with ploughing depth and in every case was substantially greater than that from the no-tillage treatment. Intensive soil cultivation breaks down soil organic matter (SOM), producing CO_2, and consequently reduces the total C content. There are many reports suggesting that soil tillage accelerates organic C oxidation, releasing large amounts of CO_2 to the atmosphere over a few weeks (Scala et al, 2008). Holland, (2004) in a review of ConT in Europe highlighted significant reductions in CO_2

emissions through the adoption of ConT methods. Álvaro-Fuentes et al, (2007) conducted a study in a semiarid Mediterranean agroecosystem, and they showed that CO_2 flux was 3–15 times higher after tillage than before. It ranged from 0.17 to 6 g CO_2 m^2 h^{-1}, except in NT where the soil CO_2 flux was low and steady during the whole study period. Adoption of ConT, especially combined with retention of crop residues, can build up SOM, reduce CO_2 emissions and enhance SOC sequestration (West and Post, 2002). However, Gulde et al, (2008) have reported that the increase in soil organic C in response to C input and other management practices depends on the initial C content of the soil. Soils inherently rich in organic C are apparently much slower in their response to a change in soil quality due to management practices than are soils with low levels of organic C. Conservation tillage has been shown to result in a greater percentage of soil present in macro-aggregates and a larger proportion of carbon associated with micro-aggregates compared to that in conventional ploughing (Haddaway et al, 2017).

2.5 Environmental and nutritional require of maize production.

Maize (*Zea may*) is one of most important cereal crop in the world. Since 1961, the production of maize on a global scale has increased from 205 M tons to 1145 M tons and the area under maize production increased by 187% whereas yields of maize have increased almost three-fold (FAOSTAT, 2021). In sub-Saharan Africa (SSA), maize is grown on over 40 M ha of land and is the main cereal grown in over half of the countries in SSA (Cairns et al, 2021) and the consumption of maize by people in more than half of the countries in the sub region is 100 g per day (Prasanna et al., 2021). In Ghana, it is one of the most widely consumed staple foods and makes up between 50% and 60% of total grain production (MoFA/SRID, 2018). The national average of maize keeps increasing from the last few years. The average yield obtained from farmers field at as 2015 was 1.92 t ha^{-1} which was about 34.91% of the potential attainable yield of maize (MoFA/SRID, 2015). Maize national average yield for 2016, 2017 and 2018 were 1.99 t ha^{-1}, 2.05 t ha^{-1} and 2.26 t ha^{-1} respectively (MoFA/SRID, 2016; MoFA/SRID, 2017; MoFA/SRID, 2018). However, in 2021 the average yield obtained from farmers field was 3 t ha^{-1} representing about 50% of the potential yield (FAOSTAT, 2021). Various environmental (temperature, moisture) and soil factors (low soil organic matter, imbalanced nutrient in the soil, insufficient use of fertilizer) come into play for sustainable maize production. Maize is grown on a wide range of climatic conditions due to its different varieties (Ramirez-Cabral et al, 2017). Maize requires warm temperatures throughout its active stage. The temperature ranges within which maize thrive best is from 21 to 27 °C (Xu et al, 2017).

Day temperature of less than 19 °C and night temperature of less than 14 °C affect proper growth and development of maize (Khaeim et al, 2022). Maize can tolerate high temperatures up to 35°C, however, yields are affected when the high temperature coincide with grain filling stage (Kim et al, 2007). Maize requires a minimum moisture of 480-880 mm that is well distributed over the entire growing season depending on the variety (Kamara et al, 2020). The moisture requirement of maize varies with the growing stage of the plant. At the early stages it requires less water, then the water requirement increases rapidly during the flowering stage and finally drops at the mature stages of the plant (Comas et al, 2019). Water stress especially during the flowering and grain filling stage drastically reduce the yield of the maize.

The plant requires nutrient in a proper balance for better growth and development. A combination of organic and inorganic fertilizers is required for a sustainable yield in the proportion of 1 organic and 3 inorganic fertilizers in the savannah soils (Attigah et al, 2013). For maize to produce good yields in Ghana, it is recommended to supply the crop with 90-60-60 kg NPK ha^{-1} and 100-40-40 in the Forest savannah transition zone and the Guinea savannah zone respectively (Tetteh et al, 2017). The nutrients taken up by the plant play different role in the plant tissue. Nitrogen plays a significant and crucial role in cellular metabolism (Nunes-Nesi et al, 2010). N is a component of photosynthetic pigment and other secondary metabolites (Krapp, 2015). Maize yield is enhanced when the N requirement of the plant is achieved. However, over application of nitrogen had serious environmental consequences. It pollutes surface water as well as under ground waters as a result of leaching from agriculture fields (Zhang et al, 2018). Inadequate application of N impedes plant growth and affect crop yield (Dong et al, 2012). Phosphorus is another essential nutrient that maize require to grow and develop. Unlike nitrogen P is not mobile in the soil and it is very important in root and shoot development as well as seed formation of maize (Razaq et al, 2017). Most of the P available in the soil are fixed and are unavailable to the maize plant especially in acidic soil (Wisawapipat et al, 2009). Neutral to slightly alkali soil is required to make P available in the soil (Malhotra et al, 2018). Strategies aimed towards raising the pH of the soil is encourage to be practiced in order to make P available to crops in the soil. Potassium is essentially require by maize to support its growth and productivity. It plays a vital role in the uptake of water, nutrient and carbohydrate by the plant (Prajapati et al, 2012). These functions stimulate early growth and enhance water use efficiency as well as disease resistant capacity of the plant. Zinc is one of the essential micro nutrients required by maize. Zinc is very important for maintaining structural and functional integrity of protein in the plant (Das and Green, 2013). It also acts as a vital barrier against the highly harmful oxygen free radicals that result from metabolism (Broadley et al, 2007; Cakmak, 2000). Zinc is a component of photosynthesis, chlorophyll synthesis and responsible for the production of growth hormone indole acetic acid that results in higher auxin content leading to increased growth and yield of maize (Tohidi Moghadam et al, 2013). To achieve good maize yield the essential plant nutrients required by maize should be in a proper balance.

2.6 Nutrient use efficiency of maize

Nutrient use efficiency (NUE) refers to the crops ability to take up and utilize nutrients for optimal yields, the NUE concept entails three major processes in plants: uptake, assimilation, and utilization of nutrients (Fixen et al, 2015). Population growth is expected to increase by 2050, therefore there is the need to increase food production to meet the demand of the growing world (United Nations, 2017). Improving nutrient use efficiency as well as water use efficiency is critically important in the food production system (Singh et al, 2018.). NUE is vital in assessing the crop production system and greatly influence fertilizer management as well as soil-and-plant-water relationship. The quest by farmers to increase yield to meet the food demand necessitate the use of fertilizers. NUE indicates how the nutrients applied are utilized by the crop and its potential loss from the production system to the environment (Sharma and Bali, 2018). The most appropriate NUE expression is determined by the spatial or temporal scale of primary interest for which reliable data are available. For a plant breeder or geneticist, the scale of interest could be as little as one plant, or it could be as broad as a country or group of countries for policy reasons, educational purposes, or marketing considerations. Issues of interest can be centered on a single method or item over the course of a single growing season or on a cropping system over many years (Fixen et al, 2014). The information available may be rather comprehensive, taking into account all significant nutrient inputs and particular nutrient losses in a comprehensive research effort, or it may be restricted to information that nutrient managers have access to. To address the requirements of this vast range of situations, numerous expressions and measurements have been developed; they are collectively referred to as "NUE". The specific method used must be specified for the results to be understood correctly (Dobermann, 2005).

Dobermann, (2005) reviewed various NUE measurements and calculation, their application and the limitation of each method used (Table 1). The various NUE methods and their applications are presented below.

Partial factor productivity (PFP) is a simple production efficiency expression, calculated in units of crop yield per unit of nutrient applied. For any farm that records inputs and yields, it may be calculated with ease. If accurate information are available on input usage and crop yields, it can also be estimated at the regional and national levels. However, partial factor productivity values vary among crops in different cropping systems, because crops differ in their nutrient and water needs. A comparison between crops and rotation is difficult if it is based on fresh matter yields, since these differ greatly depending on crop moisture contents (e.g. potato vs cereals). Therefore, geographic regions with different cropping systems are difficult to compare with this indicator.

Agronomic efficiency (AE) is calculated in units of yield increase per unit of nutrient applied. It more accurately depicts how a fertilizer application would directly affect productivity and has a direct bearing on the economic returns. The calculation of AE requires knowledge of yield without nutrient input, so is only known when research plots with zero nutrient input have been implemented on the farm. If it is calculated using data from annual trials rather than long-term trials, NUE of the applied fertilizer is often underestimated because of residual effects of the application on future crops. Estimating long-term contribution of fertilizer to crop yield requires long-term trials.

Partial nutrient balance (PNB) is the simplest form of nutrient recovery efficiency, usually expressed as nutrient output per unit of nutrient input (a ratio of "removal to use"). Less frequently it is reported as "output minus input." PNB can be monitored or estimated at the local, regional, or national level as well as by agricultural producers. A PNB near 1 is assume that soil fertility will be maintained at a constant level. However, using a PNB of 1 as an indicator of soil fertility sustainability can be misleading, especially in areas with very low native soil fertility and low inputs and production, like Sub-Saharan Africa. This is because the balance calculation is a partial balance and nutrient removal by processes, like erosion and leaching, are typically not included.

Apparent recovery efficiency (RE) is one of the more complicated NUE expressions, and is typically defined as the difference in nutrient uptake in above-ground plant portions between treated and unfertilized crops relative to the amount of nutrient applied. When analyzing how a crop responds to nutrients, scientists frequently use this NUE expression. Like AE, it can only be measured when a plot without nutrient has been implemented on the site, but in addition requires measurement of nutrient concentrations in the crop. And, like AE, when calculated from annual response data, it will often underestimate long-term NUE.

Internal utilization efficiency (IE) is defined as the yield in relation to total nutrient uptake. It changes depending on genotype, environment, and management. An extremely high IE shows that a nutrient is lacking. Low IE suggests poor internal nutrient conversion due to other stresses (deficiencies of other nutrients, drought stress, heat stress, mineral toxicities, pests, etc.)

Physiological efficiency (PE) is defined as the yield increase in relation to the increase in crop uptake of the nutrient in above-ground parts of the plant. Like AE and RE, it needs a plot without application of the nutrient of interest to be implemented on the site. It also requires measurement of nutrient concentrations in the crop and is mainly measured and used in research. When analyzing any management strategy, it is usually beneficial to include more than one NUE term since it enables a better understanding and quantification of the crop response to the given nutrient.

Table 1: Common NUE terms and their application (taken from Dobermann, 2007).

Term	Calculation	Question Addressed	Typical use
Partial factor productivity	PFP = Y/F	How productive is this cropping system in comparison to its nutrient input?	As a long-term indicator of trends.
Agronomic efficiency**	AE = $(Y-Y_0)/F$	How much productivity improvement was gained by use of nutrient input?	As a short-term indicator of the impact of applied nutrients on productivity. Also used as input data for nutrient recommendations based on omission plot yields.
Partial nutrient balance	PNB = UH/F	How much nutrient is being taken out of the system in relation to how much is applied?	As a long-term indicator of trends; most useful when combined with soil fertility information.
Apparent recovery efficiency by difference**	RE = $(U-U_0)/F$	How much of the nutrient applied did the plant take up?	As an indicator of the potential for nutrient loss from the cropping system and to access the efficiency of management practices
Internal utilization efficiency	IE = Y/U	What is the ability of the plant to transform nutrients acquired from all sources into economic yield (grain, etc.)?	To evaluate genotypes in breeding programs; values of 30-90 are common for N in cereals and 55-65 considered optimal.
Physiological efficiency**	PE = $(Y-Y_0)/(U-U_0)$	What is the ability of the plant to transform nutrients acquired from the source applied into economic yield?	Research evaluating NUE among cultivars and other cultural practices; values of 40-60 are common

PFP=partial factor productivity, AE= agronomic efficiency, PNB= partial nutrient balance, RE= apparent recovery efficiency by difference, IE= internal utilization efficiency, PE= physiological efficiency, Y= yield of plot with fertilizer, F=fertilizer applied, Y_0= yield of plot without fertilizer, U= uptake by fertilized plot, U_0= uptake by non-fertilized plot.

2.7 Integrated Soil Fertility Management (ISFM) contribution to agriculture productivity

2.7.1 Concepts of ISFM

Crop production can be raised in a profitable and environmentally responsible manner by using integrated soil fertility management Vanlauwe et al, (2010) and thus to eliminate one of the main factors that perpetuates rural poverty and natural resource degradation in sub-Saharan Africa (SSA). The widespread demonstration of the advantages of typical ISFM treatments at the plot scale, such as the combined use of organic manure and mineral fertilizers, has contributed to the current interest in ISFM Zingore et al, (2008), dual-purpose legume–cereal rotations Sanginga et al, (2003), or micro-dosing of fertilizer and manure for cereals in semiarid areas (Tabo et al, 2007). ISFM also adheres to the sustainable intensification principles Pretty et al, (2011), one of the principles guiding efforts is to raise small-holder farming systems' production. By diversifying agricultural systems, primarily with legumes, and enhancing the accessibility of organic resources within farms, primarily as crop residues and/or farmyard manure, ISFM can raise crop productivity and probably improve other ecosystems' services and resilience. The simultaneous application of fertilizer and organic resources is one of the tenets of ISFM, and it has been pushed since the late 1980s (Vanlauwe et al, 2001), because of (i) the failure of Green Revolution-like interventions in SSA and (ii) the lack of adoption of low-external-input technologies by small-holder farmers, including herbaceous legume-based technologies. The combined application of fertilizer and organic inputs made sense since (i) In small-holder farming systems, both organic and fertilizer inputs are frequently in short supply since they are not always affordable or readily available (ii) Both inputs have different combinations of nutrients and/or carbon, addressing various soil fertility-related constraints (iii) Positive direct or indirect interactions between fertilizer and organic inputs frequently result in increased crop production (Vanlauwe et al, 2001). In 1995, Sanchez, (1995) introduced the "second paradigm" for managing tropical soil fertility, to “overcome soil constraints by relying on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity, and optimizing nutrient cycling to minimize external inputs and maximize their use efficiency”. In this context, he had already emphasized the importance of incorporating better germplasm, the second ISFM tenet, within any enhanced nutrient management strategy. The goal of integrated soil fertility management is to make the best possible use of the soil's nutrient reserves, mineral fertilizers, organic amendments, and improved germplasm (Vanlauwe et al, 2001).

2.7.2 Principles of ISFM

Maximize use of Organic inputs (crop residues and animal manures) are also an important source of nutrients, but their N, P, Mg and Ca content is only released following decomposition. Contrarily, because K is present in the cell sap, it is quickly liberated from animal manures and crop leftovers. Further, the nutrients in organic resources are typically insufficient to maintain necessary levels of agricultural yield and realize the full economic potential of a farmer's land and labour resources (Alun, 2020). Judicious use of inorganic fertilizer (mineral fertilizers) are required to supplement the nutrients recycled or added in the form of crop residues and animal manures. Fertilizers are concentrated sources of necessary nutrients in a form that is easily absorbed by plants. They are often less costly than animal manures in terms of the cost of the nutrients that they contain but often viewed as more costly by farmers because they require a cash outlay (Alun, 2020). Use of improved germplasm; It is important that the farmer uses the crop planting materials (usually seed but sometimes seedlings) best adapted to the particular farm in terms of (Alun, 2020): i) responsiveness to nutrients (varieties differ in their responsiveness to added nutrients); ii) adaptation to the local environment (soils, climate); and iii) resistance to pests and diseases (unhealthy plants do not take up nutrients efficiently).

2.7.3 Effect of ISFM for soil fertility improvement

Soil fertility is the ability of the soil to meet the physical, chemical, and biological requirements for plant growth, reproduction and quality, relevant to plant and soil type, land use and climatic conditions (Abbott and Murphy, 2007). Maintaining the organic matter content of the soil is the primary step to maintain soil fertility. This can be done by using appropriate crop husbandry practices and by applying organic manure or compost together with mineral fertilizer. In contrast to organic fertilizers, which slowly add nutrients to the soil, chemical fertilizers can immediately restore the fertility of the soil. The combination of both, organic and mineral fertilizers is crucial as they influence different soil properties. Mineral fertilizers are distinguished by their high concentration of nutrients that are available to plants. Numerous studies revealed that the application of mineral fertilizer significantly increased grain yield. Drechsel et al, (2001) is claiming that fertilizer application is increasing with increasing population pressure at small-holder level. At small-holder level organic material is applied in form of farmyard manure (FYM) as it is often the source of organic matter (Dunjana et al, 2012).

2.7.4 Residual advantage of integrated soil fertility management

According to Cooke, (1970) application of farmyard manure and fertilizers leaves residues of nitrogen, phosphorus and potassium in soil that benefit succeeding crops. He further indicated that the residues of inorganic nitrogen fertilizers usually last only for a season, but the residual effects of continued manuring with phosphorus and potassium may last for many years. Akande et al, (2004) also recorded an increase in soil available P after applying rock phosphate with poultry manure on okra for two season in the range of 112% and 115% and 144% and 153% respectively. Akande et al, (2005) further reviewing the effect of rock phosphate amended with poultry manure on the growth and yield of maize and cowpea reported that when rock phosphate application had continued over a period of several years a large pool of undissolved rock phosphate could accumulate. Residual effects of manure or compost application can maintain crop yield level for several years after manure or compost application ceases since only a fraction of the N and other nutrients in manure or compost become plant available in the first year after application (Eghball, 2002). Eghball and Power, (1999) found that 40% of beef cattle feedlot manure N and 20% of compost N became plant available in the first year after application, indicating that about 60% of manure N and 80% of compost N became plant available in the succeeding years, assuming little or no loss of N due to NO_3^- leaching or denitrification. Even years after an application has stopped, the residual impacts of organic compounds on soil characteristics can help improve the soil's quality (Ginting et al, 2003). Further results showed that when soil contains residues of inorganic nitrogen, larger maximum yields are possible than may be obtained from soil without residues. The results also showed that dressings of inorganic N fertilizers had large residual effects in the first year after the dressings stopped but much smaller effects in the second and third years. Therefore for resource poor farmers combined application of farmyard manure and mineral fertilizer is very economical than sole NP application (Assefa, 2015).

2.7.5 Effect of integrated soil fertility management on climate mitigation

Healthy soils provide the largest store of terrestrial carbon. Soils can store carbon (carbon sequestration and lower greenhouse gas emissions in the atmosphere when they are maintained sustainably, which is crucial for preventing climate change. Conversely, if soils are managed poorly or cultivated through unsustainable agricultural practices, soil carbon can be released into the atmosphere in the form of carbon dioxide (CO_2), which can contribute to climate change. The greatest terrestrial carbon reservoir is found in soil, and its biogeochemical activities control how much of those gases are exchanged with the atmosphere (Scharlemann et al, 2014). Sustainable soil and land management interventions that are designed to increase soil organic matter should be accompanied by actions that address the drivers of degradation and help preserve existing soil carbon stocks, particularly in soils with high soil organic carbon content (Smith et al, 2014). Soil carbon sequestration will aid in the adaptation and mitigation of climate change. It will also make agricultural production systems more sustainable; increase the overall resilience of agricultural ecosystems; and maintain the ecosystem services that are supported by soils. Through soil respiration, mineralization, and decomposition, a sizeable portion of the world's CO_2 is produced. So when fertilizers were added to the soil through integrated way the decomposition rate was reduced and carbon dioxide emission was altered (Jabro et al, 2008). Climate change mitigation involves reducing the amount of greenhouse gases in the atmosphere or enhancing their sinks, e.g., by reducing the use of fossil fuels, planting trees, or enhancing mineralization of organic matter into soil organic carbon. Adopting the ISFM strategy is essential to SOC sequestration. The sink capacity of SOM for atmospheric CO_2 is greatly enhanced when soils are treated with integrated soil fertility management instead of treating it with organic or inorganic source of nutrient (Lal, 2004).

2.7.6 Effect of integrated soil fertility management on agricultural sustainability

The efficiency of applied chemical fertilizers is also increased when applied along with organic manures. Therefore, better management of soil nutrients is required that delivers sustainable agriculture and maintains the necessary increases in food production while minimizing waste, economic loss and environmental impacts (Goulding et al, 2008). Various long-term research results have shown that neither organic nor mineral fertilizers alone can achieve sustainability in crop production. Rather, integrated use of organic and mineral fertilizers has become more effective in maintaining higher productivity and stability through correction of deficiencies of primary, secondary and micronutrients (Aulakh, 2010). Therefore, the use of integrated soil fertility management is best alternative to supply nutrient to crop needs and improve soil conditions. So far, many research findings have shown that neither inorganic fertilizers nor organic sources alone can result in sustainable productivity (Satyanarayana et al, 2002). For sustainable crop production, integrated use of chemical and organic fertilizer has proved to be highly beneficial. Research has shown that that combinations of organic and mineral fertilizers result in greater crop yields compared with sole organic or sole mineral fertilizers (Assefa, 2015). Vanlauwe et al, (2001) reported that grain yield increases of up to 400% over the control in cases where the control yields are low. This increase in grain yield has been attributed to improved N synchrony with combined inputs through direct interactions of the organic and N fertilizers.

2.7.7 Effect of Integrated soil fertility management on crop productivity

The weakness in the productivity of crops across sub-Saharan Africa is not only related to the poor soils in many countries (Assefa, 2015) but also to the limited use of essential inputs that are needed to raise the productivity level. These inputs include the use of improved seeds, fertilizers, irrigation, pesticides. The hypothesis is that the use of these inputs would boost the productivity of crops (Alun, 2020). Research results indicated that productivity of wheat was significantly affected by different soil fertility treatment levels. Applications of inorganic and organic nutrient sources either alone or in combination had a significant ($p < 0.001$ and $p < 0.01$) effect on grain yield, total biomass and harvest index of wheat, but not on its thousand grain weight. Analysis of variance over two years indicated that the year by soil fertility treatment level interaction effect was significant ($p < 0.05$ and $p < 0.001$) for wheat grain yield, total biomass and harvest index; but not for thousand grain weight (Agegnehu et al, 2016).

2.7.8 Effect of Integrated soil fertility management on environmental sustainability

The soil sustains most living organisms, being the ultimate source of their mineral nutrients. Good management of soils ensures that mineral elements do not become deficient or toxic to plants, and that appropriate mineral elements enter the food chain. Soil management is important, both directly and indirectly, to crop productivity, environmental sustainability, and human health. Because of the projected increase in world population and the consequent necessity for the intensification of food production, the management of soils will become increasingly important in the coming years. To achieve future food security, the management of soils in a sustainable manner will be the challenge, through proper nutrient management and appropriate soil conservation practices. Research will be required to avoid further degradation of soils, through erosion or contamination, and to produce sufficient safe and nutritious food for healthy diets (Philip et al, 2012). Long-term sustainability of agro-ecosystems requires soil protection from degradation and reduction of greenhouse gas emissions and of environmental pollution. Soil protection needs judicious and prudent use of conservation agriculture to prove its potential as a conservation effective technology, climate resilient agriculture, and a viable option for sustainable intensification of agro-ecosystems for advancing food security and for adaptation to/mitigation of climate change. Conservation agriculture refers to a farming system comprised of crop residue mulch, cover cropping, integrated nutrient management, and no tillage techniques in a rotation cycle for effective soil and water conservation, carbon sequestration, sustainable intensification and climate change adaptation and mitigation.

CHAPTER THREE

3.0 Materials and Methods

3.1. Study areas

The development and laboratory validation of the CO_2 and ET measuring system was done at the Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg-Germany. The field validation of the developed system was carried out in “PatchCrop” located near the village of Tempelberg, Northeast Germany (52°44’86.2’’ N, 14°14’05.1’’E) (Figure 3). The temperate climate is characterised by a mean annual air temperature of 9.7°C and mean annual precipitation of 544 mm (ZALF weather station, 2010-2019). The medium loamy, sand textured soil can be classified as Luvisol based on world reference base classification (WRB).

The testing of the developed CO_2 system under experimental setup was carried out at the experimental field of the Council for Scientific and Industrial Research-Savanna Agricultural Research Institute (CSIR-SARI) in Northern region of Ghana. The site was located at latitude 09° 24' 15.9" N and longitude 001° 00' 12.1" W (Figure 4). The vegetation cover in the area is mainly grasses with scattered trees. It is a tropical area and has a mean daily temperature of 26 °C and a uni-modal rainfall pattern, averaging about 1100 mm annually (SARI, 2014). It has a marked seasonality with a rainy season from June to October, followed by a dry season which commences from November to May (Alua et al, 2018). The soil is sandy loam textured and is classified as Acrisols according to world reference base classification (WRB).

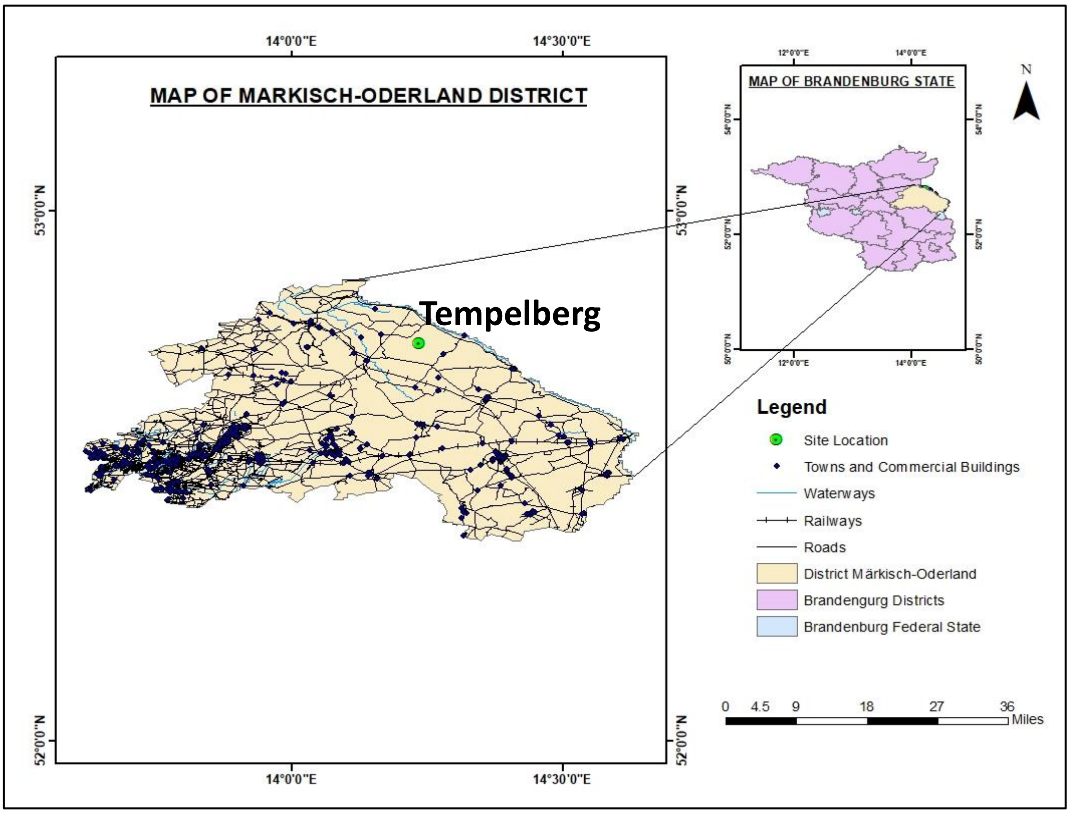

Figure 3: Map showing the experimental site (Tempelberg, Germany)

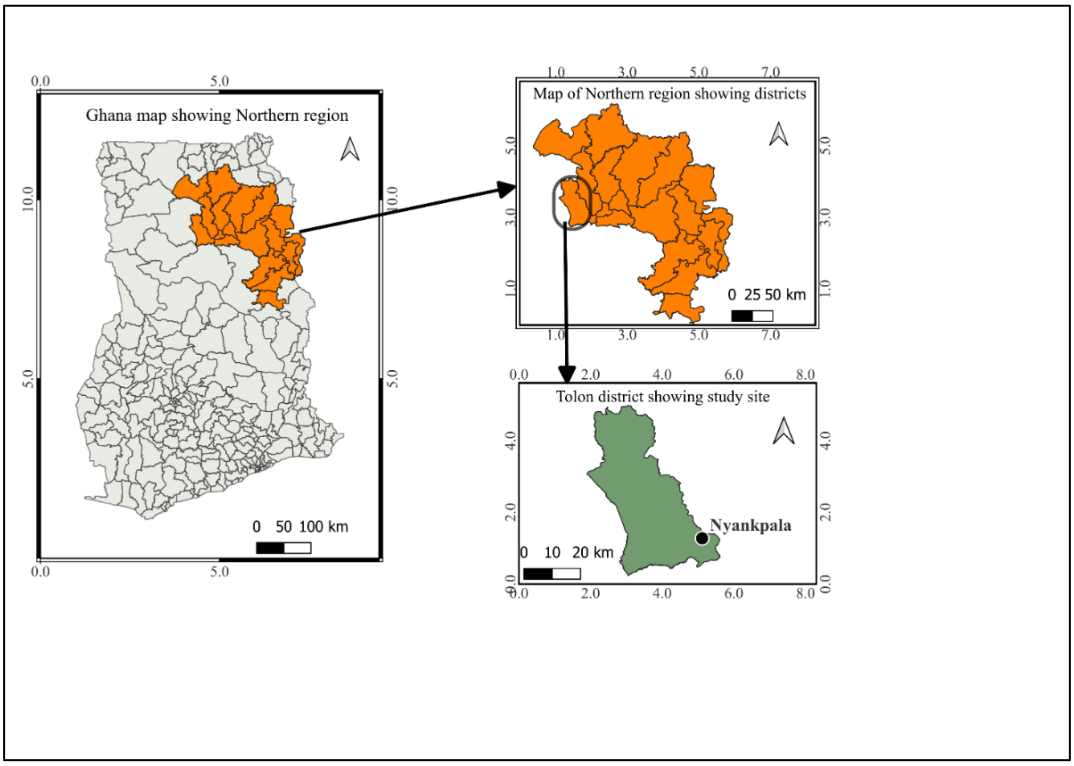

Figure 4: Map of Ghana showing the experimental field at CSIR-SARI Nyankpala-Ghana

3.2. Equipment

The major equipment used for the experiment are listed below:

i. Li-COR 850 IRGA (LI-850, LI-COR, USA) used for CO_2 measurement.

ii. Minions (The developed CO_2 and ET system) used for CO_2 measurement.

iii. TMS-4 datalogger (TOMST s.r.o, Michelská 964/78 Praha, Czeck Republic) was used to measure air and soil temperature.

iv. Soil moisture meter (VG-Meter-200, Vegetronix, Inc. Riverton, USA).

v. PAR sensor (SQ 420x Apogee instrument Inc. USA) for measuring photosynthetic active radiation.

3.3 Methods used for the experiment

3.4. Development of CO_2 and ET system

3.4.1 Hardware and software implementation

The developed, highly portable CO_2 and ET flux measurement device consists of a logger and sensor unit both assembled out of a combination of various low-cost, off-the-shelf components. A complete list of used components, distributors and prices are given in (Table 2). Figure 5, shows the assembled logger and attachable sensor unit, together with a schematic representation of the wiring.

The logger unit consists of an Arduino Uno like microcontroller (Atmega328, AZ-Delivery Vertriebs GmbH, Germany) with attached Logger Shield module (AZ-Delivery Vertriebs GmbH, Germany) including a SD card reader and SD card (2GB) to store sensor readings and a real time clock (RTC) which helps to keep the time and date even when the system is switched off. A BME280 air temperature (±1◦C), air humidity (±3 %) and air pressure sensor (±1 hPa; reichelt elektronik GmbH & Co., Germany) as well as an LCD display (AZ-Delivery Vertriebs GmbH, Germany) and HC-05 bluetooth module are part of the logger unit and connected to the microcontroller (Figure 5c). The logger unit is fitted into a weather and shock resistant outdoor housing (B&W Outdoor Case Type 500, Overhaul Media GmbH, Germany) (Figure 5a). The external sensor unit consists of a nondispersive infrared (NDIR) based CO_2 (0-10,000 ppm, ±30 ppm ±3 % accuracy; K30FR, Senseair AB, Sweden) and an air humidity (RH) and air temperature sensor (SHT31, DHT22). Both sensors were connected through a seven core cable to the logger unit using UART (K30FR) and I2C (SHT31) data communication, respectively (Figure 5b). The power supply of the microcontroller is ensured by 6 rechargeable

AA NiMH batteries (1.2 V; 2600 mAh) in a 6xAA battery holder, which supply 7.2 V. Due to the power requirements of the external sensor unit (K30FR and SHT31), an additional 6xAA battery holder is attached to the housing to supply it directly. Software implementation was done using Arduino IDE 2.0.3.

Table 2: Sensor components and cost (in Euro) at time of writing, including weather and shock-proof housing, and energy supply (batteries). Components needed for optional semi-automatic mode are listed in addition.

Component	Amount	Description	Price (Euro)	Distributor
B&W Outdoor Case Type 500	1	Outdoor case for housing electrical components	28.75	www.profikoffer.de
PVC hard foam plate	1	PVC 5mm hard foam plate to create interior of housing for electronic components	1.5	www.amazon.de
Luster terminals	12	Luster terminals for wiring electrical components within housing	0.6	www.amazon.de
0.2mm² 24awg Electrical wire		Electrical wires for wiring electrical components within housing		www.amazon.de
7 Pin Aviation connector	2	Aviation connector to connect logger unit within weatherproof housing with passive NDIR sensor installed in the closed chamber to be attached	2.9	www.amazon.de
7 core rubber cable (1.5m)	1	Cable to connect logger unit within weatherproof housing with passive NDIR sensor installed in the closed chamber to be attached	3.75	www.conrad.de
WS R13-112 AAAA Rocker switch	1	Rocker switch for switching on and off	1	www.reichelt.de
Atmega 328	1	Arduino Uno like microcontroller	5	www.az-delievery.de

DataLogger Module	1	Loggershield for Arduino UNO like microcontroller with SD card reader and RTC unit	4.6	www.az-delievery.de
HAMA Class 4, SD memory card, 2 GB, 10 MB/s	1	SD memory card to save sensor readings	6	www.saturn.de
HC-05 Bluetooth Wireless RF-Transceiver-Module RS232	1	Bluetooth module for wireless communication	5.2	www.az-delievery.de
16x2 LCD or OLED Display with I2C adapter	1	LCD or OLED display for data visualization	3.7	www.az-delievery.de
BMP280	1	Air pressure, air humidity and air temperature sensor	1.7	www.reichelt.de
DHT22 or SHT31 modul	1	Air temperature and air humidity sensor	6.4	www.az-delievery.de
SenseAir K30 FR (fast response)	1	CO_2 measuring module with fast response time; Measuring range: 0 to 5000 ppm CO_2, operating range: 0 to 50 °C	85	www.driessen-kern.de
Goobay 11467 6x (4x) Mignon (AA) Battery holder	2 (1)	Battery holder for 6x NiMH rechargeable mignon (AA) batteries	4.6	www.conrad.de
Conrad energy HR06 Mignon (AA)-Akku NiMH 2600 mAh 1.2 V	12 (16)	NiMH rechargeable mignon (AA) batteries	38	www.conrad.de
4.5V metal brush air pump	2	Air pump for flushing headspace of small chambers	9.45	www.berrybase.de
IRLZ44N Mosfet	1	Mosfet to control power supply to pumps	0.75	www.reichelt.de
Total costs			199.0	

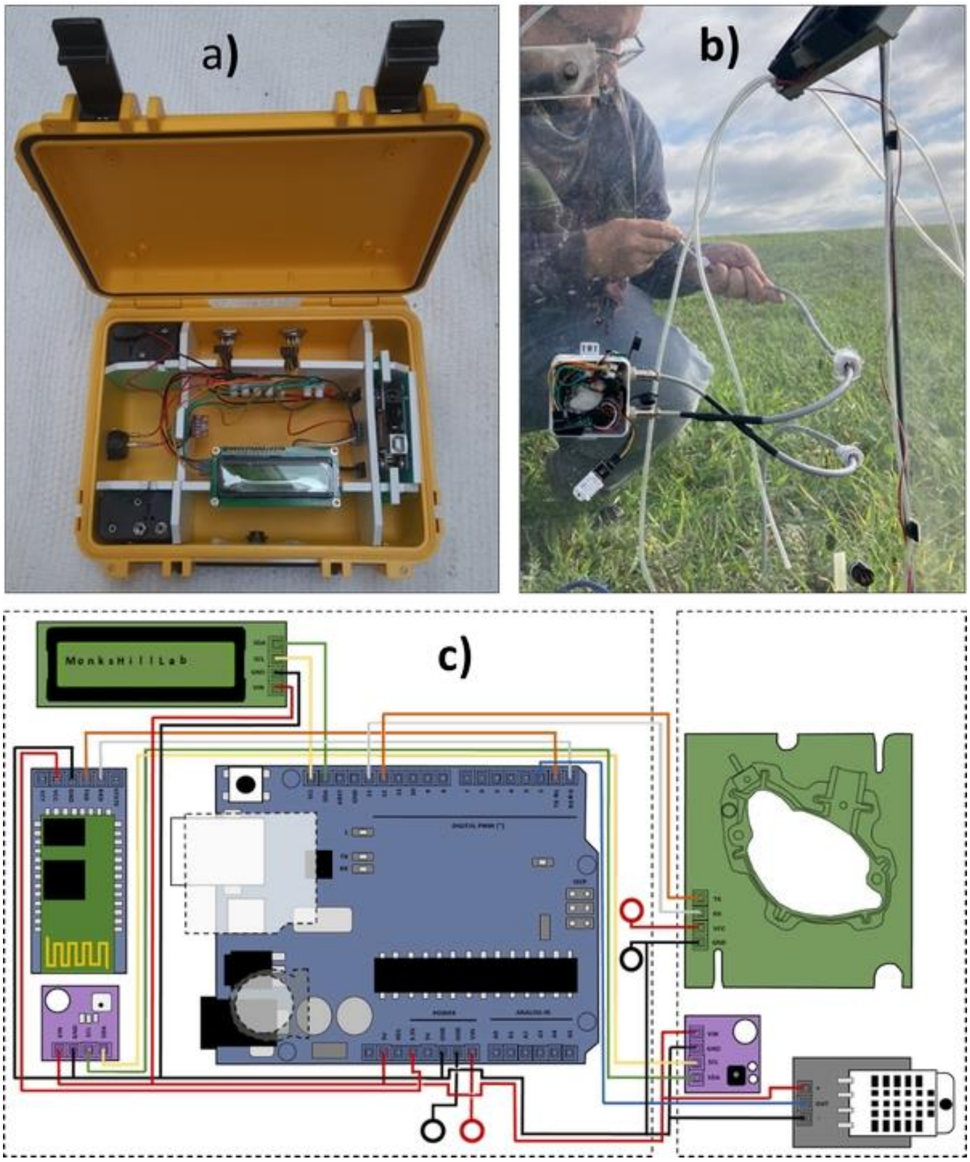

Figure 5: (a) Logger unit in weather and shock resistant housing, (b) external sensor unit attached to a transparent non-flow-through non-steady-state closed chamber and (c) schematic representation of the wiring.

3.4.2 Laboratory validation of the developed CO_2 system

To identify the NDIR sensor, most suitable for *in-situ*, dynamic closed chamber measurements, four different NDIR-based sensors, namely 1.) MHZ-19 (Zhengzhou Winsen Electronics Technology CO., LTD, China), 2.) MHZ-14 (Zhengzhou Winsen Electronics Technology CO., LTD, China), 3.) SCD30 (Sensirion AG, Switzerland) and 4.) K30 FR (Senseair AB, Sweden) were tested and validated regarding their precision and accuracy during a laboratory experiment. For this, sensors were placed separately into a sealed, ventilated, cylindrical vessel (Figure 6) with a volume of 1425.5 cm^3 and connected to the developed low-cost logger system.

All sensors were calibrated in ambient prior to use according to manufacturer instructions. Afterwards different distinct amounts (5 to 30 ml; in 5 ml steps) of a technical gas containing 10,000 ppm CO_2 (Linde, Germany) were repeatedly (n=30 per sensor) injected into the sealed vessel using a syringe and a closable valve. In between injections, the vessel was flushed with ambient air by two pumps (1.5l min^{-1}) connected to it (semi-automatic measurement mode of the developed system). Finally, CO_2 concentration increases inside the vessel, measured in a 5s interval by the NDIR-based sensors, from before to after injection (ΔCO_2 in ppm) were compared against mixing-induced CO_2 concentration increases. Sensors that performed best in terms of accuracy and precision were subsequently validated in field setting.

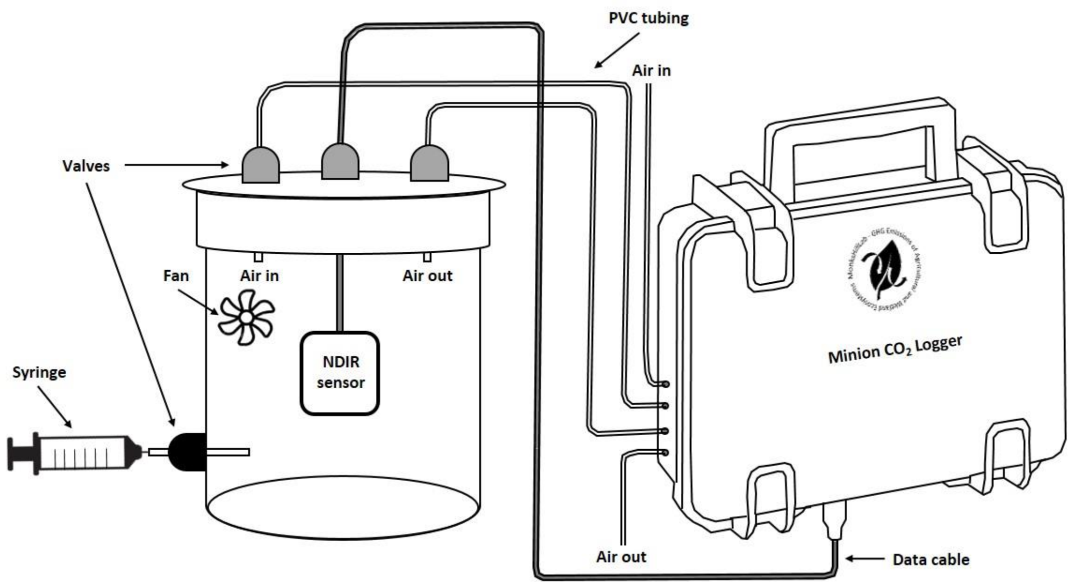

Figure 6: Experimental setup of the performed laboratory validation of four different NDIR CO_2 sensors connected to the developed low-cost CO_2-flux measurement system (MHZ-14, MHZ-19, SCD30 and K30FR) through injecting distinct amounts of technical gas (Linde, Germany; 10,000 ppm CO_2) into a air-tight sealed cylindrical vessel.

3.4.3 Field validation of the developed CO_2 system

Field validation of the low-cost CO_2 and ET flux measurement system was performed through parallel manual closed chamber measurements using an infrared gas analyzer (IRGA; LI-850, LI-COR, USA) and NDIR/RH sensors passing previous laboratory validation. Measurements were conducted at the "PatchCrop" experimental field, managed by the Leibniz-Centre for Agricultural Landscape Research (Figure 7). "PatchCrop" features multiple smaller patches (72 x 72 m), with diverse and site-specific crop rotations, aiming to create synergies and interactions between fields. CO_2 exchange (NEE and R_{eco}) and ET measurements were conducted for a mixture of Phacelia and *Guizotia abyssinica* at three repetitive plots, established at one of the patches through installing PVC collars (A: 0.5625 m^2; 5 cm deep). Measurements started shortly after sunrise and lasted till late afternoon during two consecutive days, using a dynamic, non-flow-through non-steady-state (NFT-NSS) manual closed chamber system. Used transparent (86% light transmission; NEE flux measurements) and opaque (ecosystem respiration (R_{eco}) flux measurements), cubic shaped PVC chambers had a total volume of 0.296 m^3 and were equipped with a fan for efficient headspace mixing. CO_2 and H_2O concentrations, as well as RH, during chamber deployment were recorded in parallel using a LI-850 IRGA and the developed, low-cost measurement system, equipped with a K30FR, SCD30, SHT31 and DHT22 sensor, respectively. NEE, R_{eco}, and ET fluxes were measured by alternately deploying the opaque and transparent chambers on the three pre-installed PVC frames. During an individual 4 min measurements, CO_2 and H_2O concentration, as well as RH, changes in the chamber headspace, air temperature inside and outside the chamber, soil temperature and humidity (TMS-4, TOMST, Czech Republic) as well as PAR (outside the chamber, Skye, UK) were recorded at a 3s (Li-850) to 5s interval (NDIR and RH sensors). To validate the low-cost CO_2 and ET flux measurement system, measured R_{eco}, NEE and ET fluxes, as well as derived temperature (R_{eco}) and PAR dependency functions (GPP), were directly compared against results obtained in parallel with the IRGA. A total of 41 closed chamber measurements (R_{eco}: 21; NEE: 20) was measured during the two days of field validation using the LI-850 as reference for both NDIR sensors passing the laboratory validation (CO_2) and the two tested RH sensors (ET). While 41 valid CO_2 exchange fluxes (R_{eco}: 21; NEE: 20) could be calculated for the LI-850, 35 (R_{eco}: 21; NEE: 14) and 36 (R_{eco}: 21; NEE: 15) valid fluxes were obtained for K30FR and SCD30, respectively. For ET, 13 valid fluxes could be calculated for the LI-850 as well as the SHT31 and DHT22. Only transparent chamber measurements were taken into account to avoid systematic impact of opaque chambers on plant transpiration via stomatal closure upon darkening (Larcher, 1995).

3.4.4 CO_2 calculation for laboratory validation

For laboratory validation, the changes in CO_2 concentrations in the vessel, expressed as ΔCO_2 in ppm, were calculated as the mixing-ratio of measured ambient air and injected technical gas CO_2 concentration (10,000 ppm). These were compared with the ΔCO_2 obtained for the different NDIR sensors as the difference in mean CO_2 concentrations measured for one minute right before and two minutes after injection.

Figure 7: Parallel opaque (Reco) manual closed chamber measurements with a Li-COR 850 IRGA (LI-850, LI-COR, USA) and the developed, low-cost CO_2 and ET flux measurement system at ZALF experimental field near the village of Tempelberg, North-East Germany (52°44’86.2’’ N, 14°14’05.1’’ E). The developed system was equipped with a K30 FR and SCD30 NDIR, as well as SHT31 and DHT22 sensor.

3.5 Field application of the developed system (experimental setup in Ghana)

3.5.1 Experimental design and treatments application

The experiment was a split plot design with 3 replications. The main plot was assigned with tillage practices (conventional vrs reduced tillage) and the sub-plot treatments was a factorial combination of organic and inorganic fertilizers. Three levels of organic fertilizers were used, i. Fertisoil at 5 t ha^{-1} (commercial organic fertilizer produced in Tamale-Ghana), ii. Farmyard manure at 5 t ha^{-1} and no organic amendment. Inorganic fertilizers were also used at three levels (90-60-60 kg NPK ha^{-1}, 60-40-40 kg NPK ha^{-1} and 0-0-0 kg NPK ha^{-1}). The experimental field area was 2,470.4 m^2 with an individual plot size of 5.6 m x 6 m (Figure 8).

Figure 8: Experimental setup at Nyankpala in Northern region of Ghana

3.5.2 Agronomic practices

The experiment was conducted in two cropping seasons (2021 and 2022 cropping seasons). The experimental field was previously planted with maize. The land was divided into two and one half of the land was ploughed with a tractor and harrowed (conventional tillage) and bullock was used to plough the other half (reduced tillage). The organic fertilizer (Fertisoil and farmyard manure) was incorporated into the soil a week before sowing. The fertisol was obtained from Deco a local company based in Tamale, northern Ghana. The farmyard manure was prepared with farmers in Kpalsogu a community near the study area.

The maize (*Zea mays)* was plant on 2nd July, 2021 for the first season and the second season was planted on 6th July, 2022. The maize variety Sanzal sima was used as a test crop for both seasons. The maize seed was obtained from CSIR-SARI Ghana and was selected base on it high yielding potential (5.4 t ha^{-1}), medium maturity (110-115 days), drought tolerant, tolerant to lodging and its availability in the locality. The maize was planted at a distance of 40 cm x 80 cm and was planted two seeds per hill. Manual weeding was done two weeks after planting and the basal fertilizer application was done immediately after the first weeding. The top dress was done 5 weeks after planting. Emasta (Emamectin benzoate 48g/l + Acetameprid 64g/l EC) was used to control fall army worm on the maize.

3.5.3 Soil sampling and analysis

Initial soil samples were taken as composite samples (n=7) at depths of 0–20 cm before treatment application to determine the initial Physico-chemical status of the soil at the experimental site (Table 3). The soil was sampled with a soil auger and the composite samples were air-dried, sieved to remove roots and other plant debris. The soil was then analyzed for standard soil parameters including particle size distribution, pH, organic carbon, total nitrogen, Available P and Potassium.

Table 3: Selected soil physical and chemical properties in the study area during 2021 season

pH H2O (1:2.5)	% OC	% N	mg/kg P (Bray 1)	mg/kg K	Cmol^{+} kg^{-1} Ca	Cmol^{+} kg^{-1} Mg	(%) Sand	(%) Silt	(%) Clay
4.96	1.053	0.015	4.249	84	1.6	0.3	45.52	48.16	6.32

a) Analysis of soil physical and chemical properties

Soil Bulk Density**:** Bulk density is a measure of the weight of the soil per unit volume expressed in g cm^{-3} or Mg m^{-3} usually given on an oven-dry basis. A mallet was gently used to drive the core sampler into the soil. Soil at both ends of the sampler was snipped with a straight – edged knife. The core sampler with its content was then dried in the oven at 105 ^{0}C to a constant weight. The height and radius of the core sampler was used to determine its volume:

$$P_b = \frac{W2 - W1}{V}$$

where P_b = Dry Bulk Density

W_2 = Weight of core cylinder + oven – dried soil

W_1 = Weight of empty core cylinder

V = Volume of core cylinder ($\pi r^2 h$), where:

π= 3.142

r = radius of the core cylinder

h = height of the core cylinder

Particle size distribution**:** The particle size analysis of soil gives an approximation of the percentage sand, silt and clay contents and is normally given as percentage by weight of oven-dry and organic matter-free soil. The hydrometer method was used for the analysis of particle size as outlined by (Anderson and Ingram, 1993). A 50 g air dry soil was weighed into a conical flask and sodium hexametaphosphate was added as a dispersing agent. After shaking on a reciprocal shaker at 400 rpm for 18 hours, the samples were transferred to 1 L sedimentation cylinders and made up to the mark with distilled water. A hydrometer was used to measure the density of the suspension of soil and water at various times.

Calculation:

% Sand = 100 – [H_1 + 0.2 (T_1 - 20) – 2] x 2

% Clay = [H_2 + 0. 2 (T_2 – 20) – 2] x 2

% Silt = 100 – (% Sand + % clay)

where

W_T= Total Weight of air-dried soil

H_1 = 1^{st} Hydrometer reading at 40 seconds

T^1 = 1^{st} Temperature reading at 40 seconds

H_2 = 2^{nd} Hydrometer reading at 3 hours

T_2 = 2^{nd} Temperature reading at 3 hours

– 2 = Salt correction to be added to hydrometer reading

0.2 (T – 20) = Temperature correction added to hydrometer reading, and T = degrees Celsius.

Soil chemical parameters

The soil pH was determined by weighing 10 g of air- dried soil into a 100 ml beaker and 25 ml distilled water was added. The suspension was stirred vigorously for 20 minutes and was left to stand for about 30 minutes. The pH value was read using HT 9017 pH meter and the values recorded.

The total N content was determined by the Kjeldahl procedure modified to include the mineral nitrates in the soil by the use of salicylic acid to convert all the nitrates into ammonium salts (Tel and Hegatey, 1984). Ten gram of soil was weighed into a 250 ml Kjeldahl digestion flask and 10 ml of distilled water added to it. Ten ml of concentrated H_2SO_4 was added followed by one tablet of selenium and potassium sulphate mixture and 0.10 g salicylic acid. The mixture was left to stand for 30 minutes and heated mildly to convert any nitrates and nitrites into ammonium compounds. It was then heated more vigorously (300-350^{o} C) to digest the soil to a permanent clear colour. The digest was cooled and transferred to a 100 ml volumetric flask and top up to the mark with distilled water. A 20 ml aliquot of the solution was transferred into distillation flasks and 10 ml of 40 % NaOH solution was added and steam from the Tecator apparatus allowed to flow into flask. The ammonium distilled was collected into 10 ml boric acid/ bromocresol green and methyl red solution. The distillate was titrated with 0.01 *M* HCl solution. A blank digestion, distillation and titration were also carried out as a check against traces of nitrogen in the reagents and water used.

$$\%N = \frac{(a - b) \times 1.4\, M \ \times V}{s \ \times t}$$

where a = ml HCl used for sample titration

b = ml HCl used for titration of blank

s = weight of soil taken for digestion in grams

M = molarity of HCl

1.4 = 1.4 10^{-3} × 100% (14 = atomic weight of N)

V = total volume of digest

t = volume of aliquot taken for distillation

Organic carbon was determined by the modified Walkley and Black Procedure outlined by Nelson and Sommers, 1982). Organic carbon is oxidized by potassium dichromate ($K_2Cr_2O_7$), and the reaction was possible as a result of the heat generated by the addition of concentrated sulphuric acid (H_2SO_4) with 1*M* (0.1667 M) $K_2Cr_2O_7$ solution. The excess $Cr_2\ O_7^{2-}$ is determined by titrating with standard ferrous sulphate solution. The quantity of substances oxidized is then calculated from the amount of $Cr_2\ O_7^{2\ -}$ reduced. The equations below summarises the reactions involved.

$$2Cr_2O_7^{2-} + 3C + 6H^+ \rightarrow 4Cr^{3+} + 3CO_2 + 8H_2O$$

$$Cr_2O_7^{2-} + 14H^+ + 6Fe^{2+} \rightarrow 6Fe^{3+} + 2Cr^{3+} + 7H_2O$$

Two gramms of soil sample was weighed into a 500 ml Erlenmeyer flask and 10 ml of 1.0 *M* potassium dichromate solution added, then 20 ml of conc. H_2SO_4. About 200 ml of distilled water was added followed by 10 ml of orthophosphoric acid (H_3PO_4).

The mixture was titrated with 1.0*M* ferrous sulphate solution from blue-black colour to a permanent greenish colour. A blank reagent mixture was similarly treated. This was done to standardize the ferrous sulphate which is not a primary standard but oxidizes gradually in air:

$$\%\ C = \frac{M \ \times (Vbl - Vs) \times 0.39}{g}$$

where

M = molarity of the $FeSO_4$

V_{bl} = ml $FeSO_4$ of blank titration

V_s = ml $FeSO_4$ of soil sample titration

g = weight of soil in grams

mcf = moisture correction factor to oven dried weight (100 + moisture)/100

$0.39 = 3 \times 0.001 \times 100\% \times 1.3$ where (3 is equivalent weight of C)

1.3 = a composition factor for the complete combustion of organic C.

The exchangeable bases Ca^{2+}, Mg^{2+} and K^+ were extracted with 1.0 *M* neutral NH_4OAc solution. After the extraction, the Ca^{2+} and Mg^{2+} were determined using a Jenway 7305 Spectrophotometer at wavelength of 422 nm for Ca^{2+} and 285 nm for Mg^{2+}. K^+ was also determined by Jenway PFP7 flame photometer at wavelengths of 766 nm.

The CEC was calculated by the summation of the basic cations.

The Bray 1 extraction solution procedure (Bray and Kurtz, 1945) was used for available P. Phosphorus in the extract was determined on a Jenway 7305 spectrophotometer at a wavelength of 660 nm with blue ammonium molybdate as reducing agent. A 2 g soil sample was extracted with 20 ml of Bray 1 solution (0.03 *M* NH_4F and 0.025 *M* HCl). The suspension was shaken for one minute with the hand and filtered through Whatman No. 42 filter paper. A standard series of 0, 1.2, 2.4, 3.6, 4.8 and 6.0 was prepared by measuring 0, 10, 20, 30, 40, 50 ml of 12.0 mg P/L respectively into a 100 ml volumetric flask and made up to the mark with distilled water. Spectrophotometer was used for the measurement as stated above;

$$\text{P (mg/kg)} = \frac{(a - b) \times vs \ \times df}{g}$$

wher

a =mgP/L in sample extract

b = mgP/L in blank

vs = volume of extract

df = dilution factor

g = sample weight in grams

b) Plant sample preparation and analysis

The above ground biomass of maize was cut at the ground level and weighed. A sub-sample was taken from a pile and oven dried at 70° C for 48 hours until a constant weight was obtained. The dried sample was finely ground using a biomass grinding machine and stored at room temperature (25^{o} C), then it was used to analyzed i) organic carbon (modified Walkley and Black) ii) Nitrogen (Kjeldahl) iii) Phosphorus (Bray 1) etc.

3.5.4 Grain yield, Nitrogen use efficiency and N recovery

The plants in the middle four rows of each plot were harvested and the cobs were dehusked, counted and weigh using a digital balance. The grain moisture content of each plot at harvest was taken with grain moisture meter (ATI-230 Acmas Technologies Inc, Indian). About 1 kg of cobs were sub-sampled from a number of piles and dried for grain nutrient content analysis. An 80% shelling percentage was used to determine the grain yield. Partial factor productivity of applied N (often simply called nitrogen use efficiency or NUE) was estimated as kg harvest product per kg N applied. N-PFP is an important indices for NUE because it integrates the use efficiency of both indigenous and applied N resources (Dobermann, 2005).

$$NPFP = \frac{Yield\ N}{Applied\ N\ Fertilizer}$$

Where NPFP is nitrogen partial factor productivity, yield N is nitrogen found in the harvested grain.

Nitrogen recovery was also estimated as kg increase in N uptake per kg N applied

$$REN = \frac{Un - Uo}{FN}$$

Where REN is the nitrogen recovery, Un is nitrogen uptake by the fertilized plot, Uo is N from unfertilized plot and FN is the fertilizer N applied.

3.5.5 Preparation of farmyard manure

The farmyard manure was prepared by putting rice straw as bedding material for cattle for about a month. The bedding material made up of cow dung, excreta and rice straw were collected and put into a pit with dimension 5 m long, 2 meters width and 1 meter deep. The bedding material were packed as layers to fill the pit. The pit was filled about 50 cm over its capacity. The pit was then covered with soil mixed with cow dung to form a crust. The bedding material was in the pit for 5-6 months before digging it out for use. Pictures from the preparation are presented in annex 3 to 8.

3.5.6 CO_2 measurement during tillage operation

CO_2 was measure immediately after tillage operations to determine the CO_2 emissions from the various tillage methods. The measurement was conducted in July, 2022 and lasted for 2 days. It started immediately after the tillage operation till about seven hours after the operation in the first day. Measurement in day 2 started about 24 hours after the tillage operation and lasted for about four hours. The tillage methods we employed include tractor plough (TP; 20

cm), bullock plough (BP; 9-11cm), tractor plough and harrow (PH; 20 cm), harrow only (H; 12-15 cm) and no tillage (NT). All the tillage methods with the exception of plough and harrow were measured concurrently. An opaque cylindrical shaped polyvinyl chloride (PVC) chamber with a volume of 0.0038 m^3 was used for the measurement (Figure 9). A PVC pipes with a diameter of 16 cm and a height of 25 cm were used as the flux chamber collars. The collars were pushed into to the soil to a depth of 20 cm leaving about 5 cm as the height above the soil level. CO_2 concentration changes were measured with Nondispersive infrared (NDIR) CO_2 sensor called K30-Fr. The K30-Fr was connected with a portable inexpensive Arduino base CO_2 logging system (Minions) from the work of Maccaga et al, (2023). The logging system was designed semi-automatically with pumps to flash out air from the chambers. CO_2 concentration were recorded continuously for 10 minutes and flashes out air for 5 minutes until an hour for the chamber to be deployed at different point.

Figure 9: cylindrical chamber connected to the developed CO_2 system for the measurement of heterotrophic respiration after tillage operation in Nyankpala experimental field.

3.5.7 CO_2 exchange measurement during the entire growing season

The main experiment was conducted on two tillage practices that is reduced tillage (bullock plough) and conventional tillage (tractor plough). Each tillage practice had nine treatments and due to resources and time constraint, measurement was taken on six out of the nine treatments. The treatments on which measurement were taken include, i. Fertisol at 5 t ha^{-1} (FT_0) ii. Farmyard manure at 5 t ha-^{1} (FM_0) iii. Fertisoil at 5 t ha^{-1} + 90-60-60 kg NPK ha^{-1} (FT_90) iv. Farmyard manure at 5 t ha^{-1} + 90-60-60 kg NPK ha^{-1} (FM_90) v. 90-60-60 kg NPK ha^{-1} (NM_90) vi. 0-0-0 kg NPK ha^{-1} (NM_0). The measurement was carried out in the 2021 and 2022 cropping season from July to November. The CO_2 exchange was measured with a customized non-flow-through non-steady-state closed chamber system (NFT-NSS). The system was made up of a portable inexpensive Arduino base logging unit (Minions) connected with K30FR NDIR-CO_2 sensor. For the measurement of net ecosystem exchange (NEE) a cubic transparent chamber made of acrylic glass (86% light transmission) with a volume of 1.2 m^3 and a ground area of 0.96 m^2 was used (Figure 10). An opaque PVC chamber with similar dimension was also used to measure the ecosystem respiration (Reco) (Figure 11). For the chamber volume to adapt to the plant height an extension of the chamber with a volume of 0.68 m^3 was added. For efficient and effective headspace mixing the chambers were equipped with adjustable fans. CO_2 campaign was usually carried out from sunrise till late afternoon every two weeks during the growing season. The measurement was done by alternating the transparent and the opaque chambers on permanently installed PVC collars (1.2 m x 0.8 m) for 5 minutes. Measurement of soil temperature with tomst sensor (TMS-4 datalogger Czeck Republic), soil moisture (VG-Meter-200, Vegetronix, Inc. Riverton, USA) and photosynthetic active radiation (PAR)(SQ 420x Apogee instrument Inc. USA) were taken parallel to the gas exchange measurement. Air temperature as well as air pressure was continuously measured by the logging system every 3 seconds.

Figure 10: transparent chamber for measuring net ecosystem exchange in Nyankpala Ghana

Figure 11: opaque chamber for measuring ecosystem respiration in Nyankpala Ghana

3.5.8 CO_2 and ET flux calculation at field level

For the field validation and field trial application, measured CO_2 and ET fluxes were calculated using a modular R script, described in detail by Hoffmann et al, (2015) and Dahlmann et al, (2022), respectively. Prior to CO_2 and ET flux calculation a death-band of 10% was applied to the data of each chamber measurement. CO_2 concentrations measured using the IRGA were additionally corrected for changes in water vapour during chamber measurements (Webb et al, 1980). Unlike the IRGA which provided H_2O as mole fraction, used low-cost RH sensors (DHT22 and SHT31) required additional post processing. RH measurements were converted into a mass concentration following (Hamel et al, 2015):

$$H20 = \frac{RH\ x\ es}{100\ x\ P} \qquad \text{[Eqn. 1]}$$

where RH is the relative humidity and e^s is the saturated vapour pressure (Pa), calculated according to (FAO, 1998). Thereafter, CO_2 and ET fluxes were calculated based on the ideal gas law using a linear regression approach (Equation 2):

$$f = \frac{MpV}{RTA} x \frac{\Delta c}{\Delta t} \qquad \text{[Eqn. 2]}$$

where M denotes the molar mass of the gas (g mol^{-1}), p denotes the ambient air pressure (Pa) and V denotes the chamber volume (m^3). Since plants accounted for < 0.1% of the total chamber volume, a static chamber volume was assumed. R denote the gas constant (8.314 m^3 Pa K^{-1} mol^{-1}), T denote temperature inside the chamber (K), A denotes the basal area (m^{-2}) and $\Delta c/\Delta t$ denotes the linear CO_2 (e.g., (Leiber-Sauheitl et al, 2014) and H_2O concentration change over time (Dahlmann et al, 2022.). The variables T as well as more importantly dc/dt, were obtained by applying a variable moving window (0.5 to 3 min.) to each chamber measurement. Thus, resulting multiple ET and CO_2 fluxes per measurement (based on generated variable moving window data subsets) were further evaluated according to the following criteria: 1.) fulfilled prerequisites for applying a linear regression (normality (Lillifor´s adaption of the Kolmogorov-Smirnov test), homoscedasticity (Breusch-Pagan test) and linearity); 2.) significant regression slope ($p \leq 0.1$, t-test); 3.) range of within-chamber air temperature not larger than ± 1.5 K and a PAR deviation (only transparent chamber measurements) not larger than ± 20% of the average to ensure stable environmental conditions within the chamber throughout the respective measurement; 4.) no outliers present (±6 x IQR). Calculated CO_2 and ET fluxes that did not meet all criteria were discarded. In cases where more than one flux per measurement met all criteria, the CO_2 and ET flux with steepest slope and closest to chamber deployment were chosen.

For field validation and field trial application CO_2 fluxes were additionally separated into its flux components R_{eco}, GPP and NEE and in the case of the latter gap-filled through deriving empirical models. In the case of R_{eco}, a temperature-dependent Arrhenius-type function was used and fitted for air as well as soil temperatures in different depths (Lloyd and Taylor, 1994; Equation 3).

$$R_{eco} = R_{ref} \cdot e^{E0\left[\frac{1}{T_{ref} - T_0} - \frac{1}{T - T_0}\right]} \qquad \text{[Eqn. 3]}$$

Where R_{ref} is the respiration rate at the reference temperature (T_{ref}; 283.15 K), E0 is an activation energy-like parameter, T_0 is the starting temperature constant (227.13 K) and T is the mean air or soil temperature during the flux measurement. Out of the four obtained R_{eco} models (one model for air temperature; soil temperature at 2, 5 and 10 cm depth), the model with the lowest Akaike information criterion (AIC) was finally used. In case of GPP a PAR-dependent, rectangular hyperbolic light-response function, based on the Michaelis–Menten kinetic, was used (Elsgaard et al, 2012; Hoffmann et al, 2015; Wang et al, 2013; equation 4). Since GPP cannot be measured directly, GPP fluxes were calculated as the difference between measured NEE and modelled R_{eco} fluxes, using campaign specific, previously derived parameters R_{ref} and T_0.

$$GPP = \frac{GPmax \cdot \propto \cdot PAR}{\propto \cdot PAR + GPmax} \qquad \text{[Eqn. 4]}$$

Where GP_{max} is the maximum rate of C fixation at infinite PAR (µmol CO_2 m^{-2} s^{-1}), α is the light use efficiency (mol CO_2 mol^{-1} photons) and PAR is the photon flux density (corrected for chamber light transmission) of the photosynthetically active radiation ($µmol^{-1}$ photons m^{-2} s^{-1}). In cases where the rectangular hyperbolic light-response function did not result in significant parameter estimates, a non-rectangular hyperbolic light-response function was used (Gilmanov et al, 2007, 2013). R_{eco} and GPP parameter sets were evaluated and discarded in case of non-significant parameter estimates. If no fit or a non-significant fit was achieved, averaged flux rates were used for R_{eco} and GPP instead. R_{eco}, GPP and NEE were modelled in half hourly steps for the entire period based on continuously monitored temperature and PAR.

For ET, campaign-wise average daily ET fluxes (for night-time ET fluxes measured before, for daytime ET fluxes measured after 8:00) were determined and linearly interpolated between campaigns for the entire crop growth period.

To test for normal distribution (p<0.05) of the data obtained from laboratory and field validation measurements, Kolmogorov-Smirnov test was performed. In case of normal distribution, significant differences between ΔCO_2 in ppm or R_{eco}, NEE, and ET fluxes measured from low-cost sensors and mixing ratio ΔCO_2 or IRGA-based R_{eco}, NEE, and ET fluxes (p<0.05) were determined using one-sample t-test. Error calculation for CO_2 and ET fluxes, as well as crop season CO_2 exchange and ET, were quantified using a comprehensive error prediction algorithm described in detail by Hoffmann et al, (2015).

3.5.9 Estimating net ecosystem carbon balance (NECB)

The NECB was adopted from the method used by (Hoffmann et al, 2015; Smith et al, 2010). The NEE obtained during flux calculation together with the carbon in the harvested shoot (NPP_{shoot}) and carbon in applied fertilizer were used to calculate the seasonal NECB (Equation 1).

$$NECNn = \sum_{i=1}^{n}(\text{NPP}shooti + NEEi) - \text{C}_{\text{input}} \qquad \text{(Eq 1)}$$

The NECB refers to the total change in below ground C, positive value means carbon loss from the system as negative value indicates carbon uptake into the system. A number of components were not considered in the estimation of the NECB due to their negligible carbon inputs they include carbon from seed, methane emission (Hoffmann et al, 2015), vertical fluxes of dissolved organic and inorganic carbon (Rieckh et al, 2014) and lateral fluxes by erosion (Doetterl et al, 2016). The carbon exchange obtained at plot scale was extrapolated to per m^2 basis using the correlation between NEE and NPP_{shoot} relating to NPP_{shoot} harvested per m^2 in the field experiment. Uncertainty in the calculated NECB based on modeled NEE and NPP_{shoot} was performed according to (Hoffmann et al, (2015, 2017) following the laws of error propagation.

3.6 Data analysis

The R statistical software (3.6.3) was used for all the CO_2 calculations and the agronomic data were subjected to analysis of variance (ANOVA) using GenStat (12^{th} Edition) (Payne et al, 2009) and the treatment means were compared using the Duncan's Multiple Range Test at ($P < 0.05$).

CHAPTER FOUR

4.0 Results and Discussions

4.1 Environmental conditions

The total amount of rainfall (1313.2 mm) received in 2022 was more than the long-term average of 1100 mm (1991-2020, SARI weather station). However, the amount received in 2021 (991.1 mm) was less than the long-term average (Figure 12). The rainfall was erratic with intermittent dry spells at the beginning of each season. May and July were the wettest months in 2021. However, August was the month with the highest rainfall in 2022. In 2021 there were three months with no rain activity (January, February and December) whiles in 2022 four months were with no rain (January, February, November and December) out of the 12 months. The temperatures recorded in both years (29 ^{o}C in 2021) and (28 ^{o}C in 2022) were higher than the long-term mean temperature (26 ^{o}C). There was no significant difference between the treatments regarding the soil temperature recorded at 5 cm irrespective of the tillage practices

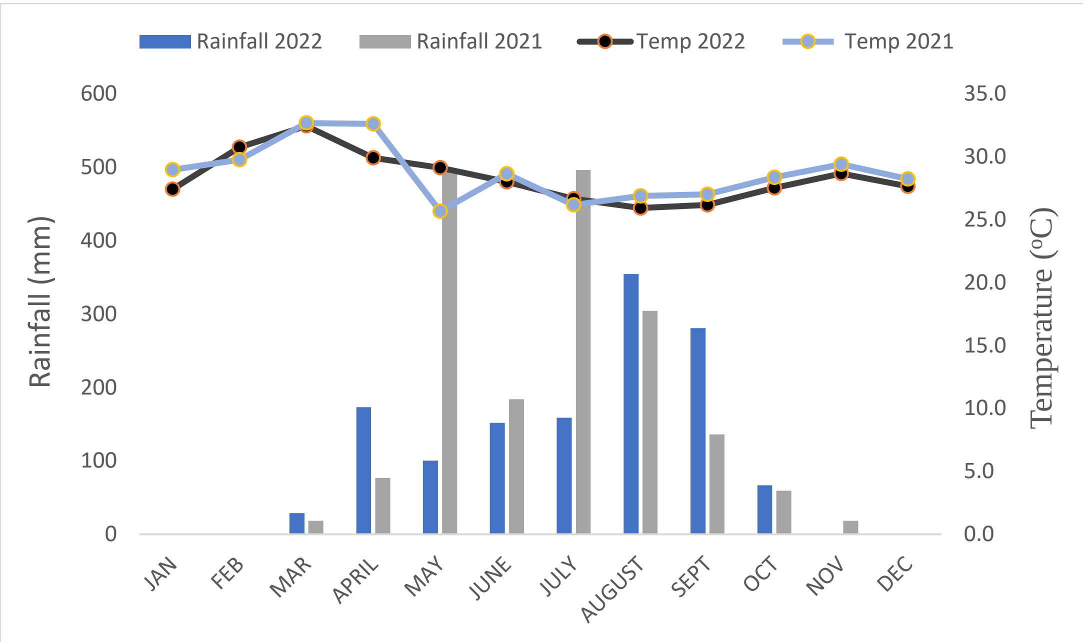

Figure 12: the weather conditions at the experimental field in Nyankpala- Ghana during the 2021 and 2022 cropping season

4.2 Laboratory validation of the developed CO_2 system

The results from the four different low-cost NDIR sensors tested, are presented in figure 13 (a-d) as 1:1-agreement plots between mixing-ratio derived (calculated) and measured ΔCO_2. While accuracy can be assessed as deviation from the 1:1-agreement line, precision is determined by the residual standard deviation (SD) and the coefficient of determination (r^2) of the linear regression fitted on calculated and measured ΔCO_2. The K30FR (Figure 13d) showed the highest accuracy among all tested sensors, reflecting well the increase in CO_2 concentration (ΔCO_2) derived through mixing-ratio. Correspondingly, no significant difference (one sample t-test, $p=0.80$) was found between calculated and measured ΔCO_2. The SCD30 (Figure 13c), even though fairly accurate at lower, failed to reflect higher calculated ΔCO_2 values and generally tends to overestimate actual ΔCO_2. Neither the MHZ-14 (Figure 13b) nor the MHZ-19 (Figure 13a) were sufficiently accurate and able to reflect calculated ΔCO_2. While the MHZ-14 showed a rather constant offset from the 1:1-agreement by 28 ppm, the MHZ-19 tends to increasingly overestimate higher ΔCO_2 values derived through mixing ratio. Hence, unlike the K30FR, all other NDIR sensors measured significantly higher ΔCO_2 when compared to calculated ΔCO_2 (One sample t-test, $p<0.01$). Unlike the accuracy, overall precision and measurement repeatability among all four NDIR sensors was generally high and fairly comparable, showing a residual SD of 2.78 ppm, 4.23 ppm, 2.52 ppm and 3.58 ppm, respectively.

Regarding the response time (defined as mean time from injection to measured initial CO_2 concentration increase) all four NDIR sensors differed substantially, with only 44 seconds for the K30FR and more than 280 seconds for the MHZ-14. The same was true for the response strength (defined as the mean time from beginning to end or steepness of measured CO_2 concentration increase), with 61, 160 and 265 seconds for the K30FR, SCD30 and MHZ-19 respectively. In case of the MHZ-14, response strength could not be evaluated, since no clear saturation after injection induced CO_2 concentration increase could be observed. While accuracy and precision are of course highly relevant, response time and response strength in particular play a key role in determining the extent to which the tested NDIR sensors can be used for *in-situ* NFT-NSS closed chamber measurements. With a response time of almost 2 min and 5 min, respectively, as well as low response strength, MHZ-19 and MHZ-14 will likely fail to correctly reflect CO_2 concentration changes during short-time (<4min) closed chamber measurements, regardless of their low accuracy, which makes them additionally unsuitable. Laboratory validation performed by (Brändle and Kunert, 2019) using similar MHZ-14 sensor from the same manufacturer against a reference gas exchange fluorescence system (GFS-3000) also observed sensor delay before matching reference sensor concentrations and found an overall offset of ~ 40 ppm. Their field validation implied similar limitation with measurement time and suggested that it is unsuitable for very short measurements (<5 mins).

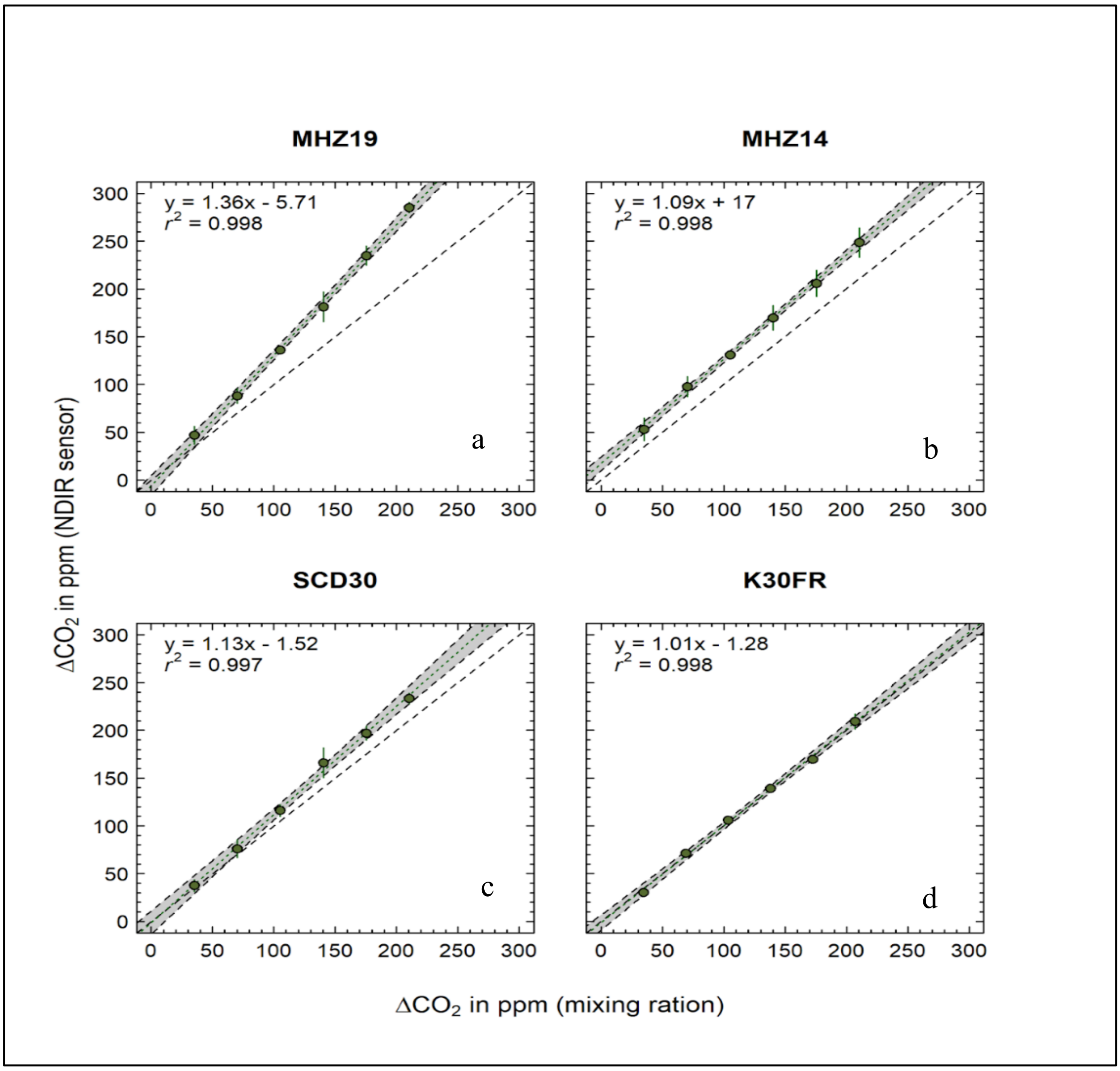

Figure 13: 1:1-agreement between measured ΔCO_2 in ppm from the four low-cost sensors tested(K30FR, SCD30, MHZ-14 and MHZ-19) and ΔCO_2 in ppm of mixing ratio. The dashed black line indicates the 1:1-agreement. The dotted green line shows the linear regression through the measurement dots. The grey shaded area represents the respective confidence interval of the regression line. Error bars indicate ±1.96 SD.

The Sensirion SCD30 also showed acceptable accuracy and response time, which is consistent with the findings of Rivero et al, (2023) where the sensor measurements were highly accurate in measuring reference calibration gas concentration in a closed box experiment. Multiple studies (Ali et al, 2016; Blackstock et al, 2019; Mendes et al, 2015) that have tested and determined the accuracy of the K30 sensor for CO_2 measurement also support our results. Laboratory testing by Blackstock et al, (2019) validated the accuracy of SenseAir K30 sensor against known CO_2 concentrations using span gas measurements and found that it falls within the accuracy stated by manufacturer. Their experiment also verified the sensor accuracy since it was capable to measure the reference gas mixture within the analytical error. Similarly, performance test performed by Mendes et al, (2015) found that the K30 sensor has nearly perfect linear response against calibration gas CO_2 concentration. Lastly, the study by Ali et al, (2016) also determined that the sensor K30 can measure CO_2 concentration in an indoor environment setting with high accuracy based on the strong correlation found when compared against reference commercial CO_2 sensors. They also highlighted the advantage of its self-calibration capabilities that contributes to its stable performance and high repeatability with minimal maintenance. Therefore, only the K30FR (and to a much lower extent the SCD30) with its fast response time and high response strength passed laboratory validation and met all necessary requirements for accurate and precise *in-situ* measurements of CO_2 exchange.

4.3 Field validation of the developed CO_2 measuring system

The 1:1-agreement plots in figure 14 (a-d) show the differences in accuracy and precision for CO_2 and ET fluxes calculated based on NDIR (a-b) and RH measurements (c-d) compared to CO_2 and ET fluxes calculated based on LI-850 measurements. While the comparison between R_{eco} and NEE fluxes calculated from LI-850 and K30FR CO_2 concentration measurements (Figure 14a), was in accordance with the laboratory validation and showed again the overall accuracy and precision of this NDIR sensor, a small positive offset was found. This resulted in significantly higher R_{eco} (mean diff. 1.12 µmol m^{-2} s^{-1}; one sample t-test, $p<0.05$) and less negative NEE (mean diff. 1.41 µmol m^{-2} s^{-1}; one sample t-test, $p<0.05$) fluxes for the K30FR when compared to LI-850. No such offset was found in case of the SCD30 (Figure 14b), which showed significantly lower R_{eco} (mean diff. -1.33 µmol m^{-2} s^{-1}; one sample t-test, $p<0.05$) and much less negative NEE fluxes (mean diff. -4.18 µmol m^{-2} s^{-1}; one sample t-test, $p<0.05$) compared to LI-850. Since neither of the NDIR sensors showed a similar effect, nor an overestimation was found for the K30FR during the laboratory validation, it can be assumed that the detected offset in case of the K30FR is not a direct result of microclimatic effects (e.g., increasing humidity) or incorrect sensor readings. Instead, inter-alia differences within the chamber headspace and the position of the NDIR sensor right below the chamber top, approximately 10 cm above the LI-850 inlet and outlet, might help to explain it. Compared to the K30FR, especially NEE fluxes obtained by the SCD30, were characterised by a very low precision. The reason for this is certainly the lower CO_2 concentrations (<400 ppm) in the NEE measurements, which are far outside the measurement range specified by the manufacturer

(400 to 10000 ppm). This also explains the decreasing precision with increased negative NEE fluxes obtained by SCD30, since these are likely related to CO_2 concentration measurements well below 400 ppm. The general underestimation of R_{eco} and NEE fluxes derived from SCD30, however, is probably a result of its rather long response time and lower response strength when compared to the K30FR.

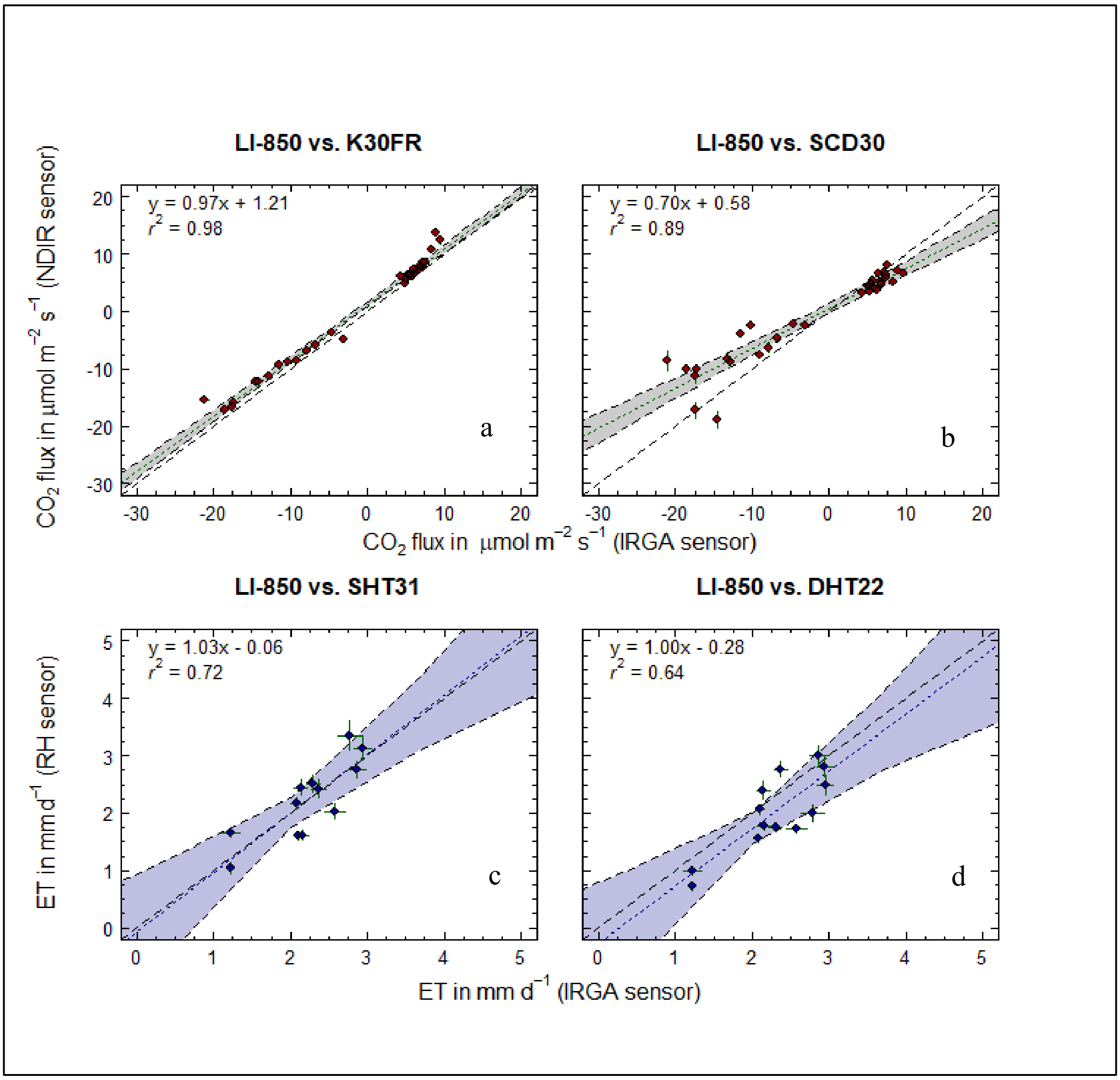

Figure 14: 1:1-agreement between (a-b) CO_2 and (c-d) ET fluxes measured with infrared gas analyzer (IRGA; LI-850, LI-COR, USA) and low-cost NDIR sensors (K30FR and SCD30). The dashed black line indicates the 1:1-agreement. The dotted red/blue line shows the linear regression through the measured CO_2/ET fluxes. The grey/blue shaded area represents the respective confidence interval of the regression line. Error bars indicate calculated flux error (α=0.9).

No significant difference (mean diff. -0.01 mm d^{-1}; one sample t-test, $p=0.89$) was found between ET fluxes calculated from H_2O concentration and RH measurements, using the LI-850 and SHT31, respectively (Figure 14c). Together with an r^2 of 0.72, this indicates a reasonable accuracy of SHT31 derived ET flux estimates. Compared to that, ET fluxes, determined through RH measurements using the DHT22 (Figure 14d), were significantly smaller (mean diff. 0.28 mm d^{-1}; one sample t-test, $p<0.05$) than LI-850 based ET fluxes and with a r^2 of 0.64 less accurate. The overall precision of SHT31 and DHT22 derived ET fluxes was fairly similar, but with a residual SD of 0.36 and 0.39 mm d^{-1} rather high.

Figure 15 (a-d) shows R_{eco} (a-b) and GPP (c-d) parameter estimates for flux measurements performed with the LI-850 compared to K30FR (15a, 15c) and SCD30 (15b, 15d), respectively. Since the Reco and GPP parameters are based on the fluxes presented in figure 14, similar differences between LI-850, K30FR and SCD30 could be obtained. With an R_{ref} and E0 of 4.60 and 212.71, the K30FR had similar, but slightly higher R_{eco} parameters (15a) when compared to the LI-850 (R_{ref}: 4.14; E0: 195.01). This indicates not only in general higher R_{eco} fluxes but more importantly also a stronger increase of R_{eco} fluxes with rising temperature. In the case of the SCD30 (R_{ref}: 2.54; E0: 270.07), differences in R_{eco} parameters were, however, much more pronounced. The same tends to be true for obtained GPP parameters, which were highly comparable for LI-850 (α: -0.048; GP_{max}: -39.83) and K30FR (α: -0.042; GP_{max}: -38.42), but distinctly different for SCD30 (α: -0.029; GP_{max}: -31.83). As a result, the fitted K30FR PAR dependency function was fully within the confidence band of the LI-850 PAR dependency function. In summary, the K30FR well represented Reco and GPP fluxes measured with the LI-850 and theron based parameter estimates for Reco and GPP, while the SCD30 was only conditionally able to reflect the measured Reco and GPP fluxes and to make accurate parameter estimates. Instrument validation by Brown et al, (2020) of the K30 sensor supports our results since the sensor also showed comparable accuracy against reference commercial sensors such as the PP-Systems EGM-4 Infrared Gas Analyzer (IRGA) and the Los Gatos Ultraportable Greenhouse Gas Analyzer (UGGA). Our results concur with the findings of Curcoll et al, (2022) where the K30 sensor integrated in a NSS-NTF measurement system was able to accurately measure CO_2 flux for a grassland ecosystem, which were comparable to those obtained in other studies.

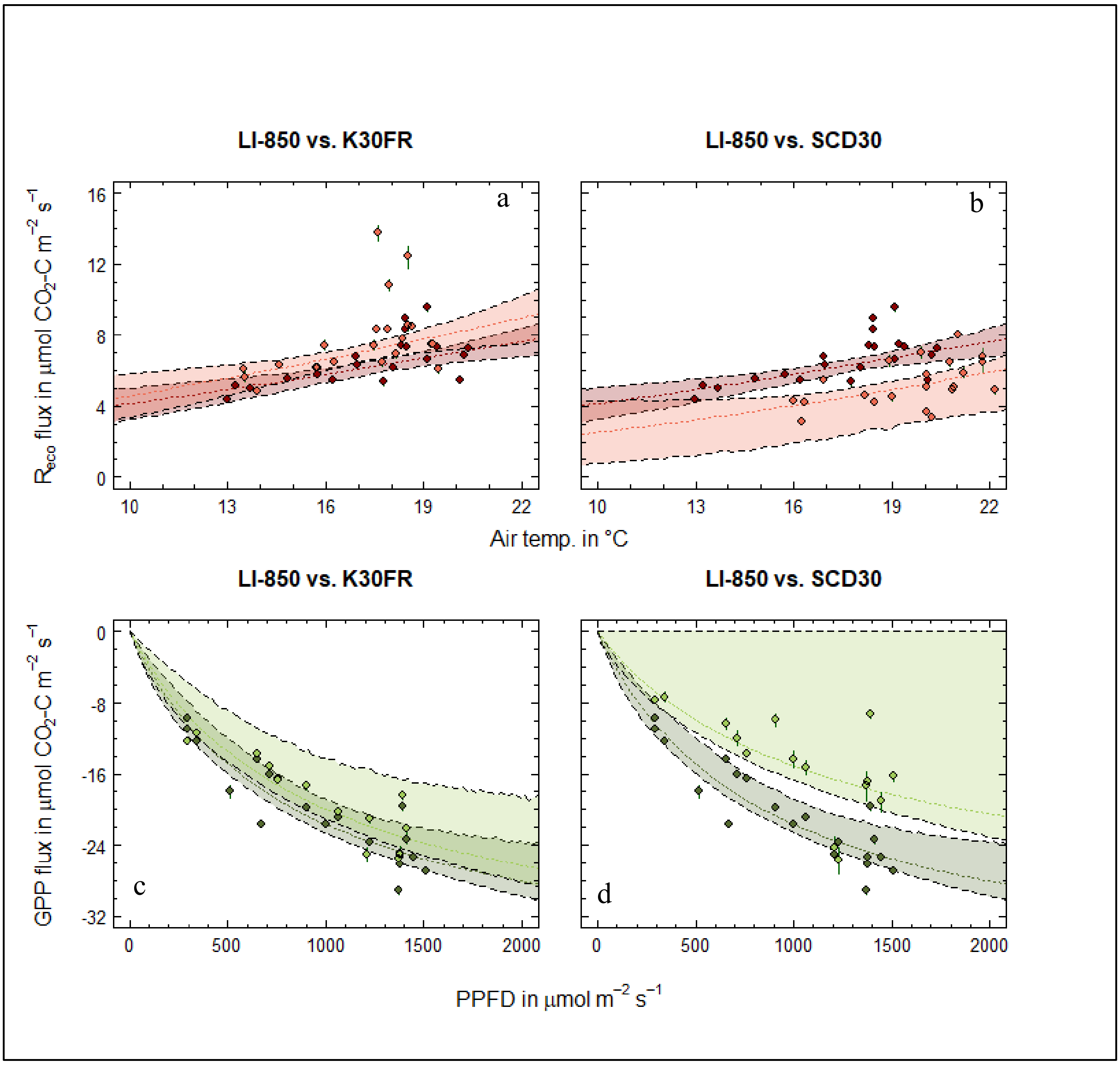

Figure 15: comparison of Reco temperature dependency (dotted red lines) and GPP PAR dependency functions (dotted green lines) between LI-850 (dark red/green) and K30FR and SCD30 (light red/green), respectively. Shaded red/green areas indicate confidence band around functions. Dots represent measured R_{eco} and derived GPP fluxes. Error bars indicate calculated flux error (α=0.9).

4.4 CO_2 emission during tillage operation

Carbon dioxide emission on five different tillage practices were measured immediately after tillage operations for 11 hours in two days and the result obtained is presented in (Figure 16). The CO_2 measured in our study targeted the soil emission and did not include CO_2 from the combustion of fuel during the operation. Tractor plough (TP) which we define as conventional tillage emitted the highest CO_2 (6.3 g CO_2-C m^{-2} d^{-1}) into the atmosphere which was significantly different from the rest of the treatments with No tillage (NT) treatment having the lowest CO_2 emission of 0.8 g CO_2-C m-^{2}-d-^{1} (Figure 16). The increase in CO_2 emissions was in the order TP > PH > H > BP > NT. The tractor plough (conventional tillage) and bullock plough (reduced tillage) were the treatments of interest in this study because they were the widely used tillage practices in the study area. The tractor plough emitted about 65% more CO_2 from the soil into the atmosphere than the bullock plough after the tillage operation. In line with the hypothesis set for this objective, more carbon was released and less sequestered in the soil. Emission of CO_2 from the soil as a result of tillage practices correlate well with the level and volume of soil disturbed by the tillage implements used (Albert et al, 2016; Melland et al, 2017) and tillage depth (Farhate et al, 2018). The disc used by the tractor to plough the experiment had a cutting depth of 20 cm, the harrow (12-15 cm) and the bullock plough with 9-11cm. The Tractor plough producing the highest CO_2 could be linked to that fact that its plough depth was much bigger than the rest of the treatments as similar results was obtained by Dabhi et al, (2016) and Pratibha et al, (2019) suggesting that tillage implement with smaller cutting depth and minimum soil disturbance is perfect for reducing CO_2 emission which positively affect the greenhouse effect and thus help mitigate climate change. Findings by Prior et al, (1997) suggested that high amount of CO_2 after tillage operation was associated with the depth and degree of soil disturbance. According to Silva et al, (2019) the disc after cutting the soil breaks the soil clods into smaller particles thus accelerating soil aeration and microbial activities directly in the soil. This further enhance the soil biochemical process by exposing the small soil particle leading to organic matter decomposition and organic carbon mineralization thus boosting CO_2 emission into the atmosphere (Bajracharya et al, 2000). Other works also believe that the soil microbes having the right moisture content (Almeida et al, 2018) and conducive temperature (Morell et al, 2010) will increase their activities and accelerate organic substrate decomposition and also induce respiration by roots. The lower CO_2 emission observed in the NT and bullock plots could be ascribe to low microbial activities due to smaller soil disturbance thus reducing the rate of decomposition. Also, it could be linked to the reduction in soil macro pore volume which could hinder gas exchange in the soil (Wang et al, 2017). Results obtained by Buragiene et al, (2015) support our findings as no tillage plot in their work emitted less CO_2 than deep ploughing in Lithuania. Adopting the reduced tillage practice for crop production is ideal. Aside, reducing CO_2 emission the level of soil compaction caused by the weight of the tractor together with the implement is also reduced (Shah et al, 2017). The soil health under reduced tillage is enhanced as much carbon is sequestered (Tiefenbacher et al, 2021). Also, the plant architecture as well as the crop yield is improved. However, some farmers fail to adopt this practice because of the difficulty they go through in controlling the animals. Again, the practice is not best for commercial farming as it will take a longer time for the animals to cover a reasonably large area. An alternative solution to the aforementioned problems regarding bullock ploughing is to reduce the plough depth of the disc used by the tractor to have a minimal soil disturbance and thus reduce the carbon been emitted from the tractor plough.

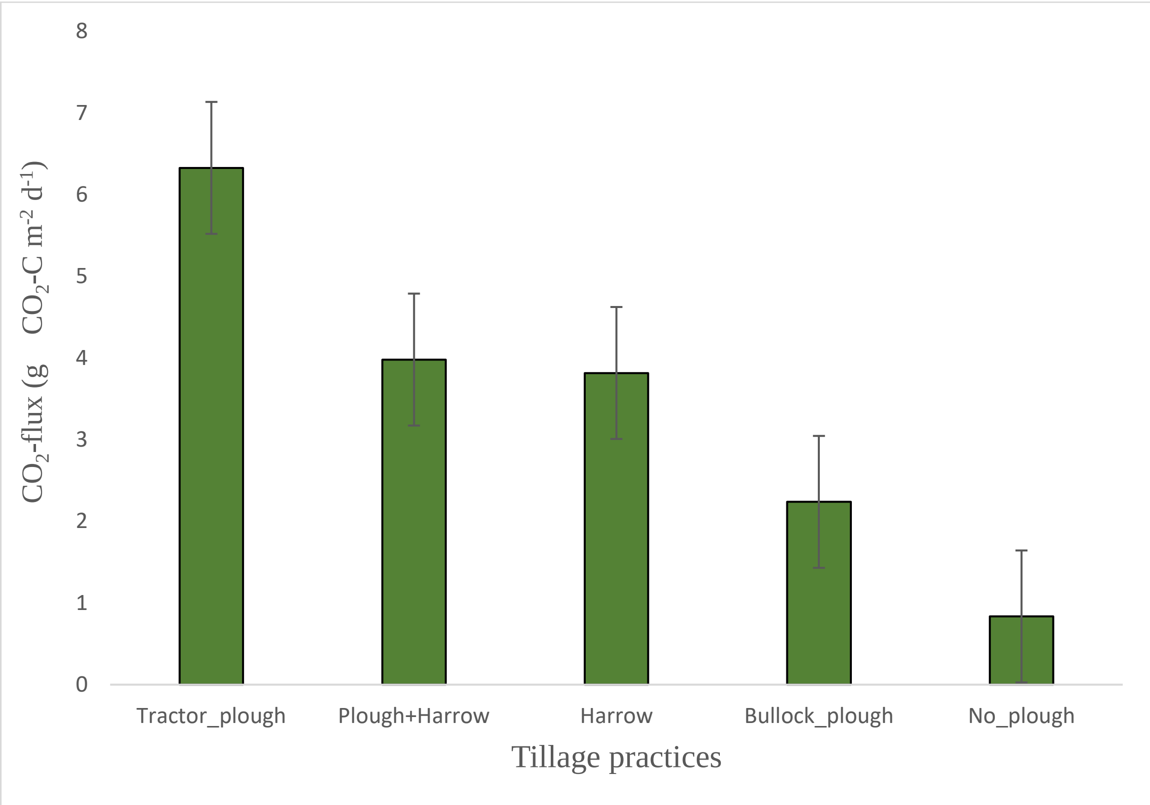

Figure 16: CO_2 emission under different tillage practices after tillage operation in Northern Ghana. Error bars indicate standard error of difference.

4.5 CO_2 emissions during the entire growing season

The developed CO_2 measurement system was used to differentiate Reco, GPP, NEE and ET fluxes among different ISFM treatments on both conventional and reduced tillage practices. Based on these measurements we estimated the net ecosystem carbon balance (NECB) and water use efficiency (WUE). From the daily CO_2 measurements, we observed that the treatments that had both organic and inorganic fertilizers produced robust plants irrespective of the tillage practices. They respire, photosynthate and gain more carbon into the system than the sole application of either organic or inorganic fertilizers (Figure 17 and 18). This gives an indication that both FT_90 and FM_90 emitted less CO_2 into the atmosphere than the rest of the treatments on both tillage practices (Figure17(bd) and 18(bd). The Reco, GPP, and NEE parameters were assessed cumulatively throughout the growing season. On the reduced tillage system FT_90 had the highest cumulative Reco of 480 ±45 g C m^{-2} with the smallest Reco (222 ±18 g C m^{-2}) observed on NM_0 (Figure 19a) during the growing season. The cumulative NEE obtained was highest in FM_90 (-209 ±44 g C m^{-2}) with the lowest value of -26 ±18 g C m^{-2} observed in NM_0 plot (Figure 19c). Similar trend was observed in the derived GPP with FT_90 having the highest cumulative productivity of -655 ±12 g C m^{-2} and lowest productivity was seen in the NM_0 plot (-248 ±9 g C m^{-2}) (Figure 19b).

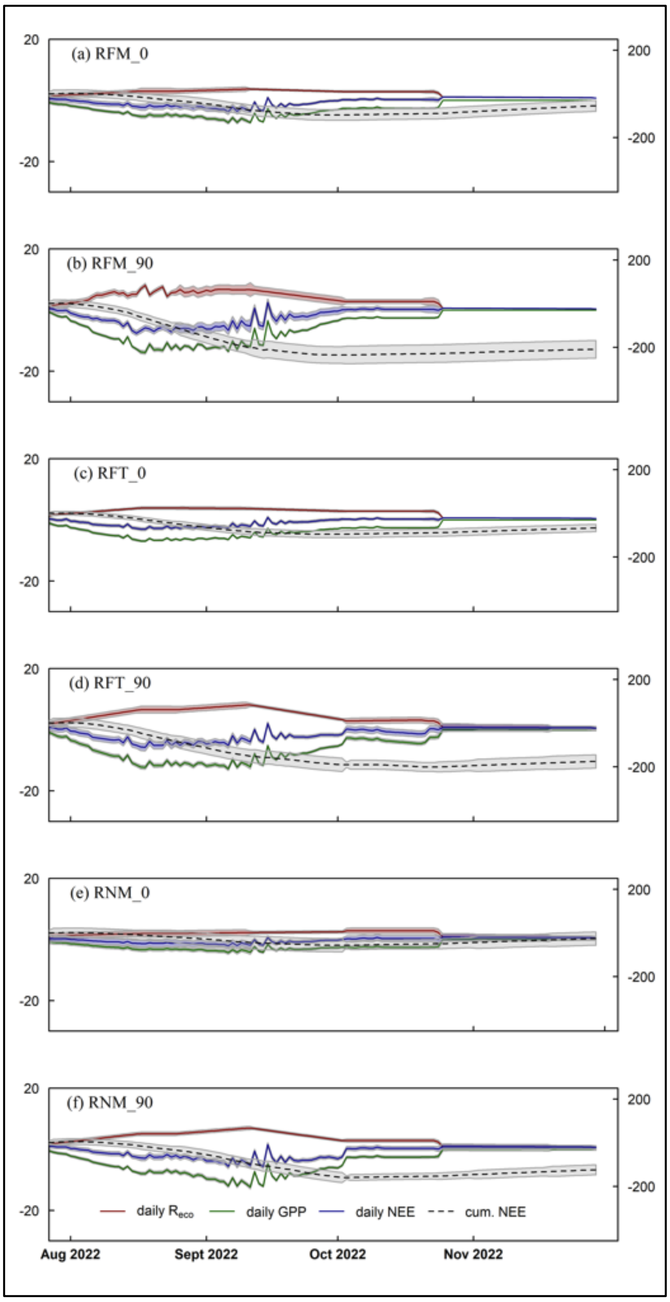

Figure 17: daily Reco, GPP, NEE (g C m^{-2}) of different treatments applied on reduced tillage system in Ghana.

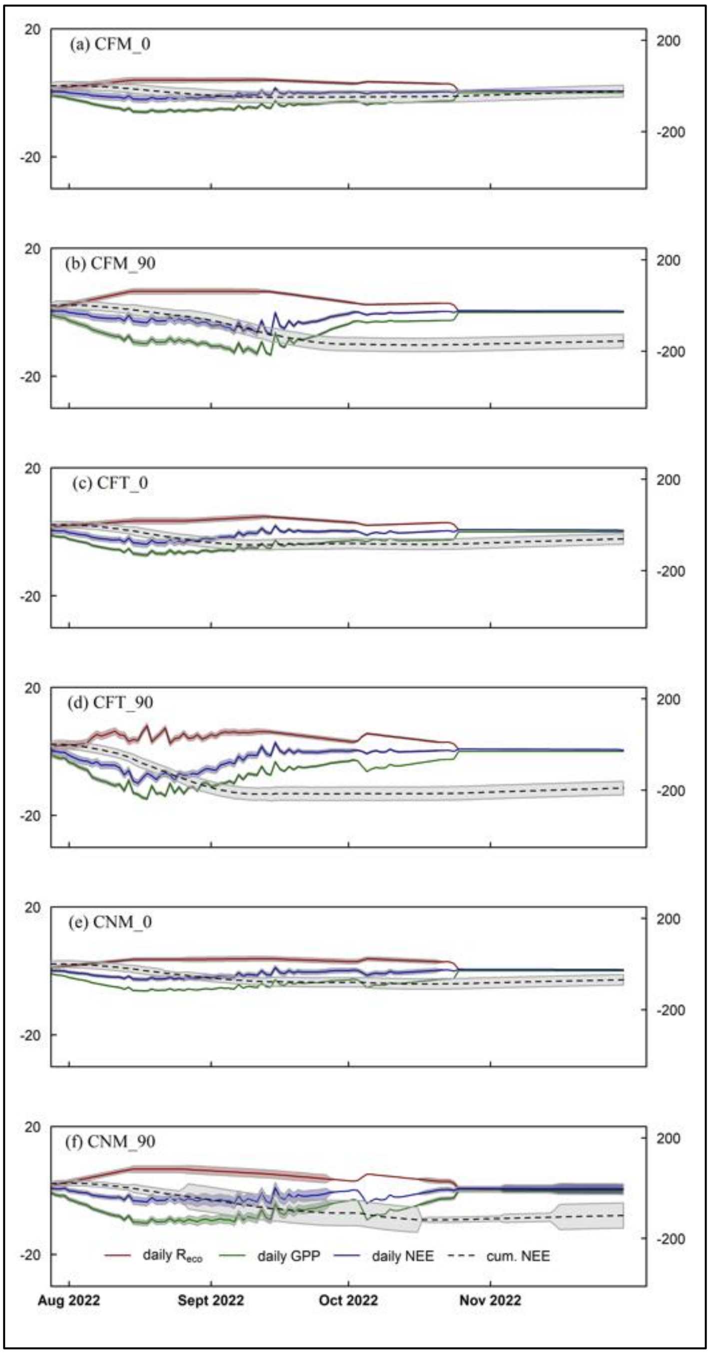

Figure 18: daily Reco, GPP, NEE (g C m^{-2}) of different treatments applied on conventional tillage system in Ghana.

The NECB obtained after carbon input and output indicated that all the treatments that had sole organic fertilizer and the combined organic and inorganic fertilizers applied on reduced tillage were carbon sink. However, the no fertilizer plot (NM_0) and the sole inorganic (NM_90) were carbon source on reduced tillage system (Figure 19e). The measured evapotranspiration was high on FM_90 treated plot (266 mm) and low on NM_0 plot with 211 mm (Figure 19d). There was no much difference observed between the treatments applied on the reduced tillage system regarding water use efficiency. However, FT_90 had the highest WUE with 2.85 g of straw produced mm/ET and the lowest WUE was observed on NM_0 (control plot) with 1.64 g of straw produced mm/ET (Figure 19f).

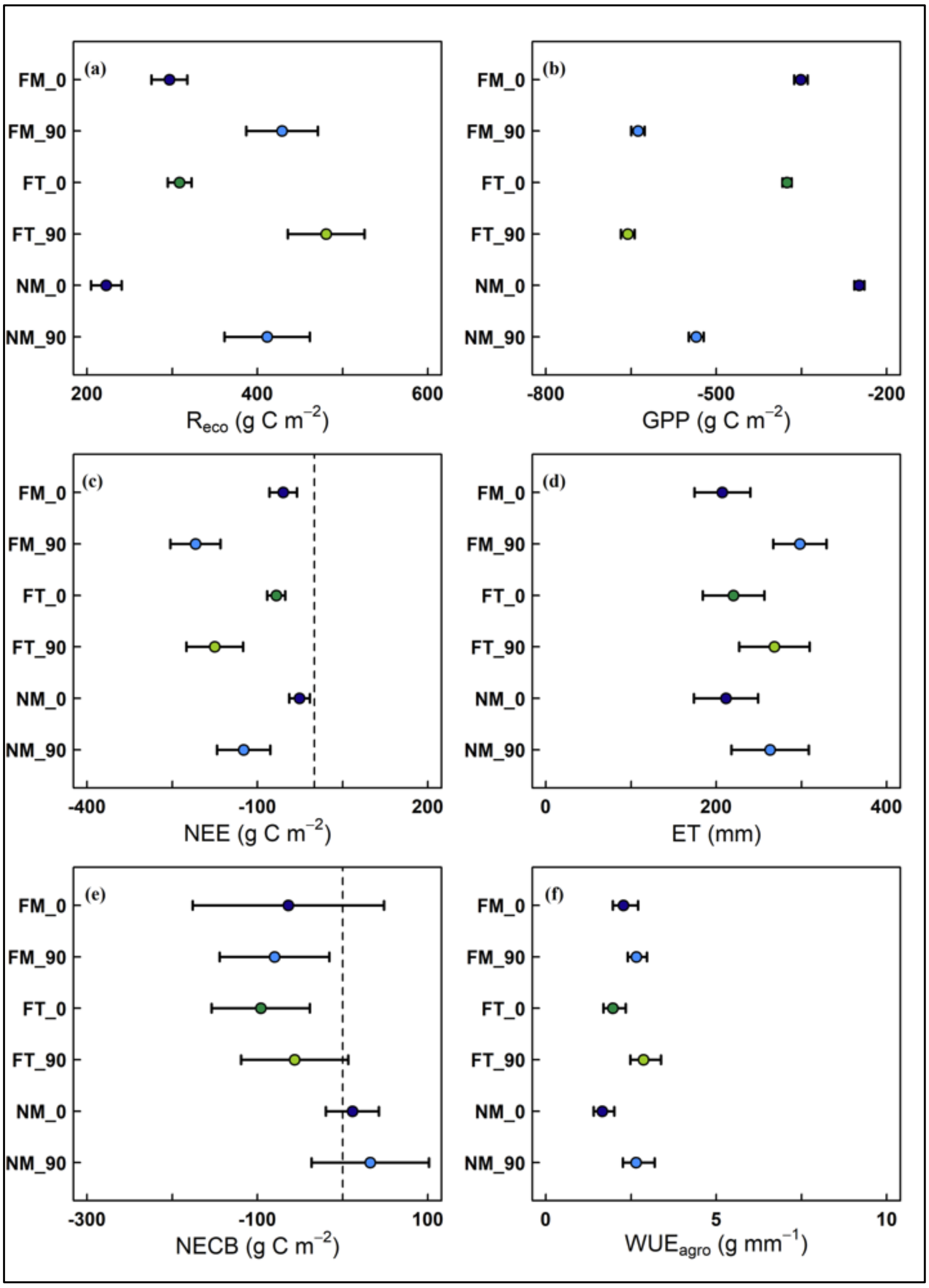

Figure 19: cumulative (a-d) Reco, GPP, NEE (g C m^{-2}) and ET fluxes (mm) as well as thereon based estimates of (e-f) NECB (g C m^{-2}) and WUE (g mm^{-1}) on reduced tillage system in Ghana

Different trend was observed when the same treatments were applied on conventional tillage system. The highest cumulative Reco was observed on the NM_90 (437 ±24 g C m^{-2}) plot with NM_0 having the lowest Reco (302± 25 g C m^{-2}) (Figure 20a). Treatments with combined application of organic and inorganic fertilizer emitted less CO_2 compared to the rest of the treatments on conventional tillage system. The highest cumulative NEE (carbon gain into the system) was observed on FT_90 treated plot with -191 ±30 g C m^{-2} and the lowest value of -23 ±30 g C m^{-2} was observed on FM_0 treated plot (Figure 20c). FT_90 cumulatively had the highest productivity through photosynthesis with the lowest productivity observed on the NM_0 plot (Figure 20b). The NECB on the conventional tillage showed that all the treatments applied were carbon sink though NM_90 gain a slight carbon into the system (Figure 20e). The evapotranspiration measured on the conventional tillage system increased in the order FM_0 < NM_0 < FT_0 < FT_90 < FM_90 < NM_90 (Figure 20d). Similar to the reduced tillage system FT_90 utilize water efficiently on the conventional tillage with 2.89 g straw Produced mm/ET and the lowest was observed on FM_0 with 1.66 g straw produced mm/ET (Figure 20f).

After observing the general performance of the ISFM treatments applied on both tillage practices, comparison regarding the factors used were done to assess which factor perform better against each other throughout the growing season. We compared the dynamics of carbon on both tillage practices for the whole growing season which was different from the results obtained just after the few hours of tillage operation. There was significant difference ($P<0.05$, two sample t test) in terms of the carbon dynamics between the conventional and reduced tillage practices for the growing season. The conventional tillage had the highest ecosystem respiration (autotrophic and heterotrophic respiration) of 369 g C m^{-2} as against 359 g C m^{-2} for the reduced tillage. CT had more carbon intake through photosynthesis (GPP). However, the net carbon exchange (NEE) indicated that reduced tillage emitted less CO_2 to the atmosphere than conventional tillage (Table 4). Though the NECB of both tillage practices indicated that they are all carbon sink with CT putting more carbon into the system (soil) than reduced tillage. The WUE efficiency estimated on both tillage practices were significantly different ($p<0.05$) with RT having more efficient use of water than CT (Table 4).

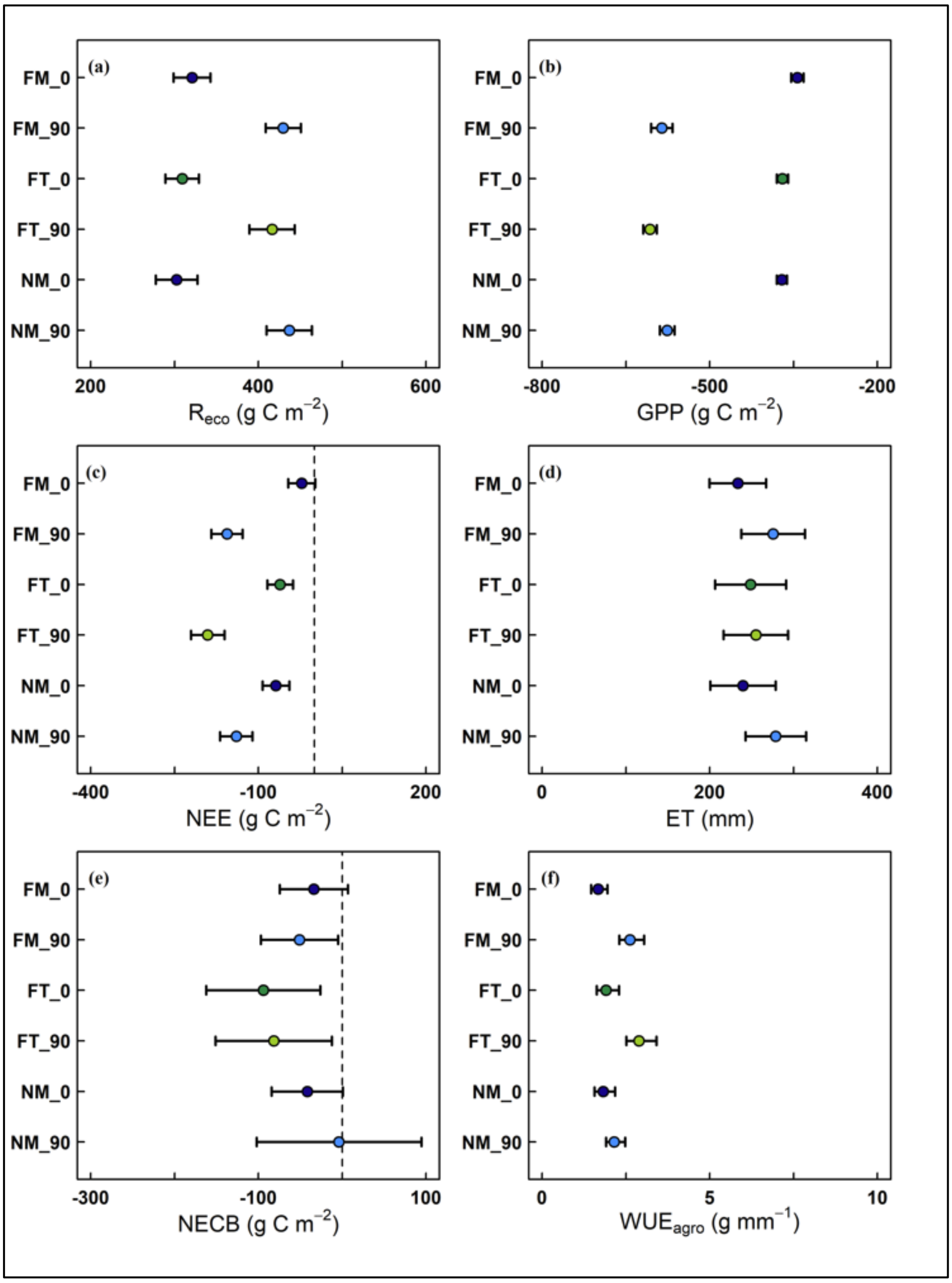

Figure 20: cumulative (a-d) Reco, GPP, NEE (g C m^{-2}) and ET fluxes (mm) as well as thereon based estimates of (e-f) NECB (g C m^{-2}) and WUE (g mm^{-1}) on conventional tillage system in Ghana.

The carbon dynamics and the WUE of the organic amendments applied is presented in (Figure 21). The Reco generated by the organic amendments showed significant difference ($P<0.05$) among the treatments. Fertisoil (FT) had the highest Reco of 378 g C m^{-2} with No organic amendment (NM) having the least Reco (343 g C m^{-2}). The highest carbon uptake through photosynthesis of -502 g C m^{-2} with net carbon exchange of -124 g C m^{-2} were observed in FT treated plot while the No amendment plot gave the lowest C uptake and NEE of -343 g C m^{-2} and -90 g C m^{-2} respectively (Figure 21a). All the amendments type showed that they were carbon sink. However, FT was able to sequester carbon from the atmosphere into the system than the rest with no amendment gaining a slight carbon from the atmosphere (Figure 21b). The WUE for both FM and FT were not significantly different (P>0.05) from each other. However, they were all significantly different from the no amendment plot (Figure 21c).

Regarding the inorganic fertilizer applied the 90 kg N ha^{-1} gave highest Reco, GPP and was able to gain more carbon through photosynthesis than the 0 kg N ha^{-1} plot (Figure 22a). The NECB showed that both were able the gain carbon from the atmosphere into the system hence they are carbon sink. However, the 0 kg N ha^{-1} gained more carbon (-53 g C m^{-2}) than the 90 kg N ha^{-1}(Figure 22b). The 90 kg N ha^{-1} plots utilize water more efficiently than the 0 kg N ha^{-1} plots (Figure 22c).

Table 4: cumulative Reco, GPP, NEE, NECB and WUE performance on CT vrs RT in northern Ghana

Treatment	Reco	GPP	NEE	NECB	WUE
Conventional	369.08	-475.70	-106.62	-51.12	2.17
Reduced	357.97	-467.51	-109.54	-42.21	2.34
s.e.d	0.076	0.069	0.073	0.049	0.041

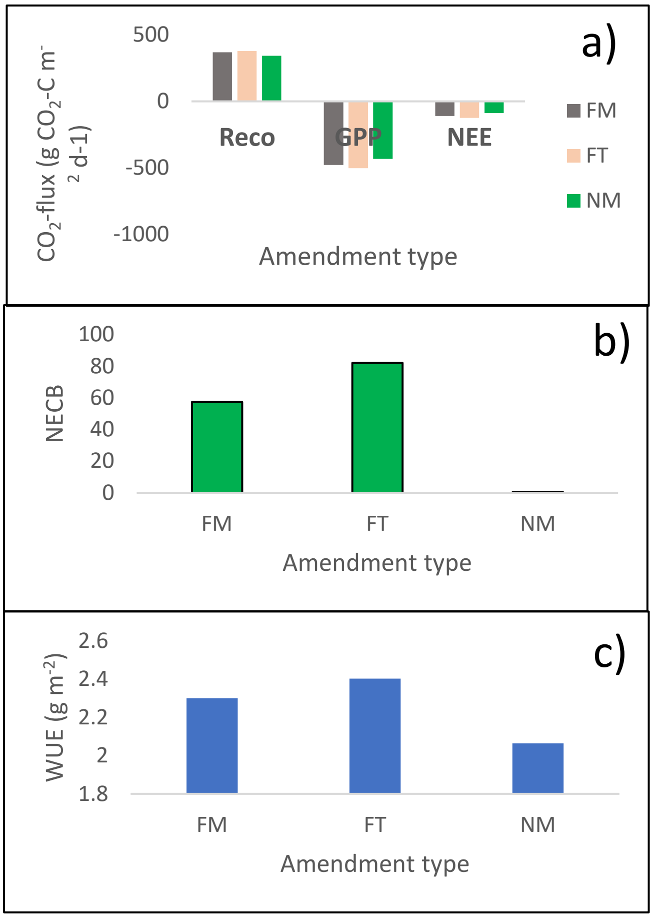

Figure 21: influence of organic amendment on CO_2 fluxes, NECB and WUE under maize cultivation in Ghana.

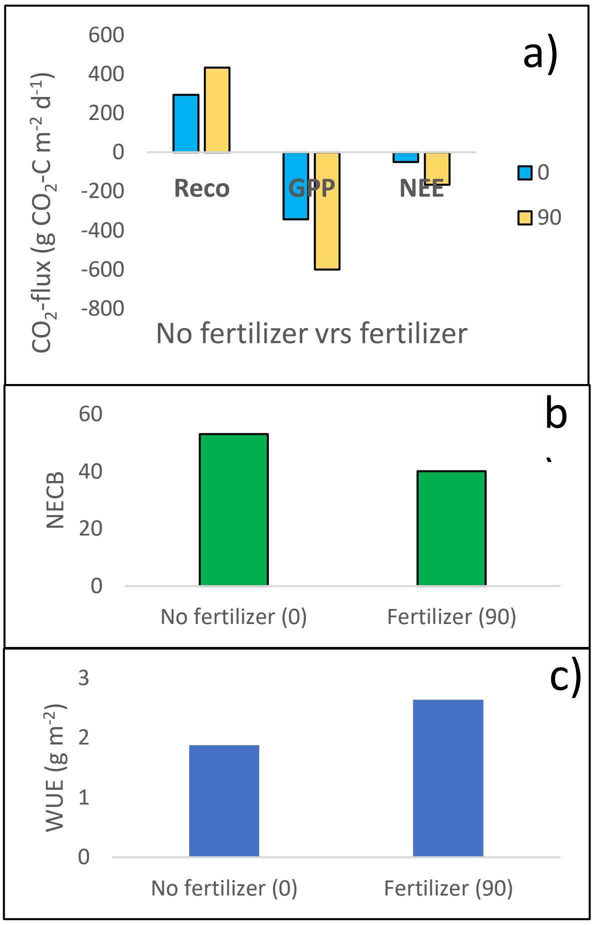

Figure 22: effect of inorganic fertilizer on CO2 fluxes, NECB and WUE under maize cultivation in Ghana.

From the results obtained it is evident that treatments with combined application of organic and inorganic fertilizers (FT_90 and FM_90) increased productivity, reduced CO_2 emissions, sequester more carbon and utilized water more efficiently than the rest of the treatments irrespective of the tillage practices. As expected, the results confirm the third hypothesis set for this experiment. The ISFM technologies having combined application of organic and inorganic fertilizers irrespective of the tillage practices used were perfect to reduce CO_2 from the agricultural landscape to the atmosphere. This will have a great impact on the greenhouse effect and thus help mitigate the global climate crises. The parameters measured (Reco, NEE and GPP) are affected by factors such as light, soil water content, rainfall, temperature and plant biomass (Liu et al, 2021; Raj et al, 2016; Zhang et al, 2021). In our current study, the high R_{eco}, GPP and NEE values observed in plots treated with combined application of organic and inorganic fertilizers could be ascribed to the robustness of the biomass. The R_{eco} value of 222 g C m^{-2} observed in our studies on the control plot (non-fertilized) was consistent with the value obtained by Verchot et al, (2020). In their work they recorded a cumulative R_{eco} of 218.5 g C m^{-2} in one growing season (3 months period) on an unfertilized cropland system located in Southern Cameroon. Quansah et al, (2015) used the EC method to obtain cumulative NEE, GPP and Reco in a study site with a mixture of fallow and cropland. Considering similar three months measurement period, the average fluxes NEE, GPP and R_{eco} they obtained were 27 g C m^{-2}, 195 g C m^{-2}, 222 g C m^{-2}, respectively. This values are found to be similar with the average NEE, GPP and Reco obtained from our unfertilized plot which are -26 g C m^{-2}, 248 g C m^{-2} and 222 g C m^{-2} respectively. Wagle et al, (2018) cumulatively recorded NEE, GPP and Reco on wheat production under conventional and reduced tillage practices. They also used EC method and on CT they had NEE of -542 g C m^{-2}, GPP of 1643 g C m^{-2} and Reco of 1101 g C m^{-2} and on NT they recorded NEE of -469 g C m^{-2}, GPP of 1571 g C m^{-2} and Reco of 1102 g C m^{-2}. Their values were higher than the values we obtained in our study under the different tillage practices (Table 4) and the reason being that their growing season lasted for six months whiles ours lasted for three months. The highest ET in our study was found on FM_90 plot (275 mm) which resulted to the highest demand of water compared to the other treatments. This is a close estimate when compared to the FAO, (2020) database for ET (with crop factor for grain maize) in the study area which is an average of 263 mm during the measurement period. The result we obtained was higher than the measured ET flux using EC method by Mamadou et al, (2016), which was 238 mm for a three month-period in a study region dominated by C4 plants in South Benin. The NECB in our study indicated that all the plots treated with combined application of organic and inorganic fertilizers are carbon sink. FM_90 had the highest NECB of -80 g C m^{-2} in our study and it is far higher than the value (-5.4) obtained by Liu et al, (2021) when organic and inorganic fertilizers were applied on rice in China. All the ISFM treatments applied were carbon sink and also utilized water efficiently on both tillage practices. However, the sole application of inorganic fertilizer on reduced tillage was a carbon source with a slight gain on conventional tillage. Organic matter addition improves soil physical and chemical properties of the soil (Paul, 2016). Manure addition was able to create a conducive environment that was able to hold mineralized nutrients from the inorganic fertilizer for plant used. Result obtained by Mukumbuta et al, (2017) is in agreement with our findings as manure only and manure plus inorganic fertilizer all gained carbon into the system. The two organic amendment we applied reduced CO_2 emission, gained carbon into the system, used water efficiently. However, FT out performed FM in terms of the dynamics of carbon. Organic matter addition into the soil also has the ability to hold enough water for plant use (Williams et al, 2016). This could be the reason why the combined application of organic and inorganic fertilizer plots used water efficiently. The results indicated that the ISFM plots had decreased water penalty per unit total biomass produced compared to the sole application of either organic or inorganic fertilizer. However, the highest WUE was observed on the FT_90 treatment with 2.9 g mm^{-1} during the growing season. The result was consistent with the value 3.9 g mm^{-1} reported by Abraha et al, (2016) on maize using EC method.

4.6 Grain yield and yield components

4.6.1 Grain yield

Grain yield obtained from the study showed that treatments on the reduced tillage produce higher yields than their counterparts on the conventional tillage system. Combined application of organic fertilizers and 90-60-60 kg NPK ha^{-1} had more yields than the rest of the treatments irrespective of the tillage practices (Figure 23). FT_90 produced the highest grain yield on both reduced and conventional tillage with 4.6 t ha^{-1} and 4.3 t ha^{-1} respectively. Though, it was not statistically different from the FM_90 treated plots on both tillage practices. However, significant difference ($p<0.05$) was observed when compared with the rest of the treatments irrespective of the tillage practices used. NM_0 gave the lowest yield (0.6 t ha^{-1}) on conventional tillage and 0.8 t ha^{-1} on reduced tillage (Figure 23).

4.6.2 Stover yield

Stover yield results revealed that all the treatments with 90 kg N ha^{-1} produced more stover than treatments without 90 kg N ha^{-1}. FM_90 produced the highest stover yield of 7.9 t ha^{-1} which was statistically different from the other treatments except FT_90 on reduced tillage with NM_0 producing the lowest stover yield of 3.5 t ha^{-1} (Figure 24). On conventional tillage FT_90 had the highest stover yield of 7.4 t ha^{-1} with FM_0 producing the lowest stover yield of 3.9 t ha^{-1} (Figure 24). FT_90 and FM_90 produced statistically similar ($p>0.05$) stover yield on conventional tillage but they were significantly different ($p<0.05$) from the rest of the treatments applied.

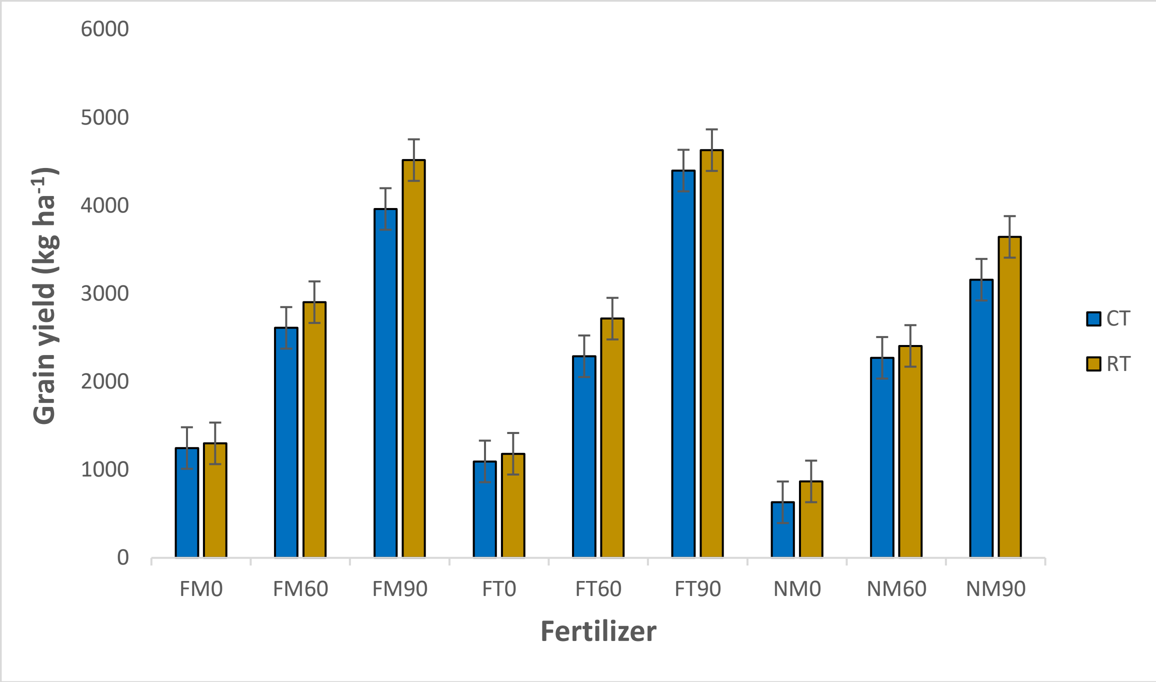

Figure 23: grain yield on reduced and conventional tillage as influence by integrated soil fertility management practice in Nyankpala, Ghana. Bars represent standard error of difference.

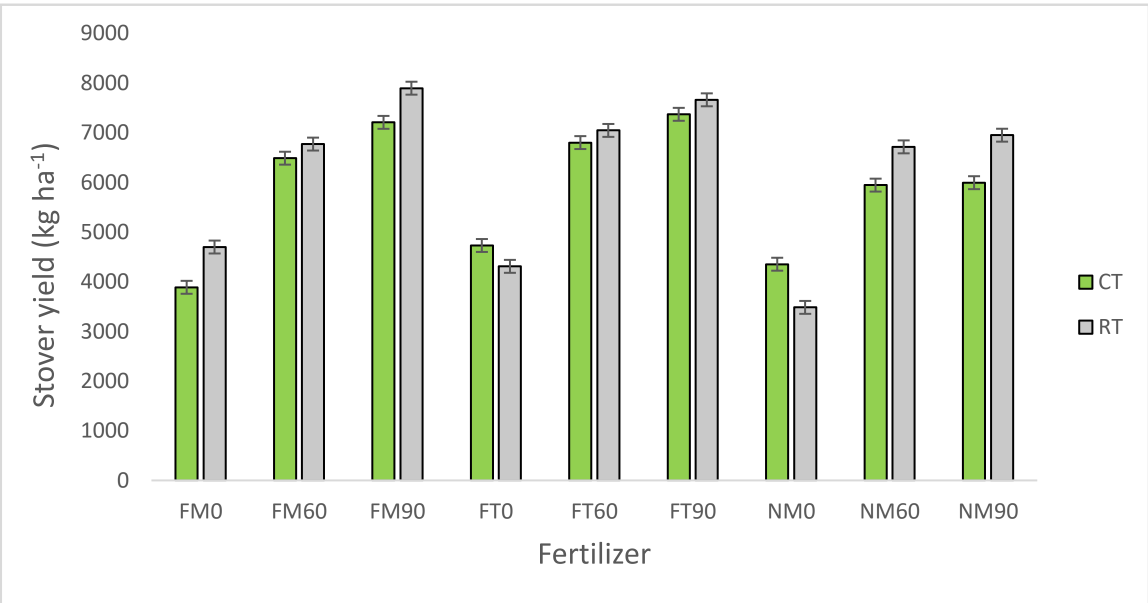

Figure 24: stover yield on reduced and conventional tillage as influence by integrated soil fertility management practice in Nyankpala, Ghana. Bars represent standard error of difference.

The yield results obtained from the study indicate that plants on reduced tillage generally perform better than those on conventional tillage irrespective of the treatment applied. The high grain and stover yields obtained by the application of organic and inorganic fertilizers (FT_90, FM_90) could be ascribe to favourable temperature, soil moisture, proper balance of the fertilizer applied and the timely release of nutrients from both the organic and inorganic fertilizers for proper plants uptake in the study area. it might have also enabled the plants to intercept more solar radiation for assimilation of dry matter as it is obvious in the yield obtained by organic and inorganic treated plot. The soil nutrient stock can be affected and thus limits crop nutrient uptake due to prolong imbalanced fertilizer application (Bhattacharyya et al, 2016). According to Hartmann et al, (2015) the mineralization of organic matter is favoured by high temperature and soil moisture. Report from several works indicate that addition of organic matter improves soil physical and chemical properties as well as productivity of crops (Liang et al, 2011; Rasool et al, 2008). It also serves as a chelating material by holding nutrients and water for plant use as well as addition of nutrient into the soil system thus enhancing N supply capacity of the soil (Gurmu, 2019). Kanton et al, (2016) conducted an experiment in northern Ghana and tested different fertilizer input on maize. Their results indicated that mineral fertilizer produced grain yield of 2.9 t ha^{-1} and manure gave a grain yield of 1.9 t ha^{-1}. This result was similar to our finding when we used sole inorganic and sole organic fertilizer on conventional tillage with 3.1 t ha^{-1} and 1.2 t ha^{-1} respectively. From our study the combined application of organic and inorganic fertilizers gave the highest yield of 4.6 t ha^{-1} and 4.3 t ha^{-1} on reduced and conventional tillage respectively. Findings by Kiboi et al, (2019) in an experiment on maize in Kenya is in agreement with our work. They obtained a grain yield of 4.7 t $ha^{-1}$and 3.5 t ha^{-1} in Kandara and Chuka respectively when they applied organic and inorganic fertility together. Similar trend was observed regarding the stover yield we obtained and those by the aforementioned authors. However, Otieno et al, (2021) obtained a grain yield of 3.9 t ha^{-1} and a stover yield of 13.2 t ha^{-1} when combined application of organic and inorganic fertilizer were applied on maize in Kenya. Their stover yield was far higher than what we obtained (7.9 t ha^{-1}) under combined organic and inorganic treatment.

4.6.3 Nitrogen use efficiency

We estimated the nitrogen use efficiency (NUE) and N recovery for the treatments we applied. The nitrogen partial factor productivity (N-PFP) was use as a reference for the nitrogen use efficiency and the value obtained in this study ranged from 22 to 67% irrespective of the tillage practice. The nitrogen recovery we estimated also ranges from 8 to 59% (Table 5). The treatments with combined application of organic and inorganic fertilizers used nitrogen efficiently compared to the sole application of either organic or inorganic fertilizer. Similarly the combined organic and inorganic treatment recovered nitrogen more than the rest of the treatments. The results indicated that the combined application of farmyard manure at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} (FM_90) utilized N efficiently and recovered N more than the rest of the treatments on conventional tillage with 58.1% and 52% respectively (Table 5). Similar trend was observed on the reduced tillage system with FM_90 having the highest NUE of 67.6% and N recovery percentage of 59.4 (Table 5).

Table 5: integrated soil fertility management effect on maize nitrogen use efficiency and nitrogen recovery under different tillage practices.

Treatment	N-PFP (%)	N recovery (%)
CT_FM_90	58.06	52.12
CT_FM_60	40.14	32.38
CT_FM_0	43.14	22.99
CT_FT_90	47.27	42.62
CT_FT_60	25.00	19.29
CT_FT_0	19.56	9.15
CT_NM_90	42.18	36.01
CT_NM_60	31.82	17.88
CT_NM_0	23.10	
RT_FM_90	67.61	59.44
RT_FM_60	46.11	35.44
RT_FM_0	44.97	17.25
RT_FT_90	53.75	47.35
RT_FT_60	32.73	24.88
RT_FT_0	22.74	8.43
RT_NM_90	51.64	43.16
RT_NM_60	36.31	25.08
RT_NM_0	31.78	

(N-PFP= nitrogen partial factor productivity, CT= conventional tillage, RT= reduced tillage)

The nitrogen partial factor of productivity (N-PFP) takes into consideration the efficiency of N applied and soil N (Ladha et al, 2005). The N-PFP of FM_90 was increased by 20-30% on both tillage practices relative to the sole application of inorganic fertilizer (90-60-60 kg NPK ha^{-1}) in our study. Our result was different from those reported by Zhang et al, (2016) with 8-15% increment over the sole inorganic application. The N-PFP obtained by Kiwia et al, (2019) on maize plus inorganic fertilizer intercropped with pigeon pea in different African countries are Tanzania 52.2, Mozambique 42.9 and Kenya 63.9. These results were consistent with our results but their organic source was from both biological nitrogen fixation and plant biomass. The N-PFP value (51%) we obtained when we applied inorganic fertilizer at 90 kg N ha^{-1} was smaller than the value (75%) obtained by Ngosong et al, (2019) when they applied 100 kg N ha^{-1} on maize in Cameroon. The nitrogen recovery value we obtained from our study when we combined organic and inorganic fertilizers was in the range of 47 to 67%. The value (48%) obtained by MacCarthy et al, (2020) when they applied organic and inorganic fertilizers on rice in Ghana support our findings. Omar et al, (2020) obtained a nitrogen recovery of 58% when they applied organic and inorganic fertilizer on maize in Malaysia. Their result is consistent with the result we obtained when organic and inorganic fertilizers were applied on maize in our experiment. The results from our study showed that the combined application of organic and inorganic fertilizers increased grain yield, enhance stover yield, utilized the nutrient that was applied efficiently and recovered more of the nutrient than any of the treatments applied irrespective of the tillage system. The application of fertisol at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} produced the highest grain yield which was not statistically different from the yields obtained by the application of farmyard manure at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} on both tillage practices. However, FM_90 performed better than FT_90 in terms of N-PFP and N recovery rate in the study. To sustain maize yield and improve soil health in the study area the combined application of farmyard manure at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} will be the best bet technology to use. The hypotheses set for the experiment were duly affirmed by the results obtained from the study.

CHAPTER FIVE

5.0 Conclusions and Recommendations

5.1. Conclusions

Results from the laboratory and field validation showed that CO_2 and ET fluxes can be measured reliably and in a stable manner over time using inexpensive NDIR and RH sensors in conjunction with a manual closed chamber system. we were able to develop a CO_2 monitoring system with components that are low-cost connected to K30FR and DHT22 sensors for CO_2 and ET measurement respectively. The developed CO_2 monitoring system reliably measured CO_2 and ET fluxes from which NECB and WUE were estimated respectively.

A number of tillage systems were assessed regarding their CO_2 emission rate and the result showed that tractor plough (conventional tillage) emitted the highest CO_2 into the atmosphere relative to no tillage and to some extent bullock plough (reduced tillage). The tillage systems we used did not differ much from each other when compared during the entire growing season regarding CO_2 emissions. However, significant difference was seen between them during the tillage operation. The tractor plough emitted about 65% more CO_2 from the soil into the atmosphere than the bullock plough after tillage operation.

Results from the dynamics of carbon on ISFM technologies under different tillage systems indicated that plots treated with combined application of organic and inorganic fertilizers thus Fertisoil at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} (FT_90) and Farmyard manure at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} (FM_90) reduced CO_2 emission, sequester carbon (carbon sink) and utilized water efficiently than the rest of the treatments irrespective of the tillage practice. FM_90 emitted less CO_2 than any other treatment on reduced tillage whiles FT_90 emitted less on conventional tillage. FT_90 utilized water efficiently on both tillage practices in the study area.

Results from the study also showed that the combined application of organic and inorganic fertilizers increased grain yield, enhance stover yield, utilized the nutrient that was applied efficiently and recovered more of the nutrient than any of the treatments applied irrespective of the tillage system. FT_90 produced the highest grain yield which was not statistically different from the grain yield obtained by FM_90 on both tillage practices. However, FM_90 performed better than FT_90 in terms of N-PFP and N recovery rate in the study.

5.2. Recommendations

We recommend that scientists in the area of gas exchange analysis (CO_2 and ET) especially in Sub-Sahara Africa and South East Asia should adopt and use the newly developed CO_2 and ET system. Because the developed CO_2 and ET measurement system can be a valuable tool in evaluating and assessing global carbon and water flux models, ultimately expanding the network for carbon budget and evapotranspiration research that are both critical for climate change mitigation.

Also, we recommend the use of reduced tillage (minimum soil disturbance) or no tillage system during land preparation in the study area. These tillage systems safeguard the environment by reducing CO_2 emission from the soil into the atmosphere and enhanced the health of the soil.

Again, we recommend the use of organic fertilizer (fertisoil or farmyard manure) at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} if CO_2 reduction, carbon sequestration and efficient use of water are to be achieved in the study area.

Furthermore, we recommend the use of farmyard manure at 5 t ha^{-1} and 90-60-60 kg NPK ha^{-1} irrespective of the tillage system if maize sustainability and enhancement of soil health are to be attained.

Finally, we recommend that further work should be carried out to include CO_2 emission from fuel combustion during tillage operation in the study area to get a fair idea of the total CO_2 emitted during such operations.

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Annexes

Annex I: bullock ploughing in Nyankpala Ghana

Annex 2: disc plough fixed to a tractor in Nyankpala Ghana .

Annex 3: collecting rice straw used as cattle bedding from cattle kraal in Kpalsougu-Ghana

Annex 4: transporting farmyard manure for storage

Annex 5: pilling the farmyard manure in a pit

Annex 6: a layer of the pilled farmyard manure covered with thin soil and ready for next layer.

Annex 7: the farmyard manure was stored in a pit and crust with soil and cowdung for 5 to 6 months.

Annex 8: the farmyard manure was dig out from the pit after 6 months.

Annex 9: bird-eye view of the field setup in Nyankpala, Ghana.

Annex 9: farmyard manure + 90-60-60 kg NPK ha^{-1} plot in the setup at Nyankpala, Ghana

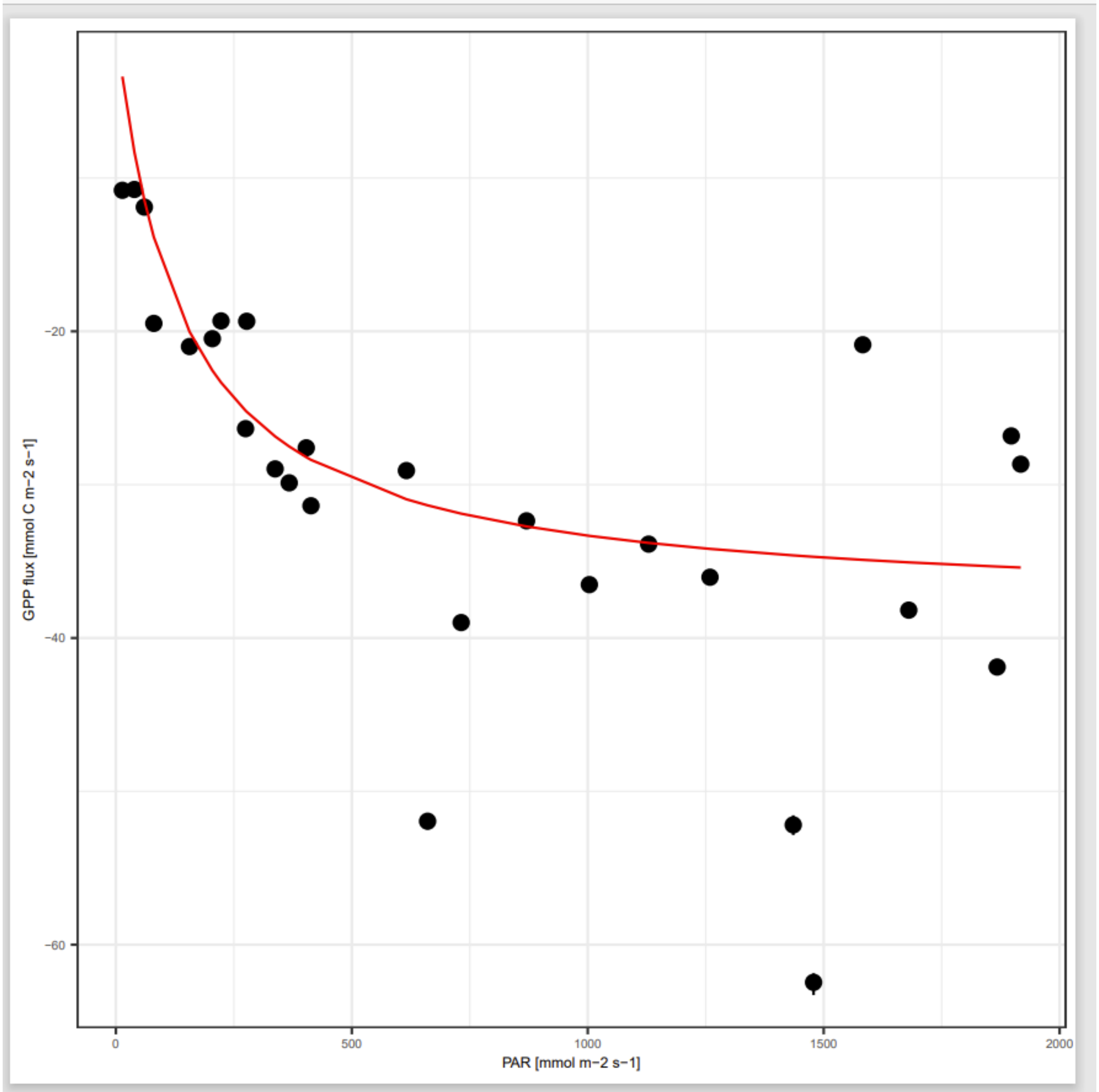
Annex 10: measurement of CO_2 in the soil (heterotrophic respiration) at Nyankpala field setup.

Annex 11: preparing the CO_2 measuring system at ZALF, Germany.

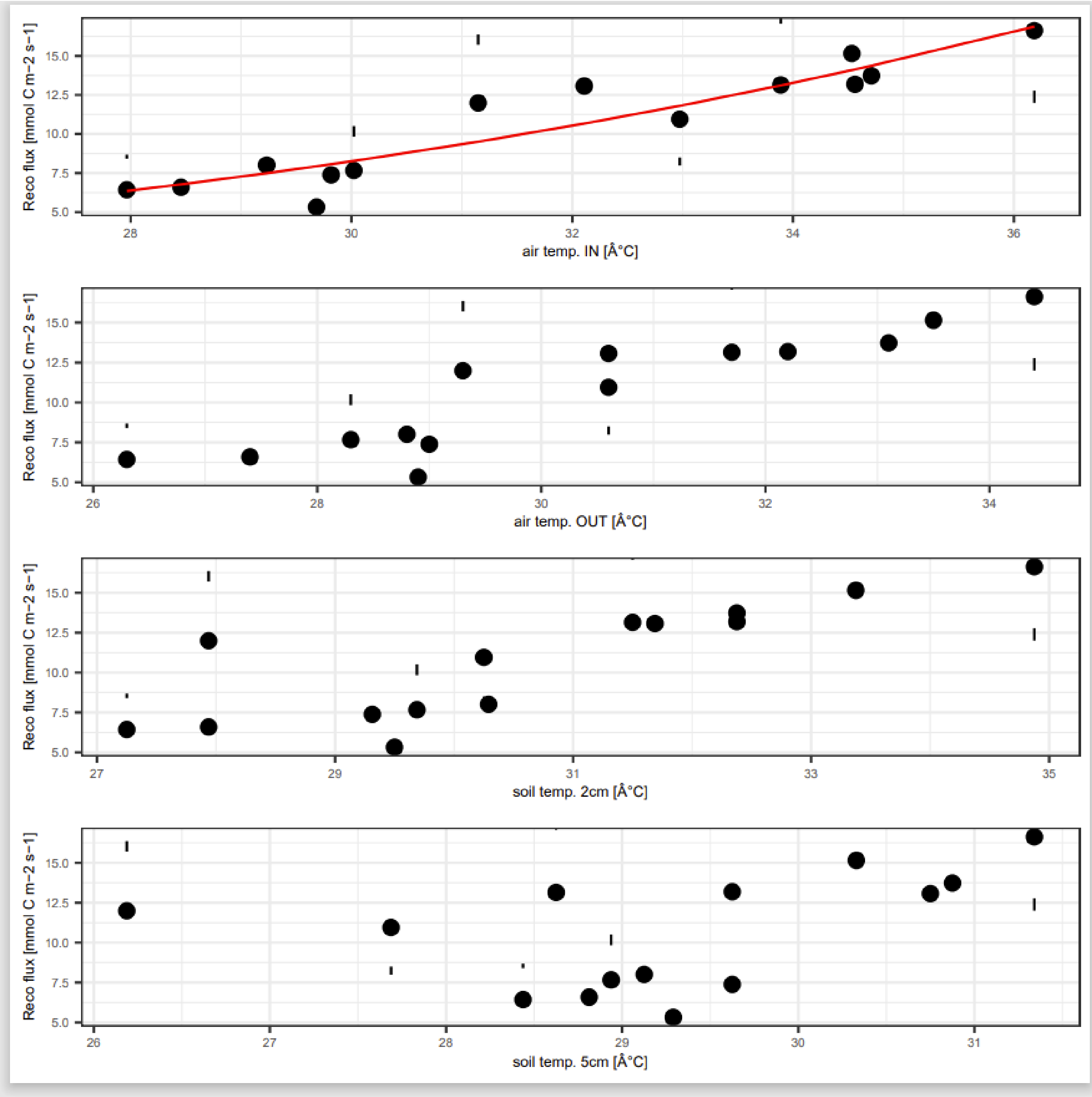
Annex 12: constructing chamber for soil respiration at ZALF, Germany.

Annex 13: loading the CO_2 programme into the newly developed system.

Annex 14: wiring and the complete setup of the developed CO_2 system.



Annex 14: GPP fit obtained with the developed CO_2 monitoring system



Annex 15: Reco fit obtained with the developed CO_2 monitoring system

Annex 16: Analysis of variance for Grian yield

Variate: dry_grain_yield_kg_ha_1
Covariate: No_of_plt_harvested

Source of variation	d.f.	s.s.	m.s.	v.r.	cov.ef.	F pr.
Rep stratum						
Covariate	1	68002.	68002.	19.62		0.141
Residual	1	3466.	3466.	0.08	10.31	
Rep.Tillage stratum						
Tillage	1	1019965.	1019965.	24.59	0.98	0.127
Covariate	1	36515.	36515.	0.88		0.520
Residual	1	41476.	41476.	3.17	0.94	
Rep.Tillage.organic_inorganic stratum						
organic_inorganic	8	79876232.	9984529.	763.12	0.95	<.001
Tillage.organic_inorganic						
	8	354486.	44311.	3.39	0.97	0.007
Covariate	1	3044.	3044.	0.23		0.633
Residual	31	405596.	13084.		0.98	
Total	53	87977382.				

Tables of means (adjusted for covariate)

Variate: dry_grain_yield_kg_ha_1
Covariate: No_of_plt_harvested

Grand mean 2546.

Tillage	CT	RD
	2407.	2685.

organic_inorganic	FM0	FM60	FM90	FT0	FT60	FT90
	1274.	2757.	4239.	1139.	2502.	4513.

organic_inorganic	NM0	NM60	NM90
	749.	2338.	3401.

Tillage	organic_inorganic	FM0	FM60	FM90	FT0	FT60
CT		1247.	2611.	3961.	1095.	2289.
RD		1300.	2903.	4516.	1182.	2716.

Tillage	organic_inorganic	FT90	NM0	NM60	NM90
CT		4397.	631.	2271.	3158.
RD		4629.	868.	2406.	3644.

Standard errors of differences of means

Table	Tillage	organic_inorganic	Tillage organic_inorganic
rep.	27	6	3
s.e.d.	56.1	67.9	106.3
d.f.	1	31	10.30
Except when comparing means with the same level(s) of			
Tillage			95.4
d.f.			31

Least significant differences of means (5% level)

Table	Tillage	organic_inorganic	Tillage organic_inorganic
rep.	27	6	3
l.s.d.	712.8	138.5	235.9
d.f.	1	31	10.30
Except when comparing means with the same level(s) of			
Tillage			194.6
d.f.			31

Stratum standard errors and coefficients of variation (adjusted for covariate)
Variate: dry_grain_yield_kg_ha_1
Covariate: No_of_plt_harvested

Stratum	d.f.	s.e.	cv%
Rep	1	13.9	0.5
Rep.Tillage	1	67.9	2.7
Rep.Tillage.organic_inorganic	31	114.4	4.5

Annex 17: Analysis of variance for stover weight

Variate: stover_wgt_kg_ha_1
Covariate: No_of_plt_harvested

Source of variation	d.f.	s.s.	m.s.	v.r.	cov.ef.	F pr.
Rep stratum						
Covariate	1	42782.	42782.	42.14		0.097
Residual	1	1015.	1015.	0.35	21.57	
Rep.Tillage stratum						
Tillage	1	1235677.	1235677.	430.63	0.98	0.031
Covariate	1	28457.	28457.	9.92		0.196
Residual	1	2869.	2869.	0.11	5.46	
Rep.Tillage.organic_inorganic stratum						
organic_inorganic	8	80825598.	10103200.	374.65	0.95	<.001
Tillage.organic_inorganic	8	3815200.	476900.	17.68	0.97	<.001
Covariate	1	4648.	4648.	0.17		0.681
Residual	31	835976.	26967.		0.97	
Total	53	101668277.				

Tables of means (adjusted for covariate)

Variate: stover_wgt_kg_ha_1
Covariate: No_of_plt_harvested

Grand mean 6016.

Tillage	CT	RD
	5863.	6169.

organic_inorganic	FM0	FM60	FM90	FT0	FT60	FT90
	4292.	6628.	7551.	4519.	6923.	7515.

organic_inorganic	NM0	NM60	NM90
	3918.	6329.	6471.

Tillage	organic_inorganic	FM0	FM60	FM90	FT0	FT60
CT		3887.	6486.	7207.	4729.	6800.
RD		4698.	6770.	7895.	4309.	7045.

Tillage	organic_inorganic	FT90	NM0	NM60	NM90
CT		7369.	4352.	5944.	5993.
RD		7661.	3483.	6714.	6949.

Standard errors of differences of means

Table	Tillage	organic_inorganic	Tillage organic_inorganic
rep.	27	6	3
s.e.d.	14.8	97.5	130.0
d.f.	1	31	31.66
Except when comparing means with the same level(s) of			
Tillage			137.0
d.f.			31

Least significant differences of means (5% level)

Table	Tillage	organic_inorganic	Tillage organic_inorganic
rep.	27	6	3
l.s.d.	187.5	198.8	264.9
d.f.	1	31	31.66
Except when comparing means with the same level(s) of			
Tillage			279.3
d.f.			31

Stratum standard errors and coefficients of variation (adjusted for covariate)

Variate: stover_wgt_kg_ha_1
Covariate: No_of_plt_harvested

Stratum	d.f.	s.e.	cv%
Rep	1	7.5	0.1
Rep.Tillage	1	17.9	0.3
Rep.Tillage.organic_inorganic	31	164.2	2.7

Annex 18: Two-sample t-test for Reco

Variates: CT Vrs RT.

Message: Sample size should be greater than 5 for a reliable t-test or confidence interval.

Test for equality of sample variances

Test statistic F = 2.65 on 1 and 1 d.f.

Probability (under null hypothesis of equal variances) = 0.70

Summary

Sample	Size	Mean	Variance	Standard deviation	Standard error of mean
CT	2	369.1	0.008390	0.09160	0.06477
RT	2	357.9	0.003167	0.05628	0.03979

Difference of means: 11.2154
Standard error of difference: 0.0760

95% confidence interval for difference in means: (10.89, 11.54)

Test of null hypothesis that mean of CT is equal to mean of RT

Test statistic t = 147.54 on 2 d.f.

Probability < 0.001

Annex 19: Two-sample t-test GPP

Variates: CT Vrs RT.

Message: Sample size should be greater than 5 for a reliable t-test or confidence interval.

Test for equality of sample variances

Test statistic F = 1.04 on 1 and 1 d.f.

Probability (under null hypothesis of equal variances) = 0.99

Summary

Sample	Size	Mean	Variance	Standard deviation	Standard error of mean
CT	2	-475.8	0.004941	0.07029	0.04970
RT	2	-467.6	0.004768	0.06905	0.04883

Difference of means: -8.1891
Standard error of difference: 0.0697

95% confidence interval for difference in means: (-8.489, -7.889)
Test of null hypothesis that mean of CT is equal to mean of RT

Test statistic t = -117.54 on 2 d.f.

Probability < 0.001

Annex 20: Two-sample t-test NEE

Variates: CT vrs RT.

Message: Sample size should be greater than 5 for a reliable t-test or confidence interval.

Test for equality of sample variances

Test statistic F = 1.28 on 1 and 1 d.f.

Probability (under null hypothesis of equal variances) = 0.92

Summary

Sample	Size	Mean	Variance	Standard deviation	Standard error of mean
CT	2	-106.7	0.006036	0.07769	0.05494
RT	2	-109.6	0.004728	0.06876	0.04862

Difference of means: 2.9163
Standard error of difference: 0.0734

95% confidence interval for difference in means: (2.601, 3.232)

Annex 21: Two-sample t-test NECB

Variates: CT Vrs RT.

Message: Sample size should be greater than 5 for a reliable t-test or confidence interval.

Test for equality of sample variances

Test statistic F = 38.31 on 1 and 1 d.f.

Probability (under null hypothesis of equal variances) = 0.20

Summary

Sample	Size	Mean	Variance	Standard deviation	Standard error of mean
CT	2	-51.11	0.000122	0.01105	0.00781
RT	2	-42.26	0.004679	0.06840	0.04837

Difference of means:	-8.8462
Standard error of difference:	0.0490

95% confidence interval for difference in means: (-9.057, -8.635)

Test of null hypothesis that mean of CT is equal to mean of RT

Test statistic t = -180.55 on 2 d.f.

Probability < 0.001

Annex 22: Two-sample t-test WUE

Variates: CT vrs RT.

Message: Sample size should be greater than 5 for a reliable t-test or confidence interval.

Test for equality of sample variances

Test statistic F = 3.96 on 1 and 1 d.f.

Probability (under null hypothesis of equal variances) = 0.59

Summary

Sample	Size	Mean	Variance	Standard deviation	Standard error of mean
CT	2	2.192	0.000663	0.02575	0.01821
RT	2	2.374	0.002624	0.05123	0.03622

Difference of means: -0.1820
Standard error of difference: 0.0405

95% confidence interval for difference in means: (-0.3564, -0.007540)

Test of null hypothesis that mean of CT is equal to mean of RT

Test statistic t = -4.49 on 2 d.f.

Probability = 0.046