

**Testing the Effects of Biochars on Crop Yields and Soil Properties  
In a Rice-based Cropping System of Myanmar:  
Field Experiment and Modelling**

**The Dissertation**

**Written by**

**Khin Zar Kyaw**

**Born on 05. 05. 1972 - in Myanmar**

**Submitted to the Faculty of Sustainability of Leuphana University of Lüneburg**

**To earn the academic degree of**

**Doctor of Natural Sciences**

**Dr.rer.nat**

**LÜNEBURG**

**2015**

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„Gedruckt mit Unterstützung des Deutschen Akademischen Austauschdienstes“

Submitted on: 21.04.2015

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## Abstract

Agricultural production of smallholder farmers in Myanmar is facing soil fertility degradation and in consequence, crop yields decline due to the imbalances of nutrient supply. In most cases, all above ground biomass is removed from the fields after harvesting the crops and during land preparation for the next crop. Higher temperatures also stimulate the higher mineralisation rates and released mineral nutrients are lost from fallow lands before sowing the next crops. Regarding the addition of mineral fertilizers, except for cash crops, farmers are reluctant to apply fertilizers for the crops that are sown for household's self-sufficiency. In the Dry Zone, irrigated agriculture is available in recent years and farmers could overcome water scarcity through irrigation. With the availability of irrigation water, farmers could prolong the cropping period, nevertheless crop yields are decreasing year by year.

In recent decades, research findings are indicating the benefits of biochar application for soil fertility improvement and food security. Smallholder farmers can produce biochar from agricultural by-products such as pigeon pea stems, cotton stems and rice husks by using biochar stoves. Large-scale production is possible by producing both biochar and thermal energy simultaneously, such as getting rice husk biochar and producing thermal energy by burning rice husks. By those means, environmental pollution due to the smokes from stubble burnings and the health hazards from smokes arise from kitchens can also be reduced.

Present research was conducted to test the effects of the application of biochars produced from different crop residues together with NPK fertilizers on crop yields and soil properties in the rice-chickpea-cotton cropping system of the Central Dry Zone area of Myanmar during 2012 and 2013 cropping seasons at Shwe Daung Farm, Mandalay Division, Myanmar. Effects of biochar applications in combination with NPK fertilizers were compared with NPK fertilizer (without biochar) application and the control (without biochar and NPK fertilizers).

Biochars used in the experiments were produced from three kinds of locally available raw materials (rice husk, rice straw and, pigeon pea stem) at temperature above 550°C by using a kiln made from a 200-Liter diesel barrel. Field experiments were conducted on sandy loam soil in the Central Dry Zone of Myanmar. After harvesting rice in 2012, chickpea was sown without application of both organic and inorganic fertilizers. After harvesting chickpea in 2013, cotton was sown on the same experimental plots.

Treatments were rice husk biochar (Rh) 20 Mg ha<sup>-1</sup> + NPK fertilizers; rice straw biochar (Rs) 20 Mg ha<sup>-1</sup> + NPK fertilizers; pigeon pea stem biochar (Ps) 20 Mg ha<sup>-1</sup> + NPK fertilizers; rice husk biochar and farmyard manure mixture (Rh biochar + FYM) 10 Mg ha<sup>-1</sup> + NPK

fertilizers; NPK fertilizers (without biochar); and the control (without fertilizer and biochar). Biochar weights represented fresh biochar weights. Equal rate of NPK fertilizers were applied in all treatments. However, fertilizer rates were different with respect to the crops. In rice experiment, 100:50:50 kg ha<sup>-1</sup> rate of Urea (N): Triple Super Phosphate (P): Muriate of potash (K) was applied. In cotton experiment, 100:30:117 kg ha<sup>-1</sup> rate of Urea (N): Triple Super Phosphate (P): Muriate of potash (K) was applied.

Crop growth data, yield component data and yield data of each treatment were recorded. Soil samples from topsoil (0-0.2 m) were taken before starting the experiments, after harvesting rice and cotton, respectively, and analysed.

A biogeochemical model, denitrification decomposition (DNDC) model, was used to estimate soil organic carbon storage and greenhouse gas emissions during crop growing seasons and to quantify the long-term impact of biochar applications on rice, chickpea and cotton yields.

The results from soil analyses indicated that although initial soil pH was at 8.0 and pH values of biochars ranged between 8.0 and 10.0 soil pH after two years of biochar application did not increase. pH values were below 8.0. That value was lower than initial soil pH. That could be due to the effect of the change of cropping system from upland to lowland rice cultivation and the effects of biochar additions to the alkaline sandy loamy soil of the experimental site.

Although total exchangeable cation value was not significantly different among the treatments, compositions of major cations were significantly different among the treatments. Exchangeable potassium increased in Rs biochar + NPK applied soils. Exchangeable sodium increased in control, and conventional NPK fertilizer applied soils. Reduction of soil bulk density from 1.8 g cm<sup>-3</sup> to 1.6-1.7 g cm<sup>-3</sup> occurred in biochar treatments compared to control and conventional NPK fertilizer application treatments. Positive changes of total carbon and total nitrogen of soils were found in biochar treatments compared to control and conventional NPK fertilizer application.

Application of pigeon pea stem biochar + NPK fertilizers showed the highest crop growth and the highest yield in rice. The highest chickpea yield was obtained from the plot that applied rice husk biochar + NPK fertilizers. Cotton crop growth and yield was the highest in rice husk biochar and farmyard manure mixture + NPK fertilizer application. The lowest crop growth and yield was obtained from the control in cotton.

The results of this study suggested that biochars from different biomass materials had different effects on soil properties and crop yields under different growing conditions and cultivated crops. Although the applied biochars had a high pH, soil pH did not increase after biochar applications. The growth and yield of tested crops were higher than that of the control

and conventional NPK fertilizer application. Rice husk biochar and farmyard manure mixture + NPK fertilizer application can be assumed as a suitable soil amendment application under upland crop cultivation. Pigeon pea stems biochar + NPK fertilizers should be applied in rice cultivation. Rice husk biochar + NPK fertilizers and rice husk biochar-farmyard manure mixture + NPK fertilizers showed as the appropriate biochar soil amendments for the study area compared to rice straw biochar + NPK fertilizers and pigeon pea stem biochar + NPK fertilizers. Application of these biochars increased total exchangeable cations, reduced bulk density, increased organic carbon, regulated soil pH and, can easily be accessed by smallholder farmers by promising crop yields for sustainable agricultural production. Rice straw biochar + NPK fertilizers and pigeon pea stem biochar + NPK fertilizers also showed positive influences on soil fertility and crop growth. However, extensive application of those biochars might require large-scale productions and distributions. To obtain the detail information regarding the impact of biochar application on the agro-ecosystem and surrounding atmosphere, further research activities may need to carry out under different agricultural production conditions.

When model fitness was tested, it was found that DNDC model was fit for the simulation of crop yields and soil organic carbon under the conditions of the experimental site. Simulation of soil organic carbon dynamics and crop yields for 30 years and 50 years after the addition of biochars in combination with NPK fertilizers showed that such applications could maintain the crop yields at the same level up to 50 years. That could maintain soil organic carbon at a level higher than conventional NPK fertilizer application. Regarding the simulation of GHGs emissions, the model simulated nitrous oxide emission close to actual emissions of agricultural soils of Myanmar. Simulated CH<sub>4</sub> emissions from control and conventional NPK fertilizer application variant were consistent with the well-known emissions of Myanmar rice fields. To confirm the accuracy of simulated CH<sub>4</sub> emissions from biochar applied soils, it may need field investigations and validations of model results.

Simulated effects of rice husk-, rice straw- and pigeon pea stem fresh biomass applications and that of rice husk-, rice straw- and pigeon pea stem biochar applications on rice, chickpea, cotton yields and soil organic carbon (SOC) were compared. Objective of this simulation was to compare the effects of fresh biomass-applications and the application of biochars produced from the same biomass on crop yields and SOC by using DNDC model. The results showed that simulated rice yields of rice husk biochar and rice straw biochar applications were 33% and 31%, respectively, higher than that of pigeon pea green manure applications. However, simulated rice yield from pigeon pea stem biochar application was 4% higher than that of

pigeon pea stem green manure application. Simulated chickpea yield from pigeon pea green manure treatment was the highest among all of biochar and biomass applications. Simulated cotton yields obtained from fresh biomass applications were lower than that of biochar applications. In estimating the future yields, all crop yields from rice husk and rice straw biomass applications were lower than that of rice husk and rice straw biochar applications in the initial year of simulation. However, in the following years, the yields remained at the same level up to the end of simulated years. In pigeon pea stem green manure application, crop yields were higher than the other treatments since the initial year up to the end of simulated years. Simulated SOC was lower in fresh biomass applications compared to biochar applications.

## **Zusammenfassung**

Die landwirtschaftliche Produktion der Kleinbauern in Myanmar leidet unter einer kontinuierlichen Verminderung der Bodenfruchtbarkeit die ihrerseits Ernterückgänge nach sich zieht. Üblicherweise wird die gesamte oberirdische Biomasse nach der Ernte von Feld entfernt um das Land für die nächste Feldfrucht vorzubereiten. Zusätzlich bedingen hohe Temperaturen hohe Mineralisationsraten der verbliebenen unterirdischen organischen Substanz und die daraus freigesetzten Nährstoffe gehen bereits vor der Einsaat der nächsten Frucht auf brach liegenden Feldern verloren. Bezüglich des Einsatzes von Mineraldüngern sind die selbstversorgenden Landwirte – außer bei Cash Crops – sehr zurückhaltend.

In den Trockengebieten ist Bewässerungswirtschaft in den letzten Jahren möglich geworden und Landwirte können dem Wassermangel durch Bewässerung entgegenwirken. Obwohl durch die Verfügbarkeit von Bewässerungswasser die Ernteperiode verlängert werden konnte, sinken die Ernteerträge jedes Jahr weiter ab.

In den letzten Jahrzehnten haben wissenschaftliche Untersuchungen den nutzbringenden Einsatz von Pflanzenkohle auf die Bodenfruchtbarkeit und die Ernährungssicherheit gezeigt. Pflanzenkohle kann von Kleinbauern aus landwirtschaftlichen Reststoffen, wie Reisspelzen selbst hergestellt werden. Auch groß-skalige Produktionen sind möglich, bei denen Pflanzenkohle und Wärme produziert werden. Auf diesem Wege könnten auch Umweltverschmutzungen durch Rauchgase beim Abbrennen der Erntereste und Gesundheitsrisiken durch Rauchentstehung in Haushalten reduziert werden.

Die hier vorgestellten Untersuchungen wurden durchgeführt, um den Effekt von Pflanzenkohle auf Ernteerträge und Bodeneigenschaften in einem Reis-Kichererbsen-Baumwoll-Anbausystem in der zentralen Trockenzone von Myanmar während der Anbausaison 2012 und 2013 auf der Shwe Daung Farm, Mandalay Division, Myanmar zu testen.

Die Pflanzenkohle für diese Untersuchungen wurde aus den drei in der Region vorhandenen Rohstoffen gewonnen: Reisspelzen, Reisstroh und Straucherbsenstängel. Die Biomasse wurde in einem Ofen aus einem 200 L Diesel Fass bei Temperaturen von über 550°C pyrolysiert.

Die Feldexperimente wurden auf einem sandigen Lehmboden durchgeführt. Nach der Reisernte 2012 wurden auf den gleichen Untersuchungsflächen Kichererbsen ohne Zufuhr von Zusatzstoffen angebaut. Nach der Kichererbsenernte 2013 wurde Baumwolle ausgesät. Es wurde die Wirkung von Pflanzenkohleapplikationen- aus Reisspelzen mit NPK Dünge, aus Reisstroh mit NPK Dünger, und aus Straucherbsenstängeln mit NPK Dünge, sowie Gemischen aus Reisspelzen-Pflanzenkohle und Gülle zusammen mit NPK Dünge und auf die Erträge von Reis, Kichererbsen und Baumwolle untersucht und mit den Varianten Kontrolle



(ohne Zuschlag von Pflanzenkohle und mineralischem NPK Dünger) und NPK Dünger Applikation (Ohne Zuschlag von Pflanzenkohle) verglichen.

Die Varianten waren Reisspelzen-Pflanzenkohle (Rh) 20 Mg ha<sup>-1</sup> + NPK Dünger, Reisstroh-Pflanzenkohle (Rs) 20 Mg ha<sup>-1</sup> + NPK Dünger, Straucherbsenstängeln-Pflanzenkohle (Ps) 20 Mg ha<sup>-1</sup> + NPK Dünger, die Mischung aus Reisspelzen-Pflanzenkohle und Gülle (Rh biochar + FYM) 10 Mg ha<sup>-1</sup> + NPK Dünger, NPK Dünger (Ohne Pflanzenkohle), und Kontrolle (ohne Zuschlag von Pflanzenkohle und mineralischer NPK Dünger). Die gleiche Menge von NPK Dünger wurden in allen Varianten addiert. Die Menge der NPK Dünger waren unterschiedlich bei den Kulturpflanzen; 100:50:50 kg ha<sup>-1</sup> von Urea (N): Triple Super Phosphate (P): Muriate of potash (K) für Reis und 100:30:117 kg ha<sup>-1</sup> von Urea (N): Triple Super Phosphate (P): Muriate of potash (K) für Baumwolle.

Das Wachstum und die Ernteerträge jeder Variante wurden aufgenommen. Proben des Oberbodens (0-0.2 m) wurden vor Versuchsbeginn sowie nach der Reis- bzw. Baumwoll-ernte entnommen und analysiert.

Da Feldmessungen der Treibhausgasemissionen, des Bodenkohlenstoffs und -Stickstoffs von dem Einfluss der unterschiedlichen Pflanzenkohle-Applikationen abhängen und veränderbar sind, konnten sie experimentell nur stichprobenartig erfasst werden. Ein biogeochemisches Model (DNDC = Denitrifikation Dekomposition Model) wurde genutzt um folgende Parameter abzuschätzen: Kohlenstoffvorrat im Boden, Treibhausgasemissionen während der Wachstumsperiode und Langzeiteffekte der Applikation von Pflanzenkohle auf Baumwolle, Kichererbsen und Reiserträge.

Die Ergebnisse der Bodenanalysen deuten darauf hin, dass obwohl der initiale Boden pH-Wert höher als 7 war und der pH-Wert der Pflanzenkohlen zwischen 8 und 10 lag, der Boden pH-Wert nach 2 Jahren Pflanzenkohleapplikation nicht erhöht war. Die pH-Werte lagen unter 8 und damit unter dem initialen pH Wert. Die Kationenaustauschkapazität (KAK) wurde im Vergleich zu den Ausgangswerten erhöht. Obwohl es keine signifikanten Unterschiede der KAK-Werte zwischen den Behandlungen gab, unterschied sich die Basen-Sättigung signifikant zwischen den Behandlungen. Außerdem kam es zu einer Verminderung der Lagerungsdichte von 1,8 zu 1,6-1,7 g cm<sup>-3</sup> nach Pflanzenkohle + NPK Dünger Applikation im Vergleich zur Kontrolle oder der konventionellen NPK-Düngergabe (Ohne Pflanzenkohle) Variante. Positive Veränderungen wurden hinsichtlich des Gesamtkohlenstoff- und -Stickstoffgehaltes des Bodens nach Pflanzenkohle Applikation im Vergleich zur Kontrolle und konventionellen NPK Düngung festgestellt.

Die Ergebnisse dieser Studie legen nahe, dass Pflanzenkohle aus verschiedenen Ausgangs-

materialien unterschiedliche Effekte auf Bodeneigenschaften und Ernteerträge unter unterschiedlichen Anbaubedingungen und kultivierten Feldfrüchten hat. Obwohl Pflanzenkohle einen hohen pH-Wert aufweist, wurde der pH des Bodens durch Pflanzenkohle-Applikation nicht verändert. Das Wachstum und die Erträge der untersuchten Feldfrüchte waren in den mit Pflanzenkohle + NPK Dünger behandelten Parzellen größer als in der Kontrolle oder der Applikation chemischer Düngemittel. Es kann angenommen werden, dass das Reisspelzen-Pflanzenkohle-Gemisch mit Gülle + NPK Dünger der am besten geeignete Bodenverbesserer für Hochland-Kulturen ist. Straucherbsen-Pflanzenkohle + NPK Dünger sollte als Bodenverbesserer im Reisanbau verwendet werden. In Anbetracht der Verbesserung der Bodenqualität, wie der KAK, reduzierter Lagerungsdichte, erhöhtem Bodenstickstoff, stabiler Boden pH-Werte und einfacher Verfügbarkeit für Kleinbauern sowie viel versprechender Erträge für eine nachhaltige landwirtschaftliche Produktion, sind Reisspelzen-Pflanzenkohle und die Mischung von Reisspelzen-Pflanzenkohle mit Gülle+NPK Dünger besser geeignet als NPK Dünger + Pflanzenkohlen aus Reisstroh und Straucherbsenstängeln. Reisstroh- und Straucherbsenstängel-Pflanzenkohle wiesen auch einen günstigen Einfluss auf Bodenfruchtbarkeit und Feldfruchtwachstum auf. Jedoch ist die Verfügbarkeit für eine großflächige Anwendung nur bei einer Produktionsanlage im größeren Maßstab für Kleinbauern finanziell tragbar. In Anbetracht des Einflusses von Pflanzenkohle auf die Umweltqualität, sind weitere Untersuchungen unter den landwirtschaftlichen Produktionsbedingungen Myanmars notwendig.

Das DNDC Model war geeignet die Ernteerträge, den organischen Bodenkohlenstoff und Lachgasemissionen der Untersuchungsflächen abzuschätzen. Die Simulation der organischen Kohlenstoff-Dynamik im Boden und der Erträge für 30 und 50 Jahre nach den Pflanzenkohleapplikationen- mit NPK Dünger ergab, dass diese dazu führt, dass die Ernteerträge und der Gehalt an organischem Kohlenstoff auch langfristig auf einem Level gehalten werden können, der über dem liegt, was konventionelle Düngung erzielen würde. In Bezug auf die Treibhausgasemissionen simulierte das Model Lachgasemissionen, die sehr nah an den aktuellen Emissionshöhen von landwirtschaftlich genutzten Böden Myanmars liegen. Simulierte CH<sub>4</sub> Emissionen der Kontrolle und der konventionellen NPK-Variante stimmten überein mit den Emissionen auf Reisfeldern in Myanmar. Um die Genauigkeit der simulierten CH<sub>4</sub> Emissionen von Pflanzenkohle beaufschlagten Reisböden zu bestätigen, sind noch mehr Felduntersuchungen und Validierungen der Modellergebnisse notwendig.

Die Auswirkungen der Biokohle aus Reisspelzen, Reisstroh und Straucherbsenstängel sowie der unverkohlten frischen Biomasse auf Reis-, Kichererbsen- und Baumwollerträge, und

Bodenkohlenstoff (SOC) wurden simuliert und mit den gemessenen Auswirkungen der Reisspelzen, Reisstroh und Straucherbsenstängel Pflanzenkohle Applikationen auf die Kulturen, und SOC zu vergleichen. Die Ergebnisse zeigten, dass die simulierten Reiserträge von Reisspelzen Pflanzenkohle und Reisstroh Pflanzenkohle Applikationen 33% und 31%, höher waren als die der Straucherbsenstängel Gründüngungs anwendungen. Jedoch simuliert Reisertrag aus Straucherbsenstängel Pflanzenkohle Anwendung war 4% höher als die der Straucherbsenstängel Gründünger-Applikation. Simulierte Kichererbsen Erträge von Straucherbsenstängel Gründünger Variante war am höchsten unter allen von Pflanzenkohle und Biomasse-Applikationen. Simulierte Baumwolle Erträge von frischer Biomasse-Applikationen waren niedriger als die von Pflanzenkohle-Applikationen. Bei der Schätzung der zukünftigen Erträge waren alle Ernteerträge aus Reisspelzen und Reisstroh frische Biomasse-Applikationen niedriger als ihre Pflanzenkohle Applikationen im ersten Jahr der Simulation. In den folgenden Jahren, jedoch blieben die Erträge in gleicher Höhe bis zum Ende der Simulationen. In Straucherbsenstängel Gründüngung Applikation, waren die Erträge höher als alle anderen Varianten, da das erste Jahr bis zum Ende der Simulation. Simulierten organischen Kohlenstoff war niedriger in frischer Biomasse-Applikationen im Vergleich zu Pflanzenkohle-Applikationen.

## **Acknowledgement**

First, I would like to thank the German Academic Exchange Service (DAAD) for providing scholarship for my Ph.D. study and the Ministry of Agriculture and Irrigation, Union of the Republic of Myanmar for allowing me to pursue my study in Germany.

I would like to thank Professor Dr. Brigitte Urban, to whom I owe my deepest respect, for providing me with valuable suggestions and inputs, starting from my arrival to Leuphana University, arranging for field experiments, assisting the convenience of my field trip to Myanmar and laboratory works in Leuphana University. I am also very grateful to Prof Dr. Soe Soe Thein for her suggestions for my field experiments and data analysis works in Myanmar. I deeply thank Professor Dr. Andreas Pacholski for taking over the supervision of my research in working with the DNDC model, giving guidelines for the data analyses, way of data presentation in the thesis and thesis writings.

I also thank to U Aung Maw, director of the Department of Industrial Crop Development, and U Kyaw Hlaing, Farm Manager of Shwe Daung Farm for all of their provisions for my field experiments in Shwe Daung Farm. Furthermore, I want to express my gratitude to Frank Krüger, Isa Schierholz, Sabine Hansen, and Mario Tucci for their supports in laboratory works.

I also thank my friends and colleagues from Germany and from Myanmar for their personal and emotional supports at University, in the field and at office, everywhere. Last, I deeply thank my family for their supports and encouragements.

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## Synonyms and Abbreviations

ACIAR	Australian Centre for International Agricultural Research
ASTM	American Society for Testing Materials
BGK	Bundesgütegemeinschaft Kompost e.V. Federal quality community compost
CCD	Convention to Combat Desertification
CEC	Cation Exchange Capacity
CH <sub>4</sub>	Methane
DIN	German Institute for Standardization
DM	Dry matter
ESP	Exchangeable Sodium Percent
FAO	Food and Agriculture Organization
FFTC	Food and Fertilizer Technology Center
GCTE	The Global Change and Terrestrial Ecosystem
GHGs	Greenhouse gases
IGES	Institute for Global Environmental Strategies
IRRI	International Rice Research Institute
K	Potassium
LIFT	Livelihood and Food Security Trust Fund
LUCF	Land Use Change and Forestry
Mg	Mega gram
N	Nitrogen
N <sub>2</sub>	Nitrogen
N <sub>2</sub> O	Nitrous Oxide
NH <sub>3</sub>	Ammonia
NH <sub>4</sub>	Ammonium
OM	Organic Matter
P	Phosphorus
PBIAS	Percent bias
Ps biochar	Pigeon pea stems biochar
Rh biochar	Rice husk biochar
RMSE	Root Mean Square Error

Rs biochar	Rice husk biochar
SAR	Sodium Adsorption Ratio
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SOMNET	Soil Organic Matter Network
UNFCCC	United Nations Framework Convention on Climate Change

## **Chapter 1: Introduction and Literature Review**

### **1.1 Soil Quality and Crop Yields**

Soil is “the unconsolidated mineral or organic material on the immediate surface of the earth that serves as a natural medium for the growth of land plants”, and soil quality is “the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health” (Soil science glossary term committee, 2008). Soil quality can be assessed commonly by chemical variables: organic carbon and nitrogen, extractable bases, pH, sodium adsorption ratio and particulate organic matter; physical variables: water infiltration, electrical conductivity, cation exchange capacity, rooting depth, penetration resistance, aggregate stability, water holding capacity and bulk density; and biological variables: potentially mineralisable nitrogen, microbial biomass, basal respiration, and earthworms (Lewandowski et al., 1999).

Starting from the germination to the harvest of cultivated crops, soil physical properties are important for nutrient supply and root penetration of those crops. For satisfactory crop growth, soil should be in a suitable condition for root development. Therefore, crop roots can exploit the soil to support necessary water and nutrients sufficiently. Soil physical properties, which itself are influencing the biologically important soil structure, are strongly depending on soil texture. Therefore, it is essential to maintain soil structure under favourable condition for the improvement of soil physical properties in crop production (Gardner et al., 1999).

Chemical properties influence crop growth through the supply of essential plant nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, sulphur and the major nutrients as iron, zinc, manganese, boron, silicon, molybdenum. Nutrient requirement can vary with the crops. Availability of these nutrients for cultivated crops will vary with the nutrient composition of respective soil. If fewer amounts of required nutrients are available, nutrient deficiency may occur. If available amount of nutrient exceeds the crop requirement, toxicity may occur. Micronutrients are equally important for the crops as macronutrients. Micro-nutrient deficiency or toxicity can affect crop growth and yield as macronutrient deficiency or toxicity does (Havlin et al., 2014).

Soil organic matter plays an important role in maintaining physical, chemical and biological properties of soil, and therefore crop productivity and the yield (Micheni et al., 2004). Crop residues are one of the sources of soil organic matter. During its life cycle, crops absorb nutrients from the soil. When the crops died or harvested, their residues should be returned to

the soil as organic matter. It is needed to replenish soil nutrients that were used up by the crops during their development stages. Therefore incorporating crop residues into the soil is an important factor to maintain soil fertility and for obtaining higher harvest as well. There are also many other management practices that affect soil fertility influencing directly or indirectly soil physical, biological and chemical properties, such as tillage operations, irrigation and drainage practices, cropping systems, and type of cultivated crops. Management practices that reduce harmful effects to soil properties and enhance proper soil functions by preserving soil organic matter can help improve soil productivity resulting higher crop yields. Gallup and Sachs (2000) studied the constraints of the development of agriculture and technology in the tropic regions. They revealed that agricultural yields for all major crop categories are lower in the tropics due to soils, rainfall variability, limited irrigation potential, pest and disease loads and the rate of photosynthesis. Typical humid tropical arable soils are low in nutrients due to the faster rate of organic matter breakdown and susceptible to erosion and acidification. Although humid tropical forests are biologically productive (Huston, 1994), when the land is cleared for agricultural purposes it quickly loses the productivity. The next factor that affects crop yields in tropical agriculture is the level of technology. Tropical agriculture faces major limitations on transferring agricultural technology and development of high yielding crop varieties (Gallup and Sachs, 2000). Gallup and Sachs (2000) also pointed out that tropical and dry climatic zones are lacking almost any measure of agricultural research. To promote the crop production, improvement of soil quality is important. To improve soil quality, agricultural technology development and dissemination of these technologies to farm level should also carry out as a priority.

## **1.2 Biochar as a Measure to Modify Soil Quality**

Biochar is a pyrolysed biomass produced under limited oxygen or oxygen absent conditions. The specific intention of biochar application to soil is to improve its agronomic and biochemical quality (Asai et al., 2009; Atkinson et al., 2010; Brown, 2009; Chan et al., 2007, 2008; Glaser et al., 2002; Laird et al., 2010; Liu et al., 2012; Major et al., 2010; Singh et al., 2010; Steiner et al., 2007; Schulz and Glaser, 2012; Sun and Lu, 2014), and to enhance carbon sequestration (Lehmann et al., 2006). The use of biochar can be an effective tool for sustainable agriculture in the long term, increasing soil carbon sequestration (C abatement strategy), fertility and productivity (soil quality) and reducing greenhouse gas emissions (Jeffery et al., 2014). It can increase soil aeration (Laird, 2008) and reduce soil emissions of N<sub>2</sub>O, a greenhouse gas (Spokas et al., 2009, Singh et al., 2010). In current years, biochar has

shown as one promising mean of reducing the atmospheric CO<sub>2</sub> concentration because biochar slows the rate at which photosynthetically fixed carbon (C) is returned to atmosphere (Lehmann, 2007; Sohi et al., 2010; and Krishnakumar et al., 2014).

Biochar amendment to soils replenishes most of the nutrients, which are removed by the cultivated crops, through its nutrient and moisture retaining properties. Because of its high surface area and high surface charge density (Liang et al., 2006), biochar increases the ability of soils to retain nutrients and moisture and reduces the leaching of nutrients and agricultural chemicals (Laird et al., 2010; Rogovska et al., 2010; Krishnakumar et al., 2014). Biochar moisture holding capacity and its capacity to promote soil microbial activities can also help the replenishment of depleted soil organic matter and reduce the moisture losses problems of semi-arid areas (Saito and Muramoto, 2002; Warnock et al., 2007; and Thies and Rillig, 2009). Resource poor farmers can reclaim their degraded lands by using an affordable soil amendment and increase agricultural productivity (Woolf et al., 2010). Improvement of rural livelihoods can be enhanced by increasing the quality and variety of cultivated crops, as well (Lehmann et al., 2006).

Biochar production cannot be properly discussed without first distinguishing it from char and charcoal. Char is defined as any carbonaceous residue obtained from pyrolysis, including natural fires. Charcoal is char produced from pyrolysis of animal or vegetable matter in kilns for use in cooking or heating. Biochars produced from crop residues are more stable than crop residues itself because a part of carbon from biomass changed to more stable forms of carbon in biochar particles after combustion under oxygen-restricted condition (Åslund, 2012).

When biochar is used as a soil amendment, impact of biochar is first on soil quality increasing its fertilizer use efficiency, and in consequence, increases crop yields. The impact of biochars on soil properties and nutrient supply for the crops depends upon the nature of feedstock and the operating conditions of pyrolysis (Chan and Xu, 2009).

Novak et al. (2012) tested the hypothesis that biochar addition to soils can improve soil-water storage capability by conducting pot experiments using nine biochars from five feedstocks at two temperatures in an Ultisol and two Andisol soils. They found that biochar amendments enhanced the moisture storage capacity. The effects varied with feedstock selection and pyrolysis temperature. Yu et al. (2013) tested the impact of woody biochar amendment on water holding capacity of a loamy sand soil. They found that by using 9% mixture of biochar with soil (equivalent to 195 Mg biochar per hectare) doubled water-holding capacity. They assumed that use of biochar has the potential to mitigate drought and increase crop yields in loamy sand soil.

Biochar also directly adds some macronutrients (P, K, Na, Ca, and Mg) and micronutrients (Cu, Zn, Fe, and Mn) which are needed for sustainable agriculture to the soil (Glaser et al., 2002). Biochar application enhanced the amount of total C, organic C, total N, available P, and exchangeable cations like Ca, Mg, Na and K, and reduction of Al in soil (Chan et al., 2007, 2008; Major et al., 2010; Van Zwiiten et al., 2010). Major et al. (2010) reported that nutrient uptake by plants increased in biochar amended soil, with increased plant yield and greater availability of Ca and Mg in soil (Krishnakumar et al., 2014). Immediate beneficial effects of biochar additions on nutrient availability are largely due to higher potassium, phosphorus, and zinc availability, and to a lesser extent, calcium and copper (Lehmann et al., 2003). Zhang et al. (2012) studied the effect of wheat straw biochar on paddy rice yield. They found that rice productivity, soil pH, soil organic carbon and, total nitrogen increased and bulk density decreased consistently in two consecutive rice growing cycles after biochar was amended to the soil having moderate soil fertility.

Alling et al. (2014) investigated the effect of biochar amendments on the retention and availability of plant nutrients and aluminum in seven acidic tropical soils of Zambia and Indonesia. Biochar was produced by using earth-mound kiln from feedstocks obtained from different species of leguminous trees. The results showed that biochar has the ability to release essential plant growth nutrients as well as alleviate Al toxicity in the tested soils.

Biochar application improved soil biological properties by providing space for soil biota and enhancing their activities. Incorporation of biochar into soils led to initial degradation of biochar by chemical oxidation and microbial processes (Bruun et al., 2008; Nguyen et al., 2008; Smith et al., 2010). Pore geometry and size distribution definitely promote the growth and activity of certain microorganisms (Lehmann et al., 2006).

Crop yields increased due to biochar application through various mechanisms including stimulation of beneficial soil microbes such as mycorrhizal fungi (Warnock et al., 2007). Increased availability of major plant nutrients after biochar application occurred due to the presence of small amount of nutrients in biochar that would be available to soil biota (Yamato et al., 2006). Biochar enhance mycorrhizal infection, as it is able to serve as a habitat for extra radical hyphae that sporulated in its micropores due to lower competition from saprophytes (Saito, 2002). Steinbiss et al. (2009) studied the effect of biochars on soil carbon balance and they found that certain biochar types influenced the microbial community. Interactions of biochar with soil microorganisms were complex. On the one hand, soil microbial diversity and population size, as well as population composition and activity, might be affected by the amount and type of biochar present or added to soil. On the other hand, microorganisms were

able to change the amount and properties of biochar in soil. Both effects could have significant influences on nutrient cycles and nutrient availability to plants.

Already 7.9 Mg C ha<sup>-1</sup> of biochar in a highly weathered soil in the tropics significantly enhanced microbial growth rates when nutrients were supplied by fertilizer (Steiner et al., 2004). This biochar rate can be assumed a small amount compared to Rousk et al. (2013). They observed the effect of biochar addition to soil on microbial growth in two case studies in the laboratory. In the first case study, 0, 25 and 50 Mg ha<sup>-1</sup> of biochar were added to UK pasture soils and in the second case study, 4 Mg ha<sup>-1</sup> of biochar were applied to Mediterranean Australian agricultural soil. Soils for the observations were collected from the field experiments conducted in UK and Australia. They found a slight increase in fungal-to-bacterial ratio as the immediate effect of biochar application in the Australian soil. In UK soils, fresh biochar addition doubled the fungal-to-bacterial ratio in 25 Mg ha<sup>-1</sup> biochar application and nearly tripled in 50 Mg ha<sup>-1</sup> biochar application, respectively. Root infection by *Arbuscular mycorrhizae* significantly increased by adding 1 kg m<sup>-2</sup> rate of biochar to the alfalfa crop sown in a volcanic ash soil. The effect of increased microbial growth was directly relating to 40 to 80% higher growth of alfalfa after biochar application compared to the growth before biochar application (Nishio and Okano, 1991; Nishio, 1996). Similarly, mycorrhizal infection increased when biochar (7 g kg<sup>-1</sup> soil) was added to the soil that was inoculated with spores of *Glomus etunicatum*, improving the yields of onion (Matsubara et al., 1995). A more rapid cycling of nutrients in soil organic matter and microbial biomass as well as better colonisation of roots by arbuscular mycorrhizal fungi will improve the nutrient availability and crop yields. That occurs because of (1) nutrient retention against the leaching in highly weathered soils of the humid tropics that have little cation exchange capacity, and (2) a better access of the plants to fixed phosphorus due to inoculation by mycorrhizae (Mori and Marjenah, 1994).

According to Wiedner and Glaser (2013), charcoal addition to soil increased the resistance of plants against pathogens and biochar has the potential to reduce the outbreak of fungal plant diseases. Charcoal can cure potato disease (Allen, 1846). Soil-borne phytopathogenic diseases decreased after charcoal addition to soil (Retan, 1915). Disease resistance of asparagus plants inoculated with mycorrhizal fungi increased after biochar addition to soil (Matsubara et al., 2002; Elmer and Pignatello, 2011). Biochar addition to sandy soils can significantly reduce the powdery mildew (*Leveillula taurica*) infestation (Elad et al., 2010). According to these research findings, biochar has the potentials to reduce fungal infestation to cultivated crops in addition to the multiplication of soil microorganisms.



### **1.3 Effects of Biochars on Crop Yields**

Olmo et al. (2014) studied the effect of slow pyrolysis biochar (450°C pyrolysis temperature) produced from olive tree pruning on wheat yield. The experiment was conducted on a clay soil with a pH of 8.2 and biochar application rate was 40 Mg ha<sup>-1</sup>. They found that the use of biochar as soil amendment in agricultural soils can improve crop yield related soil properties by increasing significantly electrical conductivity, organic carbon, total N, available P, K, Mg, Cu and Zn and the significant increase in above ground biomass of wheat crops.

Martinsen et al. (2014) studied the effect of biochar made from maize cobs in combination with conservation farming on maize (*Zea mays*) and groundnut yields (*Arachis hypogaea*) in three different regions of Zambia. They found that there was a consistent positive response of crop yields in all three sites. It was suggested that addition of biochar in combination with conservation farming might have a positive impact on crop growth and that positive effect might mainly be due to increases in plant-available water and decreased available aluminum.

Jia et al. (2012) tested the effect of maize straw biochar on the growth of vegetables: *Brassica rapa* L. ssp. *chinensis* and *Amaranthus mangostanus* L., in China. They found that 30 Mg ha<sup>-1</sup> rate of biochar application together with chemical fertilizers and manure was the most effective combination compared to control, chemical fertilizer sole application and chemical fertilizer and manure combination. Higher nutrient availability for plants is the result of both the direct nutrient additions by biochar and greater nutrient retention (Lehmann et al., 2003; Lehmann et al., 2006). Paddy rice yield was increased by 9-12 % in the first rice crop cycle and 9-28% in the second rice crop cycle compared to control and chemical fertilizer application by applying 10 Mg ha<sup>-1</sup> and 40 Mg ha<sup>-1</sup> rates of biochar (Zhang A. et al., 2012). However, increased amount of rice yields were not depending on biochar application rates.

### **1.4 Soil Quality and Yield Variability in the Central Dry Zone of Myanmar**

#### **1.4.1 Location, climate and distribution of soils in the Central Dry Zone**

Myanmar is located in Southeast Asia. Although it is known as a country of wet tropics, some of its regions are characterized by a dry climate with low rainfall. Central area of Myanmar is included in the world's semi-arid tropical regions (Fig.1.1). Because of the country's different topographic situations, climatic conditions also differ from one region to another inside the country. Center of the country is flatter and drier than the other parts (Fig. 1.2). Dry Zone of Myanmar is located in that area surrounded by Shan, Rakhine, Chin Plateau and Chin mountain ranges (Matsuda, 2013). Central Dry Zone covers about 13% of the country's total

area including large parts of Magway, Mandalay and lower Sagaing Divisions with a population of roughly 14.5 million (Poe, 2011).

There are three seasons in Myanmar: summer, winter and the rainy season. Each season lasts for four months. In the Dry Zone, rainy season lasts from mid-May to October and receives 500 – 1000 mm rainfall per year. Monthly rainfall pattern of the study area is bimodal as there are two maximum rainfall events per year (Fig. 1.3). Winter season is from October to mid-February and a dry hot season from mid-February to mid-May. Average monthly temperature is 30°C in summer, 29°C in rainy season, and 20°C in winter (Hadden 2008).

There are three main soil groups recognized as agriculturally important in Myanmar: alluvial, black and red laterite soils. The alluvial soil makes up 50% of the total areas sown and is located in river basins and deltas. Black soils that are occurred in about 30% of the area are generally distributed in the Dry Zone. Red laterite soil accounts for 20% of the area and is found in lower Myanmar. According to soil classification of Land Use Division, Myanmar Agriculture Service, based on FAO soil classification system (FAO, 1998), 24 soil types are found in Myanmar whereat soil types distributed in the Central Dry Zone can be classified as follows:

**Luvisol:** The soils are sandy and usually well drained. Soil pH ranges from 7.0 to 8.0 and it contains a certain amount of lime and is rich in calcium and magnesium. The soils are low in other nutrients except potassium. These soils are the most important land resources of the Dry Zone.

**Vertisols:** This type of soil is located in the lowland areas near the rivers of the Sagaing, Mandalay and Magway Divisions. These soils represent the second most important soil type in the Dry Zone after Luvisols. They have high clay content and pH ranges from 7.0 to 9.0 and they are calcareous. The soils contain a considerable amount of calcium, magnesium and potassium, but are deficient in nitrogen and phosphorus. These soils can be used for rice cultivation by irrigation and upland crop cultivation under rain-fed conditions.

**Nitisol:** These soils are distributed in the planes closed to Shan plateau. They are sandy and fertile receiving the nutrients from the surface run-off of nearby mountains. Upland crops like vegetables and pulses are mainly sown on those soils.

**Iritic Cambisol:** These soils are found in low upland plains of the Dry Zone area. Since the lands are dry and sandy, they are used for upland crop cultivation and for forestry.

**Calcaric Gleysol:** These soils have neutral and alkaline reaction. Although they are deficient in plant nutrients, they can be used for pulses and vegetables.

Tin Aung Shein, U. (2008), soil scientist, recorded soil properties of some townships in the Mandalay division. He studied soil properties of a top soil (0-0.15 m) layer and found that the soil has a pH of 8.3 to 10.13, the amount of sand lies between 39.2% - 47.29%, of silt between 11.48% - 27.32%, and of clay between 20.00% - 47.44%. Organic matter ranges from 0.35% - 2.12%. N ranges between 0.105% - 0.192%, Ca between 4.08-13.12 mg/100g, Mg between 0.61-2.08 mg/100g, Na between 1.63-14.19 mg/100g, P<sub>2</sub>O<sub>5</sub> between 8.10-23.98 mg/100g and, K between 12.24-29.5 mg/100g, respectively. It was assumed that the reasons for the lower crop yields were soil texture and high pH hindering the availability of phosphate and potassium for the crops. In some areas, high soil salinity causes yield reductions under drought conditions.

Based on the above-mentioned soil properties, soils in the Dry Zone of Myanmar are neither completely degraded nor infertile. Farmers can maintain profitable crop yields from farming if necessary land management and nutritional practices are applied.

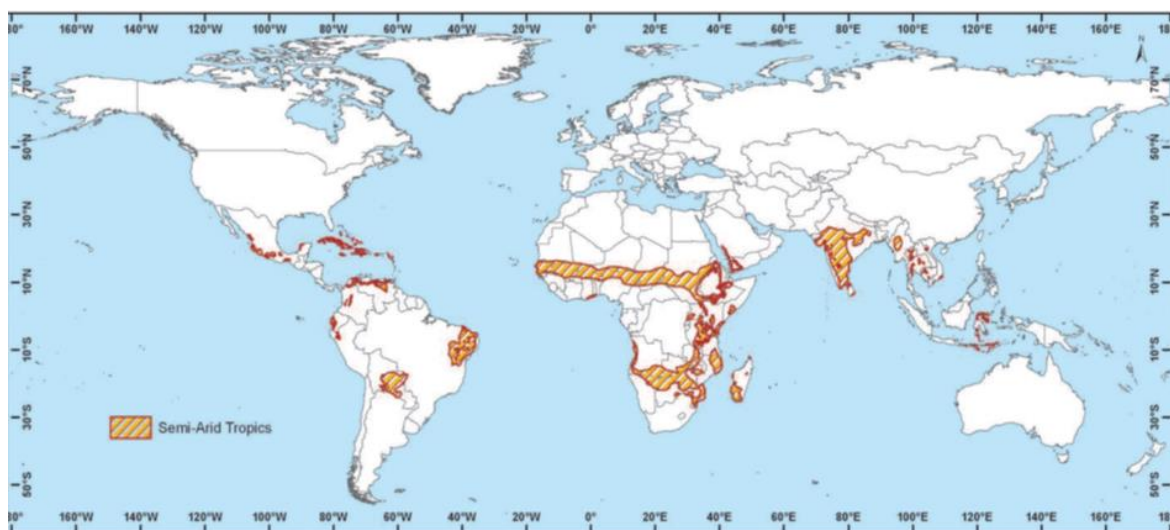


Figure 1.1: Distribution of semi-arid tropical regions in the world

<http://www.fao.org/sd/EIdirect/climate/EIsp0002.htm>, retrieved on 22.8.24.

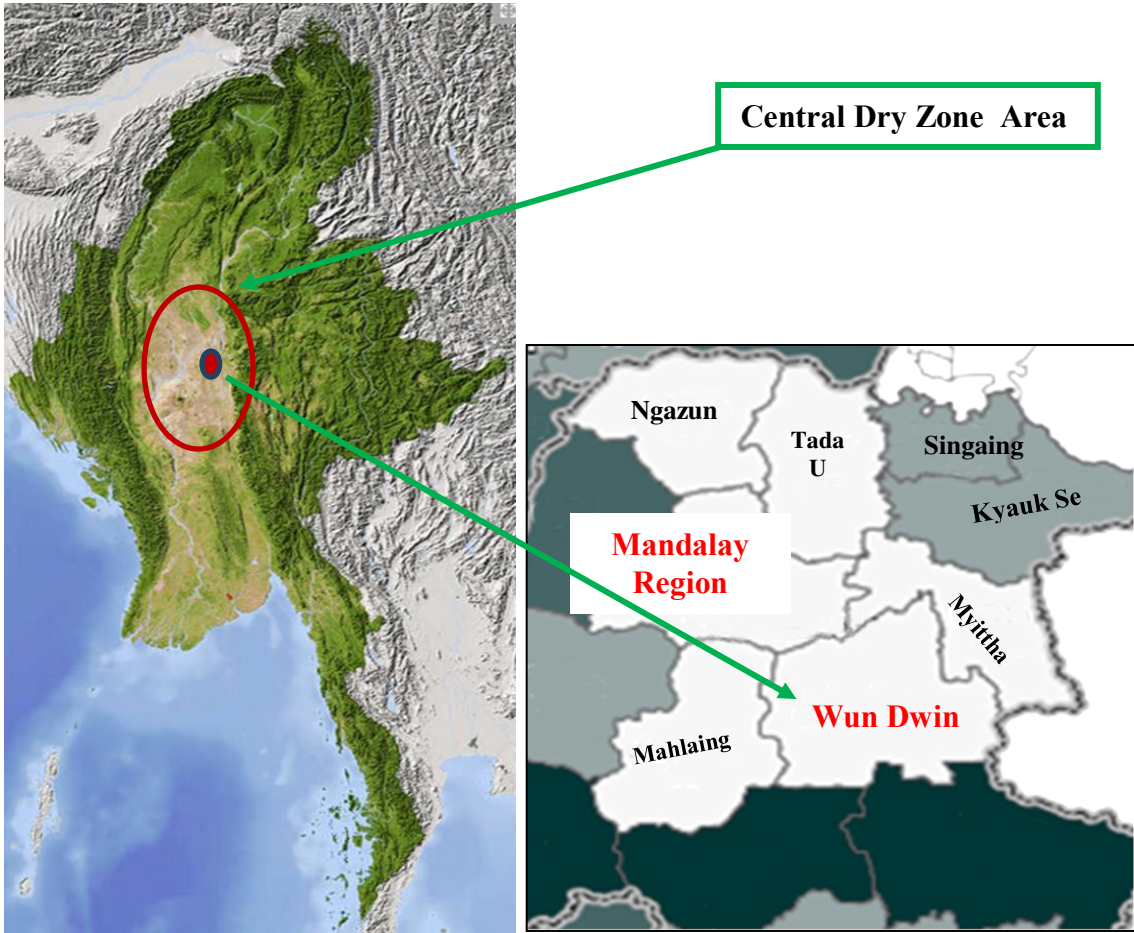


Figure 1.2: Map of Myanmar showing the location of Wun Dwin Township and the Central Dry Zone of Myanmar.

Source: <http://seasiadivensail.com/wpcontent/uploads/2013/08/myanmar-map.jpg>;  
[http://themimu.info/states\\_regions/mandalay](http://themimu.info/states_regions/mandalay)

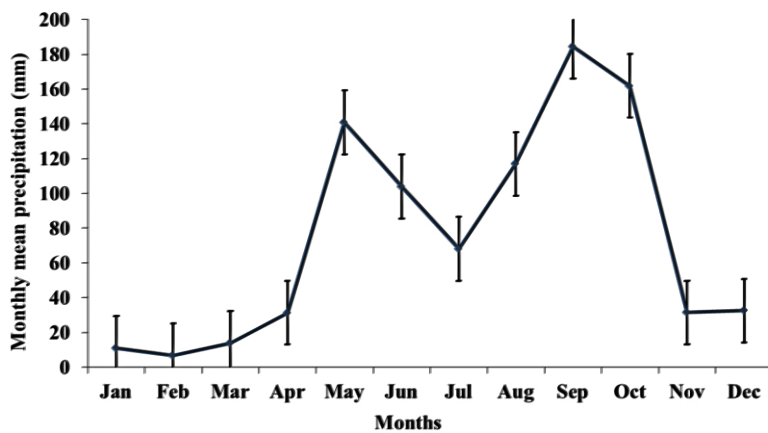


Figure 1.3: Monthly rainfall pattern of the study area (average monthly precipitation over 30 years at Shwe Daung farm from 1984 to 2013)

### 1.4.2 Typical cropping systems of Central Dry Zone

Johnston et al. (undated) defined Agroecosystem of the dry zone as follows:

- A: intensively farmed croplands with access to irrigation in all seasons
- B: croplands with access to supplementary irrigation (includes lowland and lands that grow pulses and vegetables)
- C: rainfed areas – mixed cropping and grazing
  - C-1 – rainfed lowland cropping
  - C-2 – rainfed uplands (mixed grazing and cropping)

In rainfed areas, farmers grow one to two crops per year. Winter crops such as pulses and pasture, usually follow rainy season crops such as pigeon pea, groundnut, sesame, or some farmers grow one crop per year such as traditional pigeon pea or traditional short staple cotton or intercropping these two crops on one plot of land. Pigeon pea and traditional short staple cotton are sown in rainy season (May-June) and harvest in February. Although high-yielding varieties of cotton and sesame, along with chemical fertilizers were introduced in the study area by the development agencies as well as the government agricultural extension service, their cultivation was not expanded as expected. Even though farmers preferred the high yields of cotton and sesame, they were reluctant to convert their existing systems into one dependent upon a single particular crop (Matsuda, 2013). Productivity of those farms is lower and their income is lower, compared to the farmers with access to irrigation water.

In irrigated areas, farmers grow three crops per year like pre-monsoon rice-monsoon rice-chickpea, or other pulses or sesame or groundnut. Sesame is sown in two different seasons, during summer season with irrigation water and during rainy season with rainwater. When sesame is sown as summer crop, rainy season rice follows sesame. Rice is sown in monsoon season with rainwater. After harvesting rice, chickpea or other pulses are sown as winter season crops (Izumi et al., 2010).

Most cultivated winter crops in Dry Zone are wheat, chickpea, and different kinds of peas and beans. Pulses are important cash crops for the country and provide a large share of income (Asian development Bank, 2013). After separating seeds from pods, dry shells and some leaves of pulses are kept for feeding cattle. Therefore, pulses play an important role in Dry Zone agriculture not only as cash crop but also as household food and animal fodder.

Cotton is an important crop for farmers especially in Central Dry Zone because of irregular rainfall. Cotton is resistant to drought due to its indeterminate growth type and can create cash and job for farm households (Myanmar cotton and sericulture enterprise, 2006). Households

use textile made of cotton for the family. If there is extra product after family's sufficiency, cotton was sold to local market either as seed cotton or as finished goods (cotton clothes such as towel and rugs). Median staple cotton (*Gossypium hirsutum*) is an introduced variety to Myanmar from India, Thailand and China (Matsuda, 2013). Farmers grow this variety either as sole crop or as intercropping with pigeon pea.

#### **1.4.3 Soil quality related yield variability in Central Dry Zone of Myanmar**

Inadequate plant nutrition combined with continual mining of soil nutrients and unscientific use of fertilizers is limiting the productivity in many Asia-Pacific developing countries (FAO, 2011).

According to its nature, the Dry Zone has low fertility and fragile structures to water and wind erosion. The region is characterized by low rainfall. Naturally low fertile soils led to severe environmental degradation. With declining inputs, both in terms of organic and inorganic materials, agricultural productivity is decreasing annually (Johnston, et al., undated).

As an example of fertilizer use in Dry Zone, in Nay Pyi Taw, Mandalay Division, farmers' fertilizer use varies in accordance with individual farm size (Hnin Yu Lwin, 2013). Farmers who manage the farm size less than 2 ha apply on average 119, 13.5, 9.2 and 71.3 kg ha<sup>-1</sup> rate of Urea, triple super phosphate (T-super), potash (muriate of potash) and compound fertilizer respectively (55:3:5 NPK kg ha<sup>-1</sup>). Farmers with farm size 2-4 ha apply on average 120, 16.4, 12.3 and 65.1 kg ha<sup>-1</sup> rate of Urea, T-super, potash and compound fertilizer respectively (55:3:6 NPK kg ha<sup>-1</sup>). Farmers with 4-6 ha farm size apply 154.3, 12.8, 15.9 and 70.3 kg ha<sup>-1</sup> rate of urea, T-super, muriate of potash and compound fertilizer respectively (71:3:8 NPK kg ha<sup>-1</sup>). The LIFT Fund (Livelihood and Food Security Trust Fund) baseline survey reported that, 63% of rice farmers in the delta/coastal zone and 76% of farmers in the Dry Zone used to apply inorganic fertilizers to the monsoon season crops.

In some areas, households use cow dung, as fuel (Ministry of Forestry, Myanmar, 2005). During land preparation, some farmers add farmyard manure to the fields as organic fertilizer. Some poor farmers do not apply farmyard manure because they sell out the manures for extra income. Therefore, for economic reasons, farmers do not fully utilize farmyard manure.

Some farmers who can afford for hiring or buying the tractors practice mechanized farming. Most farmers cultivate their lands with bullocks. Farmers practice tillage operation and inter-cultivation to protect weed infestation, to kill insect pests before growing the crops, and to control the weeds during the cropping season. Farmers believe that by turning soils, high soil

temperature can be reduced and enhance crop growth especially after irrigation or rainfall. Practicing reduced- or no-tillage is still inconvenient for Myanmar farmers.

Most upland fields with sandy soil types, organic matter content is low because of stubble removal and limited supply of organic materials. After harvesting the first crops, all stubbles and weeds are removed from the fields. The fields are harrowed and left fallow while waiting for the rain to grow the next crop for one or two months. Sometimes that period takes more than two months in rain-fed areas because of irregular rainfall events. In irrigated areas, farmers grow pulses after rice. When they harvest the pulses, lower part of the stems and roots remained in the fields. During the time of land preparation for the next crop, those remaining roots and stems are incorporated into the soils. The lands, which originally have higher clay content, maintain sustainable crop production by receiving chemical fertilizer applications.

Inefficient irrigation and fertilizer application methods also contribute to the causes of the degradation of cultivated lands in Dry Zone. It has universally accepted that improper agricultural activities and changing land use practices have led to the depletion of SOC in most agricultural soils with the consequent loss of soil quality (Weil and Magdoff, 2004). In some rice growing areas, rice cultivations affect soil properties such as salinity problem in ground-water irrigated areas, acidity problems in delta areas and degradation of soil structure in both areas due to puddling. Furrow irrigation is practiced in row crop cultivation such as cotton, chilli and onion. In practicing furrow irrigation, farmers cannot control both irrigated and drainage water systematically due to technical and financial deficiencies. Crops growing in structurally degraded soils are often constrained by waterlogging and poor aeration when the soil is wet. Occurrence of soil crusts on the surface soil affects the germination of cultivated crops and seedlings survival.

Convention to Combat Desertification (CCD) defined soil degradation as physical degradation- mainly driven by climate factors such as floods and droughts that cause soil erosion (by wind and water), chemical degradation- generally in the form of salinization (in irrigated lands), and biological degradation- mainly because of the oxidation of topsoil organic matter in dry lands (FAO, 2004). Soils of the Dry Zone of Myanmar are starting to face with all of those degradations. Concerning with the factors affecting the sustainability of agricultural production in the Dry Zone, given climate situation and soil types cannot be changed. Soil fertility in dry land environment can be improved by-

1) adding nutrients to the soil, a) fallowing, b) stubble grazing, c) inorganic fertilizers, d) crop rotation and association,

- 2) Reducing losses of nutrients from the soil, a) woody vegetation, b) erosion control, c) field clearing and weeding,
- 3) Recycling nutrients such as manure, crop residue management, management of organic matter
- 4) Maximizing the efficiency of nutrient uptake, a) reduced land tillage, b) precision agriculture, c) fire management (FAO 2004).

Combined effects of above mentioned soil fertility managements can be obtained by applying biochar as soil amendment. For long-term carbon sequestration (CS), carbon needs to be delivered to large pools with slow turnover (FAO 2004). As biochar contains a predominant stable fraction of carbon, soil carbon can be increased by enhancing long term CS in dry land soils.

## **1.5 Biochar as a Measure to Reduce Soil Quality Degradation that Affects the Yield of Crops**

### **1.5.1 Availability of biochar substrates and technology in the Central Dry Zone of Myanmar**

Variety of biomass such as wood wastes, crop residues, switch grass, wastewater sludge can be used to produce biochar (Méndez et al., 2012; Paz-Ferreiro et al., 2014; Sohi et al., 2010; Cely et al., 2014). Biochar can be produced- (1) in fields by burning crop residues in the ditches or digging holes near the fields, (2) in the kitchen by using biochar stoves and (3) by commercially producing biochar by constructing biochar production plants. Biochar is produced by thermochemical conversion of organic materials in an oxygen-depleted atmosphere (pyrolysis) which has physiochemical properties suitable for safe and long-term storage of carbon in the environment and potentially soil improvement. During pyrolysis, since oxygen is controlled, the amount of smoke from biomass burning can be reduced (Brownsort, 2010). Biomass from the fields can be cleared after harvesting the crops by converting that biomass to biochar instead of field burning. By that way, greenhouse gas emission through residue burning can be avoided.

Production of biochar from rice husks is a procedure recommended by the Food and Fertilizer Technology Center for the Asian and Pacific Region (FFTC, 2001). Such conversions of crop residues can be done by using locally available techniques, such as using residue mounds and firing (FFTC, 2001), simple firing chambers, or more sophisticated furnaces. Although the system is easily accessible by most of smallholder farmers of developing countries, it cannot completely control the smoke formation. Smoke emitted from charcoal kiln contains carbon



dioxide (CO<sub>2</sub>), water (H<sub>2</sub>O), carbon monoxide (CO), methane (CH<sub>4</sub>), volatile organic compounds (VOCs) and particulate matter (PM), which contributes to air pollution. Advanced biochar producing technologies such as drum pyrolysers, rotary kilns, the screw pyrolysers, the flash carboniser, fast pyrolysis reactors, and wood-gas stoves can reduce pollution; improve energy efficiency and biochar yield. They also have feedstock flexibility allowing both woody and herbaceous biomass (Brown, 2009).

Households in many parts of the world are still using charcoal as an important source of energy for food preparation (World Energy Council, 2001). An estimated 41 million tons (Mt) of charcoal were produced worldwide in 2002 (FAO 2004). Much more charcoal is produced in developing countries (40 Mt in 2002) than in developed countries (1.4 Mt). Africa is the highest producer (21 Mt), followed by South America (14 Mt) and Asia (4 Mt) (Lehmann et al., 2009). Feedstocks can be divided crudely into three categories, wastes (e.g. municipal solid waste), residues (e.g. straws) and on purpose grown feedstocks (e.g. energy crops). Residues from agricultural crops or biomass obtained from the pruning of plants from the forest produce "clean" biochar, and do not entail land use change (Brownsort, 2010).

In the Central Dry Zone area of Myanmar, charcoal production is a livelihood for rural landless peoples. Because of limited electricity supply, charcoal stoves are still in use for cooking and the demand for charcoal is still high. The same products like woodchip biochars can be obtained from by-products of charcoal production. These by-products can easily be obtained with cheap prices from charcoal making mounds and from the local sellers.

Although rice straw is used as fodder in Myanmar, there are some extra straws and stems, which are being burnt in the fields. During the period 2000-2004, rice production in Myanmar was 22.58 million tons per year, 3.8% of global share (FAO 2009). Paddy, on milling, gives approximately 20% husk, 50% whole rice, 16% broken rice and 14% bran and meal (Purseglove, 1985). Since 20% of rice husk can be obtained from rice production, according to 2004 production, 4.51 million Mg of rice husks can be obtained.

Other biomass available in Myanmar to produce biochar are pigeon pea stem, cotton plant stems, sesame stems, and stem from pulses, and wood residues from lumber processing (e.g., sawdust). As households use pigeon pea stems as fuel wood, pigeon pea stem charcoals collected from the kitchens can be applied to the fields. Other residues of agricultural products such as stems and leaves of sesame and pulses can also be pyrolysed to use as residue biochar. After taking the seeds and grains of sesame and pulses, their stems are disposed outside the villages instead of making compost or adding to the fields. Those wastes can be used to produce biochar as these are agricultural products and they are very clean to be used as soil

amendments. Since black ash obtained from rice husk has been already in application in preparing rice nursery beds and in horticultural crop plantations, and abundance of raw materials, adoption of rice husk biochar by Myanmar farmers has a high potential. Contrastingly, farmers' adoption to use biochar produced from other crop residues would require time as this practice is new for them.

### **1.5.2 Environmental effects of biochar production**

By applying biochar technology, environmental pollution through field burning of agro wastes can be reduced. In agricultural burning, CO<sub>2</sub> released is not considered net emission. The biomass burned is generally replaced by regrowth over the subsequent year. An equivalent amount of carbon is removed from the atmosphere during this regrowth to offset total carbon released from combustion. Therefore, long-term net emissions of CO<sub>2</sub> are considered zero. Agricultural burning releases other gases in addition to CO<sub>2</sub>, which are by-products of incomplete combustion, viz., methane, carbon monoxide, nitrous oxide, and oxides of nitrogen. These non-CO<sub>2</sub> trace gas emissions from biomass burning are net transfers from the biosphere to the atmosphere (IPCC, 2006).

Open-field burning of crop residues is recognised as a major contributor to reduce air quality and human respiratory ailments, particularly in China and northwestern India, which represents major irrigated rice ecosystems in Asia (Singh et al., 2008). Emission factors (gram species per kilogram dry matter) from residue burning are 1,515 kg CO<sub>2</sub>, 92 kg CO, 3.83 kg NO<sub>2</sub>, 0.4 kg SO<sub>2</sub>, 2.4 kg CH<sub>4</sub>, and 15.7 kg non-methane volatile organic compounds (Andreae and Merlet, 2001). According to the report of the Ministry of Environmental Conservation and Forestry, Union of Myanmar, in the year 2000, total CO<sub>2</sub>-equivalent greenhouse gas emission from field burning of agricultural residues accounts for 1.61 Gg.

There is also an option for the use of residues to add as raw stubbles directly into the field instead of using as biochar. Mousavi et al. (2012) found that addition of rice straw increased soil moisture content, decreased bulk density, and delayed crack formation in clay loam and sandy loam soils. Liu et al. (2014) found that straw return induced improvement of soil nutrient availability and that might favour crop growth, which can in turn increase ecosystem C input. Maintenance of a threshold level of organic matter in the soil is crucial for maintaining physical, chemical and biological integrity of the soil and for the soil to perform its agricultural production and environmental functions (Izaurrealde et al., 2001; Srinivasarao et al., 2012, 2013). Hence, conversion of organic wastes to biochar through the pyrolysis

process is one viable option that enhances natural rates of carbon sequestration in the soil, reduce farm wastes and improve soil quality (Srinivasarao et al., 2012, 2013).

Shen et al. (2013) conducted a field study and evaluated the effects of straw-based biochar and rice straw on greenhouse gas emissions from paddy fields in China. Straw-based biochar was applied in two different rates: low rate, 7.5 Mg ha<sup>-1</sup> as dry matter and high rate 22.5 Mg ha<sup>-1</sup> as dry matter, respectively. Rice straw application rates were low rate, 3 Mg ha<sup>-1</sup> as dry matter and high rate, 6 Mg ha<sup>-1</sup> as dry matter, respectively. Greenhouse gas fluxes were measured in field by closed chamber method. The results showed that CH<sub>4</sub> emissions from the fields of straw incorporation treatments were 2.6-6.4 times higher than that of biochar treatments and the global warming potentials and yield scaled global warming potentials were lower in straw incorporation treatments. They assumed that conversion of straw to straw-based biochar can be an effective mean of carbon sequestration in rice production and can even increase grain yields to some degree. Furthermore, impact of paddy cultivation to climate change through methane emissions, extensive and intensive use of water, contributing to alkalinity of soils in semi-arid areas, usage of heavy fertilizers, etc. can be reduced by biochar application.

### **1.5.3 Potential effects of biochar application on soil quality and crop yields in the Central Dry Zone of Myanmar**

In Myanmar, biochar application and understanding of the benefit of biochar to crop yields and soil properties has not yet known. Research to study the biochar type that is suitable for respective conditions and the respective crops is still a need. In Dry Zone, among the causes of land degradation and crop yield reduction as mentioned above, natural climate condition and parent materials cannot be changed. Other factors affecting the sustainability of Dry Zone farming systems can be changed or improved through land management practices. Irrigated agriculture is available in recent years and farmers can overcome water scarcity problems through irrigation.

Although most biochars are suitable to apply to acid soils since they have the properties of increasing soil pH, there are also potentials of applying biochar under various agro-ecological conditions (Lehmann et al., 2006) and research findings showed that biochar could apply to high pH soils. Liu and Zhang (2012) studied the effect of biochar application to alkaline soils through an incubation experiment. They found decreases in soil pH occurred at 0.10- 0.20 m soil layer. Since soils of the Dry Zone area have mostly high pH values, it is important not to increase soil pH furthermore by using soil amendments.

Olmo et al. (2014) studied the effects of the addition of slow pyrolysis biochar (produced from olive-tree pruning) to a Vertisol soil in wheat field experiments. Their finding was that biochar addition did not significantly affect soil parameters such as pH, dissolved organic C and N, ammonium, nitrate or microbial biomass N. However, biochar addition decreased soil compaction and increased soil water-retention capacity and nutrient content (total N and the available contents of P, K, Mg, Cu and Zn). If woodchip biochar can reduce soil compaction in Vertisols, this method is suitable to apply to both ground water and surface water irrigated fields of Myanmar Dry Zone since Vertisols from irrigated areas have the problem of soil compaction and difficult seedling emergence of the dry season crops (Soil types and distribution, Myanmar, [www.apipm.org](http://www.apipm.org)).

High clay content of Vertisol soils results high potential for shrinking-swelling and stickiness. Since the soils have high swelling pressure, deep cracks appear when the soil is dry after wetting periods and have a sticky nature under wet conditions (Favre et al., 1997; Wilding and Puentes, 1988; Sun and Lu, 2014). Results from incubation experiment of Sun and Lu (2014) indicated that straw biochar, woodchip biochar and wastewater-sludge biochar had the potential to improve the physical quality and pore-space status of clayey Vertisols. They suggested that biochar might be considered as a soil amendment to improve poor physical characteristics of clayey soils.

When upland crops were sown on such soils as rotation after rice, such as cotton, green grams, black grams, etc., difficulties occur due to this swelling and shrinking behaviour of Vertisols, first for germination and later in the growing season for crop growth. Farmers can apply biochar and soil mixture or biochar and other organic manure mixture to mulch the seedbeds to loosen the surface soil during the time of seeding. These organic materials will also provide moisture and nutrients for the seedlings during its early growth stage. For cotton, the crop needed only to overcome the germination problem and so that, in later growth stages, the crop could survive well on these soils. Cotton has been known to perform well on Vertisols (black cotton soil) allegedly because it has a vertical root system that is not severely damaged by cracking of the soil (ISRIC.org).

#### **1.5.4 Research objectives**

Considering the current soil fertility degradation and yield reduction problems in irrigated cropping systems in the Central Dry Zone of Myanmar, the aim of the study is to test the biochar technology as a mean of managing soil quality by restoring soil organic carbon,

increasing crop yields, and proper disposal of agricultural wastes for better environmental quality.

Objectives of the research are:

- 1) To test the effects of biochar amendments, that are available in Myanmar, on soil properties and the yield of rice (*Oryza sativa*), chickpea (*Cicer arietinum*), and cotton (*Gossypium hirsutum*) crops by conducting field experiments; and
- 2) to estimate the impact of biochar applications on soil carbon storage and greenhouse gas emissions from both lowland rice fields and upland crop fields in irrigated areas of Myanmar Dry Zone by model simulation (DNDC model) (Version 9.5) (DNDC, 2012).

Hypotheses of the research are:

1. Crop yields will increase when inorganic fertilizers are applied together with biochars produced by low technology compared to conventional inorganic fertilizer application.
2. Biochar produced from crop residues have the ability to reduce soil bulk density, increase soil organic carbon, and soil water holding capacity, regulate pH of alkaline soils at a level that most crops can grow well.
3. Long-term effects of biochar applications on soil carbon sequestration, greenhouse gas emissions and crop yields can be estimated by using the process based biogeochemical models.

In conducting the research to observe the effects of biochar applications together with chemical fertilizers on a rice-based irrigated cropping system in Dry Zone area of Myanmar, the following research methods were applied:

1. Conducting a field experiment to test the impacts of biochar additions together with chemical fertilizers on rice plant growth and yield compared to inorganic NPK fertilizer application and non-fertilizer input treatments.
2. Conducting a field experiment to test the impacts of biochar additions together with chemical fertilizers on cotton plant growth and yield compared to inorganic NPK fertilizer application and non-fertilizer input treatments.
3. Observing the impacts of each treatment on soil physical and chemical properties through the laboratory testing of soil samples collected from each treated plot before and after the field experiments.
4. Applying denitrification decomposition model (DNDC) to observe the long-term impact of biochar applications on crop yields and soil organic carbon storage in the sandy loam soil of Dry Zone area.

## Chapter 2: Materials and Methods

### 2.1 Description of the Study Site

Study site is located in Wun Dwin Township, Mandalay Division, 21° 5' N and 96° 2' E. This area is one of the areas of the Central Dry Zone of Myanmar.

#### 2.1.1 Climate

The distribution of precipitation is very irregular, distinguishing humid season from May to September and a dry season from October to April. Mean annual rainfall (calculated based on 30 years) was 813 mm (Fig. 2.1).

In summer and rainy seasons, average maximum daytime temperature is 43.15°C and average temperature is 31°C. In winter (from October to February), average temperature is 21°C and average minimum temperature is 18°C (Fig. 2.2).

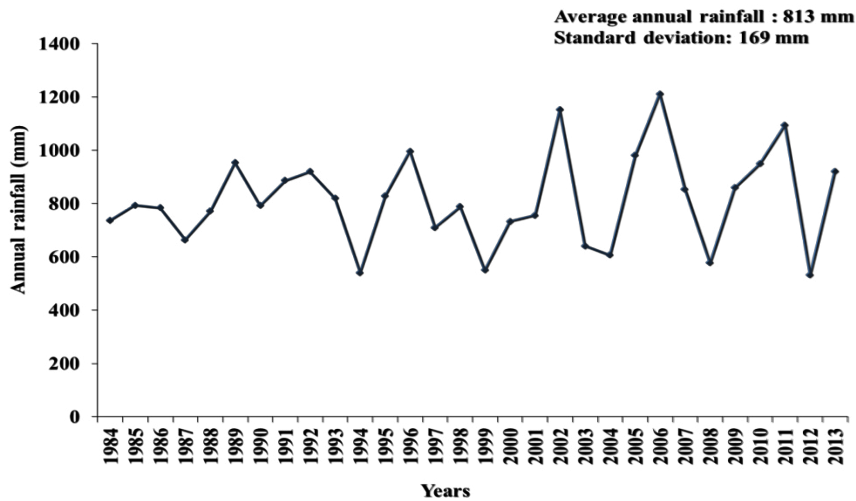


Figure 2.1: Average annual rainfall (1984-2013) of the experimental site, Shwe Daung farm, Central Dry Zone of Myanmar

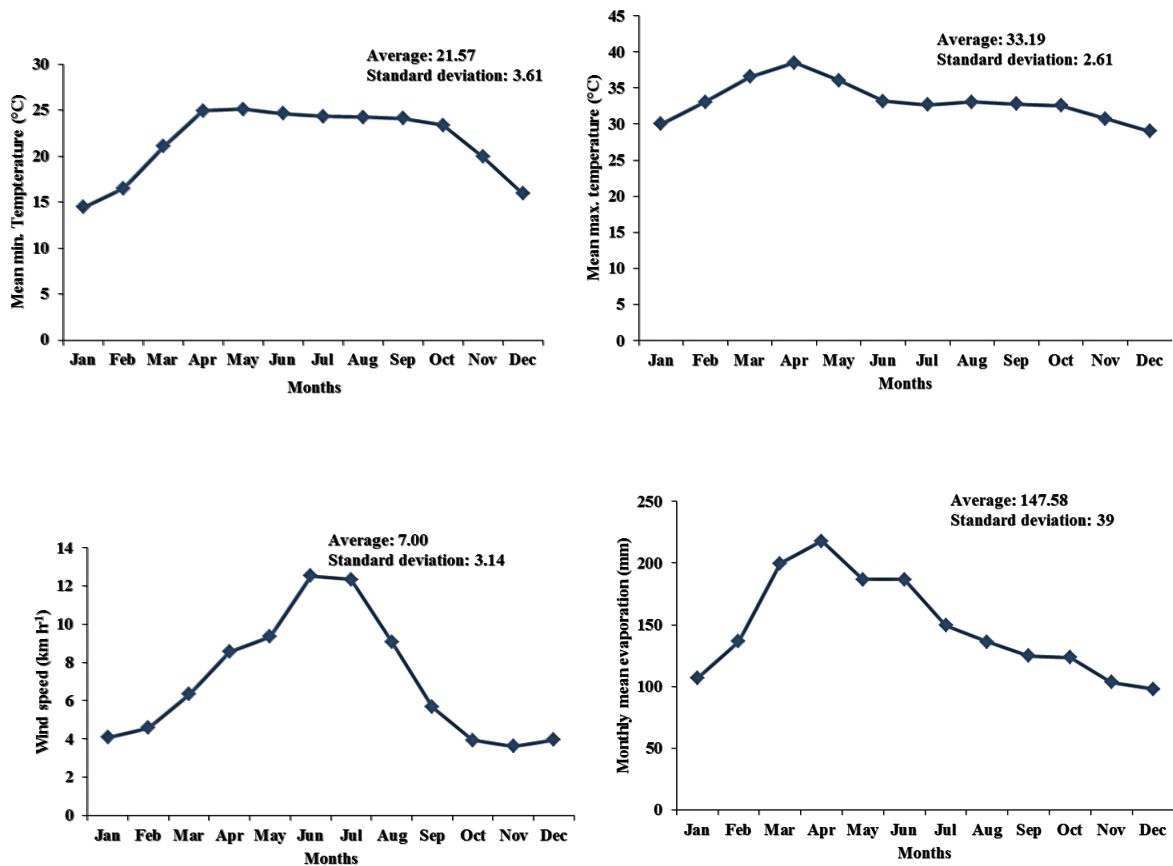


Figure 2.2: Monthly mean minimum temperature, monthly mean maximum temperature, average monthly wind speed, and monthly mean evaporation of Meikhtilar, Central Dry Zone of Myanmar. Values are averages of 30 years from 1984 to 2013.

### 2.1.2 Soil characteristics

According to the classification of Land Use Department, Myanma Agriculture Service, dominant soils in the study area are Alfisols, Luvisols and Vertisols and saline and alkaline soils are occurred in some places.

Soil of the experimental site was hard to differentiate as a specific soil type because of its physical features, mineral content and regional climate conditions. Although it receives mean annual rainfall between 500 mm and 800 mm (Fig. 2.1), the region has less effective rainfall because of having longer dry period. Effective rainfall in the tropics is always much less than the total rainfall because of high evaporation (Fig. 2.2) (Buringh, 1979). Study area has daily maximum temperature between 35°C and 45°C (Fig. 2.3 and 2.4). Organic matter content was less than 1% in the upper 0.40 m (measurement of present research).

Soil horizons were difficult to differentiate visually since both horizons had the same colour (Fig. 2.5). Because of low level of organic matter supply to the soils and removal of crop residues, only some stubbles and leaves of cultivated crops remain on the soil surface. Since the water from Kinder dam was distributing to the neighbouring areas through the canals that

flow across the farm, ground water level of the whole farm was shallow. When the soil was dug to study the profile layers, groundwater was found at 1.0-2.0 m depth.  $\text{pH}_{\text{water}}$  was greater than 8.7 at 0-0.30 m and less than 8.7 at 0.30-0.45 m. 0-0.20 m depth is forming whitish grey colour eluvia zone. Carbonate content ( $\text{CaCO}_3$  percentage) was less than 15% from 0-0.45 m. Soluble salt content was decreased when the soil gets deeper. Bluish grey colour patches were found starting from 0.30 m depth and continue to the deeper layers. Exchangeable Na was the highest in upper 0-0.20 m (2.01 me/100 g soil) and decreased in the lower layers (less than 1 me/100 g soil). According to the above properties, soil horizon from zero to 0.45 m depth of soil at the study site has ultrabasic character (non-calcic) and it must have carbonate of sodium and magnesium (FAO, 2006).

Due to shallow ground water, soil had hydromorphic properties in the horizon depth lower than 0.30 m. Reddish brown and bluish grey colour mottling can be seen in this horizon. These mottling were showing the result of alternating oxidation and reduction of iron and manganese minerals. When the soil is wet for long time, reduction processes predominate and iron and manganese become soluble to some degree. A process of reddening resulted from the dehydration of iron compounds in the dry season (Buringh, 1979). Surface 0-0.20 m was directly affected by climate conditions such as heat and rainfall. Salts from the lower horizon might have dissolved and rise to the surface layer by capillary action. That salts may remain on the surface after evaporation because of high temperature. As a result, salts may deposit on the soil of 0-0.20 m layer and that has exchangeable sodium percent greater than 15. It shows the characteristics of Solonetz. Properties of the soil of study site were presented in detail in Chapter (3).



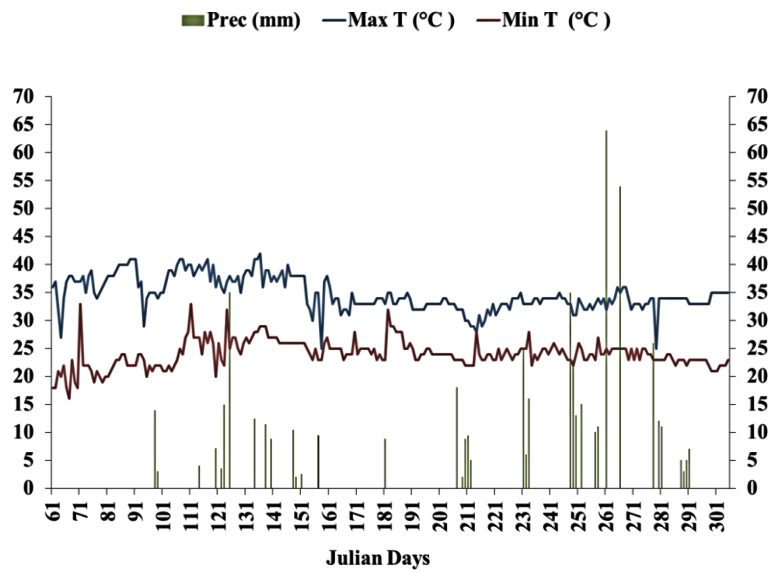


Figure 2.3: Daily precipitation, maximum and minimum temperature during 2012 cropping season

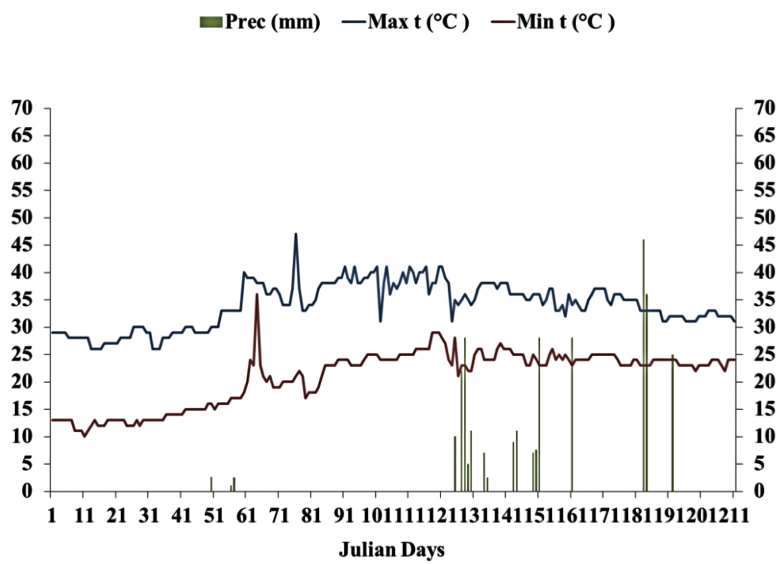


Figure 2.4: Daily precipitation, maximum and minimum temperature during 2013 cropping season

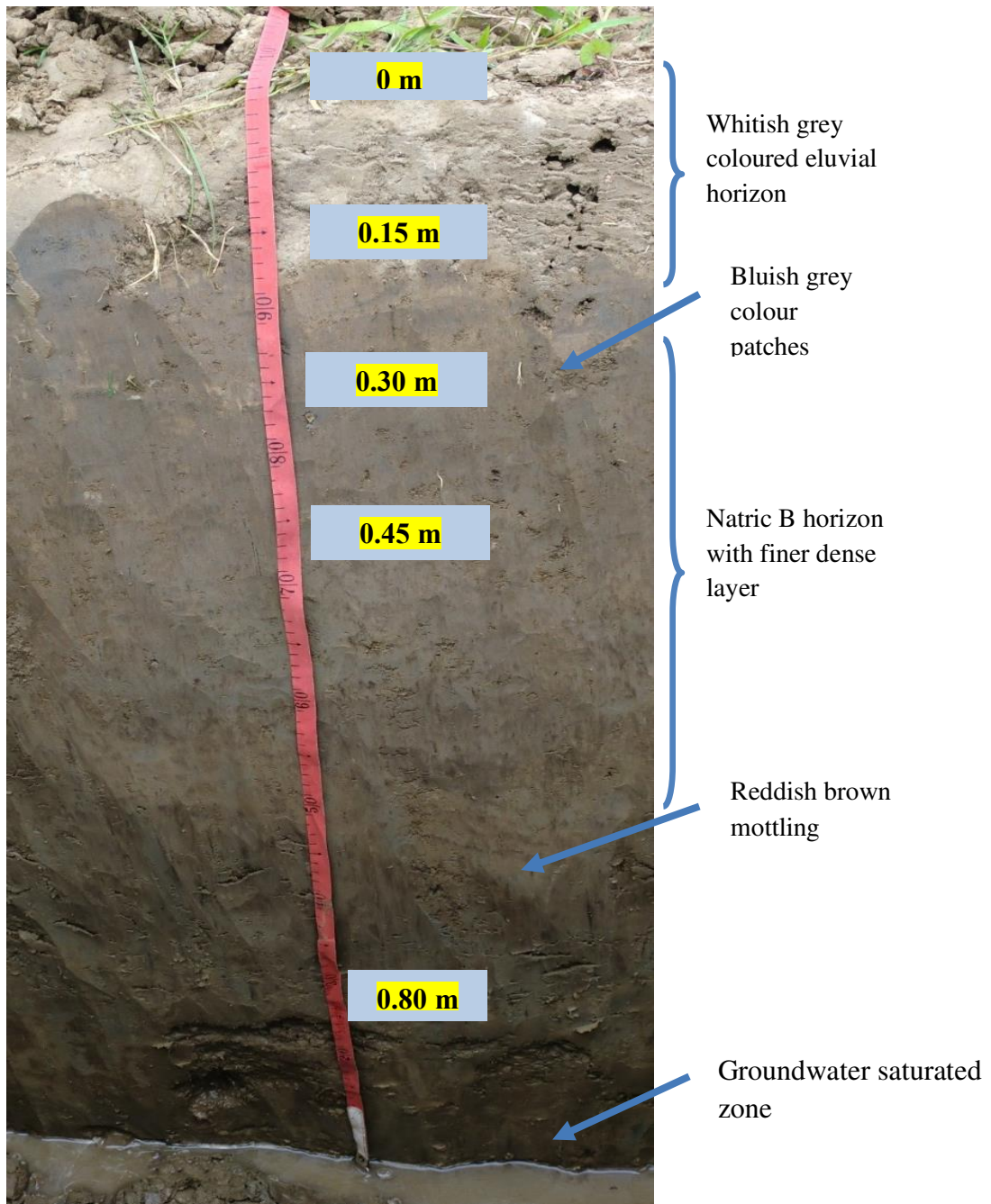


Figure 2.5: Soil profile of the experimental site measuring ground water table depth and observing the soil horizon properties for the taxonomic classification of the soil of study site

## 2.2 Biochar Production

### 2.2.1 Feedstocks collection

To use as soil amendments in field experiments, rice husk, rice straw and pigeon pea stems were selected as biochar feedstocks. These raw materials were available in the farm where field experiment was conducted. Pigeon pea stems were used as fuel wood in some areas. However, they are not woody and cannot store for long time. Therefore, households did not use pigeon pea stems as the main fuel wood and were disposed outside the villages or were burned in the fields. Rice was sown by most of farm households for the family self-sufficiency and, therefore, rice husk and rice straws are abundant in the region and in the study area as well. Although rice straw is used as fodder, there are still some wastes of rice straw to use as biochar. Rice husks can be obtained from nearby rice mills.

### 2.2.2 Feedstocks burning

The kiln for producing biochar was made from 200-Liter diesel barrel (Fig. 2.6, right). The idea of the structure of biochar kiln was based on the structure of the top loaded up draft garden kiln and the stripped top loaded up lift charcoal kiln by Günther (2012) (Fig. 2.6 left). There were larger holes at the bottom of a tin plate that was placed under the biomass container. Smaller holes were made directly at the bottom of biomass container. Air entered the biomass container first passes through the larger holes and then through the smaller ventilation holes upwards through the biomass. Biomass was burnt from the top of the container. Oxygen was under partially controlled condition. Limited amount of primary combustion air allowed the partial combustion of biomass, time required for burning the crop residues and yield of charcoal differed depending on the type of biochar raw material. Pyrolysis temperature was around 550-700°C.

The yield of the biochar was determined according to equation (1).

$$\text{Yield \%} = (W_b/W_f) \times 100 \quad \text{-----} \quad \text{Equation (1)}$$

Where,  $W_b$  and  $W_f$  are the weights of the biochar samples and that of dry feedstock, respectively.

For producing rice straw biochar, it took 35 minutes burning time and the yield was 3 kg rice straw char per 10 kg of dry rice straw. To produce pigeon pea stem biochar, it took 45

minutes to burn one barrel containing 12 kg dry pigeon pea stem. The yield was 3.5 kg charcoal from 12 kg dry biomass. It took 8 hours to burn 27 kg of rice husk in a barrel and that yielded 14.5 kg of rice husk biochar. It took altogether 25 days to complete biochar production. Rice husk biochar and farmyard manure mixture was prepared by mixing 4:1 ratio of cow dung and rice husk biochar and leaving it for four weeks before applying to the experimental plots.



Figure 2.6: Illustrated functions of biochar kiln (left), and biochar kiln used for producing biochar to apply in present research (right)

Source: Small and intermediate charring devices (Fölker Günther, 2012, Research Institute for Small-Scale Charring, Hörby, Sweden. <https://www.slf.dep.no/no/miljo-og-okologisk/klima.../>)

### 2.3 Rice Field Experiment

Land preparation was started on 11 May 2012. Harrowing and ploughing the land, constructing mud bunds for storing water and setting-up of experimental plots for the field experiment were carried out during land preparation time. Land preparation lasted for one month. Experimental design was Randomized Complete Block (RCB) design and contained 18 subplots (6 treatments and 3 replications) (Fig. 2.7 and 2.8). Experimental plots were separated by double mud bunds to minimize the lateral movement of plant nutrients. Rice seedlings were planted at a spacing of 0.02 m between rows and 0.015 m between hills. The

size of each experimental plot was 25 m<sup>2</sup>. The space between sub-plots was 1.27 m. The size of the whole experiment was 0.10 ha.

Urea, triple super phosphate and potassium fertilizers were applied as N: P: K ratio of (100: 50: 50) together with biochars during land preparation and incorporated into 0.02 m plough depth. Urea fertilizer was applied two times, 75 kg N ha<sup>-1</sup> of urea at land preparation and 25 kg N ha<sup>-1</sup> urea at the time of panicle initiation, respectively.

### **2.3.1 Land preparation and biochar application**

Biochars were applied to the experimental plots after land preparation before transplanting rice. Biochar rates were 50 kg per plot (20 Mg ha<sup>-1</sup>) each of rice husk biochar, rice straw biochar and pigeon pea stem biochar and 25 kg per plot (10 Mg ha<sup>-1</sup>) of rice husk biochar + farmyard manure mixture. Biochar application rate with respect to total carbon (C) content of biochars were 8.28 Mg carbon ha<sup>-1</sup> of rice husk biochar, 14 Mg C ha<sup>-1</sup> of rice straw biochar, 9.24 Mg C ha<sup>-1</sup> of pigeon pea stem biochar and 2.17 Mg C ha<sup>-1</sup> of rice husk biochar + farmyard manure mixture, respectively. Together with biochars, chemical fertilizers were added with the rate of 100:50:50 kg ha<sup>-1</sup> N: P: K.

Treatments are

- Rh = Application of Rice husk biochar  
(20 Mg ha<sup>-1</sup> biochar (8.28 Mg C ha<sup>-1</sup>) + 100:50:50 kg ha<sup>-1</sup> N: P: K)
- Rs = Application of Rice straw biochar  
(20 Mg ha<sup>-1</sup> biochar (14 Mg C ha<sup>-1</sup>) + 100:50:50 kg ha<sup>-1</sup> N: P: K)
- Ps = Application of Pigeon pea stem biochar  
(20 Mg ha<sup>-1</sup> biochar (9.24 Mg C ha<sup>-1</sup>) + 100:50:50 kg ha<sup>-1</sup> N: P: K)
- NPK = NPK fertilizer application (100:50:50 kg ha<sup>-1</sup> N: P: K)
- Mix = Application of rice husk biochar and farmyard manure mixture (10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture (2.17 Mg C ha<sup>-1</sup>) + 100:50:50 kg ha<sup>-1</sup> N: P: K)
- Control = Without NPK and biochar



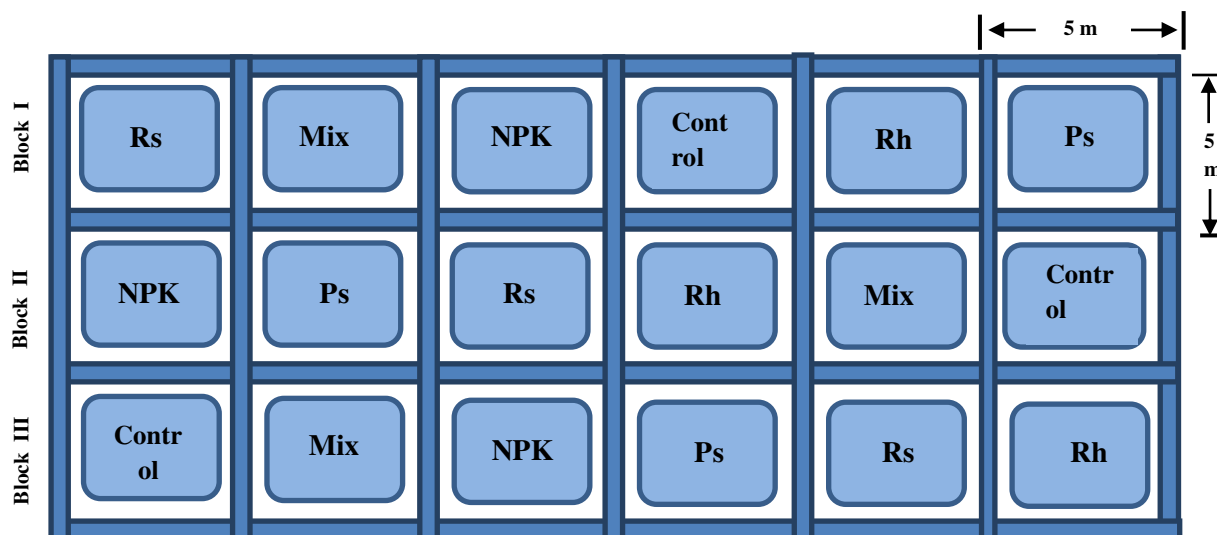


Figure 2.7: Layout of experimental plots for growing rice, chickpea and cotton experiments



Figure 2.8: Experimental plots of rice (left), chickpea (middle) and cotton (right)

### 2.3.2 Rice cultivation

Variety of rice used for the experiment was Longping 8 variety, one hybrid rice variety originated from China and multiplied at Shwe Daung Farm, Myanmar to distribute inside the country. Rice was sown by transplanting method. Before sowing paddy seeds, seedbed was prepared with the area of 30.5 m length, 12.7 m width and 0.8 m height. Seedlings started to emerge 3 to 5 days after sowing. Nursery bed was drained every morning and was irrigated every evening for better root penetration of the seedlings. To protect the seedlings from fungal and bacterial diseases and insect pests, especially stem borer *Scirpophaga incertulas* (Walker) infestations one time each of insecticide and fungicide were sprayed. Young plants were transplanted from the nursery bed to the experimental plots at 21 days after sowing with the spacing 0.15 m between plants and 0.20 m between rows.

Weeding and pest control measures were carried out according to the requirement of the crop. The field was left under flooded condition for ten days after transplanting. Irrigation and drainage were carried out every three-day intervals to reduce soil temperature. N: P: K fertilizers were applied 75:50:25 kg ha<sup>-1</sup> rate together with biochars before transplanting and 25:25 kg ha<sup>-1</sup> rate of N: P: K fertilizers were applied at the time of panicle initiation. The field was completely drained two weeks before harvesting.

### 2.3.3 Data collection

Experimental plots were harvested on 8 October 2012. Crop samples were taken from each experimental plot to analyse the paddy yield. In rice cultivation, the word “hill” represents a group of rice plants containing multiple numbers of tillers (Fig. 2.9). Calculation of rice yield and yield component factors were based on the calculations by Boumann et al. (2001). At the time of harvesting, eight hills were selected from each plot to count the total number of tillers per hill and to measure straw dry matter yield. All of the spikelet was removed from the plants. Fresh weight of rice plants without spikelet were weighed and recorded. To measure straw dry weight, 250 gram of fresh plants were selected as sub samples from total fresh samples and let them dry to reduce moisture content and dry weight was recorded. Plants from one square meter area of the center of each plot were cut to measure the number of hills per square meter. Eight plant samples were selected from the harvested plants of one square meter area to measure plant height, panicle length, number of panicle per plant, number of spikelet per panicle, and thousand grain weights. Rice grain yield per hectare was calculated by equation (2). Straw dry matter per hill was calculated by the equation (3). Grain to straw ratio was calculated to compute straw yield per hectare (equation 4). Straw dry matter yield was calculated as equation (5). Grain harvest index was calculated by equation (6).

$$\text{Rice grain yield (kg ha}^{-1}\text{)} = \frac{\text{total number of filled grain per panicle} * \text{total number of panicle per hill} * 1000 * \text{grain wt. (g)} * \text{number of hill sqm}^{-1}}{10000 / 1000 * 1000} \text{-----Equation (2)}$$

$$\text{Straw dry wt. hill}^{-1} = \frac{\text{Sample straw dry wt.} / \text{Sample straw fresh wt.}}{\text{Straw fresh wt. hill}^{-1}} \text{----- Equation (3)}$$

Grain: Straw ratio = fertile spikelet dry wt. / straw dry wt. ----- Equation (4)

Straw yield (kg ha<sup>-1</sup>) = (Grain Yield kg ha<sup>-1</sup>/Grain: Straw ratio) ----- Equation (5)

Grain harvest Index= (Grain Yield) / (Grain + Straw Yield) ----- Equation (6)



Figure 2.9: Rice hills, tillers and spikelet of rice plants at panicle initiation stage in pigeon pea stem biochar + NPK fertilizer treated plot (Photo source: by author)

## 2.4 Chickpea Field experiment

Chickpea (*Cicer arietinum*) was sown in November 2012 after harvesting rice experiments on the same experimental plots. It was harvested in the first week of March 2013 before sowing cotton (*Gossypium hirsutum*) field experiment.

### 2.4.1 Land preparation and chickpea cultivation

Chickpea was sown after harvesting rice and before cotton cultivation on the experimental plots only with the given moisture and nutrients that remained in the soil. Experimental design was the same as rice experiment with the spacing 0.1524 m between plants and 0.2032 m



between rows. Experimental plots were named according to the treatments of the previous rice experiment. Neither biochar nor NPK fertilizer was applied to chickpea experiment.

## 2.4.2 Data Collection

At the time of harvesting, chickpea yield components, such as population per plot, number of pods per plant, number of seeds per pod, and thousand-grain weight in kilograms, were recorded and chickpea yields were estimated. Chickpea yield estimation was done by the method of Sapkota et al. (CGIAR, 2015). Chickpea yield was calculated by using the following equation:

$$\text{Yield Mg ha}^{-1} = \frac{(\text{grain pod}^{-1} * \text{pod m}^{-2}) / 100}{(1000 - \text{grain wt.} / 1000)} \quad \text{----- Equation (7)}$$

## 2.5 Cotton Field Experiment

### 2.5.1 Land preparation and Biochar application

Land preparation for cotton experiment was done during first week of March 2013 at Shwe Daung Farm. Experiment layout was the same as that of rice experiment. Rice husk biochar, rice straw biochar, pigeon pea stem biochar, mixture of rice husk biochar and farmyard manure were applied to each subplot before land preparation. After cultivating the land, seedbeds were prepared to sow cotton.

Experimental design was Randomized Complete Block (RCB) design and contained 18 subplots (6 treatments and 3 replications). Size of subplots were 5 m long and 5 m width, the same size as rice experiment as cotton was sown identically on the rice experimental plots.

Treatments are

- Rh = Application of Rice husk biochar  
(20 Mg ha<sup>-1</sup> biochar (8.28 Mg C ha<sup>-1</sup>) + 100:30:117 kg ha<sup>-1</sup> N: P: K)
- Rs = Application of Rice straw biochar  
(20 Mg ha<sup>-1</sup> biochar (14 Mg C ha<sup>-1</sup>) + 100:30:117kg ha<sup>-1</sup> N: P: K)
- Ps = Application of Pigeon pea stem biochar  
(20 Mg ha<sup>-1</sup> biochar (9.24 Mg C ha<sup>-1</sup>) + 100:30:117 kg ha<sup>-1</sup> N: P: K)
- NPK = NPK fertilizer application (100:30:117 kg ha<sup>-1</sup> N: P: K)
- Mix = Application of rice husk char and farmyard manure mixture (10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture (2.17 Mg C ha<sup>-1</sup>) + 100:30:117 kg ha<sup>-1</sup> N: P: K)
- Control = Without NPK and biochar

### 2.5.2 Cotton cultivation

Cotton variety used for the experiment was traditional medium staple cotton Ngwe Chi 6. The crop has moderate resistant to boll worm attack.

Basal application of biochars and NPK fertilizer was done during land preparation and inputs were incorporated into 0.20 m plough layer by disc plough. Before cotton cultivation, biochars were broadcasted on the surface of experimental plots and then the land was cultivated first with disc plough and after that soil crusts were crushed with rotary plough. Fertilizer rate was N: P: K 100:30:117. Half of nitrogen and potassium fertilizers and all of phosphate fertilizers were applied as basal application during land preparation together with biochars (Fig 2.10). Another half of nitrogen and potassium fertilizers was applied at peak flowering time. Land preparation was done by tractors. Seedbeds were made by bullock drawn traditional inter-cultivator. Biochars applied on the surface were thoroughly mixed with the soil before sowing cotton. Therefore, cotton roots would have got the equal chance to have contact with the applied biochars in all treatments, not only on the shallow surface soil but also to the deeper plough depth.

Except biochar and fertilizers, other management practices were given equally for all treatments. Sucking pest control was done by spraying insecticides according to the severity of pest infestation. Due to the favourable rainfalls during cotton growing season, only three times of supplementary irrigation was needed. After every rainfall event and irrigation, inter-cultivation by bullock drawn traditional inter-cultivator was done to control weeds between the rows and for better aeration of the soil. Hand weeding was done to control weeds between the plants since the time of 2-3 true leaves formation up to boll setting (Fig. 2.11 (a)).

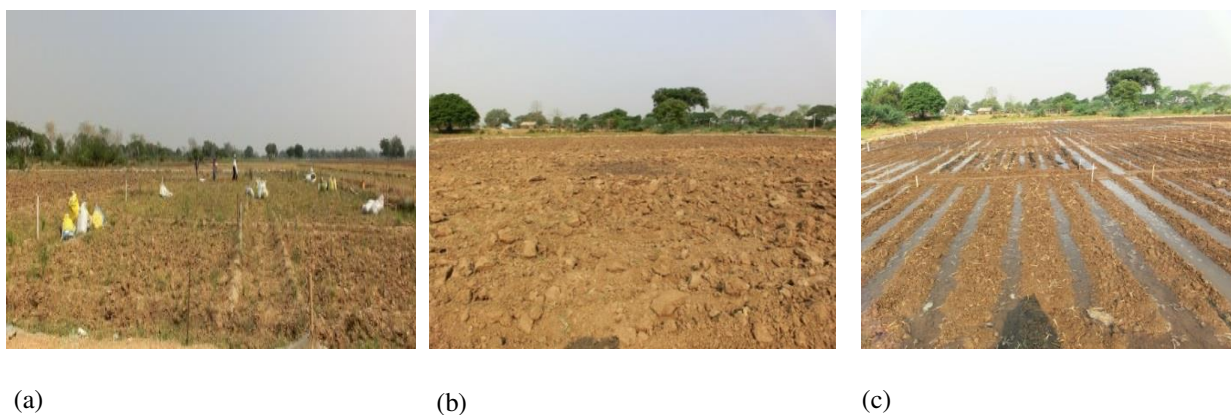


Figure 2.10: (a) Applying biochar before cotton cultivation (b) Land preparation for cotton cultivation (c) Irrigating cotton fields after sowing cotton

### 2.5.3 Data collection

Leaf samples were collected by removing 20 leaves from the uppermost fully expanded main stem leaves from each plot. Five plants from each subplot were selected as the sample plants to measure plant growth and yield components. Plant height, number of sympodial and monopodial branches, height to node ratio, and number of square, flower, small bolls and mature bolls were counted every two weeks starting from squaring time (Fig 2.11 (b)). Number of cotton plants per plot were counted and recorded for the calculation of population per hectare. Based on this growth assessment, necessary measures for regulating crop growth could be carried out. If there was excessive vegetative growth, plant growth regulators such as pix can be sprayed or mechanical topping of cotton crops can be carried out. If poor growth condition occurred, organic or inorganic fertilizer application or foliar fertilizer applications can be carried out to promote crop growth. In the data analysis for comparing the differences among treatments, data collected at 21 days after sowing (DAS), 45 DAS and 60 DAS, respectively were used.

Cotton was picked three times manually starting from the time of 50% boll opening. Cotton bolls, flowers and buds can be seen in figure 2.11 (c). The first picking was done in the first week of July 2013, the second picking was done in the third week of July 2013 and the third picking was done in the first week of August 2013. Seed cottons from the middle four rows were collected separately and weighed and average seed-cotton weight per boll (grams) was recorded as representative boll weight to compute per hectare yield.

$$\text{Seed cotton yield kg ha}^{-1} = \frac{\text{boll wt.} * \text{number of open bolls per plant} * \text{total number of plant ha}^{-1}}{1000} \text{ ----- Equation (8)}$$



(a)



(b)



(c)

Figure 2.11:(a) Cotton seedlings, two weeks after germination (b) Cotton plant at the time of squaring (c) Cotton plant with squares, bolls, and flowers at the time of boll setting (Photo source: by Author)

## 2.6 Soil Sampling

To test the initial soil properties of experimental site, soil samples were taken from 0.15 m, 0.30 m and 0.45 m depths of soil profile before starting rice experiment. Four Steel cylinders were driven into each 0.15 m soil depth horizontally by using a hammer and then carefully dug out from the soil, covered with the plastic caps and stored less than 10°C. Steel rings have the inner volume of 100 cm<sup>3</sup> with an internal diameter 57 mm and height 40.5 mm.

After harvesting rice and cotton, soil samples for measuring water retention and bulk density were collected from two random places of experimental plots from 0-0.1 m depth by using the steel cylinders and stored less than 10°C.

Soil samples for measuring other physical, chemical and biological properties were taken randomly from 10 places at 0-0.2 m depth of each experimental plot. After air-dried, soil samples were thoroughly mixed and 1 kilogram composite sample per plot was taken and put into the plastic bags and stored in the cool dry place. All soil samples were brought to the laboratory of the Institute of Ecology, Lüneburg University to measure the properties.

## **2.7 Laboratory Analyses**

### **2.7.1 Laboratory analysis of soil physical and chemical properties**

#### **Determining grain size distribution with sedimentation and hydrometer measurement**

DIN 18 123 (Elutriation analysis)

Soil textural analysis was carried out by hydrometer method (Bouyoucos, 1962). This method was used when over 10% of the grains are smaller than 0.063 mm (Urban, 2002). Since soil samples from the experimental site were fine textured soils, sedimentation method was used for the determination of grain size distribution. Texture analysis was replicated 3 times for each of 18 experimental plots.

Air dried soils of three replications for each treatment were weighed and 40 g each of soil samples were sieved through 0.063 mm sieve. Soil samples were washed on the sieve with a brush to flow down into the container tray underneath the sieve by using 700 ml distilled water and 25 ml sodium phosphate solution. Sodium phosphate was used as dispersant. The dispersant was prepared by adding 20 g of  $\text{Na}_4\text{P}_2\text{O}_7 \cdot 10 \text{H}_2\text{O}$  into distilled water and the solution was filled with distilled water up to 1000 ml.

Silt and clay portions of the samples were collected in the containers. The rest of the sample left on the sieve was collected and dried in oven at 105°C for dry sieving.

Finer portion of the samples were placed into a 1000 ml glass cylinder and filled with distilled water up to 1000 ml. Cylinders together with soil solution were left for one night to measure in the next day.

In the next day, the cylinders were closed with the rubber stoppers and thoroughly shaken. Then the stoppers were removed from the cylinders and aerometer spindle was put inside the cylinder. The value of the point on the spindle touching with the surface of water in the cylinder was read and noted.

Aerometer reading times were 30 sec. 1 min. 2 min. 5 min. 15 min. 45 min. 2 hr. 6 hr. 24 hr.

After 5 minute reading, spindle was taken out from the cylinder and temperature was measured before the next measurement. After measuring temperature, spindle was placed into the cylinder for the next measurement. This procedure was repeated for every measurement.

After finishing sedimentation measurement, soil solutions from the cylinders were transferred to the weighed glass containers and let them dry overnight in oven at 105°C. After drying, dry soil samples and glass containers were weighed and the weight of dry soil was recorded. This weight was included in grain fraction calculation.

After measuring the sand, silt and clay particle distributions, soil samples were assigned to textural classes with the help of a textural triangle.

### **Bulk density**

Bulk density was calculated based on fresh weight and oven dry weight of soil samples taken with the steel rings. Bulk density measurement was replicated two times for each experimental plot. Altogether 36 samples were measured for 18 experimental plots.

The fresh weight of each sample was measured and placed in oven at 105°C for 48 hours. Oven dry weight was measured again and gravimetric water content was calculated based on oven dry weight.

Bulk densities were calculated using the following formula:

$$\text{Bulk density (g cm}^{-3}\text{)} = \frac{W_2 - W_1 \text{ (g)}}{V \text{ (cm}^{-3}\text{)}} \text{ ..... Equation (9)}$$

Where,  $W_1$  and  $W_2$  are weights of moist and oven-dry soils respectively, and  $V$  is the volume of soil core.

### **Moisture content and dry weight**

DIN 19 683, page 4

Moisture content is the quantity of moisture contained in a soil. It is expressed in weight percent, based on the soil dried at 105°C (Urban 2002).

Each 10 g of soil samples were placed in crucibles and weight of empty crucible and weight of crucibles together with soils were noted. Sample testing repeated three times. Crucibles with soil samples were put in the drying chamber at 105°C for over-night until the sample weight reached stable condition. The next day, dry samples were taken out from drying chamber and let cool in the desiccator. After cooling, dry samples and crucibles were weighed and noted.

$$\text{Moisture content \%} = \frac{(B_{\text{moi}} - C_{\text{dry}})}{(C_{\text{dry}} - A)} * 100 \text{ ..... Equation (10)}$$

$$\text{Dry substance \%} = \frac{100}{(100 + \text{moisture cont. \%})} * 100 \text{ ..... Equation (11)}$$

Where;

$A$  = weight of crucible

$B_{\text{moi}}$  = weight of moist sample

$C_{\text{dry}}$  = weight of dry sample

### **Field capacity, permanent wilting point and plant available water**

Undisturbed soil core samples with steel rings were covered with plastic caps at both sides of the rings and the samples were kept at temperature less than 10°C.

Ceramic suction plate was used to measure water content at soil matric suction in the range of 10 kPa to 80 kPa. For the measurement of soil water in the laboratory, steel rings with the soils were placed on the waterbed until they are well saturated and then drained under specified suction power in two steps, 10 kPa for field capacity (PF 1.8) and 60 kPa for refill point (PF 2.5).

Permanent wilting point (PF 4.2) was measured at 1500 kPa suction. For measuring pf 4.2, pressure plate method (Richard's pressure plate apparatus) was applied. Pressure plate apparatus has a pressure chamber enclosing a water-saturated porous plate, which allowed water but prevented airflow through its pores. The porous plate was open to atmospheric pressure at the bottom surface, while the top surface was at the applied pressure of the chamber. Sieved soil samples (< 2mm) were placed in the retaining rubber rings in contact with the porous plate and left to saturate in water. After saturation was attained, porous plates with the saturated soil samples were placed in the chamber and a known gas (air) pressure was applied to force water out of the soil. Flow continued until equilibrium between the force exerted by air pressure and the force by which soil water was held by the soil ( $\psi_m$ ) was reached. That process was let to continue for seven days since the soil was fine textured sandy loam soil and it held water very strongly within small pores. Following equilibrium between soil metric potential and the applied air pressure, soil samples were removed from the pressure plate, weighed, and oven dried for gravimetric determination of water content. The sample's bulk density was needed to know to convert  $\theta_m$  to  $\theta_v$  since the samples used in this measurement were disturbed samples. Bulk density value was calculated during the measurement of pF 1.8 and 2.5 by using steel rings. Volumetric water content was determined by multiplying gravimetric water content with bulk density.

### **Total carbon, total nitrogen and C/N ratio (DIN 51732)**

Total carbon and nitrogen was measured by combustion method by using 2400 Series II Perkin Elmer CHN/O elemental analyser, U.S.A.

10 g of air-dried and 2 mm sieved soil samples were weighed in crucibles and placed in a drying chamber at 105°C for one night. The next crucibles were taken out from the drying chamber and put in the desiccator for cooling. Cooled samples were ground by mixer mill (Retsch MM 400, Haan, Germany) to 350  $\mu\text{m}$ . Grounded soil samples were weighed for 20

mg in tin capsules using a micro scale. Samples were triplicated for each measurement (treatment) and mean values were taken for statistical analysis.

$$C/N \text{ ratio} = \text{total C\%} / \text{total N\%} \quad \text{----- Equation (12)}$$

The results obtained were used to assess the soil quality by C/N ratio evaluations in table 2.1.

Table 2.1: C/N ratio evaluation (C/N ratio from Kunze, Roeschmann, and Schwerdtfeger: Pedology, 5th edition) (Urban, 2002)

Under 10	With a close C/N ratio under 10, the supply of C is quickly exhausted; humus may decline
10 to 20	With C/N ratio between 10 and 20, carbon mineralisation through soil microorganisms occurs relatively quickly. The C/N ratio of good arable soil is between 10 and 13.
Over 20	If the C/N ratio in tilled soil is greater than 20, C decomposition is hindered. Microorganisms consume nitrate, meaning there is none for the cultivated plants. There is a deficiency of N, and the development of the microorganisms is increasingly hindered. When crop residue containing a great C/N ratio is added to soils, the C/N ratio is even greater after the decomposition process.

### **Soil microbial respiration**

Soil respiration was measured with a respirometer BSBdigi O<sub>2</sub>/ BSBdigi CO<sub>2</sub> (SELUTECH GmbH, Hechingen, Germany). In this measurement, oxygen consumption was recorded continuously before and after glucose addition (Nordgren 1988). Basal respiration rate (oxygen consumption mg day<sup>-1</sup>) before glucose addition (BR) measured total microbial activity in soil. Substrate induced respiration (oxygen consumption mg h<sup>-1</sup>) after glucose addition (SIR) measured the active soil microbial biomass. Soil microbial respiration measurement was carried out with three replications.

Before measuring soil samples for respiration, there were some steps to prepare the samples. Soil samples were sieved by using 2 mm sieves and were weighed for 150 g, adjusting soil moisture at 60% water holding capacity. These moist soils were incubated at 20°C in the respirometer chamber for two to three days.

### ***Measuring soil dry weight and water holding capacity***

To prepare the samples for incubation and subsequent measurements of soil microbial respiration 60% water holding capacity was measured. Since soil samples taken from the experimental plots were air-dried, it was needed to set the samples at the same moisture level.

Three replications of 10 g soils were weighed in crucibles and moisture content was calculated after drying in drying chamber at 105°C. Calculation was the same as mentioned in



moisture content and dry weight calculations. This measured dry weight was used in calculating 60% water holding capacity of soil samples.

Water holding capacity was measured according to German Standard E DIN ISO 14238-2011. Three replications of 20 g soils were weighed in plastic cylinders for maximum water holding capacity measurement. Cylinders were placed on waterbed for two hours. At the same time, sand bed was prepared and moistened by letting water flow inside the sand bed for two hours. After that water outlet hole of sand bed was closed with a rubber stopper and cylinders from waterbed were transferred onto the sand bed. Bases of the cylinders that were sealed with permeable membranes should have well contact with the surface of sand bed so that water soaked in the soils in cylinders would diffuse through the semi-permeable membranes. After three hours on sand bed, cylinders were gently removed from the sand bed, and any water drop remained on cylinder and semi-permeable membrane was wiped out and weighed. Weights of empty cylinders, dry soils and cylinders and moist soils and cylinders were carefully noted for calculation.

$$\text{Mass of dry soil} = (\text{mass of soil sample} * \text{dry matter \%}) / 100 \text{ ----- Equation (13)}$$

$$\text{Water hold in soil samples (mass of water)} = (W_2 - W_1) - \text{----- Equation (14)}$$

$$(\text{mass of dry soil}) / 100$$

$$\text{Maximum water holding capacity} = 100 * (\text{mass of water} \text{----- Equation (15)}$$

$$/\text{mass of dry soil})$$

$$60\% \text{ water holding capacity} = (60 * \text{maximum water} \text{----- Equation (16)}$$

$$\text{holding capacity}) / 100$$

Where  $W_1$  is total weight of soil and cylinder before putting onto waterbed and  $W_2$  is total weight of soil and cylinder after putting onto waterbed.

Soil respiration was measured in triplicate in respirometer chamber. Total 150 g of dry soils were weighed and required amount of water was added to those dry samples to reach 60% water holding capacity. Glass containers with soil samples of 60% moisture content were placed in the incubator for 3-5 days. After 3-5 days, 150 g of moist and incubated soil samples

were divided into three 50 g samples, and placed in the bottles. Those bottles with the samples were put into the respirometer to measure the microbial respiration.

Measurement of basal respiration (BR) took 7-10 days and the results were recorded. Recorded results were basal respiration per 50 g soil. Oxygen consumption per day per 100 g soil was calculated by multiplying the average oxygen consumption by 2.

To convert oxygen consumption,  $\text{mg h}^{-1}/100 \text{ g DM}$  to  $\text{CO}_2$  released in BR,  $\text{mg CO}_2 \text{ kg}^{-1}$  dry matter (DM), the following equation was used:

$$\text{mg total organic carbon (TOC) kg}^{-1}\text{DM} = \text{O}_2 \text{ consumption} \quad \text{----- Equation(17)}$$

$$(\text{mg day}^{-1}/100 \text{ g DM})$$

$$*1.375*10$$

Here, factor 1.375 was used to calculate the amount of total organic carbon from hourly oxygen consumption.

To assess the substrate-induced respiration (SIR), glucose was added to the samples subsequently and the samples were left for further 3-5 days in the respirometer chamber. Oxygen consumption in  $\text{mg h}^{-1}$  per 100 g dry soil was calculated to estimate SIR with the same calculation as in BR.

$$\text{mg microbial organic carbon} = \text{O}_2 \text{ consumption (mg} \quad \text{----- Equation (18)}$$

$$(\text{Cmic}) \text{ kg}^{-1} \text{ DM} \quad \text{h}^{-1}/100 \text{ g DM}) * 28 * 10$$

Here, factor 28 was used to calculate the microbial organic carbon from the hourly oxygen consumption.

## pH

VDLUFA (1991) Book of Methods A 5.1.1

Soil pH was measured in a  $0.01 \text{ mol l}^{-1} \text{ CaCl}_2$  solution at 1:5 mass to volume ratio. Samples were air dried and sieved in 2 mm sieve. 10 g of air-dried soil samples were weighed and placed in 50 ml beaker glass. 50 ml of  $0.01 \text{ mol l}^{-1} \text{ CaCl}_2$  solution was added to the beaker containing the soil and stir with a glass rod. The solution was left for one hour and stirred occasionally. pH value was measured by pH-meter (pH730, WTW GmbH, Weilheim, Germany). Measuring pH for each sample was repeated three times and average value was recorded for statistical analysis.

Table 2.2: pH value evaluation: classification of soil reaction (Pedological mapping instructions 1994) (Ad-hoc-Arbeitsgruppe-Boden, 2005)

Classification of soil reaction			
7.0	Neutral		
6.5-7	Very slightly acidic	7-7.5	Very slightly alkaline
6-6.5	Slightly acidic	7.5-8	Slightly alkaline
5-6	Somewhat acidic	8-9	Somewhat alkaline
4-5	Strongly acidic	9-10	Strongly alkaline
3-4	Very strongly acidic	10-11	Very strongly alkaline
<3	Extremely acidic	>11.0	Extremely alkaline

### Soluble salt content (Salinity)

VDLUFA, Book of Methods 1 (1991)

Soil samples were sieved by using 2 mm sieves. Soil solution was prepared by adding 100 ml distilled water to 10 g soil and shake on the shaker for one hour and electrical conductivity was measured by using EC meter. Salt content was calculated by using the following equation:

$$\text{Salt content in \% (calculated as KCl)} = \text{EC (mS/cm)} * 0.528 \text{ ----- Equation (19)}$$

### Carbonate content

VDLUFA (German Agricultural Testing and Research Agency), Book of Methods Vol. 1 (1991). Soil Exploration, Method A 5.3.1

Carbonate content was measured by using calcimeter (Eijkelkamp, EM Giesbeek, The Netherlands). Sample preparation and analysis was carried out according to the instruction book provided for the calcimeter.

2.5 g of 2 mm sieved air-dried soil samples were first treated on a watch glass with 1 ml hydrochloric acid. Carbonate content was estimated over the time of bubbling lasts. Based on bubbling, carbonate content of the samples were assumed as less than 20 g kg<sup>-1</sup> and 10 g of soil samples was used for carbonate content measurement. Carbonate measurement was done by three replications. There were altogether 54 samples measured in the laboratory because 18

samples from each experimental plot (from 6×3 RCB experiment) were again replicated 3 times for laboratory measurements.

***Preparing samples for blank measurement***

Two reaction vessels were filled with 20 ml distilled water to determine the blank value. For blank measurements, starting point of water level in the burettes was set at 20 ml and 80 ml and the average of these two measurements was used as blank value. Small test tubes were filled with 7 ml hydrochloric acid, and were placed in each reaction vessels without letting acid to spill onto water by using a pair of tweezers.

***Preparing sample for standard measurement***

To measure standard CaCO<sub>3</sub>, 0.4 g and 0.2 g of dry calcium carbonate were placed in reaction vessels and 20 ml distilled water was added into it. Small test tubes were filled with 7 ml hydrochloric acid (4-mol l<sup>-1</sup>) and placed in each reaction vessel by using a pair of tweezers. Average value of the CO<sub>2</sub> resulted of these two measurements was used as standard CaCO<sub>3</sub>.

***Preparing for sample measurement***

Samples were weighed for 10 g, and were put into the reaction vessels. 20 ml of distilled water was added to the reaction vessels with soil samples. Small test tubes were filled with 7 ml hydrochloric acid, and were placed in each reaction vessels without letting the acid to spill onto the samples by using a pair of tweezers. Starting point of water levels in the burettes was set at 3 ml for measuring standard calcium carbonate and sample measurement.

After preparing blank, CaCO<sub>3</sub> standard and soil samples, reaction vessels were closed with the stoppers dampened with distilled water. Reaction vessels were tilted to let the hydrochloric acid flow from the test tube over the samples and for the initiation of the reaction. CO<sub>2</sub> gas produced would lower the level of the fluid in the burette. Reaction vessels were shaken until the sinking of the fluid stop at one measuring point. The point where the fluid stopped was read and initial value 3 ml was subtracted from the readings.

The carbonate content was calculated with the formula:

$$w (\text{CaCO}_3) = 1000 * (C (V_1 - V_3) / (m_1 (V_2 - V_3))) * \text{-----} \text{Equation (20)}$$

$$(100 + w(\text{H}_2\text{O})) / 100$$

Where:

w (CaCO<sub>3</sub>) = the carbonate content (g kg<sup>-1</sup>) of oven-dried soil

$m_1$  = the mass (g) of the test portion (sample)

$m_2$  = the mean mass (g) of the calcium carbonate standards

$V_1$  = the volume (ml) of  $\text{CO}_2$  produced by reaction of the test portion (sample)

$V_2$  = the mean volume (ml) of  $\text{CO}_2$  produced by  $\text{CaCO}_3$  standards

$V_3$  = the volume change (ml) in the blank determinations (this volume can be negative)

$W (\text{H}_2\text{O})$  = the water content, expressed as a percentage by mass, of the dried sample, determined according to ISO 11565

### **Available potassium**

Calcium-Acetate-Lactate (CAL) Method; VDLUFA Book of Methods (1991), Volume 1, Soil Exploration, Method A 6.2.1.1

Plant available potassium was washed out and filtered with the aid of calcium-acetate-lactate solution. 5 g air-dry soil was mixed with 100 ml extracting solution in 500 ml plastic bottle. Plastic bottles with soil solution were shaken for 90 minutes on the shaker. Then filtered and the first filtrate was discarded. Filtered solution was stored in plastic bottle before the measurement.

### ***Extraction solutions***

Stock solution (solution A) was prepared by mixing the dissolved 77.0 g calcium lactate ( $\text{C}_6\text{H}_{10}\text{CaO}_6+5\text{H}_2\text{O}$ ) in hot dist.  $\text{H}_2\text{O}$ , dissolved 39.5 g calcium acetate ( $(\text{CH}_3\text{COO})_2\text{Ca}\cdot\text{H}_2\text{O}$ ) in hot dist.  $\text{H}_2\text{O}$  and 89.5 ml pure acetic acid  $\text{CH}_3\text{COOH}$ . Distilled water was added to this mixture to reach up to 1 Liter.

Working solution (solution B) was prepared by adding water to 200 ml stock solution to get 1L working solution. pH value was 4.1.

### ***Determining K***

4 ml aliquot was pipetted into measuring vessel and 6 ml water was added into it. K value was measured by ICP OES Perkin Elmer optima 3300 RL plasma spectrometer, USA (wavelength 259.372 nm). Measurement was done with three replications and average values were recorded for statistical analysis.

## Total exchangeable cations

Exchangeable cations were extracted by the barium chloride-triethanolamine method of Mehlich (1938) which is buffered at pH 8.2. Triethanolamine (85%) 100 ml was diluted with 1,000 ml of water and partially neutralise with HCl to adjust to pH 8.1 to 8.2. The solution was mixed with 2 liters water to make a 2-liter solution containing 250 g BaCl<sub>2</sub>·2H<sub>2</sub>O.

Soil samples were air dried and weighed for 5 g and placed in centrifuged tubes. Samples were mixed with barium chloride triethanolamine and centrifuged for 5 minutes by 3000-rpm min<sup>-1</sup>. Centrifugation was done by three times and decants were collected in 250 ml plastic bottles. In collection of decants, centrifuged solutions were filtered by using the filter papers. First filtrate must be thrown away. Barium was again exchanged by using magnesium chloride solution (25 gm MgCl<sub>2</sub>·2H<sub>2</sub>O). Like the former centrifugation, solutions were centrifuged for three times. Centrifuged solutions were filtered and collected in 250 ml plastic bottles.

Before measuring the ion concentration, sample solutions were acidified with 2 drops of conc. HNO<sub>3</sub>. This dilution depends on the measuring capacity of spectrometer. Ion concentrations were measured by ICP-OES Perkin Elmer optima 3300 RL plasma spectrometer, U.S.A (wavelength 259.372 nm). Measurement was done with three replications.

The resulted element concentrations were converted to cation concentrations with the following equations: ([www.uidaho.edu](http://www.uidaho.edu))

$$\text{Ca}^{2+} \text{ me/100g (cmolc kg}^{-1}\text{)} = \frac{\text{mg/1000-mL (ppm)} * \text{mL extract g}^{-1} \text{ soil} * \text{dil. factor}}{20.04 \text{ mg meq}^{-1} * 1/10}$$

$$\text{Mg}^{2+} \text{ me/100g (cmolc kg}^{-1}\text{)} = \frac{\text{mg/1000-mL (ppm)} * \text{mL extract g}^{-1} \text{ soil} * \text{dil. factor}}{12.15 \text{ mg meq}^{-1} * 1/10}$$

$$\text{Na}^{+} \text{ me/100g (cmolc kg}^{-1}\text{)} = \frac{\text{mg/1000-mL (ppm)} * \text{mL extract g}^{-1} \text{ soil} * \text{dil. factor}}{22.99 \text{ mg meq}^{-1} * 1/10}$$

$$\text{K}^{+} \text{ me/100g (cmolc kg}^{-1}\text{)} = \frac{\text{mg/1000-mL (ppm)} * \text{mL extract g}^{-1} \text{ soil} * \text{dil. factor}}{39.10 \text{ mg meq}^{-1} * 1/10}$$

Sodium adsorption ratio (SAR) was calculated with the following equation:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \text{----- Equation (21)}$$

Where: Na, Ca and Mg are respectively sodium, calcium, and magnesium concentrations in  $\text{me l}^{-1}$ .

Exchangeable sodium percent (ESP) was calculated with the following equation:

$$ESP = \frac{\text{Conc. Na} + \dots}{CEC} \times 100 \quad \text{Equation (22)}$$

### **2.7.2 Laboratory analysis of biochars**

#### **pH (CaCl<sub>2</sub>): DIN ISO 10390**

5 g each of the air-dried biochar samples (< 2mm) were placed in a glass vessel. Five times the volume (25 ml) of a 0.01 M CaCl<sub>2</sub> solution was added. Suspension was stirred for 1 hour. pH value was measured with a pH meter for three times. Average values of each sample were recorded as soil pH of respective treatments.

#### **Electrical conductivity (salt content) - Method of the BGK (2003) DIN ISO 11265**

To measure salt content, each of 10 g of biochar samples were mixed with 100 ml double distilled water and shook it for 1 hour. After shaking, biochar solution was filtered and conductivity was measured in the filtrated water. Measurement was replicated three times and average value was computed for statistical analysis. Correction of temperature was automatically done in the measuring device. Electrical conductivity was given for a solution at 25°C. Salt content was calculated using the factor  $52.8 [\text{mg KCl l}^{-1}] / [10^{-4} \text{cm}^{-1}]$  and was given in  $\text{mg KCl l}^{-1}$ .

#### **Total carbon and nitrogen measurement of biochar samples**

CHN: DIN 51732

Biochar samples were dried at 105°C and ground with Retsch mixer mill (MM 400), Haan, Germany. Ground samples were weighed for 2 mg and put into tin capsules. Total carbon, hydrogen and nitrogen percent were measured with Perkin Elmer CHN analyser U.S.A (Modell 2400). Samples were measured with three replications.

#### **Determination of ash content of biochars**

Ash content (550°C) analogue DIN 51719

Ash content and moisture content of biochars were determined in an open crucible. Ash content was measured with two replications and average value was used as the ash content of

the respective biochar material. Total biochar samples measured for ash analysis were eight samples for four kinds of biochars.

First, 1.0 g each of the biochar samples were weighed and placed in a muffle furnace previously heated to 105°C, and kept for 1 hour. After that, the crucibles were left to cool at room temperature in a desiccator, and their weight was recorded. The difference in the mass loss was considered as moisture content. The crucibles were placed again in the furnace and heated to 550°C for 6 hours. After slowly cooling down to room temperature inside the furnace, the crucibles were weighed. Ash content was determined by subtracting the weight of crucible from the weight of ash and crucible.

### **Determination of the labile and stable carbon fractions of biochars**

McLaughlin et al. (2009) modified the two ASTM (American Society for Testing Materials) tests for coals to the test methods, modified thermal analysis methods that were relevant for testing biochar. Original ASTM tests intended to predict the performance of coal that would be used as fuel. According to McLaughlin et al. (2009) as biochar would be used as soil amendment, not as fuel, testing procedures would be needed to modify. There were two testing methods- (1) proximate and (2) ultimate analyses. In proximate analysis, moisture content, volatile matter (gases released when coal is heated), fixed carbon (solid fuel left after the volatile matter is driven off, but not just carbon), and ash (impurities consisting of silica, iron, alumina, and other incombustible matter) are measured. Ultimate analysis determines the amount of carbon, hydrogen, oxygen, nitrogen, and sulphur. In the current measurement, it was concerned with the proximate analysis as the objective of the analysis was for partitioning of biochar carbon.

Resident matter and mobile matter (the sum of mobile carbon and mobile hydrogen and oxygen) were determined based on the calculation of weight losses by burning biochar materials at different temperatures (105°C, 450°C, 550°C and 900°C) in a muffle furnace in the laboratory. According to the modified thermal analysis methods, threshold temperature for drying biochar samples was 105°C and vaporising the mobile matter away from the resident matter was 450°C. The ashing temperature was 500°C-550°C. Volatile matter content of biochar materials was measured after heating with 900°C temperature.

Mobile matter was obtained by calculating weight loss of biochar materials after heating 450°C for 1 hour. Weight loss between 105°C and 450°C was considered as mobile fraction because fraction of total carbon in biochar degrades during the early period after application of biochar to soil (McLaughlin et al., 2009). First, 1.0 g of biochar was weighed, in duplicate,



placed in a muffle furnace previously heated to 105°C, and kept for 1 hour. After that, the crucibles were left to cool at room temperature in a desiccator, weighed, and recorded. Crucibles and 105°C dried biochars were placed to muffle furnace at 450°C for 1 hour for removing the organic molecules produced during pyrolysis that exist on the surface of the biochars (Joseph et al., 2009).

Measuring ash content has already presented in the previous section. To determine the volatile matter, biochar samples were heated at 900°C in muffle furnace for 7 minutes, cooled down in the muffle furnace, and weighed. Weight loss after heating at 900°C was considered as volatile matter content, as volatile matter would be released by dehydration of biochar particles at that temperature. The amount of volatile free char particles was accounted as fixed carbon amount. Fixed carbon percent was obtained by subtracting the moisture content, biochar weight loss after 900°C heating process and ash content from 100. Samples were replicated to three in every measurement and average value was recorded for statistical analysis.

### **Exchangeable cations of biochar materials**

Extraction of exchangeable cations from biochars was carried out according to the same procedure as the extraction of exchangeable cations from soil samples by using barium chloride-triethanolamine method of Mehlich (1938). Ion concentrations were measured by ICP-OES Perkin Elmer optima 3300 RL plasma spectrometer, U.S.A (wavelength 259.372 nm). Measurement was done with three replications and average value was used for statistical analysis.

### **Water holding capacity (WHC)**

DIN ISO 1438-2011

Biochars were sieved with 2 mm sieve and 3 g were weighed and placed to plastic cylinders. There were three replications for each measurement. Samples were soaked in water for 24 hours. After that, cylinders were placed on a dry sand bed for 3 hours for removing free water. After three hours on sand bed, cylinders were gently removed from the sand bed. Any water drop remained on cylinder, and semi-permeable membrane was wiped out and weighed. Weights of empty cylinders, dry soil and cylinders and moist soil and cylinders were carefully noted for calculation. Calculation of water holding capacity of biochar was the same as the calculation of water holding capacity of soils as mentioned above.



## **Total carbon and nitrogen measurement of plant samples**

Rice leaves and straws were first air dried and cut into 2 mm sizes and dried in the drier at 65°C for 6 hours. Dried leaf and straw cuttings were ground with Retsch ultra-centrifugal mill (ZM 200, Haan, Germany). Samples were weighed 2 mg into tin capsules and total carbon, nitrogen and hydrogen percent were measured in 2400 Series II Perkin Elmer CHNS/O elemental analyser, U.S.A. Measurement was repeated three times. Mean values were used for statistical analyses.

To measure total carbon and total nitrogen of cotton leaves and petioles, fifteen leaf samples were collected randomly from cotton plants of the experimental plots. Third fully matured leaves on the main stem of cotton plants were collected and petioles were separated from the leaves in the field. Leaves were cleaned, air-dried, and kept in paper bags before bringing to laboratory. Leaves were ground by using Retsch ultra-centrifugal mill (ZM 200). Petiole samples were ground by using Retsch mixer mill (MM 400, Haan, Germany). Ground samples were weighed for 2 mg, total nitrogen and total carbon content were measured in Perkin Elmer CHNS/O analyser, U.S.A. Measurement of carbon and nitrogen content of cotton leaves and petiole samples were done by three replications.

## **2.8 Modelling**

### **2.8.1 Denitrification Decomposition Model (DNDC)**

In this study, denitrification decomposition model (DNDC version 9.5) (DNDC (2012)) was used to predict the effects of NPK fertilizer application, and biochar soil additions on SOM dynamics, crop yields and GHG emissions.

Several of SOM models currently in use were first developed in the late 1970s and early 1980s (e.g. Jenkinson and Rayner, 1977; Parton et al. 1983). Despite their diversity, most of these models share some basic assumptions which include the representation of SOM as multiple pools (or as a quality spectrum) with differing inherent decomposition rates, governed by first-order rate constants modified by climatic and edaphic (e.g. soil physical attributes) reduction factors (Paustian, 2001). To facilitate the scientific progress in predicting the effects of SOM on changes in land-use, agricultural practice and climate, a network of SOM modellers and long-term data holders, the global Soil Organic Matter Network (SOMNET) was established during 1995. SOMNET has since attracted contributions from 29 leading SOM modellers and over 70 long-term experimentalists from all around the world. Global distribution of models and long-term experiments participating in SOMNET were 42

experiments and 18 models in Europe, 10 experiments and 7 models in North America, 3 experiments in South America, 3 experiments in Africa, 8 experiments and 3 models in Australia, and 10 experiments and 1 model in Asia (Smith et al., 1996a, Powelson et al., 1997, Smith et al., 1996b, 1997). DNDC is one of the models developed and updated based on the data from long-term experiments conducted in North America, Europe and Asia.

Denitrification-Decomposition (DNDC) model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agro-ecosystems (Fig. 2.12). DNDC version (9.5) consists of two components and six sub models. The first component, consisting of soil climate, crop growth and decomposition sub-models predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles driven by ecological drivers (e.g. climate, soil, vegetation and anthropogenic activity). The second component, consisting of nitrification, denitrification and fermentation sub-models, predicts emissions of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), ammonia (NH<sub>3</sub>), nitric oxide (NO), nitrous oxide (N<sub>2</sub>O) and dinitrogen (N<sub>2</sub>) from the plant-soil system. Input data includes climate drivers, soil features, crop parameters, and farming practices. The output includes soil carbon and nitrogen pools and fluxes, crop growth and yield, nitrate leaching, water leaching and trace gas emission (User's guide for the DNDC model (version 9.5)).

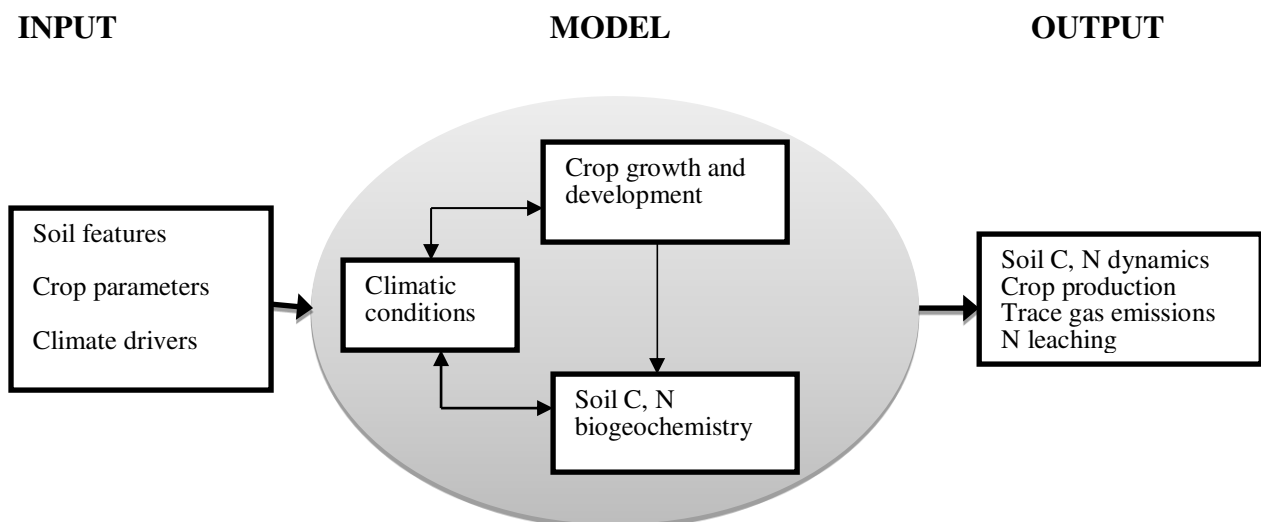


Figure 2.12: Overall structure of DNDC model

Source: Zhang, Y. et al. / Ecological Modelling 151 (2002) 75–108

DNDC model (version 1.0-7.0), was first developed by Li et al. in 1992. This first version contained three sub-models: (1) soil-climate/thermal-hydraulic flux sub-model, (2) decomposition sub-model, and (3) denitrification sub-model. These sub-models simulated N<sub>2</sub>O and N<sub>2</sub> emissions. Crop growth was estimated using a generalized crop growth curve (Li et al., 1994). Therefore impact of climate on crop growth and soil conditions were not accounted by the model (Zhang et al., 2002). During two decades, modifications of DNDC model were made by the developers aiming to bridge the gaps either in functions or in regions (Gilhespy et al., 2014).

The development of Crop-DNDC by integrating detailed crop growth algorithms to the existing soil biogeochemical model was reported by Zhang et al. (2002). In the Crop-DNDC model, crop growth was simulated not only by tracking crop physiological processes (phenology, leaf area index, photosynthesis, respiration, assimilate allocation, rooting processes, and nitrogen uptake), but also calculating water stress and nitrogen stress, which were closely related to soil biogeochemical processes and hydraulic dynamics (Fig.2.13 and Fig. 2.14). Due to the availability of crop DNDC model to simulate crop yields, soil carbon sequestration and greenhouse gas emission, it can be deployed for simultaneously predicting the effects of changes in climate or management on crop yield, soil carbon sequestration and trace gas emissions. This crop DNDC model was the origin of the newer versions of DNDC. According to Ponce-Hernandez (2004) selection criteria of a model are:

- Required inputs for the model ought to match available data in the databases.
- Output variables generated by the model need to satisfy the objectives of the modelling exercise.
- The model should have been adapted to the particular conditions of soil, climate and land management of the site or region.
- Simulation model should offer the management options that need to be modelled.
- The level of accuracy of estimates from the model should be within the target accuracy required by the project.
- There is reported evidence that the model has performed well in ecological circumstances similar to those of the site of concern.
- Accessibility and ease of the use together with the implicit assumptions in the model about the user's technical background

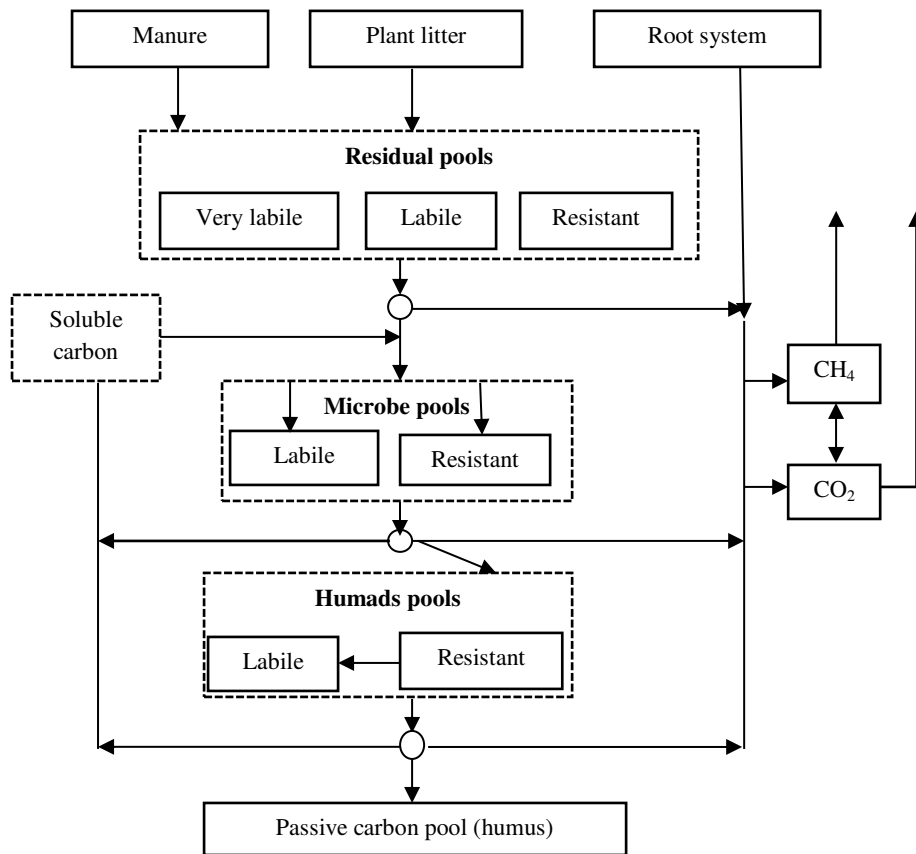
DNDC model was calculated and validated in Asian countries such as China, Thailand, Japan and the crops include both upland and lowland crops. There were researches that estimated

soil organic matter dynamics and greenhouse gas emissions from cropping systems due to the impact of different management practices using DNDC model in South East Asia region (Cai et al., 2003).

Pathak et al. (2005) studied the greenhouse gas emissions from Indian rice fields. The study suggested that the model could be applied for estimating GHG emissions and the influences of agronomic management, soil and climatic parameters on GHG emissions from rice fields in India.

Although daily weather was needed, climate data set of one year can be applied for all simulated years. Input methods are simple and user familiar. Modification of crop data can easily be done if the model user has sufficient agronomic background knowledge. Crops included in DNDC model are both lowland crops and upland crops. Since the model was validated for rice crop under flooded condition, cultivation method is consistent with the method that was used in this study.

A: Carbon processes



B: Nitrogen process

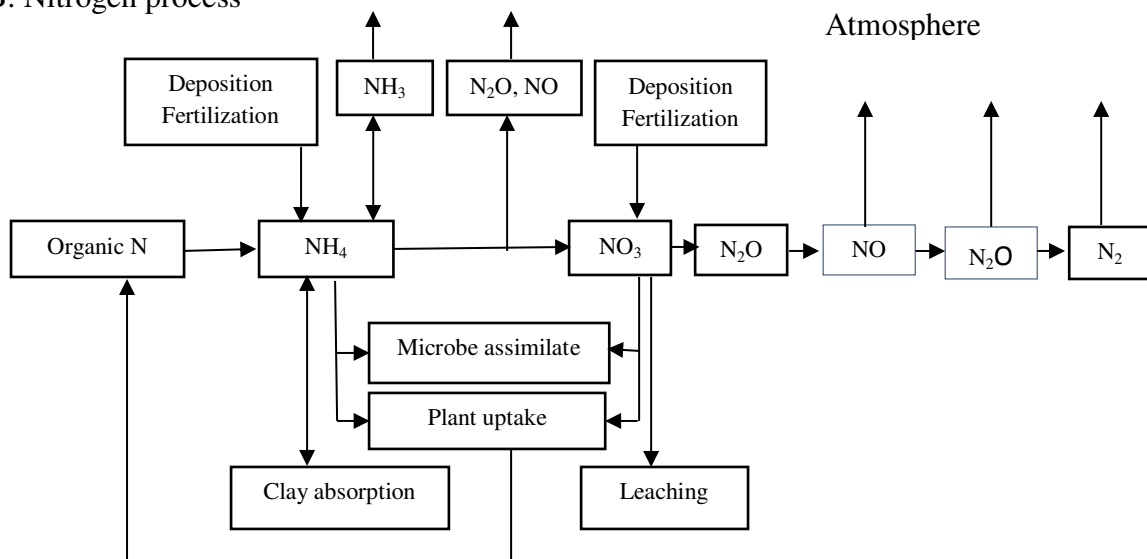


Figure 2.13: (a) Soil carbon and (b) nitrogen pools and their transformation processes considered in the Crop-DNDC model (based on Li et al., 1992a)

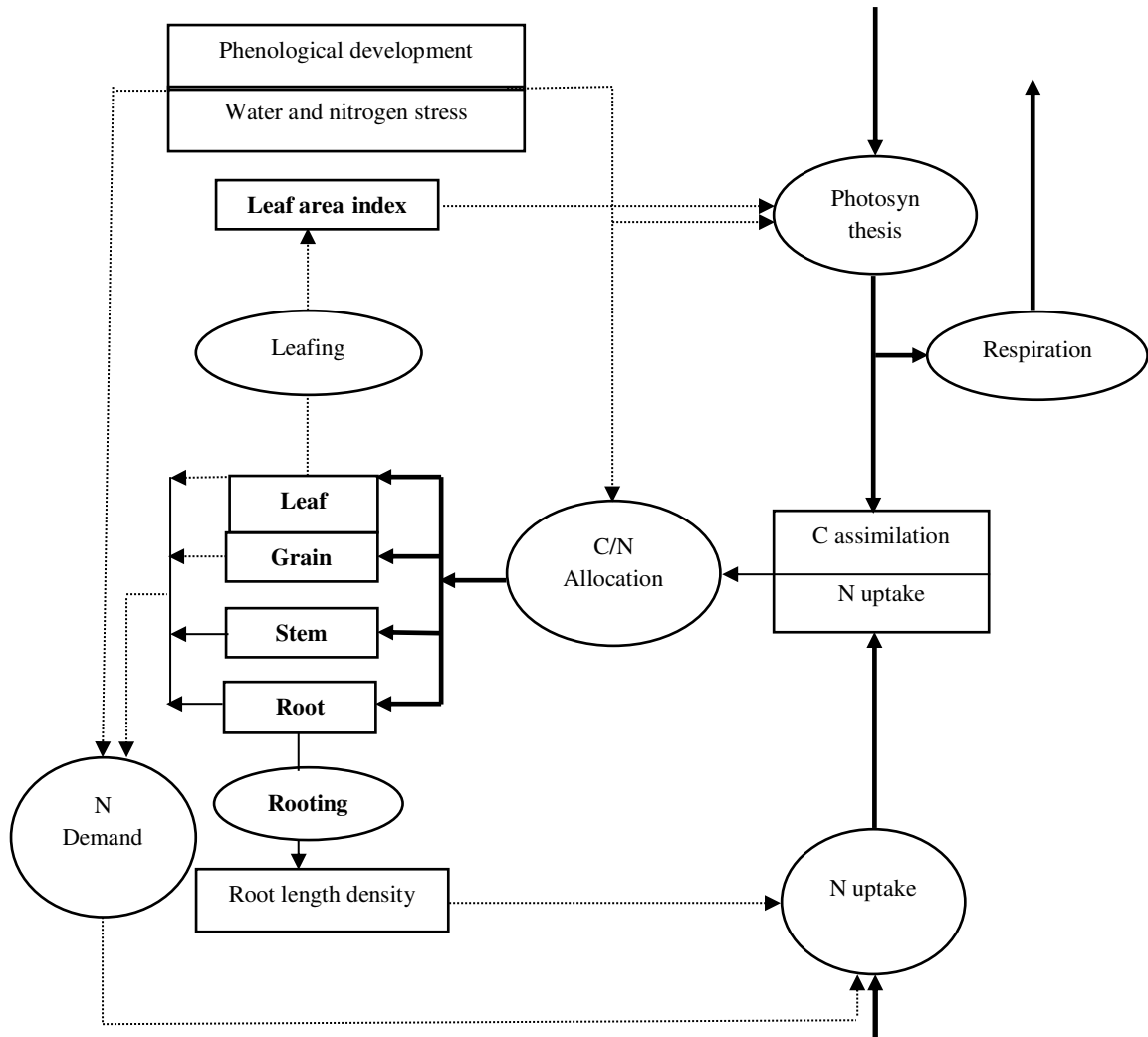


Figure 2.14: The scheme of the crop sub model (rectangles indicate state variables, and circles/ellipses processes: solid lines and dash lines indicate matter flow and information flow respectively).



### **2.8.2 Preparation of input data for modelling**

Daily minimum and maximum temperature and rainfall data were obtained from Shwe Daung farm where field experiment was conducted. Daily data of wind speed, humidity, maximum and minimum temperature were obtained from Meikhtilar weather station that is located 33 km southwest of Shwe Daung farm.

All of soil input data was obtained from the laboratory analyses of soils (Table 2.3). Crop data on yield, crop biomass fractions and biomass C/N ratio were obtained from the data collected from NPK fertilizer application treatment of field experiments and literatures (Table 2.4). Crop yields (grain C kg ha<sup>-1</sup>) were calculated by multiplying the crop yields from field experiments with carbon content of rice grain, chickpea grain and cotton boll.

Management data of rice, chickpea and cotton cultivation followed the management practices applied in field experiments conducted for this research (Table 1.1, 1.2 1.3 and 1.4 of Appendix).

Input data of carbon and nitrogen was calculated based on soil bulk density that was measured in laboratory during water retention measurement (Table 2.5); total carbon and nitrogen of applied biochar materials were measured by Perkin Elmer CHNS/O analyser, U.S.A.

Biochar total carbon was partitioned into fixed carbon and mobile carbon fractions (Table 2.6). How to obtain the fixed carbon and mobile carbon fractions were presented in Chapter 2.6.2. Partitioning of fixed carbon and mobile carbon was needed because labile carbon was applied as ‘manure carbon’ in the crop management section of DNDC model. Although biochar is non-biodegradable, it could be degraded by very slow, non-biological, ambient temperature reactions between carbonized biomass and atmospheric oxygen (McLaughlin et al., 2009). Fixed carbon fractions of biochars were added as soil organic carbon input data under the category ‘soil’. Since fixed carbon can degrade through the time that fixed carbon fraction was partitioned into different fractions of SOC pools: V.I. litter: fraction of very labile litter pool; Resistant Litter: fraction of resistant litter pool; Humads: fraction of humads (active humus) pool; Humus: Fraction of passive humus pool; and char C (Table 2.7). Mean of the partitioning of SOC pools was according to the default parameters provided by the model.

Mobile carbon was applied in modelling as the input for manure application section under the category ‘farming management practices’. Entering model input data for rice husk biochar, rice straw biochar and pigeon pea stem biochar treatments, total nitrogen and mobile carbon were applied as ‘manure carbon’ and ‘nitrogen’. Type of manure, which represented in model parameters for those three biochars was ‘straw manure’ because there was no specific manure

type for rice husk and pigeon pea stem biochars in model parameters of crop management module. For rice husk biochar + FYM mixture, manure type in the model parameters was ‘compost’ because rice husk biochar + FYM mixture was prepared as compost before applying to the experimental plots.

Table 2.3: Soil properties measured after running the field experiments used as input parameters in DNDC model simulation

Parameters	Rice husk	Rice straw	Pigeon pea stem	NPK	Mix	Control
Bulk density	1.6	1.7	1.7	1.8	1.8	1.8
pH	7.6	7.7	7.7	7.8	7.6	7.5
FC %	31	32	32	32	31	29
PWP %	9	10	9	11	10	9.97
Porosity	37	34	33	32	33	32
C org kg kg <sup>-1</sup> soil	0.01	0.006	0.006	0.005	0.005	0.005
Total C from biochar (kg ha <sup>-1</sup> a <sup>-1</sup> )	8278	13958	9239		2172	
Fixed C %	15	2.18	23.51		6.45	
Mobile C%	44	27	67		38	
Fixed C kg ha <sup>-1</sup>	1320	331	2336		151	
Mobile C kg ha <sup>-1</sup>	3875	4096	6656		887	
Total N from biochar (kg ha <sup>-1</sup> a <sup>-1</sup> )	256	118	331		37	
C/N ratio (mobile)	15	35	20.4		24	

Table 2.4: Input crop parameters for DNDC model simulation obtained from NPK fertilizer application treatment of field experiments

Crops	Yield (grain C kg ha <sup>-1</sup> )	Maximum grain yield (grain C kg ha <sup>-1</sup> )	Grain fraction	Leaf fraction	Stem fraction	Root fraction	Grain CN	Leaf CN	Stem CN	Root CN
Rice	1964	3000	0.40	0.26	0.24	0.10	30	39	104	45
Chickpea	479	750	0.40	0.09	0.22	0.22	9.2	13	22	25
Cotton	196	500	0.2	0.34	0.36	0.10	10	10	51	86

Table 2.5: Carbon and nitrogen input data for DNDC model simulation calculated based on total carbon and nitrogen of biochar materials

Biochars	Biochar rate (kg ha <sup>-1</sup> )	Biochar C concentration (%)	Biochar CN	Total C (kg C ha <sup>-1</sup> )	Total N (kg N ha <sup>-1</sup> )	Fixed C fraction	Mobile fraction	Fixed C (kg C ha <sup>-1</sup> )	Mobile C (kg C ha <sup>-1</sup> )
Rh biochar	20000	44	32	8278	256	0.15	0.42	4719	3560
Rs biochar	20000	76	119	13958	118	0.02	0.28	7956	3908
Ps biochar	20000	50	28	9239	331	0.24	0.67	3049	6190
Rh biochar +FYM	10000	23.4	32	2172	37	0.06	0.38	1347	825

Table 2.6: Carbon and nitrogen input data for DNDC model simulation calculated based on fixed and mobile carbons of biochar materials

Biochars	Calculation of N and CN ratio						Total Carbon (kg C ha <sup>-1</sup> )		
	Fixed C & N		(kg ha <sup>-1</sup> a <sup>-1</sup> )	Added mobile C&N (kg ha <sup>-1</sup> a <sup>-1</sup> )			Fixed C (kg C ha <sup>-1</sup> )*	Before biochar addition	After biochar addition
	CN	C	N	CN	C	N			
Rh biochar	500	1321	2.64	15.29	3875	253	2642	18000	20642
Rs biochar	500	331	0.66	34.91	4096	117	662	19125	19787
Ps biochar	500	2336	4.67	20.40	6656	326	4671	19125	23796
Rh biochar+FYM	500	151	0.30	24.18	887	37	301	20250	20551

\* This fixed C added to model equals to the amount of carbon that was applied to two experiments.

Table 2.7: Fixed carbon fractions used as model input for DNDC model simulation calculated according to the default carbon fractionation of the model

Biochars	Fractions			
	Char C	Humus	Humads	Resistant litter
Rh biochar	0.1280	0.8472	0.0160	0.0087
Rs biochar	0.0335	0.9390	0.0178	0.0097
Ps biochar	0.1963	0.7808	0.0148	0.0080
Rh biochar + FYM	0.0146	0.9572	0.0181	0.0099

### 2.8.3 Model testing

Modelled crop and observed crop yields and SOC 0-0.2 m were compared and model accuracy was calculated. As the experiment was conducted for one round of crop rotation, model simulation was done for one cropping cycle and the length of cropping cycle was two years.

In simulating crop yields and soil organic carbon for testing the model fitness, basic climate, soil and crop input data and management parameters were parameterized by NPK sole application treatment to obtain pure impacts of biochars for testing model performance. To simulate the effects of biochar application on crop yields and soil organic carbon, different input parameters with respect to carbon and nitrogen content of biochar materials were used. Fractionation of carbon and nitrogen input parameters were the same as mentioned in section 2.7.2 for model simulation input methods.

Fitness of DNDC model in simulating crop yields were tested by using two parameters, percent bias (PBIAS) and root mean square error (RMSE). RMSE percentage was calculated by the percent of the means of measured values. Coefficient of determination,  $R^2$  value, was also quantified to examine the correlation between model predictions and field measurements. Root mean square error (RMSE) which estimates the variation between simulated and measured values, expressed the same unit as the data (Loague and Green, 1991; Xevi et al., 1996). This parameter can be defined by the following formula:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \text{ ..... Equation 23}$$

Where:

$y_i$  = measured value

$\hat{y}_i$  = simulated value

n = number of observations

RMSE value of zero indicates a perfect fit (Moriasi et al., 2007).

PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts do. Optimal value of PBIAS is 0.0. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999, Moriasi et al., 2007).

$$\text{PBIAS} = 100 \times \frac{\sum_{i=1}^n (S_i - O_i)}{\sum_{i=1}^n O_i} \text{----- Equation (24)}$$

Where:

$S_i$  = simulated value,

$O_i$  = measured value,

$n$  = number of observations

#### **2.8.4 Simulation of the long term impacts of biochar soil applications on crop yields, soil organic carbon and GHG emissions by using DNDC model**

Long term (30 years and 50 years) impact of biochar soil application on crop yields, soil properties and GHGs emission were simulated by using climate, soil and crop input data from field experiments and literatures (Table 1.1, 1.2 and 1.3 in Appendix).

Crop yields, SOC and GHG emissions 30 years after biochar application was carried out by using the last 30 years' climate data (1984-2013). Objective of this simulation was to estimate how biochar application can maintain possible highest crop yields and SOC in soil, and how biochar application can affect GHGs emission under the given climate situations up to 30 years after biochar application compared to inorganic fertilizer application and without input application (control).

Throughout three decades, rainfall in 2012 was the lowest (532 mm a<sup>-1</sup>). Although 82% of mean annual rainfall was received during cropping season (May to September), 20% of that rainfall occurred in May (at sowing time) and 50% occurred in September (at harvesting time). Only 30% of total rainfall during cropping season was received during the important period for both vegetative and reproductive growth stages. Receiving precipitation at the time of maturity will not have any benefit to crop growth and can even damage the harvested crops. To estimate possible crop yields under such climate, SOC and GHGs emission under constantly low rainfall for successive 50 years after biochar application, DNDC model simulation was carried out by using a single year climate data of 2012.

As yield-components and yield of the crop were influenced by water and nitrogen supply (Morrow and Krieg, 1990), in this study, not only crop yields but also simulated crop nitrogen uptake and annual water leaching were compared for 30 years and 50 years after biochar application. In DNDC, water movement was simulated considering the processes of surface

runoff, infiltration, gravitational and matric redistribution, evaporation and transpiration (Zhang et al., 2002). Total water input (TWI) was calculated in model by summation of mean annual precipitation and total amount of irrigated water.

Yield differences of rice, chickpea and cotton due to the effect of biochar application and fresh biomass application (without converting to biochar), were observed by DNDC model simulation. The same climate, soil and crop input data was used in model simulations. Carbon and nitrogen input data were calculated based on total carbon and nitrogen content of rice straw (Li et al., 2013), rice husk (Hafele et al., 2011) and, pigeon pea stem (Gangil and Wakudkar, 2013) (Table 2.8). This observation can help in making decisions on organic and inorganic fertilizer input selection for profitable crop production.

Table 2.8: Carbon and nitrogen input data for DNDC model simulation to estimate the crop yields from rice husk, rice straw and pigeon pea stem raw biomass filed application

Biomass materials	Biomass nutrient content (g kg <sup>-1</sup> DM)			Application rate (kg ha <sup>-1</sup> )*	
	Carbon	Nitrogen	C/N ratio	Carbon	Nitrogen
Rice husk	362	6.9	52	7240	138
Rice straw	379	10.5	36	7580	210
Pigeon pea stem	520	34.6	15	10400	693

\*(20 Mg ha<sup>-1</sup> rate of each raw material was applied)

## 2.9 Statistical Analysis

Differences among the treatments were analysed with one-way analysis of variance (ANOVA). Pairwise comparisons of the differences of mean values between the treatments were tested by Tukey–Kramer highly significant difference (HSD) at 0.95% family-wise confidence level. Interaction effect of cropping seasons and treatments on soil microbial respiration was analysed with two-way analysis of variance (ANOVA). All statistical analyses were carried out using R-statistics version 3.1.0 (R Development Core Team, 2008). Fitness of DNDC model in simulating crop yields were tested by using two parameters, percent bias (PBIAS) and root mean square error (RMSE). Relative root mean square error (RRMSE) was calculated by the percent of the means of observed values. Coefficient of determination, R<sup>2</sup> value, was quantified to examine the correlation between model predictions and field measurements.

## Chapter 3: Results of the Effects of Biochar Applications on Soil Properties

### 3.1 Initial Properties of the Soil of the Experimental Site

Upper 0-0.45 m of the soil of the experimental site (Table 3.1) had a fine sandy loamy texture with silt 56-58%, sand 33-34%, and clay 9%. Bulk density was  $1.8 \text{ g cm}^{-3}$  in upper 0-0.15 m horizon. Plant available was higher in 0.15-0.30 m depth and 0.30-0.45 m depth than the uppermost 0-0.15 m depth. Porosity was not different from the uppermost horizon up to 0.45 m depth. It had  $\text{pH}_{\text{water}}$  of 8.5-9.6 and pH 7.4-8 in  $\text{CaCl}_2$  solution. Soluble salt content was the highest in the upper 0-0.15 m depth,  $190 \text{ CaCO}_3 \text{ g kg}^{-1}$  dry soils, and it was decreased in the lower horizons. Carbonate content was the highest in 0-0.15 m,  $24.54 \text{ CaCO}_3 \text{ g kg}^{-1} \text{ DM}$ , and carbonate content was lower in the lower layers compared to the uppermost layer. Total exchangeable cations were lower in 0.30-0.45 m than the upper two layers. Total exchangeable cation from 0.30- 0.45 m was  $12.6 \text{ me}/100 \text{ g dry soil}$ ,  $17.31 \text{ me}/100\text{g dry soil}$  in 0.15-0.30 m and  $14.52 \text{ me}/100 \text{ g dry soil}$  in 0-0.15 m, respectively.

Table 3.1 Soil properties measured from three soil layers of experimental site, for observing the original soil condition

Soil Properties	0-0.15 m	0.15-0.30 m	0.30-0.45m
pH (water)	9.6	9.2	8.5
pH ( $\text{CaCl}_2$ )	8	7.8	7.4
Carbonate ( $\text{CaCO}_3 \text{ g kg}^{-1}$ )	27.33	18.44	17.57
Soluble salt content (mg /100 g)	190.08	73.92	52.8
Texture	Sandy loam	Sandy loam	Sandy loam
Sand %	33.86	33.61	34.83
Silt%	56.78	57.29	55.64
Clay%	9.35	9.1	9.53
Porosity %	33.74	31.77	32.72
Plant available water %	16.76	22.72	27.11
Total C %DM	0.6	0.44	0.27
Total N %DM	0.04	0.04	0.01
C/N ratio	15	12.43	27
Total exchangeable cations me/100 g	14.52	17.31	12.62
Exchangeable Ca me/100 g	7.93	11.09	7.2
Exchangeable Mg me/100 g	4.28	4.98	4.39
Exchangeable K me/100 g	0.27	0.28	0.27
Exchangeable Na me/100 g	2.01	0.93	0.7
Exchangeable Al me/100 g	0.04	0.04	0.05
Exchangeable Sodium Percent (ESP)	36.91	9.31	13.03
Sodium Adsorption ratio (SAR)	1.15	0.46	0.41

### 3.2 Physical and Chemical Properties of Four Biochar Materials used in Field Experiments

Yield of rice husk biochar, rice straw biochar, and pigeon pea stem biochar (Fig. 3.1) were calculated based on biochar weight per biomass dry weight. Biochar yield in weight-by-weight percent of biochars and dry feedstocks were rice husk biochar 54%, rice straw biochar 30% and pigeon pea stem biochar 29%, respectively. Properties of four biochar materials used in the field experiments were measured in the laboratory. Rice straw biochar had the highest pH, EC, carbonate content, total carbon, exchangeable cations, ash content and water holding capacity among all biochars (Table 3.2). Since it contained higher total carbon and lower total nitrogen compared to the others, carbon to nitrogen ratio of rice straw biochar was the highest among four biochar materials (Fig. 3.2). Total value of exchangeable cations in rice straw biochar was the highest compared to the other three biochars due to higher proportion of exchangeable sodium among exchangeable cations (Fig 3.3).



Figure 3.1: Biochars used in field experiments (a) pigeon pea stem biochar (b) rice straw biochar (c) rice husk biochar



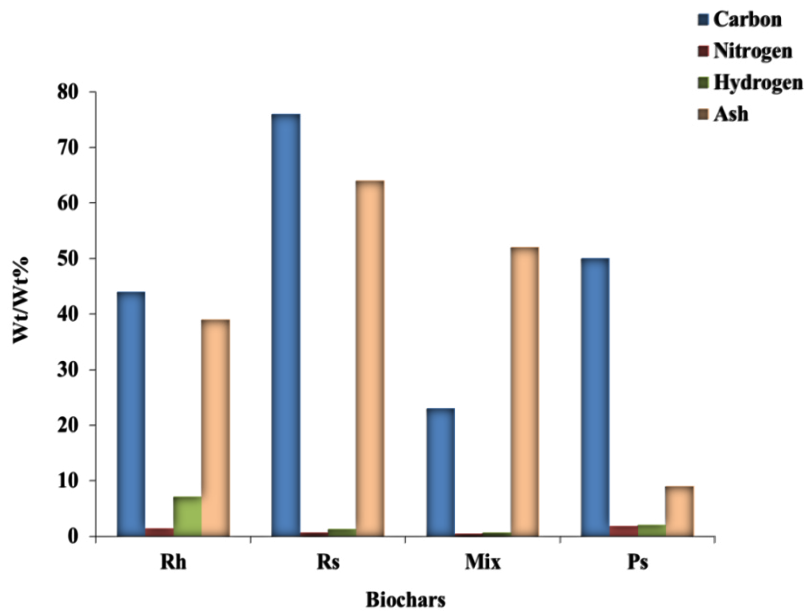


Figure 3.2: Total carbon, total nitrogen, hydrogen and ash content of biochars (wt. /wt. %) (Rh= rice husk biochar, Rs = rice straw biochar, Mix = rice husk biochar and farmyard manure mixture, Ps = pigeon pea stem biochar)

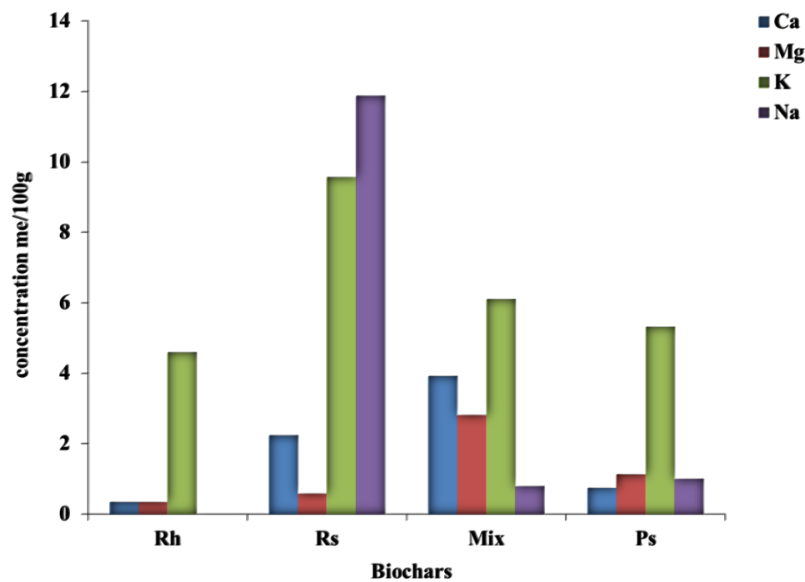


Figure 3.3: Exchangeable bases in biochars (Rh= rice husk biochar, Rs= rice straw biochar, Mix = rice husk biochar and farmyard manure mixture (FYM), Ps = pigeon pea stem biochar)

Table 3.2: Properties of four biochars used in the experiments

	Rice husk	Rice straw	Pigeon pea stem	Rice husk biochar + FYM
pH (CaCl <sub>2</sub> )	8.2	10.28	9.14	7.62
EC (mS cm <sup>-1</sup> )	1.91	8.1	3.44	2.47
CaCO <sub>3</sub> (g kg <sup>-1</sup> )	1.82	36.28	30.55	1.87
Total C DM%	44	76	50	23
Total N DM%	1.36	0.64	1.76	0.4
C/N ratio	32	119	28.22	32
Hydrogen %	7.06	1.24	1.97	0.65
Moisture content, wt. %	6.38	8.11	6.43	7.03
Ash content, wt.%	38	62	8	12
Exchangeable Ca (me/100g biochar)	0.35	2.23	0.74	3.92
Exchangeable Mg (me/100g biochar)	0.35	0.59	1.13	2.81
Exchangeable Na (me/100g biochar)	0	11.88	1	0.79
Exchangeable K (me/100g biochar)	4.6	9.57	5.32	6.1
CEC (me/100g biochar)	5.29	24.28	8.19	13.63
Maximum WHC, volumetric%	320	553	568	261

### 3.3 Effects of Biochars on Soil Properties

#### 3.3.1 Bulk density, porosity and soil water retention

Bulk density was reduced in biochar treated plots compared to the control and NPK fertilizer sole application in 2013 after harvesting cotton (Table 3.3). Bulk densities of soils from the experimental plots ranged between 1.60 g cm<sup>-3</sup> and 1.80 g cm<sup>-3</sup> after harvesting cotton. After the second biochar application, slight changes of soil bulk density were observed. Bulk density of the control and NPK fertilizer application remained the same as the initial condition (1.8 g cm<sup>-3</sup>). Bulk density decreased by 12.50% in Rh biochar variant, 5.88% in Rs biochar, Ps biochar, and Rh biochar + FYM mixture, respectively, compared to initial soil bulk density.

Although porosity was not significantly different ( $p \geq 0.05$ ) among the treatments, certain levels of changes were found in soils treated with biochar. Soils of the control and NPK fertilizer application showed the lowest porosity, 33.96% and 33.34% respectively. The highest porosity value was found in the Rh biochar variant (38.37%), followed by Rs biochar application (35.85%), Ps biochar application, and Rh biochar + FYM mixture application (34.59%).

At field capacity, rice straw biochar applied soils showed the highest water content. Water content was the lowest in soils from the control. NPK fertilized soils showed almost the same water holding capacity at field capacity (FC) as Ps biochar applied soils, 32.04% and 32.20%

respectively. Soils from Rh biochar application and Rh biochar + FYM mixture application showed the same water content at field capacity, 30.86% and 30.75%, respectively.

At field capacity, although soil of Ps biochar application contained the same percent of water filled pore space like soils of NPK fertilizer sole application and Rs biochar application, Ps biochar applied soils had the highest percent of plant available water among all of the six treatments (Table 3.5). Ps biochar applied soils held less amount of water at permanent wilting point (8.86%) than the soils of other treatments. The highest amount of water was held in the soils of NPK fertilizer sole application at permanent wilting point.

In 2012 after rice harvest, water-holding capacities of Rh-, Rs- and Ps biochar applied soils were higher than that of the control. On the other hand, water-holding capacity of NPK fertilizer and Rh biochar + FYM mixture applied soils was lower than the control. In 2013, after harvesting cotton, water-holding capacities of Rh-, Rs- and Rh biochar + FYM mixture applied soils were higher and that of Ps biochar and NPK fertilizer variants was lower than the control (Table 3.5).

Table 3.3: Bulk density, porosity, water filled pore space% at permanent wilting point and field capacity, available water content and maximum water holding capacity (mean±standard error, n=3) of topsoil (0-0.20 m) after biochar applications in 2012 rice growing season and 2013 cotton growing season compared to NPK fertilizer application and the control

Treatments	Bulk Density (g cm <sup>-3</sup> )	Porosity (%)	Water content at FC (volume %)	Water content at PWP (volume %)	Available water capacity (volume %)	Water holding capacity (%)	
	2013	2013	2013	2013	2013	2012	2013
Rh biochar	1.6±0.07 a	39.0±2.52 a	31.0±2.30 a	9.0±1.31 a	22.0±3.60 a	38.0±1.02 A	41.0±2.01 a
Rs biochar	1.7±0.06 a	36.0±2.18 a	32.0±3.34 a	10.0±0.66 a	22.0±3.60 a	39.0±0.73 A	38.0±2.30 a
Ps biochar	1.7±0.03 a	35.0±1.26 a	32.0±3.09 a	9.0±1.33 a	23.0±4.29 a	38.0±3.09 A	36.0±1.08 a
NPK	1.8±0.03 a	33.0±1.26 a	32.0±3.39 a	11.0±1.02 a	21.0±3.37 a	36.0±1.17 A	34.0±1.68 a
Mix	1.7±0.03 a	35.0±1.26 a	31.0±1.05 a	10.0±0.32 a	21.0±0.76 a	35.0±0.56 A	37.0±0.50 a
Control	1.8±0.00 a	34.0±0.07 a	30.0±1.34 a	10.0±1.06 a	20.0±1.13 a	38.0±2.10 A	37.0±1.25 a

Common letters in the columns indicate that means are not significantly different ( $p \geq 0.05$ ).

### 3.3.2 pH

Changes of pH after biochar applications were not significantly different among the treatments in both years ( $p \geq 0.05$ ) (Table 3.4). At the time of rice harvest, soil pH value was the lowest in Rh biochar application and the highest in Ps biochar application. After the second biochar application at the time of cotton harvest, pH values were the same in Rs- and Ps biochar application, NPK fertilizer application, and Rh biochar + FYM mixture application (7.7) and in Rh biochar application and the control (7.6), respectively.

### 3.3.3 Soluble salt content

In 2012, after harvesting rice, soluble salt content (KCl %) of soils in all treatments were between 0.01-0.02%. There was no significant difference between biochar treated soils and the control ( $p \geq 0.05$ ) in both years (Table 3.4). Rh biochar treated soils had the lowest soluble salt content and soils from NPK fertilizer, Ps biochar and Rh biochar + FYM mixture application had the highest soluble salt contents. In 2013, after harvesting cotton, soluble salt content of soils increased by 0.04-0.06% compared to the preceding year. The highest amount of soluble salt content was found in Rs biochar applied soils and NPK fertilizer applied soils in 2013. The lowest amount of soluble salts was found in control, Rh and Ps biochar applied soils. Soluble salt content of experimental plots were lower than the negligible level of salinity effects on cultivated crops (Table 3.5).

Table 3.4: pH and soluble salt content (mean $\pm$ standard error, n=3) of soils after biochar applications in two cropping seasons. Soil samples were collected after harvesting rice in 2012 and after harvesting cotton in 2013 from 0-0.20 m soil depth

Treatments	pH (in CaCl <sub>2</sub> )		Soluble salt content (KCl %)	
	2012	2013	2012	2013
Rh biochar	7.3 $\pm$ 0.23A	7.6 $\pm$ 0.03a	0.01 $\pm$ 0.01A	0.04 $\pm$ 0.01a
Rs biochar	7.8 $\pm$ 0.02A	7.7 $\pm$ 0.09a	0.01 $\pm$ 0.01A	0.06 $\pm$ 0.01a
Ps biochar	8.0 $\pm$ 0.17A	7.7 $\pm$ 0.09a	0.01 $\pm$ 0.01A	0.04 $\pm$ 0.01a
NPK	7.8 $\pm$ 0.08A	7.7 $\pm$ 0.15a	0.01 $\pm$ 0.01A	0.06 $\pm$ 0.02a
Rh biochar + FYM	7.7 $\pm$ 0.22A	7.7 $\pm$ 0.07a	0.02 $\pm$ 0.01A	0.05 $\pm$ 0.01a
Control	7.7 $\pm$ 0.14A	7.6 $\pm$ 0.07a	0.02 $\pm$ 0.01A	0.04 $\pm$ 0.02a

Common letters in the columns represent means are not significantly different ( $p \geq 0.05$ ).

Table 3.5: Evaluation of salinity (General Classification of ECe values (Landon, 1991))

USDA soil class	Designation	ECe (mS cm <sup>-1</sup> )	Total salt content (%)	Crop reaction
0	Salt free	0-2	< 0.15	Salinity effects are mostly negligible
		0-2	< 0.5	Salinity effects are negligible except for the most sensitive plants
1	Slightly saline	4-8	0.15-0.35	Yields of many crops restricted
2	Moderately saline	8-15	0.35-0.65	Only tolerant crops yield satisfactorily
3	Strongly saline	> 15	> 0.65	Only very tolerant crops yield satisfactorily

### 3.3.4 Carbonate content

In 2012 after harvesting rice, carbonate content of the soils in all treatments was not significantly different ( $p \geq 0.05$ ). Carbonate content of the soil of Ps biochar, NPK fertilizer and Rh biochar + FYM mixture was lower than that of Rs biochar, Rh biochar variant as well as that of the control. In 2013, after harvesting cotton, carbonate content of soils from all experimental plots was lower than that of preceding year (Fig. 3.4). Carbonate content of Rh biochar application differed significantly ( $p < 0.05$ ) from the other treatments in 2013, after harvesting cotton (Table 3.6). In the year 2013, the highest carbonate content was found in Ps biochar variant and the lowest in Rh biochar variant (Table 3.7).

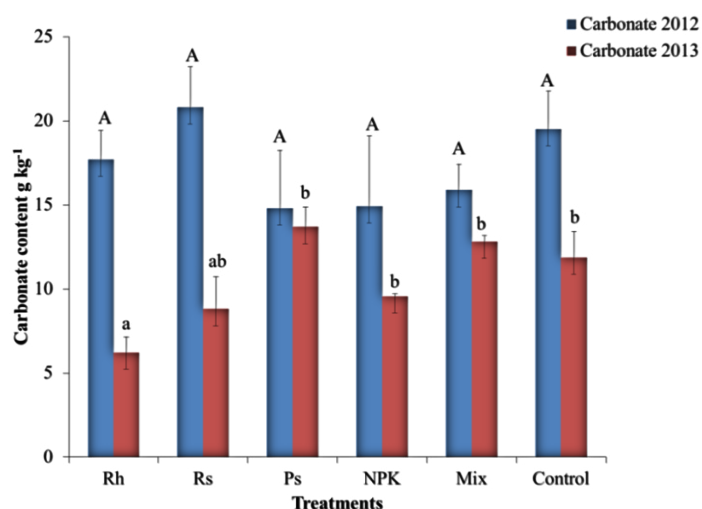


Figure 3.4: Carbonate content (g kg<sup>-1</sup>) (mean and standard error, n=3) of soils (0-0.2 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs- and Ps biochar and 10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Different letters above the error bars indicate the significant differences among the treatments ( $p < 0.05$ ). Common letters above the error bars represent that means are not significantly different ( $p \geq 0.05$ ).

Table 3.6: Tukey multiple comparisons of mean values of carbonate content in soils (0-0.20 m) after harvesting cotton (95% family-wise confidence level)

Treatments	Rh	Rs	Ps	NPK	Mix
Rs	0.6412				
Ps	0.0079	0.1056			
NPK	0.0172	0.2174	0.9965		
Mix	0.0186	0.2350	0.9943	0.9999	
Control	0.0493	0.4912	0.8765	0.9870	0.9913

Table 3.7: CaCO<sub>3</sub> (g kg<sup>-1</sup>) (mean±standard error, n=3) in topsoil (0-0.20 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs-, and Ps biochar and 10 Mg ha<sup>-1</sup> of Rh biochar + FYM mixture, in 2012 rice growing season and 2013 cotton growing season compared to control and conventional NPK application

Treatments	Carbonate 2012	Carbonate 2013
Rh	17.70 ± 1.72A	6.21 ± 0.93a
Rs	20.80 ± 2.42A	8.81 ± 1.90ab
Ps	14.81 ± 3.43A	13.69 ± 1.17b
NPK	14.91 ± 4.18A	9.57 ± 0.16b
Mix	15.88 ± 1.53A	12.82 ± 0.37b
Control	19.50 ± 2.25A	11.86 ± 1.57b

Within columns, different letters indicate that the treatments are significantly different ( $p < 0.05$ ), common letters represent that means are not significantly different ( $p \geq 0.05$ ).

### 3.3.5 Total organic carbon, total nitrogen, and carbon to nitrogen ratio

Total organic carbon TOC was significantly different among the treatments in both growing seasons ( $p < 0.05$ ) (Fig. 3.5), (Table 3.8). In 2012 after harvesting rice, TOC of soil was the lowest in the NPK fertilizer treatment (9.72% < control) (Table 3.9). Soils of Rh biochar applied plots showed 52.66% higher TOC than control. The highest amount of TOC was found in Rh biochar variant. The second highest TOC was found in Ps biochar applied soils (12% > control), followed by Rs biochar applied soils (8% > control).

In 2013 after harvesting cotton, TOC of biochar applied soils increased significantly compared to the control and NPK fertilizer variant ( $p < 0.05$ ) (Table 3.10). The highest TOC was found in Rh biochar treatment (169% > control), and the lowest was found in the control. In 2013, TOC of control and NPK treatments decreased by 28% and 22% respectively, compared to the previous year, and increased by 31.36% in Rs biochar application, 27% in Rh biochar application, 13% in Rh biochar + NPK mixture application, respectively. Ps biochar treatments did not show any changes of TOC between 2012 and 2013 measurements.

Total nitrogen was significantly different among the treatments in 2012 ( $p < 0.05$ ) (Table 3.11) and no significant difference was found among the treatments in 2013 after harvesting cotton ( $p \geq 0.05$ ) (Fig. 3.6). In 2012 after harvesting rice, total nitrogen was the highest in Rh biochar + FYM mixture applied soils followed by the control, NPK, Rh biochar, Rs biochar

and Ps biochar, respectively. In 2013 after harvesting cotton, total N in soils of all treatments decreased compared to total N after rice harvest in 2012, except for Ps biochar application. Total N increased by 10.53% in Ps biochar application. Total N decreased by 90.7% in the control, 88.84% in Rh biochar + FYM mixture application, 88% in NPK fertilizer sole application, 78% in Rh biochar application, and 69% in Rs biochar application, respectively. Carbon to nitrogen (C/N) ratio was significantly different among the treatments in both years ( $p < 0.05$ ) (Fig. 3.7). As total C increased and total N decreased, carbon to nitrogen ratio became wider in 2013 compared to 2012. In 2012 after harvesting rice, C/N ratio of the soils from Ps biochar application showed significant difference among all treatments (Table 3.12). In 2013 after harvesting cotton, significant differences of mean C/N ratio were found among the treatments ( $p < 0.05$ ) (Table 3.13). C/N ratio was the widest in soils of Rh biochar application, followed by Ps biochar application, Rs biochar application, control, Rh biochar + FYM mixture application and, NPK fertilizer application, respectively.

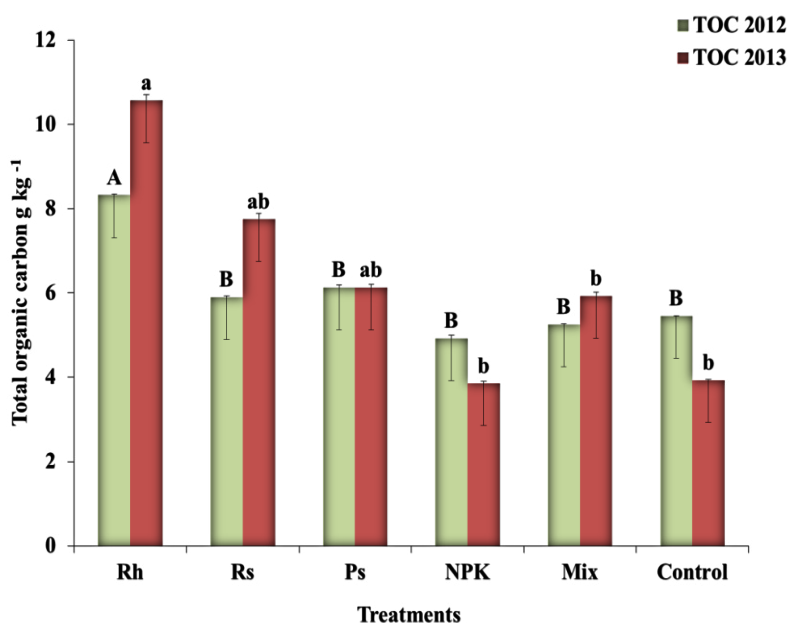


Figure 3.5: Total organic carbon ( $\text{g kg}^{-1}$ ) (mean and standard error,  $n=3$ ) of soils (0-0.20 m) after biochar application,  $20 \text{ Mg ha}^{-1}$  Rh-, Rs- and Ps biochar and  $10 \text{ Mg ha}^{-1}$  Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Different letters above the error bars indicate the significant differences ( $p < 0.05$ ). Common letters above the error bars indicate that treatments are not significantly different ( $p \geq 0.05$ ).

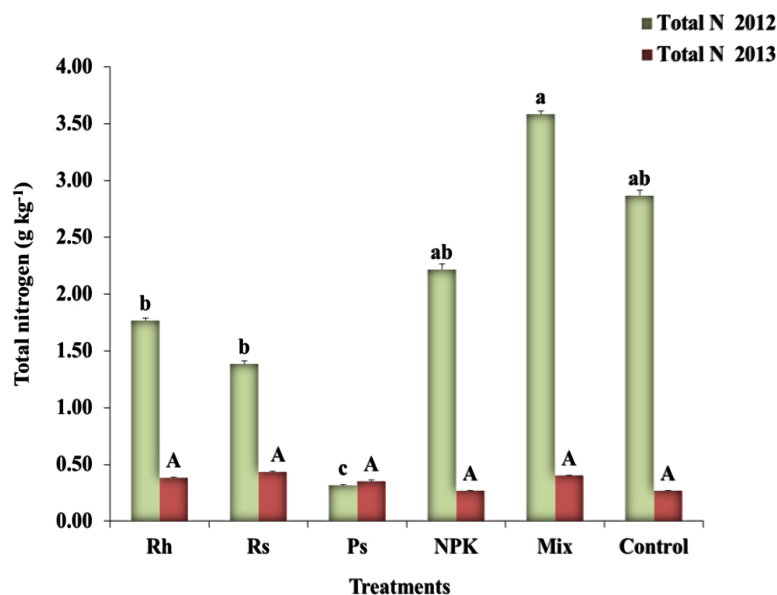


Figure 3.6: Total nitrogen ( $\text{g kg}^{-1}$ ) (mean and standard error,  $n=3$ ) of soils (0-0.20 m) after biochar applications,  $20 \text{ Mg ha}^{-1}$  Rh-, Rs- and Ps biochar and  $10 \text{ Mg ha}^{-1}$  Rh biochar + FYM mixture in 2012 and 2013. Different letters above the error bars indicate the significant differences ( $p < 0.05$ ). Common letters above the error bars indicate that means are not significantly different ( $p \geq 0.05$ ).

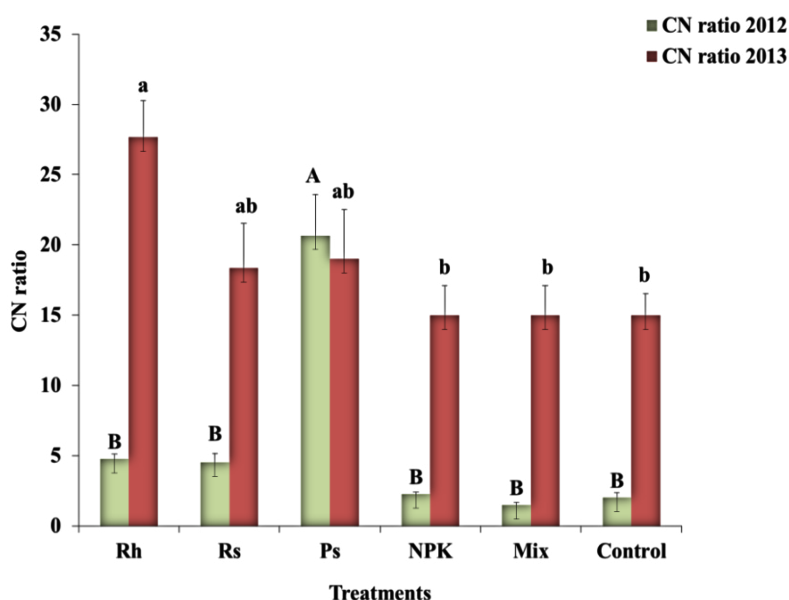


Figure 3.7: Carbon to nitrogen ratio (C/N), (mean and standard error,  $n=3$ ) of soils (0-0.20 m) after biochar applications,  $20 \text{ Mg ha}^{-1}$  Rh-, Rs- and Ps biochar and  $10 \text{ Mg ha}^{-1}$  Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Different letters above the error bars indicate the significant differences ( $p < 0.05$ ). Common letters above the error bars represent that means are not significantly different ( $p \geq 0.05$ ).



Table 3.8: Effect of biochar applications on total carbon and total nitrogen (mean±standard error) in top soil (0-0.20 m), after harvesting rice in 2012 and after harvesting cotton in 2013

Treatments	Total Carbon (g kg <sup>-1</sup> )		Total Nitrogen (g kg <sup>-1</sup> )		CN ratio	
	2012	2013	2012	2013	2012	2013
Rh biochar	8.32±0.03 A	10.57±0.14 a	1.77±0.02 b	0.38±0.01 A	4.78±0.35 B	27.81±2.64 a
Rs biochar	5.9±0.04 B	7.75±0.14 ab	1.38±0.03 b	0.43±0.01 A	4.27±0.65 B	18.02±3.13 ab
Ps biochar	6.13±0.06 B	6.13±0.08 ab	0.32±0.01 c	0.35±0.01 A	19.15±2.91 A	17.51±3.48 ab
NPK	4.92±0.08 B	3.85±0.05 b	2.22±0.05 ab	0.27±0.01 A	2.22±0.15 B	14.25±1.07 b
Mix	5.25±0.0 B	5.93±0.10 b	3.58±0.03 a	0.40±0.01 A	1.47±0.19 B	14.82±1.95 b
Control	5.45±0.01 B	3.93±0.02 b	2.87±0.05 ab	0.27±0.01 A	2.01±0.35 B	14.55±1.46 b

Within the rows, different letters indicate that the treatments are significantly different ( $p < 0.05$ ), common letters indicate that the treatments are not significantly different ( $p \geq 0.05$ )

Table 3.9: Tukey multiple comparisons of mean values of total carbon content of soils (0-0.20 m) in each treatment after harvesting rice in 2012 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.026				
Ps	0.044	0.999			
NPK	0.002	0.665	0.488		
Mix	0.005	0.913	0.780	0.994	
Control	0.008	0.974	0.895	0.999	0.999

Table 3.10: Tukey multiple comparisons of mean values of total carbon in soils (0-0.20 m) of each treatment after harvesting cotton in 2013 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.370				
Ps	0.062	0.837			
NPK	0.004	0.120	0.590		
Mix	0.050	0.778	0.999	0.659	
Control	0.004	0.130	0.617	1.000	0.686

Table 3.11: Tukey multiple comparisons of mean values of total nitrogen in soils (0-0.20 m) of each treatment after harvesting rice (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.952				
Ps	0.076	0.281			
NPK	0.913	0.481	0.015		
Mix	0.023	0.006	0.000	0.106	
Control	0.255	0.068	0.002	0.758	0.681

Table 3.12: Tukey multiple comparisons of mean values of CN ratio of soils (0-0.20 m) in each treatment after harvesting rice in 2012 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.999				
Ps	0.000	0.000			
NPK	0.707	0.787	0.000		
Mix	0.456	0.538	0.000	0.997	
Control	0.622	0.708	0.000	0.999	0.999

Table 3.13: Tukey multiple comparisons of mean values of CN ratio of soils (0-0.20 m) in each treatment after harvesting cotton in 2013 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.148				
Ps	0.193	0.999			
NPK	0.003	0.232	0.179		
Mix	0.028	0.908	0.839	0.731	
Control	0.031	0.922	0.858	0.707	1.000

### 3.3.6 Soil microbial respiration

Soil microbial respiration rate (SR) was higher in biochar-applied soils compared to the control and NPK fertilizer application in both years, after harvesting rice in 2012 and after harvesting cotton in 2013. No significant difference was found among the treatments ( $p \geq 0.05$ ) (Table 3.14).

After harvesting rice in 2012, basal respiration (BR) in Rh biochar + FYM mixture treated soil was 21.52% higher than that of the control, followed by Rs biochar (20.04%), NPK (18.48%), and Rh biochar (5.95%), respectively higher than the control. Basal respiration of Ps biochar applied soil was 10.41% lower than that of the control.

After harvesting cotton in 2013, basal respiration (BR) rates of variants were higher than that of the control. The highest amount of emitted CO<sub>2</sub> was found in the Rs biochar and Rh biochar applications (35.78% > control), the lowest was found in the control. Amount of CO<sub>2</sub> emission in BR analysis was higher in 2013 compared to 2012. It was increased by 37.01% in Rh biochar, by 29.04% in Ps biochar, and by 25.92% in Rs biochar, by 16.74% in Rh biochar + FYM mixture, 5.94% in NPK fertilizer applications, and 7.76% in the control, respectively.

After harvesting rice in 2012, substrate induced respiration (SIR) of biochar and fertilizer treatments were higher than that of control. The highest SIR was found in Rs biochar application (27.17% > control), followed by Rh biochar + FYM mixture, Rh biochar, Ps biochar and the NPK fertilizer application, respectively (Fig. 3.8). After harvesting cotton in 2013, SIR was the highest in Rs biochar variant (62.06% > control), followed by Rh biochar application (51.81%), Rh biochar + FYM mixture application (50.14%), Ps biochar

application (32.66%), and NPK fertilizer application (26.04%), compared to the control. In 2013, SIR of the treatments increased compared to previous year. SIR increased by 62.06% in the Rs biochar application, 56.82% in the Rh biochar application, 51.73% in the Rh biochar + NPK mixture application, 41.61% in the Ps biochar application, 35.87% in the NPK fertilizer application and by 27.17% in the control, compared to 2012.

For the interpretation of the response of SIR to the treatments, the ratio of biomass carbon to soil organic carbon ( $\text{mg Cmic g}^{-1} \text{Corg}$ ) were quantified based on mean values of the amount of carbon respired by substrate induced respiration (SIR) and total organic carbon. There are two kinds of values for the interpretation of soil biological parameters: reference values and comparative values. Comparative values allow the general evaluation of the results without considering chemical and physical properties (Rohr, 2010). In current analysis, mean values of ecological quotient ( $\text{mg Cmic g}^{-1} \text{Corg}$ ) of the treatments from both rice growing season and cotton growing season were compared. Interaction effects of biochars and cropping seasons on SIR was quantified by two-way ANOVA (Table 3.15). Response of ecological quotient to the treatments was significantly different ( $p < 0.05$ ) and the response of ecological quotient to the seasons was significantly different among the treatments ( $p < 0.001$ ). No significant difference was found among the treatments with the interaction effects of cropping season and biochars ( $p \geq 0.05$ ) and significant differences were found among the treatments without interaction ( $p \leq 0.05$ ) (Fig. 3.9).

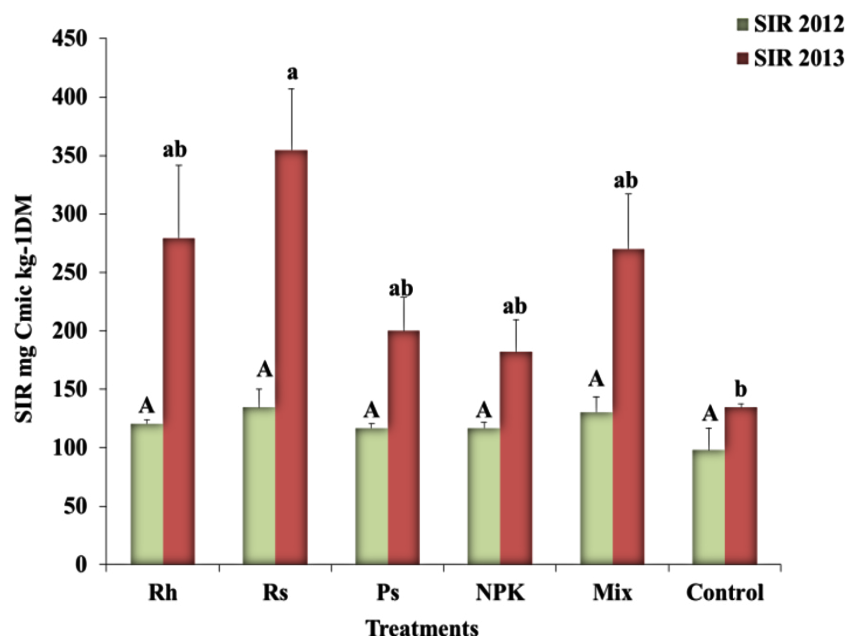


Figure 3.8: Substrate induced respiration (mean and standard error, n=3) of soils (0-0.20 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs- and Ps biochar and 10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Different letters above the error bars indicate the significant differences ( $p < 0.05$ ). Common letters above the error bars represent that means are not significantly different ( $p \geq 0.05$ ).

Table 3.14: Basal- and substrate induced respirations (mean±standard error, n=3) of soils after biochar applications in the two cropping seasons. Soil samples were collected after harvesting rice in 2012 and after harvesting cotton in 2013 from 0-0.20 m.

Treatments	Basal Respiration (mg C kg <sup>-1</sup> h <sup>-1</sup> )		Substrate Induced Respiration (mg Cmic kg <sup>-1</sup> )		Ecological Quotient (mg Cmic g <sup>-1</sup> Corg)	
	2012	2013	2012	2013	2012	2013
Rh biochar	18±0.42A	29±3.96a	121±3.39A	279±62.35ab	14.5±0.09A	28.4±9.62a
Rs biochar	22±7.86A	29±3.96a	135±15.61A	354±52.50a	22.7±1.23A	47.0±6.94a
Ps biochar	16±1.80A	22±6.32a	117±4.04A	200±28.76ab	19.4±2.16A	33.8±6.91a
NPK	21±3.06A	23±4.79a	117±4.86A	182±27.71ab	25.1±4.46A	47.0±1.65a
Rh biochar + FYM	22±2.56A	26±4.37a	13±13.48A	170±27.06ab	25.3±3.98A	46.9±5.31a
Control	17±6.44A	19±2.04a	98±18.86A	135±2.80b	17.8±3.03A	34.4±2.32a

Common letters in the columns represent means are not significantly different ( $p \geq 0.05$ ). Different letters in the columns represent that means are significantly different ( $p < 0.05$ ).

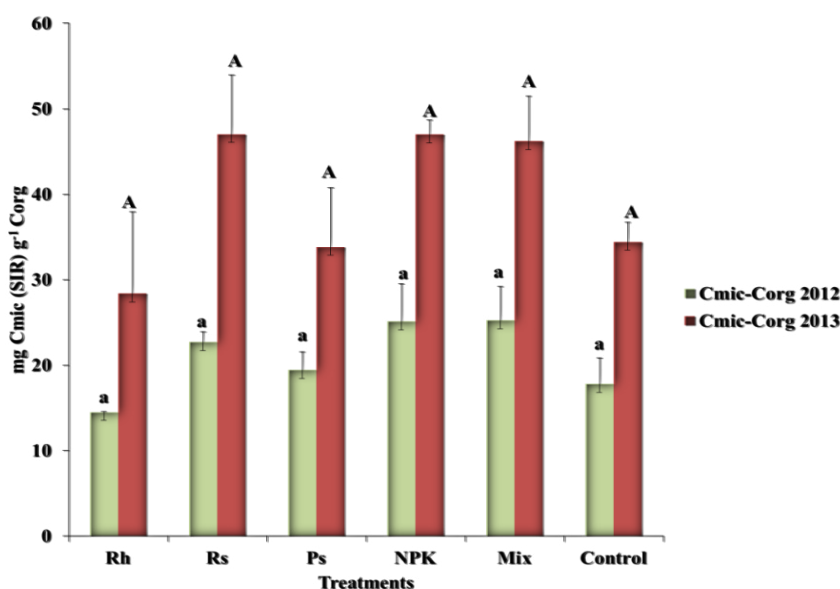


Figure 3.9: Ecological quotient (mg Cmhc g<sup>-1</sup> Corg) (mean and standard error, n=3) of soils (0-0.20 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs- and Ps biochar and 10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Different letters above the error bars indicate the significant differences (p < 0.05) Common letters above the error bars represent that means are not significantly different (p ≥ 0.05).

Table 3.15: Analysis of variance table of the response of ecological quotient (mg Cmhc g<sup>-1</sup> Corg), to the treatments (Rh biochar, Rs biochar, Ps biochar, NPK fertilizers, Rh biochar + FYM and control), the cropping seasons (upland and lowland cropping seasons), and the interaction effects of biochar applications and the cropping seasons

	Df	Sum sq	Mean sq	F value	Pr (>F)
Biochar	5	1156.1	231.2	3.354	0.0194*
Season	1	3140.3	3140.3	45.547	5.57e-07***
Biochar: Season	5	140.3	28.1	0.407	0.8392
Residuals	24	1654.7	68.9		

Significant codes: 0 “\*\*\*” 0.001 “\*\*” 0.01 “\*” 0.05 “.” 0.1 “1”

### 3.3.7 Exchangeable cations

Total of exchangeable cations was not significantly different among the treatments (p ≥ 0.05) (Fig. 3.10) in both years. Total exchangeable cation of initial soil before starting the experiment was 1.16 and major cation was calcium (1.14me/100 g). In 2012 after harvesting rice, total exchangeable cations of control increased to 13.01me/100 g. The highest amount of total exchangeable cations was found in Rs biochar applied soil, followed by the NPK fertilizer application, Ps biochar application, Rh biochar + FYM mixture, and Rh biochar application, respectively (Table 3.16). In 2013 after harvesting cotton, total exchangeable cation from control was nearly the same as that of 2012 (13.42me/100 g). Among the other treatments, the highest total exchangeable cation value was found in Rs biochar application

(10.75% > control), followed by Rh biochar, Ps biochar, NPK fertilizer, and Rh biochar + FYM mixture variant, respectively (Table 3.16).

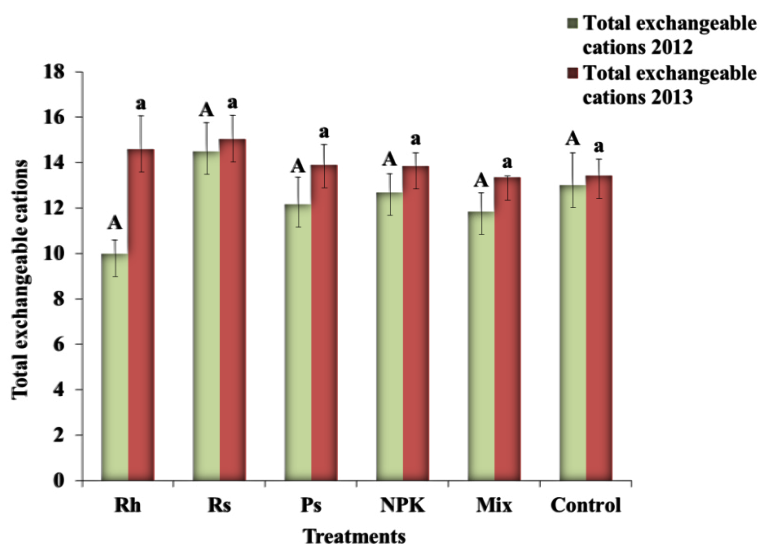


Figure 3.10: Total exchangeable cations (mean and standard error, n=3) of soils (0-0.20 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs- and Ps biochar and 10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Common letters above the error bars represent that means are not significantly different ( $p \geq 0.05$ ).

Table 3.16: Exchangeable cations and total exchangeable cations (mean±standard error) of topsoil (0-0.20 m) after biochar applications in 2012 rice growing season and 2013 cotton growing season

Treatments	Exchangeable Ca (me/100g)		Exchangeable Mg (me/100g)		Exchangeable K (me/100g)		Exchangeable Na (me/100g)		Total exchangeable cations (me/100g)	
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Rh biochar	6.3±0.37A	8.6±0.76a	3.3±0.24A	5.2±0.71a	0.25±0.03A	0.28±0.02b	0.19±0.03A	0.53±0.07ab	10±0.60A	15±1.49a
Rs biochar	8.7±0.94A	8.5±0.76a	5.3±0.21A	4.4±0.31a	0.32±0.09A	1.68±0.03a	0.21±0.06A	0.46±0.04a	15±1.28A	15±1.05a
Ps biochar	8.6±0.12A	8.5±0.60a	3.3±1.11A	4.5±0.29a	0.24±0.01A	0.39±0.06b	0.10±0.01A	0.44±0.05b	12±1.21A	14±0.90a
NPK	7.9±0.48A	8.7±0.17a	4.2±0.30A	4.3±0.45a	0.33±0.05A	0.25±0.05b	0.28±0.09A	0.53±0.19ab	13±0.83A	14±0.57a
Rh biochar + FYM	7.5±0.78A	7.8±0.19a	4.0±0.09A	4.3±0.05a	0.2±0.03A	0.32±0.04b	0.16±0.03A	0.87±0.13ab	12±0.81A	13±0.07a
Control	9.2±0.71A	7.7±0.49a	3.4±0.81A	4.5±0.30a	0.25±0.04A	0.27±0.04b	0.15±0.03A	0.97±0.06b	13±1.41A	13±0.74a

Within the columns, different letters indicate that the treatments are significantly different ( $p < 0.05$ ), and same letters indicate that the treatments are not significantly different ( $p \geq 0.05$ )

In both years, exchangeable Ca was not significantly different among the treatments ( $p \geq 0.05$ ) (Fig. 3.11). In 2012, after harvesting rice, exchangeable Ca in all treatments was lower compared to the control. In 2013, after harvesting cotton, exchangeable Ca of the treatments except control increased compared to the previous year. The highest exchangeable Ca was found in the soil of NPK fertilizer application, followed by Rh biochar, Rs biochar, Ps biochar, and Rh biochar + FYM mixture application, respectively. In 2013, exchangeable Ca decreased by 20% in the control compared to previous year. Although exchangeable Ca decreased in Rs biochar and Ps biochar variants, the rate of reduction was lower than 2% compared to the preceding year. After harvesting cotton in 2013, exchangeable Al in soils increased in all treatments compared to 2012. The highest amount of exchangeable Al was found in the control and the lowest amount in Rs biochar application.

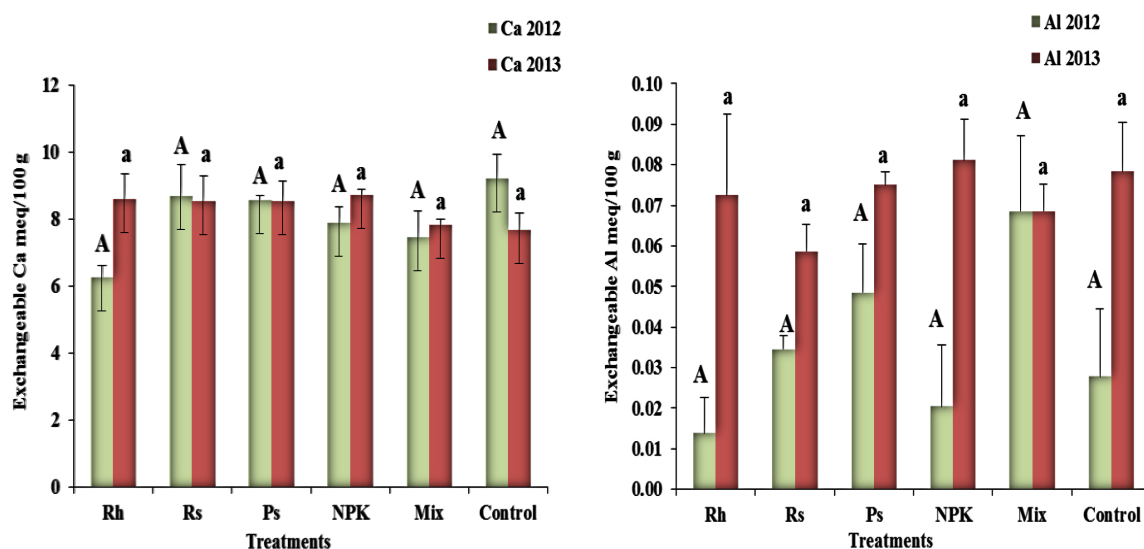


Figure 3.11: Exchangeable calcium and Exchangeable aluminum (mean and standard error,  $n=3$ ) of soils (0-0.20 m) after biochar applications  $20 \text{ Mg ha}^{-1}$  Rh-, Rs- and Ps biochar and  $10 \text{ Mg ha}^{-1}$  Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Same letters above the error bars indicate that treatments are not significantly different ( $p \geq 0.05$ ).

The difference in exchangeable Mg among treatments was not significant ( $p \geq 0.05$ ) in both years (Fig. 3.12). In 2012 after harvesting rice, exchangeable Mg of Rh biochar and Ps biochar applied soils were 3.12% and 4.02% respectively lower than that of control. The highest exchangeable Mg was found in Rs biochar applied soil (35.65% > control). After harvesting cotton in 2013, the same level of exchangeable Mg was found in all treatments except Rh biochar application. Rh biochar applied soils had higher exchangeable Mg than the control (13% > control).



Exchangeable K was not significantly different among the treatments in 2012 ( $p \geq 0.05$ ). In 2012 after harvesting rice, the highest exchangeable K was found in NPK fertilizer applied soils ( $22\% >$  control), followed by Rs biochar application, Ps biochar application, and Rh biochar + FYM mixture application, respectively (Fig. 3.12). The highest amount of exchangeable K was found in Rs biochar applied soils after harvesting cotton in 2013 as Rs biochar contained the highest exchangeable K compared to the other three biochars (Fig. 3.12). In 2013, exchangeable K was significantly different among the treatments ( $p < 0.05$ ) (Table 3.17). Exchangeable K of the control and NPK application treatments decreased compared to the previous year. Exchangeable K of biochar treated soils increased in 2013 by, 80.88% in Rs biochar applied soils, 40.41% in Ps biochar applied soils, 35.55% in Rh biochar + FYM mixture applied soils and 8.26% in Rh biochar applied soils, respectively compared to 2012.

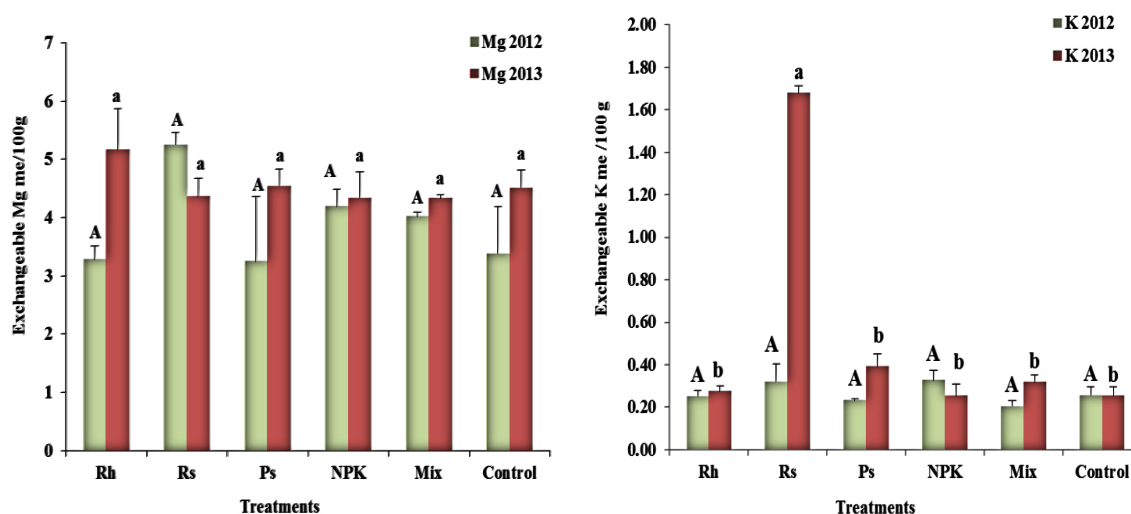


Figure 3.12: Exchangeable magnesium and potassium (mean and standard error,  $n=3$ ) of soils (0-0.20 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs- and Ps biochar and 10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Same letters above the error bars indicate that treatments are not significantly different ( $p \geq 0.05$ ). Different letters above the error bars indicate the significant differences ( $p < 0.05$ ).

Table 3.17: Tukey multiple comparisons of mean values of exchangeable K after harvesting cotton in 2013 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.000				
Ps	0.432	0.000			
NPK	0.999	0.000	0.261		
Mix	0.976	0.000	0.823	0.872	
Control	0.999	0.000	0.281	0.999	0.893

### 3.3.8 Exchangeable sodium percent

The effect of biochar applications on exchangeable Na was not significantly different among the treatments in 2012 after harvesting rice ( $p > 0.05$ ) (Fig. 3.13). In 2012, after harvesting rice, the highest exchangeable Na was found in NPK fertilizer applied soils (45.32% > control). The lowest exchangeable Na was found in Ps biochar applied soils (57% < control). In 2013, after harvesting cotton, exchangeable Na increased in all treatments compared to 2012 and significantly different among the treatments ( $p < 0.05$ ) (Table 3.18). The highest amount of exchangeable Na was found in the control and Rh biochar + FYM mixture application. Rh biochar, Rs biochar, Ps biochar and NPK fertilizer applied soils had lower exchangeable Na than the control.

Exchangeable sodium percent (ESP) was not significantly different among the treatments in 2012 after harvesting rice (Fig. 3.13) (Table 3.19). ESP was the highest in NPK fertilizer applied soils (41% > control). The second highest ESP was found in soils of Rh biochar applied plots, (33% > control). The lowest ESP was found in Ps biochar applied soils (58% < control). After harvesting cotton in 2013, ESP was significantly different among the treatments ( $p < 0.05$ ). Among biochar treatments, the highest ESP was found in Rh biochar + FYM applied soils. Among all treatments, the highest ESP was found in the control followed by Rh biochar + FYM mixture, NPK fertilizer application, Rh biochar, Ps biochar, and Rs biochar application, respectively.

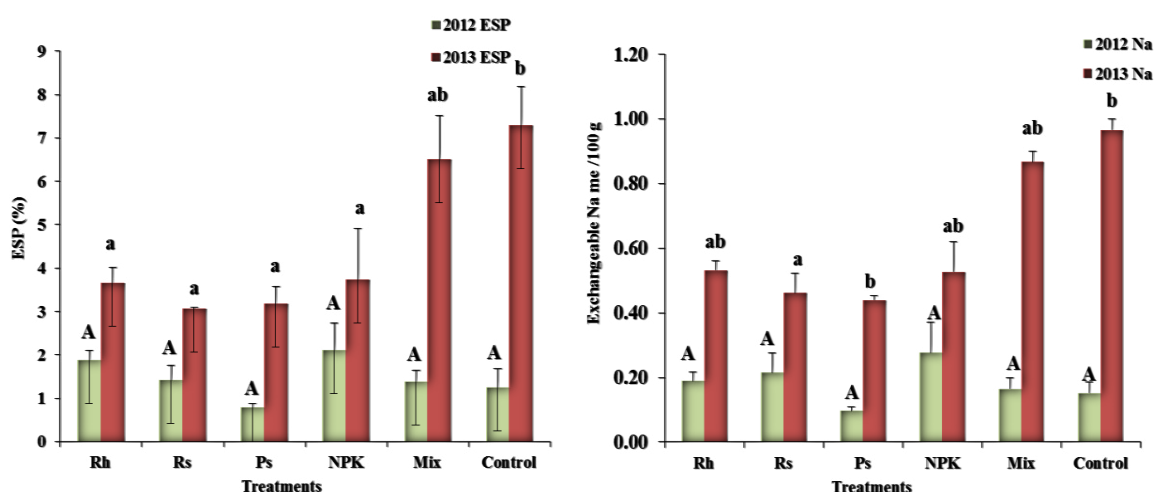


Figure 3.13: Exchangeable sodium and exchangeable sodium percent ESP (mean and standard error,  $n=3$ ) of soils (0-0.20 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs- and Ps biochar and 10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Same letters above the error bars indicate that treatments are not significantly different ( $p \geq 0.05$ ). Different letters above the error bars indicate that treatments are significantly different ( $p < 0.05$ )

Table 3.18: Tukey multiple comparisons of mean values of Exchangeable Na after harvesting cotton in 2013 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.995				
Ps	0.986	0.999			
NPK	1.000	0.997	0.990		
Mix	0.285	0.136	0.110	0.267	
Control	0.102	0.045	0.036	0.095	0.982

Table 3.19: Tukey multiple comparisons of mean values of ESP after harvesting cotton in 2013 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.993				
Ps	0.997	0.999			
NPK	0.999	0.988	0.995		
Mix	0.163	0.068	0.081	0.181	
Control	0.050	0.020	0.024	0.056	0.975

### 3.3.9 Sodium adsorption ratio

Sodium adsorption ratio (SAR) in 2012 was not significantly different among the treatments ( $p \geq 0.05$ ) (Fig. 3.14) (Table 3.20) and (Table 3.21). The highest SAR was found in soils of NPK fertilizer applied plots, (43.65% > control) and the second highest SAR was found in Rh biochar applied soils (27.58% > control), followed by Rs biochar and the Rh biochar + FYM mixture application. The lowest SAR was found in Ps biochar applied soils (57.79 % < control). In 2013 after harvesting cotton, SAR of all treatments was lower than that of the control. SAR of all treatments had increased compared to the previous year. According to the classification and properties of salt-affected soils by Havlin et al., 2014, (Table 3.22), soil from the experimental plots were in normal condition, without affected by salts, except having alkaline pH.

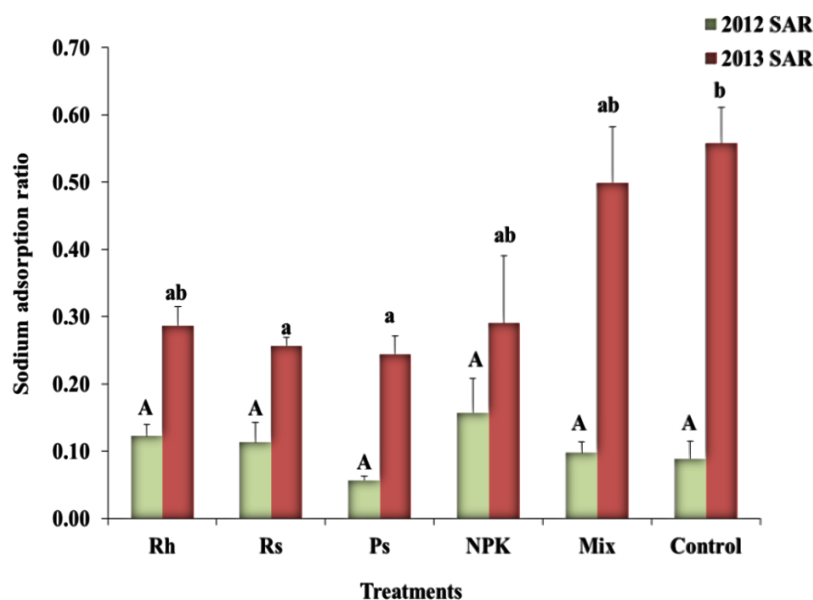


Figure 3.14: Sodium adsorption ratio (mean and standard error, n=3) of soils (0-0.20 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs- and Ps biochar and 10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Same letters above the error bars indicate that treatments are not significantly different ( $p \geq 0.05$ ). Different letters above error bars indicate the significant differences ( $p < 0.05$ ).

Table 3.20: Tukey multiple comparisons of mean values of sodium adoption ratio after harvesting cotton in 2013 (95% family-wise confidence level)

Treatments	Rh	Rs	Ps	NPK	Mix
Rs	0.999				
Ps	0.995	0.999			
NPK	1.000	0.998	0.992		
Mix	0.204	0.118	0.091	0.216	
Control	0.066	0.037	0.028	0.071	0.977

Table 3.21: Sodium adsorption ratio (mean±standard error, n=3) of top soil (0-0.20 m) after biochar applications in 2012 rice growing season and 2013 cotton growing season

Treatments	SAR		ESP	
	2012	2013	2012	2013
Rh biochar	0.12±0.02A	0.29±0.03ab	1.89±0.22A	3.66±0.36a
Rs biochar	0.11±0.03A	0.26±0.01a	1.43±0.33A	3.06±0.04a
Ps biochar	0.05±0.01A	0.24±0.03a	0.79±0.08A	3.18±0.39a
NPK	0.16±0.05A	0.29±0.10ab	2.11±0.62A	3.73±1.19a
Rh biochar + FYM	0.10±0.02A	0.50±0.08ab	1.39±0.25A	6.5±1.01ab
Control	0.09±0.03A	0.56±0.05b	1.25±0.42A	7.3±0.89 b

Within the columns, different letters indicate that the treatments are significantly different ( $p < 0.05$ ), and common letters indicate that the treatments are not significantly different ( $p \geq 0.05$ )

Table 3.22: Classification and properties of salt-affected soils (Havlin et al., 2014)

Classification	ECe (mmho cm <sup>-1</sup> )*	Soil pH	ESP%	Physical Condition
Saline	>4	<8.5	<15	Normal
Sodic	<4	>8.5	>15	Poor
Saline-sodic	>4	<8.5	>15	Normal

### 3.3.10 Available potassium

Significant differences in changes of available potassium were found among the treatments in both years ( $p < 0.05$ ) (Fig. 3.15) (Table 3.23) (Table 3.24) and (Table 3.25). After harvesting rice in 2012, the highest available K was found in soils of Rh biochar + FYM mixture application and the lowest was found in soils of Rh biochar application. The second highest amount of available K was found in Ps biochar application, followed by Rs biochar application, control and NPK fertilizer application, respectively. After harvesting cotton in 2013, available K of all biochar applied soils and NPK fertilizer applied soils were higher than that of control. Significant increment of available K was found in soils of Rs biochar application. After harvesting cotton in 2013, the highest available K was found in Rs biochar applied soil (94% > control), followed by Ps biochar application (64.77% > control), NPK fertilizer application (47.04% > control), Rh Biochar + FYM mixture application (43.81% > control), and Rh biochar application (38.96% > control), respectively.

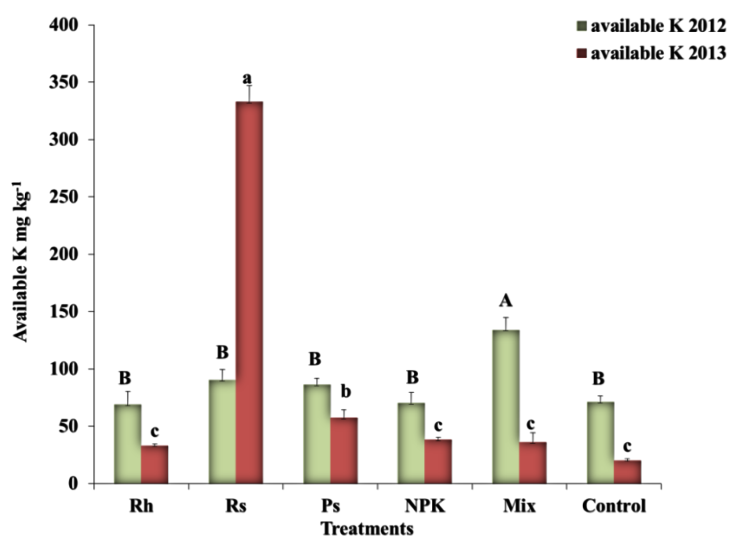


Figure 3.15: Plant available potassium (mean and standard error,  $n=3$ ) in topsoil (0-0.20 m) after biochar applications, 20 Mg ha<sup>-1</sup> Rh-, Rs- and Ps biochar and 10 Mg ha<sup>-1</sup> Rh biochar + FYM mixture in 2012 rice growing season and 2013 cotton growing season. Same letters above the error bars indicate that treatments are not significantly different ( $p \geq 0.05$ ). Different letters above the error bars indicate that treatments are significantly different ( $p < 0.05$ ).

Table 3.23: Tukey multiple comparisons of mean values of available K after harvesting rice in 2012 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.541				
Ps	0.722	0.999			
NPK	0.999	0.614	0.789		
Mix	0.002	0.039	0.023	0.003	
Control	0.999	0.650	0.820	0.999	0.003

Table 3.24: Tukey multiple comparisons of mean values of available K after harvesting cotton in 2013 (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.000				
Ps	0.235	0.000			
NPK	0.995	0.000	0.453		
Mix	0.999	0.000	0.347	0.999	
Control	0.797	0.000	0.031	0.521	0.644

Table 3.25: Available potassium (mean±standard error) of topsoil (0-0.20 m) after biochar applications in 2012 rice growing season and 2013 cotton growing season

Treatments	Available K (mg kg <sup>-1</sup> )	
	2012	2013
Rh biochar	68.78±11.57A	59.29±2.78b
Rs biochar	90.32±8.96A	594.40±24.86a
Ps biochar	86.37±5.73A	102.74±11.98b
NPK	70.36±9.00A	68.34±3.69b
Rh biochar + FYM	134.00±10.69A	64.40±14.38b
Control	71.15±5.07A	36.19±2.81b

Common letters in the columns indicate that means are not significantly different ( $p \geq 0.05$ ) and different letters indicate that means are significantly different ( $p < 0.05$ ).

## Chapter 4: Results of the Effects of Biochar Applications on the Growth and Yield of the Crops

### 4.1 Effects on Rice Growth and Yield

#### 4.1.1 Effects of the treatments on rice crop growth

The effects of biochars on crop growth were not significantly different from that of the control and NPK fertilizers application (Table 4.1). Crop growth stages were differentiated according to BBCH-scales for rice by Lancashire et al. (1991).

Differences of plant height were not statistically significant among the treatments ( $p \geq 0.05$ ) although rice plants from the control plots were shorter than the plants of other treatments (Table 4.1). Maximum plant height was found in plants of Rs biochar application, followed by Rh biochar, NPK fertilizer, Ps biochar, Rh biochar + FYM mixture application, and the control, respectively.

Flag leaf length was not significantly different among the treatments ( $p \geq 0.05$ ) (Table 4.1). The longest flag leaf was found in Ps biochar application, followed by Rh biochar, Rh biochar + FYM mixture, NPK fertilizer application, Rs biochar application and the control, respectively.

Panicle length was not significantly different among the treatments ( $p \geq 0.05$ ) (Table 4.1). The highest panicle length was found in Rs biochar application, followed by Ps biochar, NPK fertilizer application, Rh biochar, Rh biochar + FYM mixture application, and the control, respectively.

Table 4.1: Rice grain yield ( $\text{kg ha}^{-1}$ ), plant height (m), panicle length (m), flag leaf length (m) and straw yield ( $\text{kg ha}^{-1}$ ), (mean $\pm$ standard error,  $n=3$ ), of experimental plots after biochar application in 2012 rice growing season compared to the control and NPK fertilizer application

Growth factors	Rh	Rs	Ps	NPK	Mix	Control
Yield ( $\text{kg ha}^{-1}$ )	6176 $\pm$ 407a	5177 $\pm$ 181ab	6616 $\pm$ 465a	4270 $\pm$ 368b	5167 $\pm$ 86b	2939 $\pm$ 29c
Tiller nr. per hill	11.13 $\pm$ 0.40a	11.67 $\pm$ 0.44a	11.58 $\pm$ 0.44a	10.79 $\pm$ 0.11a	11.38 $\pm$ 0.44a	11.63 $\pm$ 0.14a
Plant height (m)	1.29 $\pm$ 6.35a	1.30 $\pm$ 8.22a	1.27 $\pm$ 5.47a	1.29 $\pm$ 3.97a	1.23 $\pm$ 2.06a	1.14 $\pm$ 2.39a
Panicle length (cm)	24.67 $\pm$ 0.51a	25.42 $\pm$ 0.05a	25.17 $\pm$ 0.92a	25.11 $\pm$ 0.58a	24.39 $\pm$ 0.31a	23.61 $\pm$ 0.15a
Flag leaf length (cm)	26.98 $\pm$ 0.56a	25.08 $\pm$ 1.67a	30.06 $\pm$ 1.45a	25.31 $\pm$ 0.20a	26.25 $\pm$ 1.66a	24.78 $\pm$ 0.09a
Straw yield ( $\text{kg ha}^{-1}$ )	12000 $\pm$ 0.23	14000 $\pm$ 0.11	15 000 $\pm$ 0.26	13000 $\pm$ 0.07	14000 $\pm$ 0.11	9000 $\pm$ 0.13
	a	a	a	a	a	a

Common letters in the rows indicate that mean values are not significantly different ( $p \geq 0.05$ ). Different letters in the rows indicate that mean values are significantly different ( $p < 0.05$ ).

#### **4.1.2 Effects of the treatments on yield and yield components of rice**

Rice yield was significantly different among the treatments ( $p < 0.05$ ) (Table 4.2). The highest rice yield was obtained from Ps biochar application (125% higher than control and 55% higher than NPK fertilizer application). The lowest yield was found in control. The second highest rice yield was obtained from Rh biochar application (110% higher than control, 45% higher than NPK fertilizer application), followed by Rs biochar (76% higher than control, 21% higher than NPK fertilizer application), Rh biochar + FYM mixture (76% higher than control, 21% higher than NPK fertilizer application), and NPK fertilizer application (45% higher than control), respectively (Fig. 4.1).

The larger the tiller numbers the more chance for getting high yield when the tillers bear fertile spikelet. In the present research, total number of tillers per hill was not significantly different among the treatments ( $p \geq 0.05$ ) (Table 4.3). All treatments including control had total tiller numbers of between 9 and 12.

Number of fertile spikelet per panicle was significantly different among the treatments ( $p < 0.05$ ) (Fig 4.2) and (Table 4.4). The highest number of fertile spikelet per panicle was found in Ps biochar application. The second highest number of fertile spikelet per panicle was found in Rh biochar application followed by Rs biochar, Rh biochar + FYM mixture, NPK fertilizer application, and the lowest number of fertile spikelet per panicle was found in control.

Percent unfilled grains was significantly different among the treatments ( $p < 0.05$ ) (Fig. 4.3) and (Table 4.5). The highest number of unfilled grains was found in Ps biochar application, followed by control, Rh biochar + FYM mixture, Rh biochar, Rs biochar, and NPK fertilizer application, respectively.

Thousand grain weights were significantly different among the treatments ( $p < 0.05$ ) (Fig. 4.4) and (Table 4.6). There was no significant difference between biochar treatments and NPK fertilizer application ( $p \geq 0.05$ ). The highest thousand grain weight was found in Rh biochar application (35% > control). The second highest thousand-grain weight was found in Ps biochar treatment followed respectively by Rs biochar, Rh biochar + FYM mixture, and NPK fertilizer application, respectively.

Harvest index was significantly different among the treatments ( $p < 0.05$ ) (Fig. 4.5) and (Table 4.7). The highest harvest index was found in Rh biochar application followed by Ps biochar, Rs biochar, Rh biochar + FYM mixture, NPK fertilizer application, and the control, respectively.



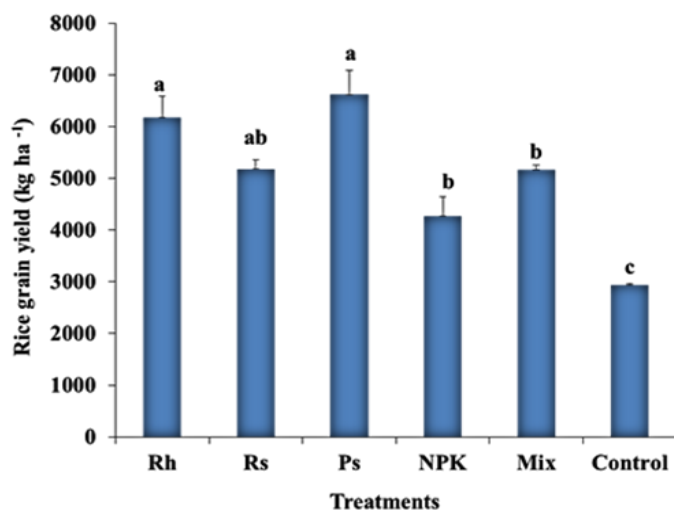


Figure 4.1: Effect of biochar applications (20 Mg ha<sup>-1</sup>, Rh-, Rs-, Ps- biochars and 10 Mg ha<sup>-1</sup> Rh biochar + FYM) on rice yields (mean and standard error, n=3) compared to NPK fertilizer application and the control. Different letters above the error bars indicate the significant differences between treatments ( $p < 0.05$ ).

Table 4.2: Tukey multiple comparisons of mean rice yields (95% family-wise confidence level)

Treatments	Rh	Rs	Ps	NPK	Mix
Rs	0.259				
Ps	0.903	0.052			
NPK	0.009	0.347	0.002		
Mix	0.251	1.000	0.050	0.357	
Control	0.000	0.002	0.000	0.079	0.002

Table 4.3: Thousand grain weight (g), number of spikelet per panicle, total tiller per hill, percent unfilled grain, and harvest index, (mean±standard error, n=3), of experimental plots after treated with biochar in 2012 rice growing season compared to the control and NPK fertilizer application

Yield factors	Rh	Rs	Ps	NPK	Mix	Control
1000 grain weight (g)	30±0.37a	29±0.47a	30±0.54a	28±0.57a	29±0.34a	19±0.65b
Nr. of fertile spikelet per panicle	57±4.16a	48±0.77ab	60±2.76a	43±3.18b	46±2.43b	41±1.1b
% unfilled grain	5±0.12cd	5±0.20cd	11±0.12a	4±0.78d	6±0.29bc	8±0.64b
Harvest Index	52±2.67a	39±0.13b	44±0.05ab	34±0.10b	37±0.03b	33±0.08b

Within the rows, different letters indicate that the treatments are significantly different ( $p < 0.05$ ), common letters indicate that the treatments are not significantly different ( $p \geq 0.05$ ).

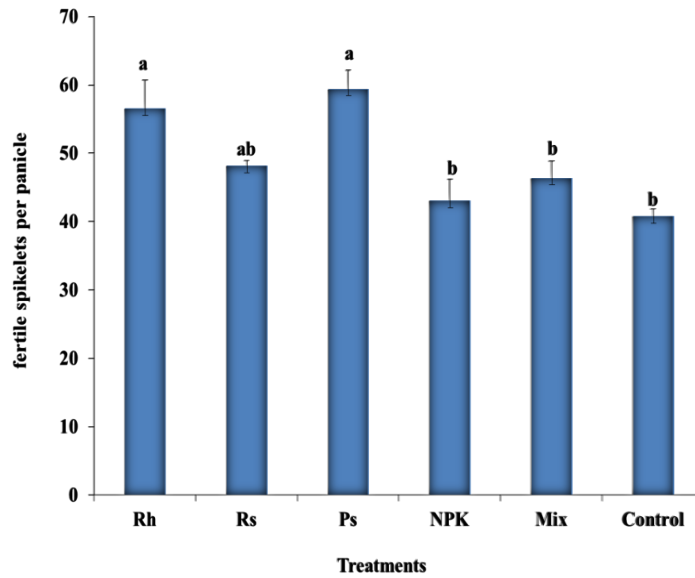


Figure 4.2: Effect of biochar applications (20 Mg ha<sup>-1</sup>, Rh-, Rs-, Ps biochars and 10 Mg ha<sup>-1</sup> Rh biochar + FYM) on the number of fertile spikelet per panicle of rice (mean and standard error, n=3) compared to NPK fertilizer application and the control. Different letters above the error bars indicate the significant differences between treatments ( $p < 0.05$ ).

Table 4.4: Tukey multiple comparisons of mean values of fertile spikelet per panicle (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.295				
Ps	0.969	0.093			
NPK	0.035	0.754	0.009		
Mix	0.149	0.996	0.043	0.943	
Control	0.012	0.417	0.003	0.988	0.675

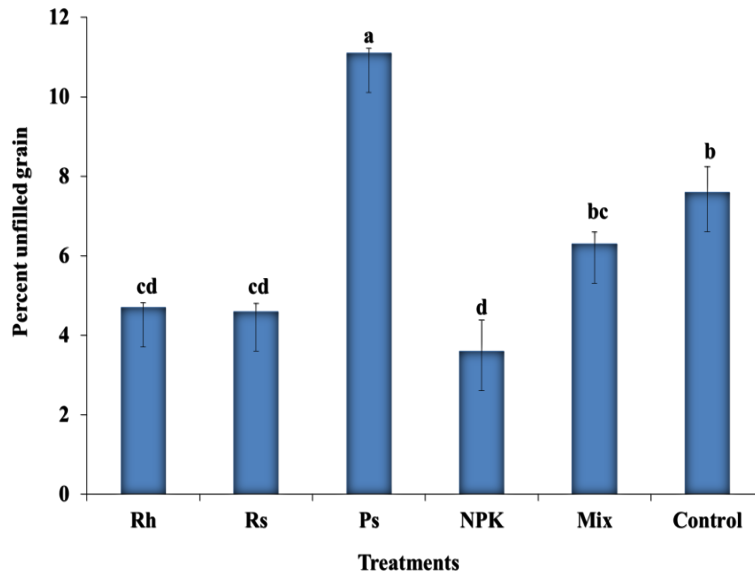


Figure 4.3: Percent unfilled grain of rice (mean and standard error, n=3) in each biochar application (20 Mg ha<sup>-1</sup>, Rh-, Rs-, Ps biochars and 10 Mg ha<sup>-1</sup> Rh biochar + FYM) compared to NPK fertilizer application and the control. Different letters above the error bars indicate the significant differences between the treatments (p < 0.05)

Table 4.5: Tukey multiple comparisons of mean values of percent unfilled grain (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.999				
Ps	0.000	0.000			
NPK	0.518	0.612	0.000		
Mix	0.154	0.119	0.000	0.008	
Control	0.005	0.004	0.001	0.000	0.357

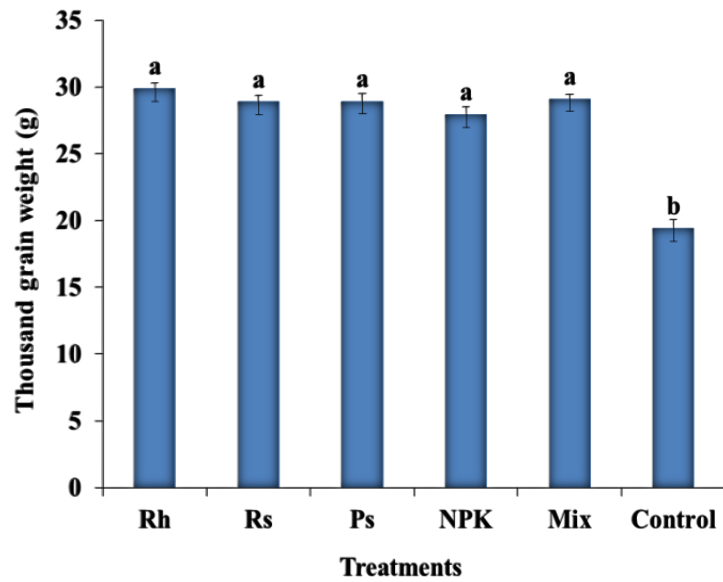


Figure 4.4: Thousand grain weight of rice (mean and standard error, n=3) in each biochar application (20 Mg ha<sup>-1</sup>, Rh-, Rs-, Ps biochars and 10 Mg ha<sup>-1</sup> Rh biochar + FYM) compared to NPK fertilizer application and the control. Common letters above the error bars indicate that treatments are not significantly different ( $p \geq 0.05$ )

Table 4.6: Tukey multiple comparisons of mean values of 1000 grain weight (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.722				
Ps	0.761	0.999			
NPK	0.142	0.775	0.739		
Mix	0.883	0.999	0.999	0.589	
Control	0.000	0.000	0.000	0.000	0.000

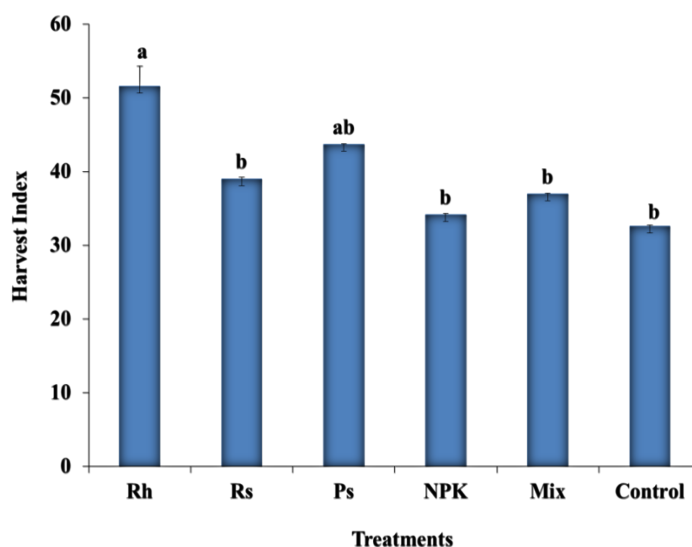


Figure 4.5: Harvest index of rice (mean and standard error, n=3) in each biochar application (20 Mg ha<sup>-1</sup>, Rh-, Rs-, Ps biochars and 10 Mg ha<sup>-1</sup> Rh biochar + FYM) compared to NPK fertilizer application and the control. Different letters above the error bars indicate the significant differences among the treatments ( $p < 0.05$ )

Table 4.7: Tukey multiple comparisons of mean values of harvest index (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.027				
Ps	0.248	0.739			
NPK	0.002	0.704	0.121		
Mix	0.010	0.988	0.401	0.956	
Control	0.001	0.449	0.058	0.997	0.790

#### 4.2 Effects of the Treatments on Chickpea Yield

There were no significant differences of chickpea yield and yield components among the treatments ( $p \geq 0.05$ ) (Table 4.8). The highest chickpea yield was found in Rh biochar application (30% higher than control and 35% higher than NPK fertilizer application) and the second highest yield was found in Rs biochar application (10% higher than control and 14% higher than NPK fertilizer application) (Table 4.8). Yields of Rh biochar + FYM mixture application were lower than that of the control (8% and 3%, respectively). Yield of Ps biochar application was the same as control.

Table 4.8: Yields and yield components of Chickpea (mean±standard error, n=3), sown after harvesting rice experiments without organic and inorganic fertilizer addition.

Yield components	Rh	Rs	Ps	NPK	Mix	Control
Yield (kg ha <sup>-1</sup> )	1536±725 a	1300±240 a	1180±248 a	1140 ± 271 a	1090±120 a	1180±123 a
Total seed per plant	23.23±4.35 a	17.57±5.39 a	24.26±10.1 a	16.78±6.52 a	21.39±1.85 a	16.16±0.90 a
Percent mature seed	92.91±2.17 a	75.01±10.08 a	83.87±2.99 a	85.77±3.23 a	85.77±4.58 a	87.57±2.46 a
Hundred seed weight (g)	24.28±1.06 a	30.47±3.69 a	23.67±2.19 a	25.41±1.72 a	24.11±0.09 a	25.37±1.14 a
Plant weight (g)	12.04±1.57 a	11.89±2.4 a	13.22±3.40 a	8.94±2.16 a	11.78±1.60 a	9.20±0.75 a
Harvest Index	46.00±2.23 a	43.00±5.7 a	38.00±4.87 a	44.00±5.56 a	45.00±4.01 a	45.00±2.88 a

Common letters in the rows indicate mean values are not significantly different ( $p \geq 0.05$ ).

### 4.3 Effects of the Treatments on Cotton Crop Growth and Yield

#### 4.3.1 Effects of the treatments on cotton crop growth

Crop growth data was measured every two weeks after true leaf formation. Growth stages were differentiated based on the phenological development stages of cotton crops according to BBCH scale for dicotyledonous plants of Munger et al. (1998). Plant height was significantly different among the treatments at 45 days after sowing (DAS) ( $p < 0.05$ ) (Fig. 4.6) (Table 4.9). Although plant heights were not significantly different among the treatments during vegetative growth stage of cotton plants, plant height became significantly different after flower initiation. Control showed the lowest plant height compared to biochar and fertilizer treatments at 45 DAS. Different crop growths of Rh biochar + FYM mixture application and the control can be seen in figure (4.7). The highest plant heights of the crops were found in Rs biochar applied plots, followed by Ps biochar applied plots, Rh biochar applied plots, Rh biochar + FYM mixture, and NPK fertilizer applied plots, respectively.

Height node ratio (H/N) was recorded every two weeks since the time cotton plants started to set squares (small cotton flower buds) to decide whether the crops were either at the normal range of growth or having excessive vegetative growth or having poor growth. No significant difference was found by H/N ratio of cotton plants among the treatments (Table 4.10). In all treatments including control, the balance between plant height and the number of main stem nodes were in optimum range of crop growth (0.025 m-0.0375 m). However, at 60 DAS, H/N ratios of cotton plants from Rh biochar, Rs biochar and Ps biochar applied plots exceeded the

optimum range having the values of 4.14, 4.21, and 4.04, respectively due to excessive growth of internodes. That growth did not affect the development of reproductive organs.

The number of fruiting branches per plant was not significantly different among the treatments ( $p \geq 0.05$ ) (Table 4.10). The highest number of fruiting branches were found in plants of Ps biochar applied plots, followed by Rs biochar, Rh biochar + FYM mixture, NPK fertilizer application, Rh biochar applied plots and the control, respectively.

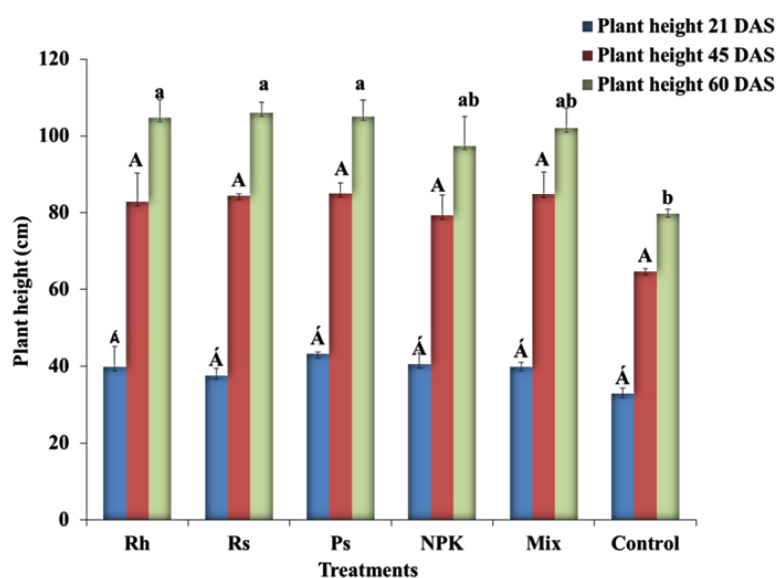


Figure 4.6: Effect of biochar applications on plant height of cotton (mean and standard error,  $n=3$ ) compared to NPK fertilizer application and the control at three growth stages (21, 45, and 60 days after sowing). Different letters above the error bars indicate the significant differences between treatments ( $p < 0.05$ ).

Table 4.9: Tukey multiple comparisons of mean values of plant height of cotton at 60 das (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.999				
Ps	0.999	0.999			
NPK	0.880	0.790	0.860		
Mix	0.998	0.989	0.997	0.981	
Control	0.029	0.020	0.026	0.168	0.056



(a)



(b)



(c)



(d)

Figure 4.7: Effect of treatments on cotton crop growth at 45 days after sowing, (a) cotton plants of rice husk biochar + FYM mixture treatment (b) cotton plants of control plot (c) cotton plants of rice husk biochar treatment (d) cotton plants of NPK fertilizer application treatment



Table 4.10: Effect of biochar applications on cotton yield, growth and yield components (mean±standard error, n=3) compared to NPK fertilizer application and the control

Yield/Growth factors	Rh	Rs	Ps	NPK	Mix	Control
Yield (kg ha <sup>-1</sup> )	3020±401a	3351±116a	2921±354a	2455±65a	3768±436a	927±19b
Plant height (21 DAS) (cm)	40±5.28a	38±1.92a	43±0.59a	41±2.94a	40±1.18a	33±1.51a
Plant height (45DAS) (cm)	83±7.48a	84±0.59a	85±2.72a	79±5.38a	85±5.66a	65±0.74a
Plant height (60 DAS) (cm)	105±4.8a	106 ±2.66a	105±4.27a	97±7.72ab	102±5.22ab	80±1.17b
HN ratio (21 DAS) (cm)	2.6±0.30a	2.4±0.07a	2.7±0.12a	2.6± 0.18a	2.6±0.04a	2.1±0.29a
HN ratio (45 DAS) (cm)	3.7±0.27a	3.8±0.10a	3.7±0.18a	3.6±0.21a	3.6±0.29a	3.2±0.07a
HN ratio (60 DAS) (cm)	2.1±0.28a	4.2±0.11a	4.0±0.44a	3.8±0.64a	3.5±0.44a	3.5±0.14a
Nr. of fruiting branches	9.0±0.44a	11±0.37a	11.0±0.29a	9.0±1.05a	10.0±0.70a	8.0±0.13a
Nr. of bolls per plant	15±1.35a	17±1.08a	13±0.62a	11±0.23ab	16.0±2.24a	7.0±0.37b
Single boll weight (g)	4.8±0.35a	4.6±0.06a	4.6±0.14a	5.1±0.21a	5.1±0.14a	3.5±0.05b

Within the rows, different letters represent that treatments are significantly different ( $p < 0.05$ ). Common letters represent that treatments are not significantly different ( $p \geq 0.05$ )

#### 4.3.2 Effects of the treatments on cotton yield (seed cotton) and yield components

Seed cotton yield was significantly different among the treatments ( $p < 0.05$ ) (Fig. 4.8). The highest seed cotton yield was obtained from Rh biochar + FYM mixture application (306% higher than control and 53% higher than NPK fertilizer application). The second highest yield was obtained from Rs biochar application (261% higher than control and 36% higher than NPK fertilizer application), followed by Rh biochar application (226% higher than control and 23% higher than NPK fertilizer application), Ps biochar application (215% higher than control and 10% higher than NPK fertilizer application), and NPK fertilizer application (165% higher than control). Control had the lowest yield.

Number of bolls per plant was significantly different among the treatments ( $p < 0.05$ ) (Fig. 4.9) (Table 4.12). The highest number of bolls per plant was found in Rs biochar application, followed by Rh biochar + FYM mixture, Rh biochar, Ps biochar, and NPK fertilizer application, respectively. The lowest number of boll per plant was found in control.

Single boll weight was significantly different among the treatments ( $p < 0.05$ ) (Fig. 4.10) (Table 4.13). The highest boll weight was found in Rh biochar + FYM mixture application, followed by NPK fertilizer application, Rh biochar, Rs biochar, Ps biochar application and the control, respectively.

Seed cotton was harvested three times (Fig 4.11). The proportion of harvested seed cotton in each harvest differed among the treatments in the first harvest and in third harvest ( $p < 0.05$ ) (Table 4.14) and (Table 4.15). Significant difference in the first cotton picking was due to significant highest harvested seed cotton from control plots. 43.25 % of total yield from control was obtained in the first harvest. The second highest amount of seed cotton was harvested from Rh biochar application, followed by Rs biochar, Ps biochar, Rh biochar + FYM mixture, and NPK fertilizer application, respectively. In the second harvest, harvested seed cotton was not significantly different among the treatments ( $p \geq 0.05$ ) (Table 4.16). Around 40% of total yield was obtained from the second harvest in all treatments. In third harvest, harvested seed cotton was different among the treatments. The smallest proportion of seed cotton was harvested from control plots and the largest proportion was obtained from NPK applied plots followed by Ps biochar application, Rs biochar application, Rh biochar application, and Rh biochar + FYM mixture application, respectively.

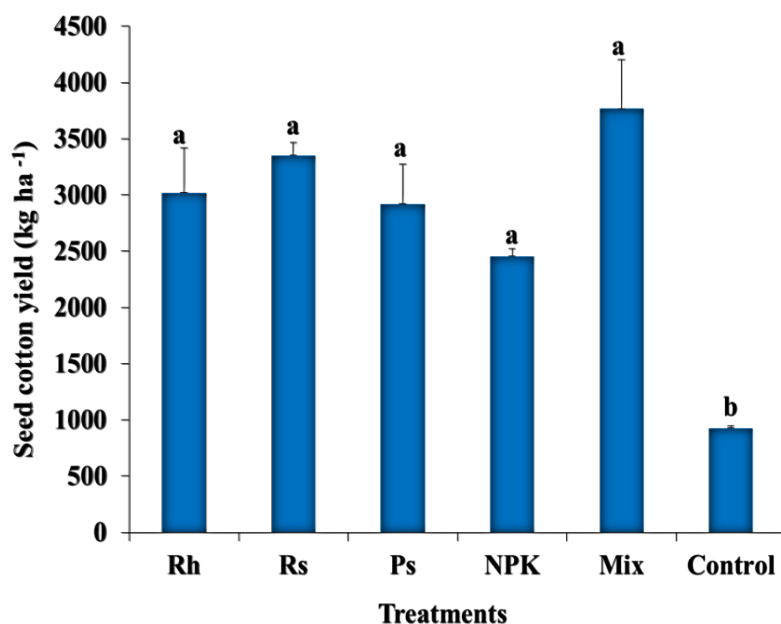


Figure 4.8: Effect of biochar applications on cotton yield ( $\text{kg ha}^{-1}$ ) (mean and standard error,  $n=3$ ) compared to the effect of NPK fertilizer application and the control. Different letters above the error bars indicate the significant differences between the treatments ( $p < 0.05$ ). Same letters above the error bars indicate that means are not significantly different ( $p \geq 0.05$ ).

Table 4.11: Tukey multiple comparisons of mean values of the number of mature boll per plant (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.959				
Ps	0.999	0.888			
NPK	0.732	0.301	0.852		
Mix	0.477	0.900	0.354	0.062	
Control	0.003	0.001	0.004	0.025	0.000

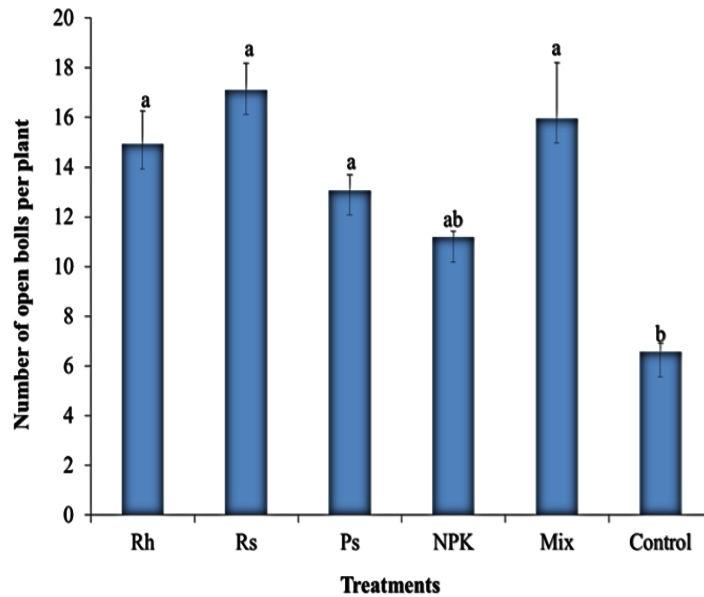


Figure 4.9: Effect of biochar applications on the number of open boll per plant (mean and standard error, n=3) compared to NPK fertilizer application and the control. Different letters above the error bars indicate that means are significantly different ( $p < 0.05$ ). Same letters above the error bars indicate that means are not significantly different ( $p \geq 0.05$ ).

Table 4.12: Tukey multiple comparisons of mean values of the number of mature bolls per plant (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.785				
Ps	0.874	0.235			
NPK	0.301	0.040	0.866		
Mix	0.989	0.982	0.551	0.120	
Control	0.004	0.001	0.022	0.140	0.001

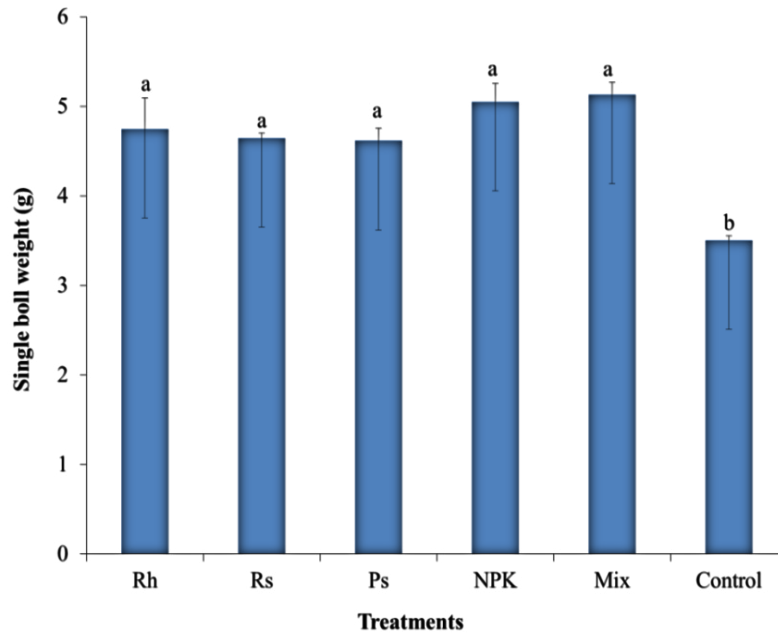


Figure 4.10: Single boll weight in each treatment, (g) (mean and standard error, n=3), boll weight is seed cotton weight without burrs. Different letters above the error bars indicate that means are significantly different ( $p < 0.05$ ). Same letters above the error bars indicate that means are not significantly different ( $p \geq 0.05$ ).

Table 4.13: Tukey multiple comparisons of mean values of single boll weight of each treatment group (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.999				
Ps	0.995	0.999			
NPK	0.850	0.651	0.585		
Mix	0.687	0.472	0.412	0.999	
Control	0.005	0.009	0.012	0.001	0.000

Table 4.14: Tukey multiple comparisons of mean values of the proportion of first harvested yields from total yields (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.960				
Ps	0.947	0.999			
NPK	0.883	0.999	0.999		
Mix	0.989	0.999	0.999	0.996	
Control	0.001	0.000	0.000	0.000	0.000

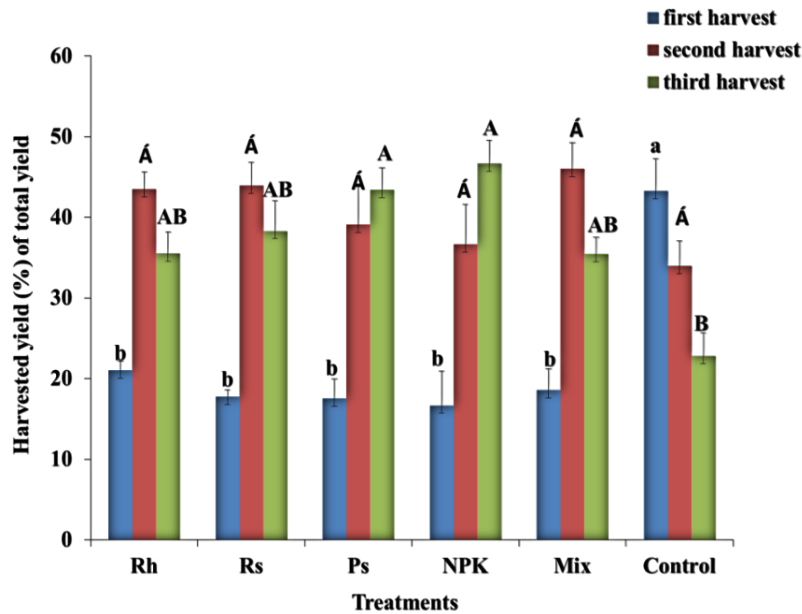


Figure 4.11: Comparing the differences in the proportion of seed cotton weight in each time of cotton picking, (mean and standard error, n=3) from biochar application treatments, NPK fertilizer application and the control. Different letters above the error bars indicate the significant differences between the treatments ( $p < 0.05$ ).

Table 4.15: Tukey multiple comparisons of mean values of the proportion of third harvested yield from total yield (95% family-wise confidence level)

	Rh	Rs	Ps	NPK	Mix
Rs	0.978				
Ps	0.418	0.801			
NPK	0.130	0.360	0.958		
Mix	1.000	0.976	0.408	0.126	
Control	0.071	0.022	0.002	0.000	0.074

Table 4.16: Harvested proportion in each harvest of seed cotton (mean±standard error, n=3)

	Rh	Rs	Ps	NPK	Mix	Control
First harvest	20.99±1.17 b	17.74±0.87 b	17.50±2.44 b	16.67±4.22 b	18.59±2.60 b	43.25±3.99 a
Second harvest	43.52±2.12 A	43.95±2.88 A	39.10±4.74 A	36.62±4.93 A	45.99±3.24 A	33.95±3.12 A
Third harvest	35.49±2.66 AB	38.31±3.73 AB	43.40±2.69 A	46.70±2.87 A	35.42±2.05 AB	22.80±2.89 B

Within the rows, different letters indicate that the treatments are significantly different ( $p < 0.05$ ), common letters indicate that the treatments are not significantly different ( $p \geq 0.05$ )

## Chapter 5: Estimation of Soil Organic Carbon and Greenhouse Gas Emissions by using Denitrification Decomposition (DNDC) Model

### 5.1 Testing the Model by Comparing Modelled Crop Yields and SOC (0-0.2 m) with Measured Crop Yields and SOC (0-0.2 m)

#### 5.1.1 Comparing measured yields and modelled yields

In simulating rice yields, the model slightly overestimated rice yields (percent bias (PBIAS) = - 3.59%, relative root mean square error (RRMSE) = 18% of measured mean grain C yield) (Fig. 5.1), slightly underestimated chickpea yields (PBIAS) = 6.56 %, RRMSE = 7.52% of measured mean grain C yield) (Fig.5.2), and underestimated cotton yields (PBIAS = 8.86%, RRMSE = 24.63% of measured mean grain C yield) (Fig. 5.3).

Correlation between measured and simulated crop yields was strong in rice ( $R^2 = 0.8153$ ) and chickpea ( $R^2 = 0.8804$ ), and slightly weak in cotton ( $R^2 = 0.6396$ ). Positive percent bias (PBIAS) value of 8.86% showed overestimation of cotton yield by model in general. Model overestimated cotton yields from rice husk biochar and pigeon pea stem biochar treatments and underestimated the other treatments (Table 5.1).

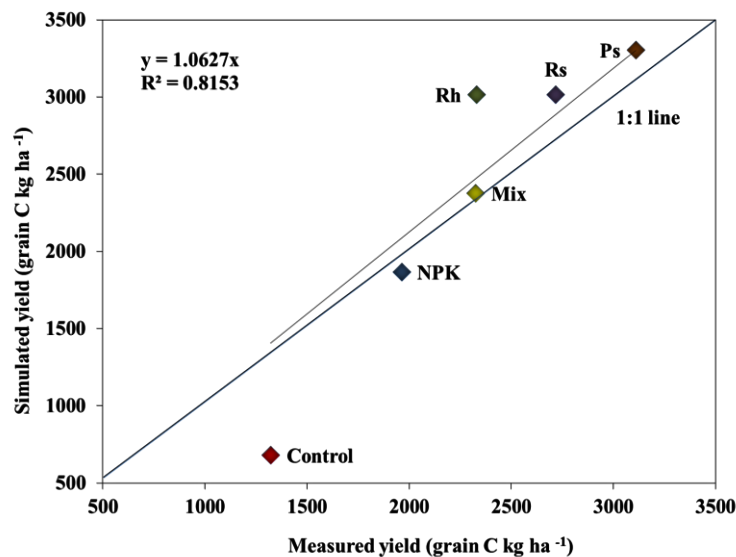


Figure 5.1: Correlation between measured and simulated rice yields

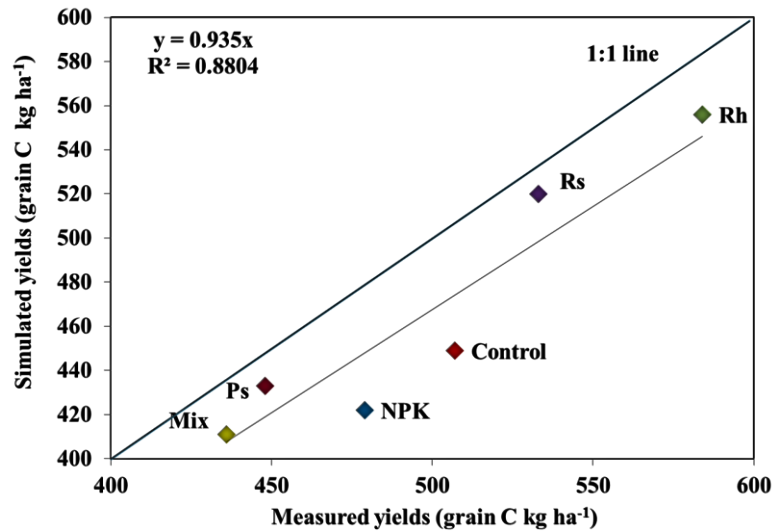


Figure 5.2: Correlation between measured and simulated chickpea yields

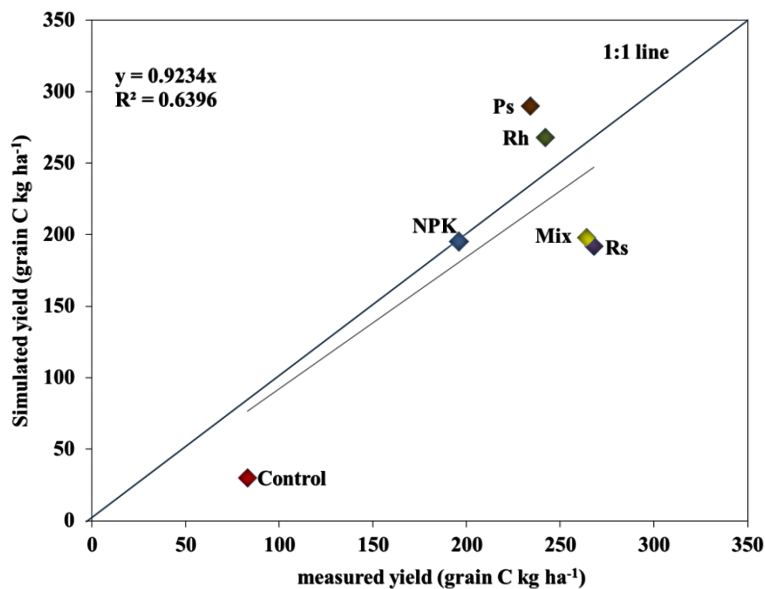


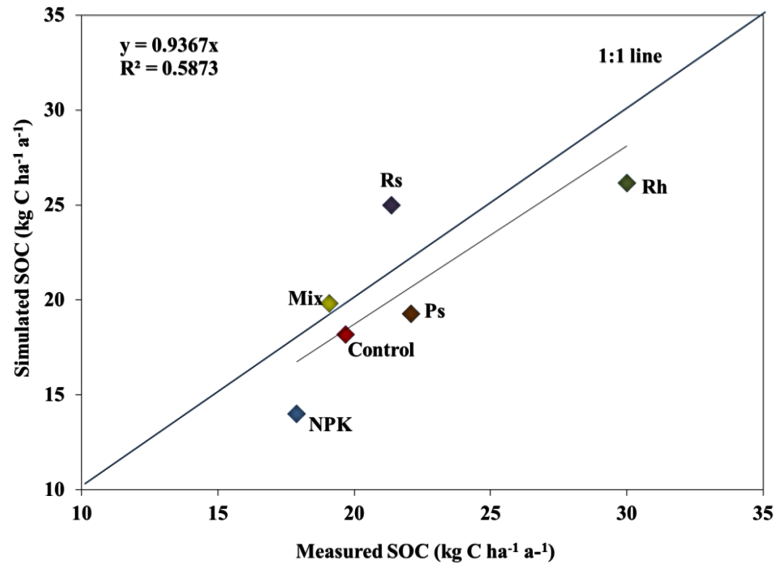
Figure 5.3: Correlation between measured and simulated cotton yields

In both of rice growing season in 2012 and cotton growing season in 2013, biochar application rates were 20 Mg h<sup>-1</sup> rate of each of Rh, Rs and Ps biochars and 10 Mg ha<sup>-1</sup> rate of Rh biochar + FYM mixture, respectively. Measured and simulated SOC of topsoil (0-0.2 m) after harvesting rice in 2012 was quantified to test the model fitness (Fig. 5.4 a). Model slightly underestimated the SOC (PBIAS = 5.89%). According to root mean square error (RMSE), simulated SOC was close to measured SOC (RMSE = 0.99 kg ha<sup>-1</sup> and RRMSE = 4.57% of measured mean SOC). Measured SOC in 0-0.2 m soil depth was the highest in Rh biochar applied soils, followed by Rs biochar, Rh biochar + FYM mixture, Ps biochar, the control, and NPK fertilizer application, respectively (Table 5.1).

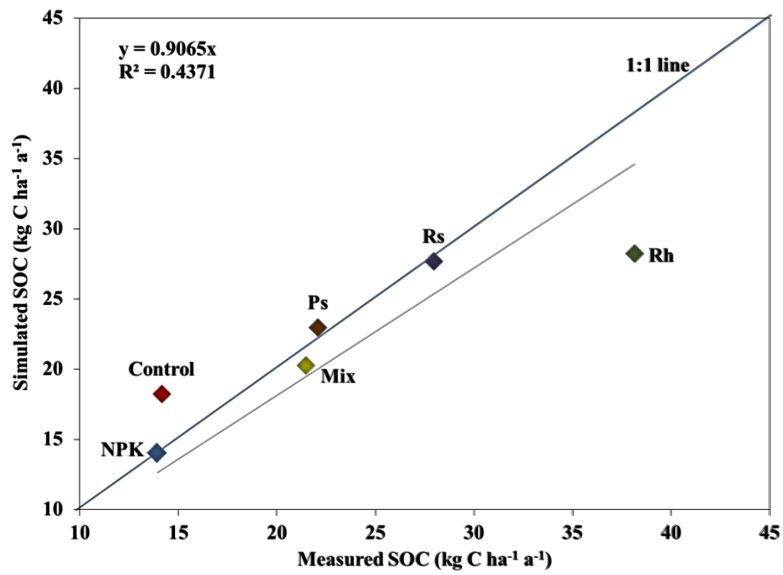


In 2013 after the second time biochar application and under upland condition, the model slightly underestimated the SOC of soils (PBIAS = 4.65%). Variability between measured and simulated SOC was 4.43% (RMSE = 4.43 Mg SOC ha<sup>-1</sup> and 19% of measured mean SOC). R<sup>2</sup> was 0.4371 because of high residuals in rice-husk biochar treatments (Fig. 5.4 (b)).

Calculated, measured and simulated SOC (0-0.2 m) of Rh biochar application, NPK fertilizer application and control were at the same level after harvesting rice in 2012 (Fig. 5.5 (a)). In soils of Rs biochar, Ps biochar and Rh biochar + FYM mixture applications, measured and simulated SOC (0-0.2 m) were lower than calculated SOC (0-0.2 m). Calculated SOC (0-0.2 m) was obtained by multiplying biochar carbon content and per hectare biochar application rate (20 Mg ha<sup>-1</sup>a<sup>-1</sup> of Rh, Rs and Ps biochars and 10 Mg ha<sup>-1</sup>a<sup>-1</sup> of Rh biochar + FYM mixture) (Table 5.1). Calculated and measured SOC in soils of NPK fertilizer treatment and control was the same because additional carbon was not added to those treatments except measured SOC. Measured SOC was SOC values obtained from the results of laboratory measurements of soil samples. Simulated SOC from 0-0.2 m soil depth was obtained from model simulation of SOC during the respective cropping seasons from each treatment. Model provided the simulated SOC results through the interaction among crop types and crop growth, climate conditions, soil conditions and fixed- and mobile biochar carbon fraction. In 2013 after harvesting cotton, measured SOC (0-0.2 m) was higher than calculated and simulated SOC (0-0.2 m) only in Rh biochar treatment. Calculated SOC (0-0.2 m) was higher than measured and simulated SOC (0-0.2 m) in the other treatments including the control (Fig. 5.5 (b)).



(a)



(b)

Figure 5.4: Correlations between simulated soil organic carbon and measured soil organic carbon (0-0.2 m soil layer) (a) SOC after harvesting rice in 2012 (b) SOC after harvesting cotton in 2013

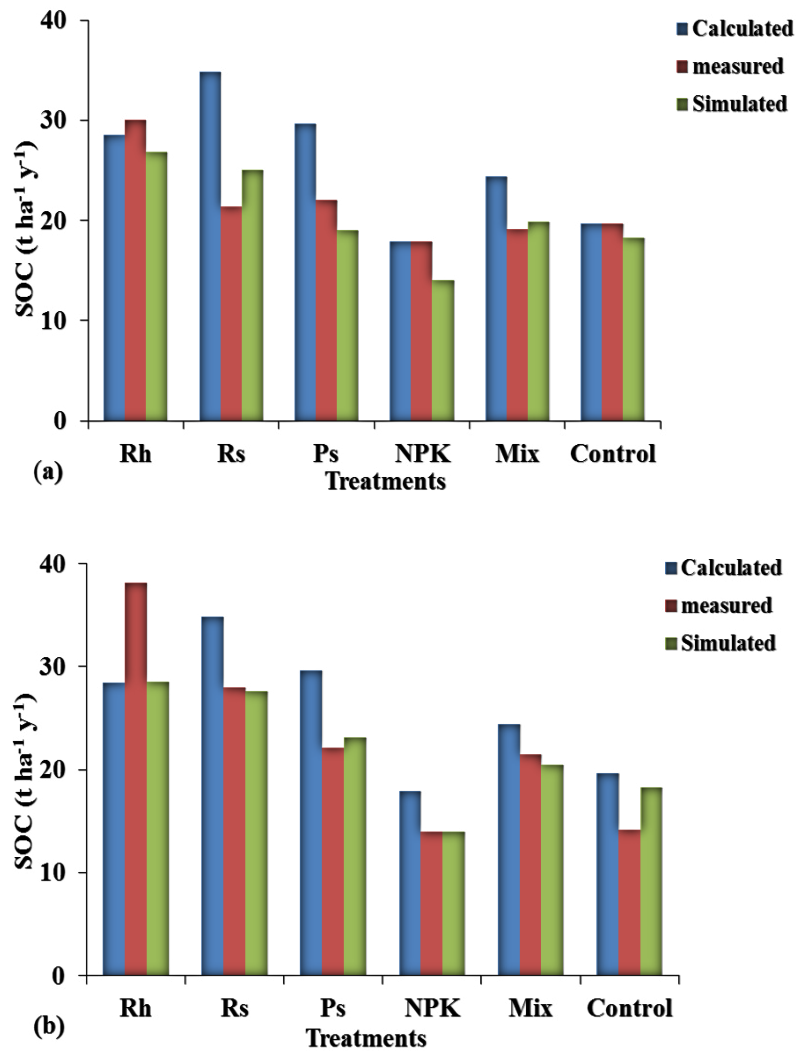


Figure 5.5: Calculated-, measured- and simulated-SOC (0-0.2 m) (a) after harvesting rice in 2012 (b) after harvesting cotton in 2013. Calculated SOC from 0-0.2 m soil depth was obtained by multiplying biochar SOC with biochar per hectare application rates. Measured SOC was SOC values obtained from the results of laboratory measurements of soil samples. Simulated SOC from 0-0.2 m soil depth was obtained from model simulation of SOC during the respective cropping seasons from each treatment.

Table 5.1: Calculated-, measured- and simulated-SOC of topsoil (0-0.2 m) in biochar applied soils, NPK fertilizer applied soils and control after harvesting rice in 2012 and after harvesting cotton in 2013

Biochar	SOC (0-0.2 m) Mg ha <sup>-1</sup> in 2012			SOC (0-0.2 m) Mg ha <sup>-1</sup> in 2013		
	Calculated*	measured†	Simulated‡	Calculated	measured	Simulated
Rh biochar	28.48	30.00	26.81	28.48	38.16	28.57
Rs biochar	34.86	21.36	25.07	34.86	27.96	27.63
Ps biochar	29.62	22.08	19.03	29.62	22.08	23.09
NPK	17.88	17.88	14.00	17.88	13.92	14.00
Control	24.36	19.08	19.91	24.36	21.48	20.48
Rh biochar + FYM mixture	19.68	19.68	18.28	19.68	14.16	18.25

\*SOC was calculated based on biochar carbon, initial total carbon in soil and soil bulk density and SOC of NPK application and control were assumed the same as observed SOC.

† SOC was calculated based on total carbon in soil samples of experiments and soil bulk density

‡ Simulated SOC by DNDC

## 5.2 Model Simulations

### 5.2.1 Crop yields

#### Rice yields

In 30-year simulation, simulated rice yields in biochar application treatments were higher in the initial year of simulation and decreased by 11%-29% in the second year and yields remained constant in the following years of simulation although there were some fluctuations of yields (less than 1% of initial yield) due to different climatic conditions (Fig. 5.6 (a)). Simulated yields of NPK fertilizer application and control were stable around 2300-2400 kg ha<sup>-1</sup> and 1000-1080 kg ha<sup>-1</sup> respectively from the initial year up to the end of simulation although some slight fluctuations (less than 3% of initial yield) occurred towards the end of simulation. Although the decreasing trend of rice yield was found in biochar treatments, yield of those treatments were still higher than that of NPK and control until 30 years after biochar application. When the average yields over 30 years were compared, yield from biochar applications were 2-7% higher than the yield of NPK fertilizer application and 125-135% higher than control.

In the 50-year simulation, under the same climate condition, rice yields of NPK fertilizer application and control showed increasing trends (3-6% of initial yield) from the initial year onwards the end of simulation (Fig. 5.6 (b)). Yields of Biochar treatments were resulted with decreasing trends (11-22% decrease of initial yield in Rh, Rs and Ps biochar applications and 1-3% of initial yield in Rh biochar + FYM mixture application). However, when the average yields over 30 years were compared, yield of biochar treatments were 1-4% higher than NPK fertilizer application and 125-135% higher than control.

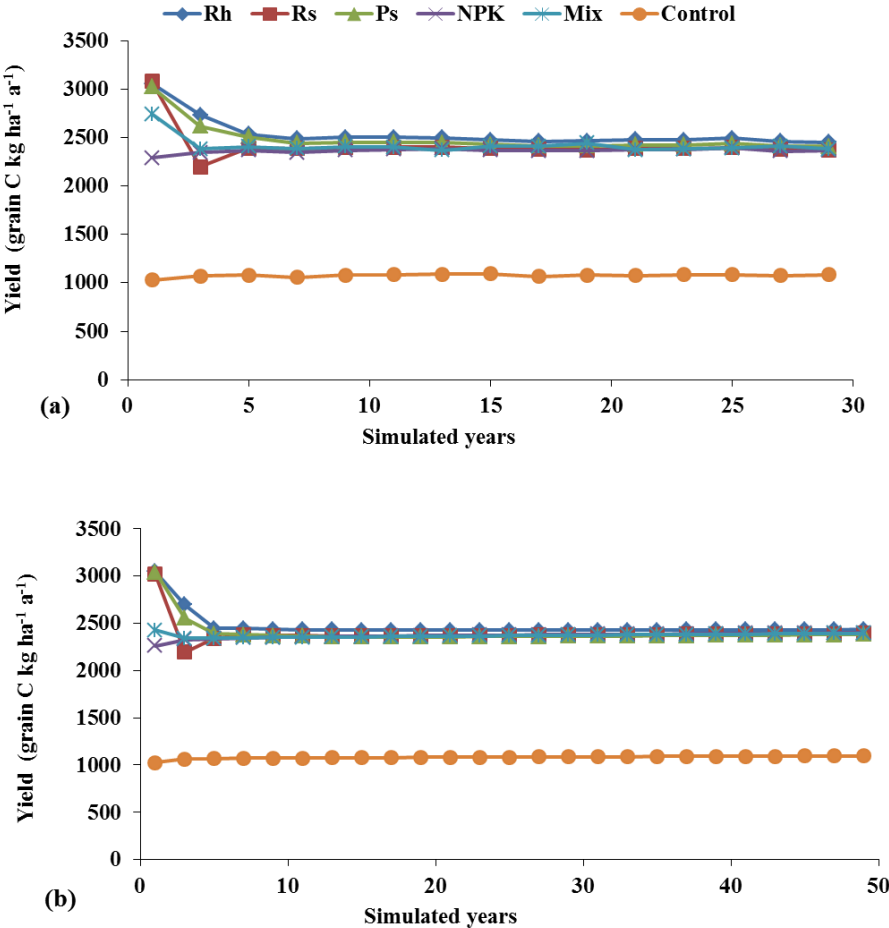


Figure 5.6: Simulated rice yields of biochar application treatments compared to NPK fertilizer application and the control (a) 30 years after biochar applications by using the climate data from 1984 to 2013 (b) 50 years after biochar applications by using a single year climate data from the year 2012 with the lowest rainfall (532 mm mean annual rainfall)

**Chickpea yields**

Neither chemical fertilizer nor biochar were applied before chickpea cultivation. Under different climatic conditions in 30-year simulation, Rh biochar + FYM mixture maintained the most stable yield throughout all simulated years compared to other biochar applications (485-512 grain C kg ha<sup>-1</sup>). An increasing yield trend was found in the 50-year simulation in all

treatments. When the average yield of all simulated years were compared, Rh biochar application showed the highest yield (520 kg grain C ha<sup>-1</sup> in 30-year simulation and 530 kg grain C ha<sup>-1</sup> in 50-year simulation) (Fig. 5.7 (a) and (b)).

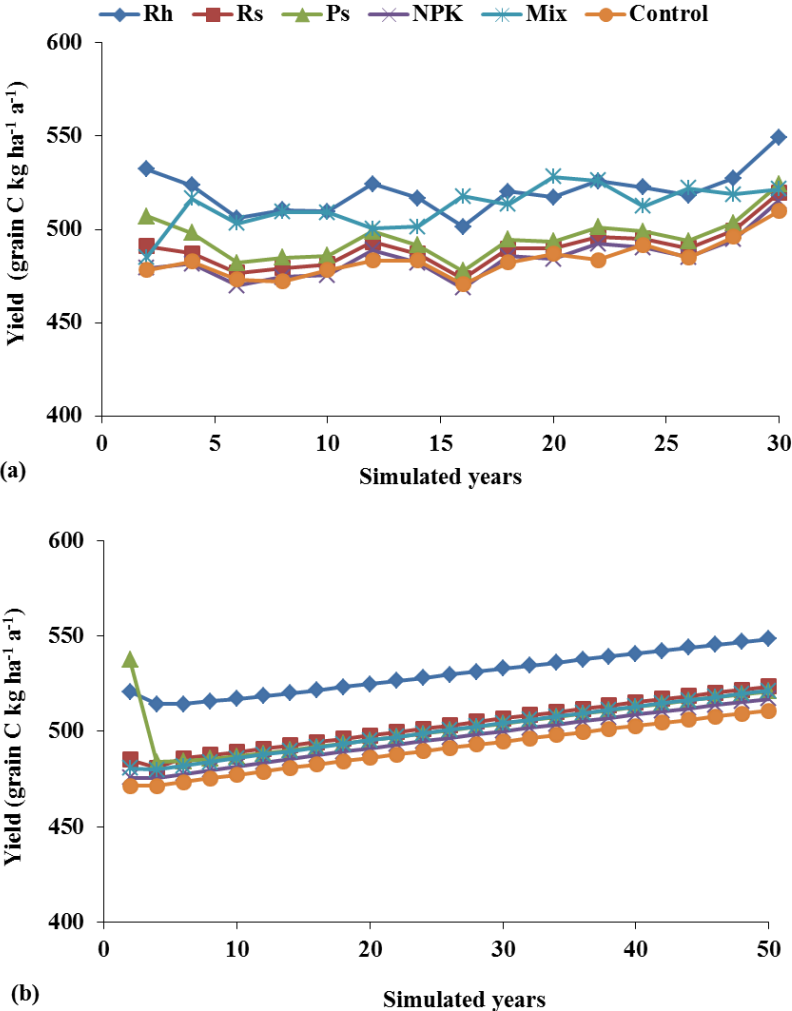


Figure 5.7: Simulated chickpea yields of biochar application treatments compared to NPK fertilizer application and the control (a) 30 years after biochar applications by using the climate data from 1984 to 2013 (b) 50 years after biochar applications by using a single year climate data from the year 2012 with the lowest rainfall (532 mm mean annual rainfall)

**Cotton Yields**

Simulated cotton yields were not differing among all treatments in both 50-year simulation (Fig. 5.8 (b)) and 30-year simulation (Fig. 5.8 (a)) except control. In both of 30-year and 50-year simulations, cotton yields from Rh biochar application and Ps biochar application were

the highest among all treatments in the initial year of simulation and decreased in the following years of simulation. In the final year of simulation, yields of these two treatments were lower than Rs biochar application, Rh biochar + FYM mixture application and NPK fertilizer application. In the latter three treatments, although the yields in the initial year were lower than Rh- and Ps biochar applications, their yields went with increasing trend.

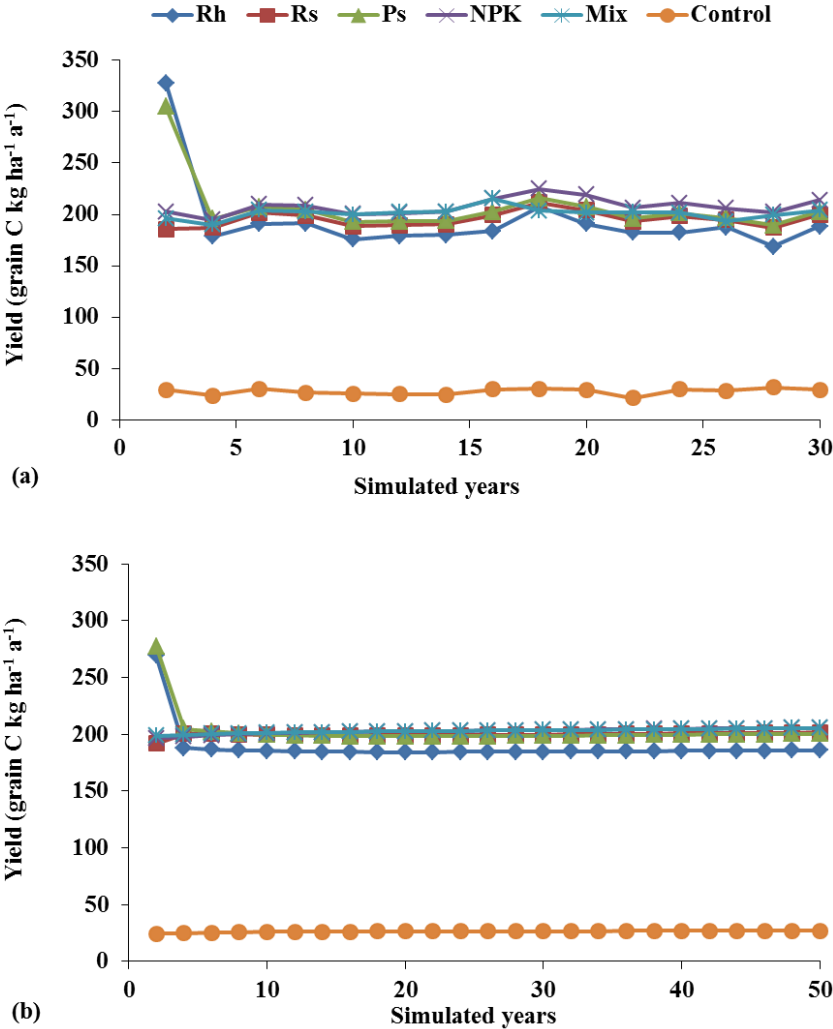


Figure 5.8: Simulated cotton yields of the biochar application treatments compared to NPK fertilizer application and the control (a) 30 years after biochar applications by using the climate data from 1984 to 2013 (b) 50 years after biochar applications by using a single year climate data from the year 2012 with the lowest rainfall (532 mm mean annual rainfall)

**5.2.2 Soil organic carbon (SOC) 0-0.2 m**

In both 30-year and 50-year simulations, simulated SOC (0-0.2 m) was at the same level for all simulated years although there were slight reductions in Rh biochar applications. In Rh biochar treatment, SOC was decreased by 2% in the following years after 13<sup>th</sup> year (Fig. 5.9

(a) and Fig. 5.9 (b)). The highest SOC was found in Rh biochar variant followed by Ps biochar, NPK fertilizer application and Rh biochar + FYM mixture, Rs biochar application and the control, respectively.

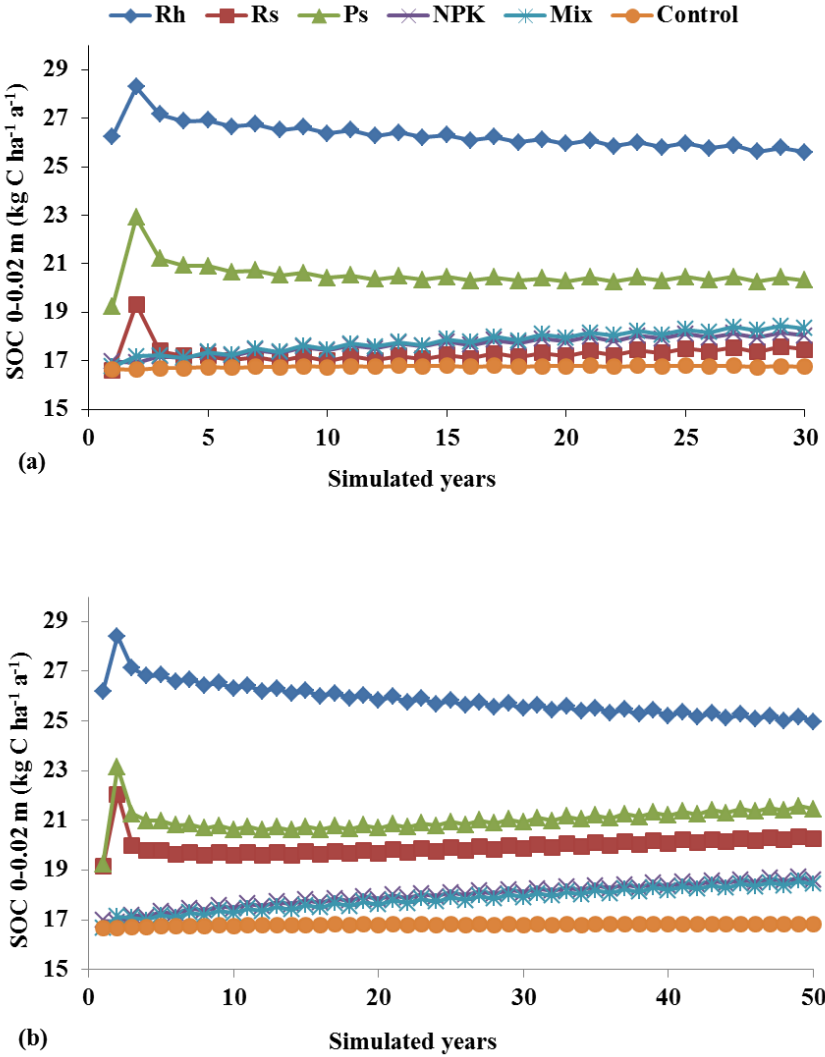


Figure 5.9: Simulated SOC from the topsoil 0-0.2 m of biochar applications, compared to NPK fertilizer application and the control after harvesting cotton (a) 30 years after biochar applications by using the climate data from 1984 to 2013 (b) 50 years after biochar applications by using a single year climate data from the year 2012, with 532 mm mean annual rainfall

**5.2.3 Soil CO<sub>2</sub> emission**

**Year 1 (Rice and chickpea growing seasons)**

In both 50-year and 30-year simulations of CO<sub>2</sub> emission under lowland condition, emissions from biochar treatments were higher than NPK fertilizer application and control (Fig. 5.10 (a) and Fig. 5.11 (a)). In 30-year simulation, the highest CO<sub>2</sub> emission was found in Rh biochar + FYM mixture (2031 kg C ha<sup>-1</sup>a<sup>-1</sup>), followed by Ps biochar application (1942 kg C ha<sup>-1</sup>a<sup>-1</sup>), Rs



biochar application ( $1746 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rh biochar application ( $1752 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), NPK fertilizer application ( $1395 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), and control ( $721 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), respectively. In this simulation,  $\text{CO}_2$  emissions from Rh-, Rs- and Ps biochar applications went with decreasing trends 32-80% of initial year's emission and emission from Rh biochar + FYM mixture, NPK fertilizer treatments and control went by increasing trends (ranged from 2% to 19% of initial year's simulation). In 50-year simulation, the highest  $\text{CO}_2$  emission was from Ps biochar application ( $1720 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), followed by Rs biochar application ( $1650 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rh biochar application ( $1625 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rh biochar + FYM mixture ( $1471 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), NPK fertilizer application  $1439 \text{ kg C ha}^{-1}\text{a}^{-1}$ , and control ( $738 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), respectively. In 50-year simulation,  $\text{CO}_2$  emission of biochar applications was higher in the year of biochar application and it went with decreasing trend in the following simulated years (ranging between 9-80%). Emissions from conventional NPK fertilizer application and control were initially lower than that of biochar treatments and that went with increasing trend (ranging between 1-21%). Although there were increasing trends of  $\text{CO}_2$  emission in NPK fertilizer application and control, 50-year average emissions from those treatments were still lower than that of biochar treatments since emissions of biochar treatments were higher in the initial years.

## **Year 2 (Cotton growing seasons)**

Under upland condition, in both 50-year and 30-year simulations,  $\text{CO}_2$  emission in the initial year was higher in biochar treatments and went with decreasing trend in the following years (ranged 16-73% of initial year's emission) (Fig. 5.10 (b) and Fig 5.11 (b)). In 30-year simulations, average  $\text{CO}_2$  emission was the highest in Ps biochar application ( $899.39 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), followed by Rh biochar application ( $897.92 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rs biochar application ( $816.38 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rh biochar + FYM mixture application ( $763.97 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), NPK fertilizer application ( $650.02 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), and control ( $433.40 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), respectively. In 50-year simulations, average  $\text{CO}_2$  emission was the highest in Rs biochar application ( $848.38 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), followed by Rh biochar application ( $800.27 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Ps biochar application ( $798.36 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rh biochar + FYM mixture application ( $707.54 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), NPK fertilizer application ( $694.80 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), and control ( $448.42 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), respectively.

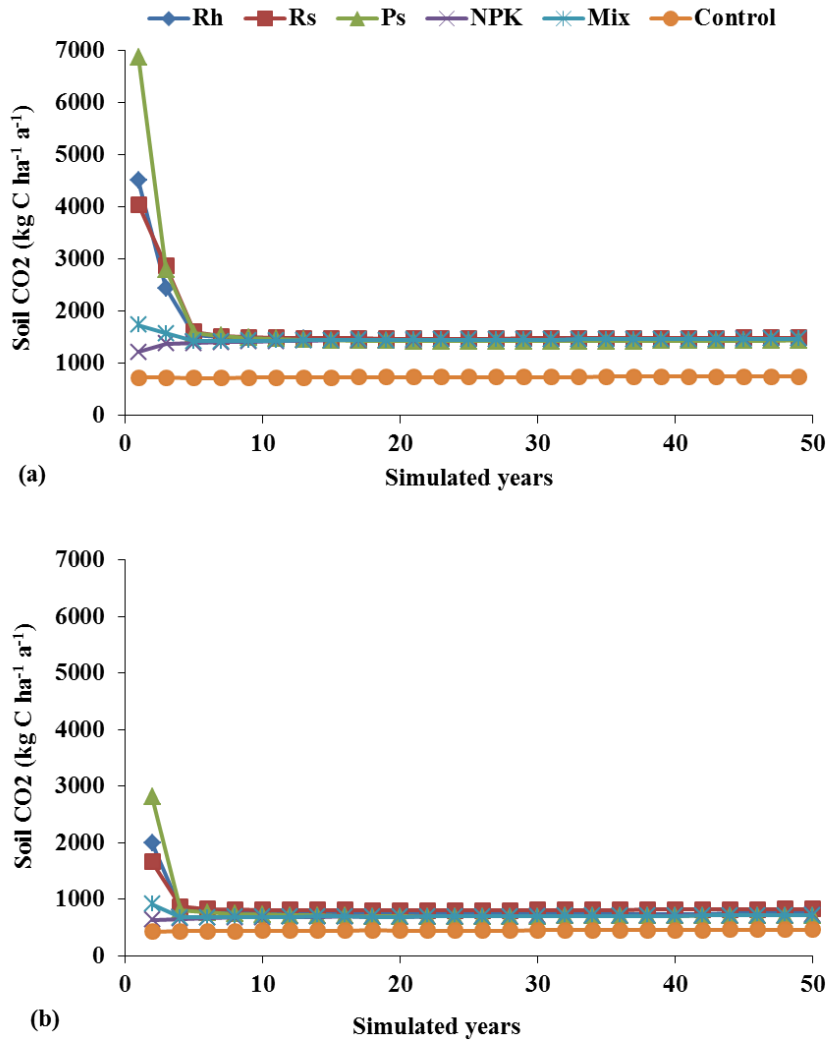


Figure 5.10: Simulated soil CO<sub>2</sub> after biochar applications compared to NPK fertilizer application and the control for 50 years by using a single year climate data from the year 2012 with the lowest rainfall (532 mm mean annual rainfall) for all simulated years (a) CO<sub>2</sub> emission during rice growing seasons (b) CO<sub>2</sub> emission during cotton growing seasons

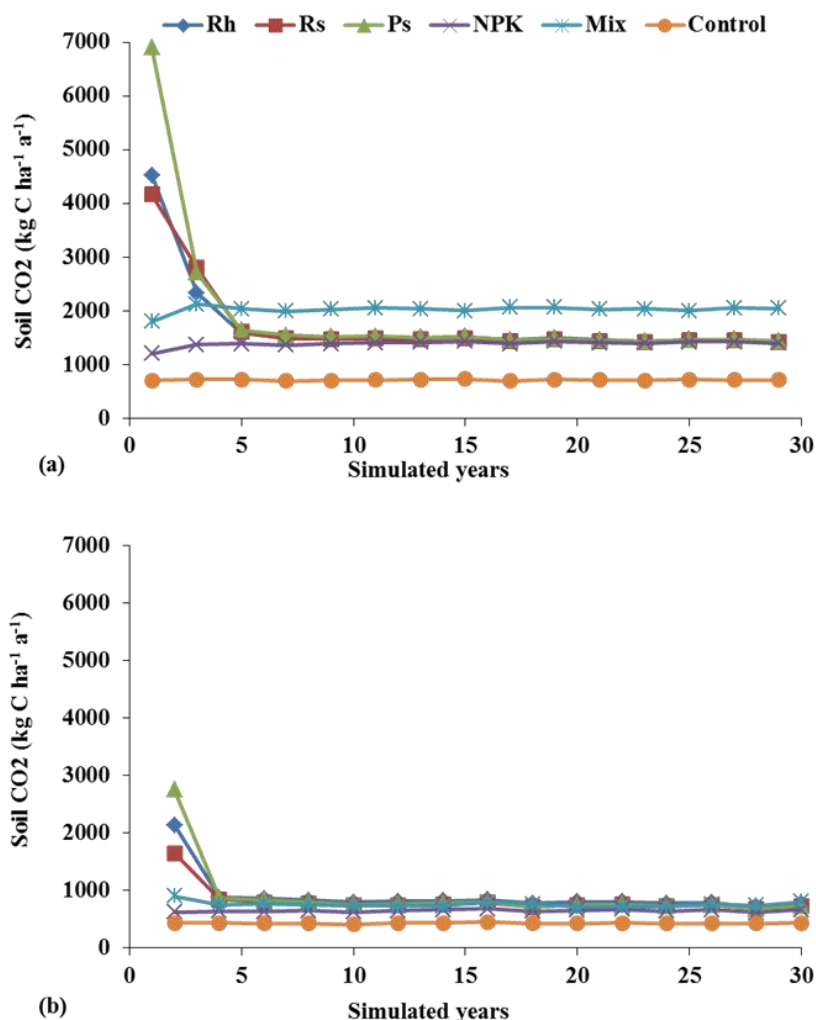


Figure 5.11: Simulated soil CO<sub>2</sub> after biochar applications compared to NPK fertilizer application and the control for 30 years by using the climate data from 1984 to 2013 (a) CO<sub>2</sub> emission during rice growing seasons (b) CO<sub>2</sub> emission during cotton growing seasons

### 5.2.4 N<sub>2</sub>O fluxes

#### Year 1 (Rice and chickpea growing seasons)

In both 50-year simulation and 30-year simulation under lowland condition, N<sub>2</sub>O emissions (average of simulated years) were higher in biochar applications than NPK fertilizer application and control. When all the treatments were compared, N<sub>2</sub>O emission was the highest in Rh biochar application and the lowest in control (Fig. 5.12 (a) and Fig. 5.13 (a)). In 30 year simulation, average N<sub>2</sub>O emission from Rh biochar application was 1.80 kg N ha<sup>-1</sup> a<sup>-1</sup>, followed by Ps biochar application (0.61 kg N ha<sup>-1</sup> a<sup>-1</sup>), Rh biochar + FYM mixture application (0.55 kg N ha<sup>-1</sup> a<sup>-1</sup>), Rs biochar application (0.51 kg N ha<sup>-1</sup> a<sup>-1</sup>), NPK fertilizer application (0.48 kg N ha<sup>-1</sup> a<sup>-1</sup>), and control (0.37 kg N ha<sup>-1</sup> a<sup>-1</sup>), respectively. In 50-year simulation, average N<sub>2</sub>O emission from Rh biochar application was 0.39 kg N ha<sup>-1</sup> a<sup>-1</sup>, followed by Ps biochar application (0.30 kg N ha<sup>-1</sup> a<sup>-1</sup>), Rs biochar application (0.29 kg N ha<sup>-1</sup> a<sup>-1</sup>), Rh biochar + FYM

mixture application ( $0.28 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), NPK fertilizer application ( $0.26 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), and control ( $0.15 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), respectively.

### **Year 2 (Cotton growing seasons)**

Under upland condition in both 50-year and 30-year simulations,  $\text{N}_2\text{O}$  emissions from biochar treatments were higher than the emissions from NPK fertilizer application and control (Fig 5.12 (b) and Fig. 5.13 (b)). In the initial year of simulation,  $\text{N}_2\text{O}$  emission was the highest in Rh biochar and Ps biochar applications among all treatments. In 50-year simulation,  $\text{N}_2\text{O}$  emissions of Rh biochar, Ps biochar and Rh biochar + FYM mixture applications went with decreasing trends and  $\text{N}_2\text{O}$  emission of Rs biochar, NPK fertilizer application and control went with increasing trends. In 30-year simulation, average  $\text{N}_2\text{O}$  emission from Rh biochar application was  $1.80 \text{ kg N ha}^{-1}\text{a}^{-1}$ , followed by Ps biochar application ( $1.32 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), Rs biochar and NPK fertilizer applications ( $1.11 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), Rh biochar + FYM mixture application ( $1.04 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), and control ( $0.95 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), respectively. In 50-year simulations, average  $\text{N}_2\text{O}$  emission from Rh biochar application was the highest ( $1.12 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), followed by Ps biochar application ( $0.83 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), Rs biochar application ( $0.73 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), Rh biochar + FYM mixture ( $0.68 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), NPK fertilizer application ( $0.67 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), and control ( $0.51 \text{ kg N ha}^{-1}\text{a}^{-1}$ ), respectively.

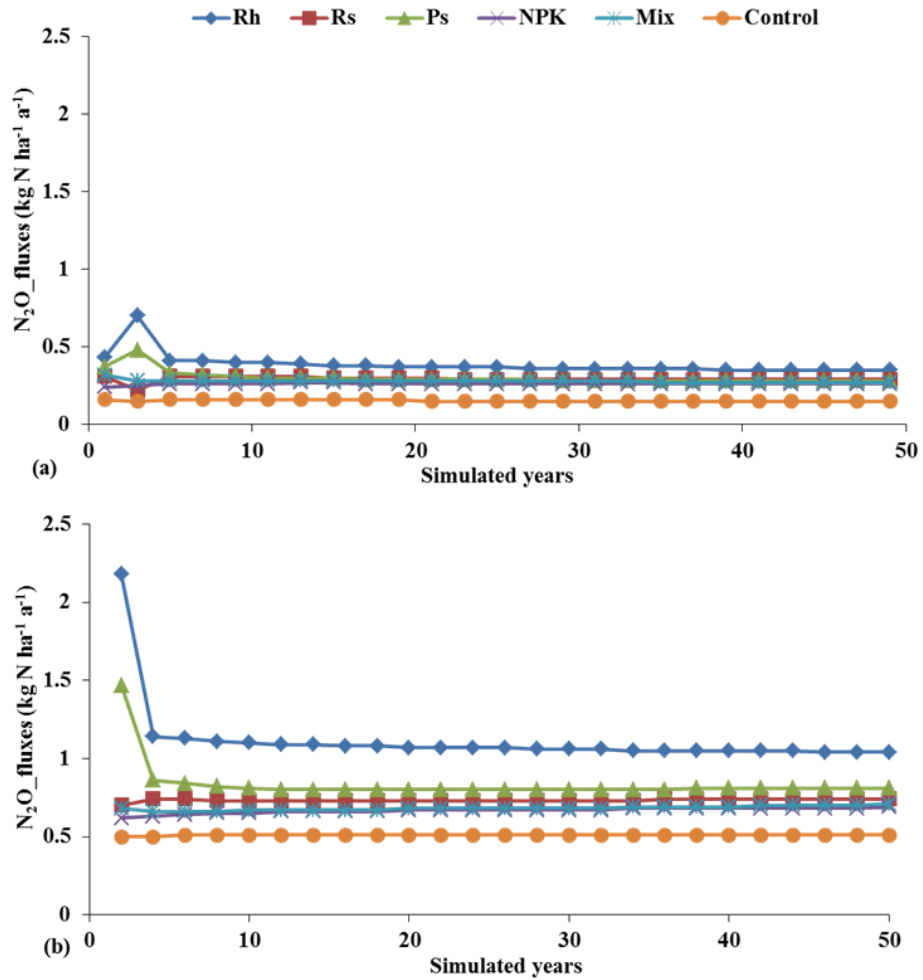


Figure 5.12: Simulated N<sub>2</sub>O-fluxes after biochar applications compared to NPK fertilizer application and the control for 50 years by using a single year climate data from the year 2012 with the lowest rainfall (532 mm mean annual rainfall) for all simulated years (a) N<sub>2</sub>O-fluxes during rice growing seasons (b) N<sub>2</sub>O-fluxes during cotton growing seasons

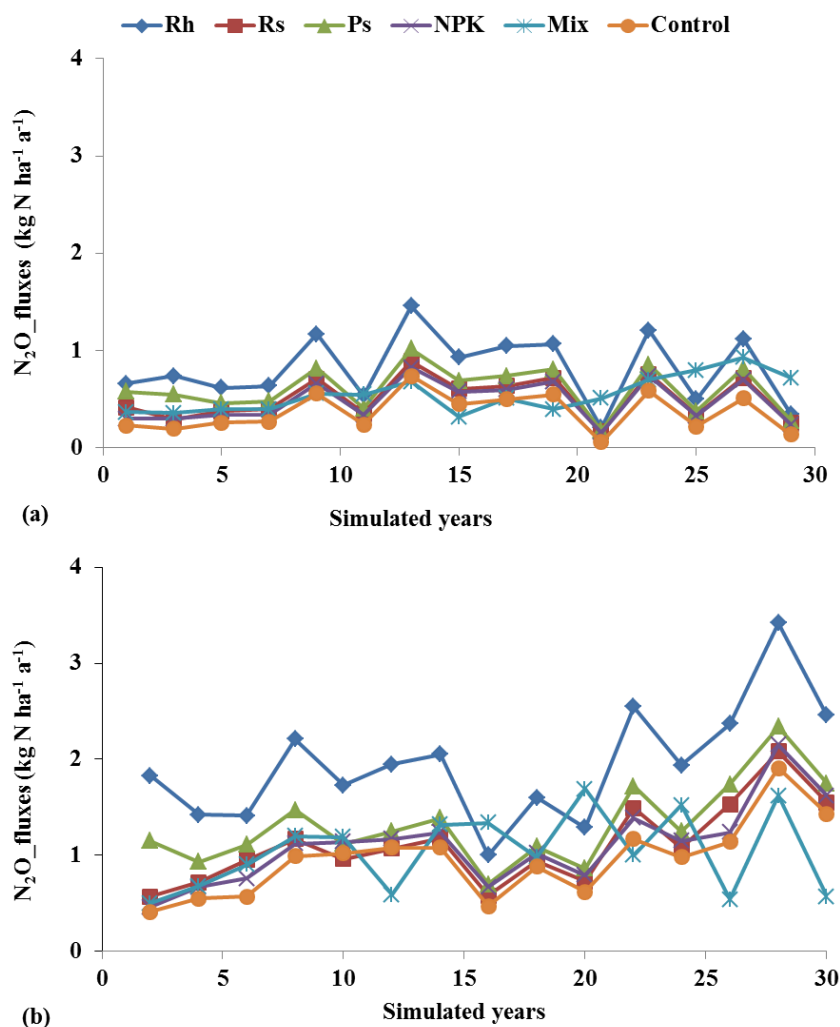


Figure 5.13: Simulated N<sub>2</sub>O-fluxes after biochar applications compared to NPK fertilizer application and the control for 30 years by using the climate data from 1984 to 2013 (a) N<sub>2</sub>O-fluxes during rice growing seasons (b) N<sub>2</sub>O fluxes during cotton growing seasons

## 5.2.5 CH<sub>4</sub> Fluxes

### Year 1 (Rice and chickpea growing season)

Simulation of CH<sub>4</sub> emissions under upland condition showed zero emission. In rice growing season, simulated CH<sub>4</sub> emissions were higher in biochar applications than in NPK fertilizer application and control in both 30-year and 50-year simulations (Fig. 5.14). In both simulations, CH<sub>4</sub> emissions from biochar applications and control went with decreasing trends and only CH<sub>4</sub> emission from NPK fertilizer application went with increasing trend (ranging 4-9% of initial year's emission).

In 30-year simulations, average CH<sub>4</sub> emission was the highest in Rh biochar + FYM mixture (354.35 kg C ha<sup>-1</sup> a<sup>-1</sup>), followed by Ps biochar application (261.48 kg C ha<sup>-1</sup> a<sup>-1</sup>), Rh biochar

application ( $248.53 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rs biochar application ( $247.86 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), NPK fertilizer application ( $197.83 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), and the control ( $78.11 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), respectively.

In 50-year simulations under low rainfall condition, average  $\text{CH}_4$  emission was the highest in Rs biochar application ( $245.51 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), followed by Ps biochar application ( $240.51 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rh biochar application ( $231.63 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), Rh biochar + FYM mixture ( $220.15 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), NPK fertilizer application ( $202.29 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), and control ( $79.58 \text{ kg C ha}^{-1}\text{a}^{-1}$ ), respectively.

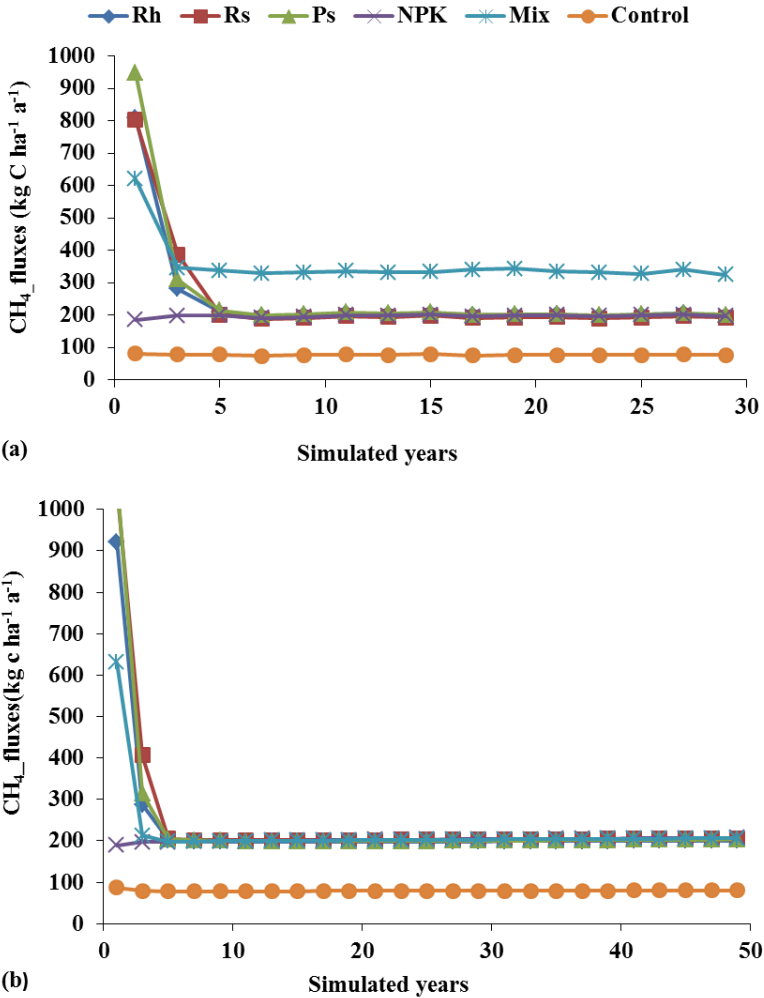


Figure 5.14: Simulated  $\text{CH}_4$ -fluxes after biochar applications compared to NPK fertilizer application and the control (a) 30-year simulation by using the climate data from 1984 to 2013 and (b) 50-year simulation by using a single year climate data from the year 2012 with the lowest rainfall (532 mm mean annual rainfall)

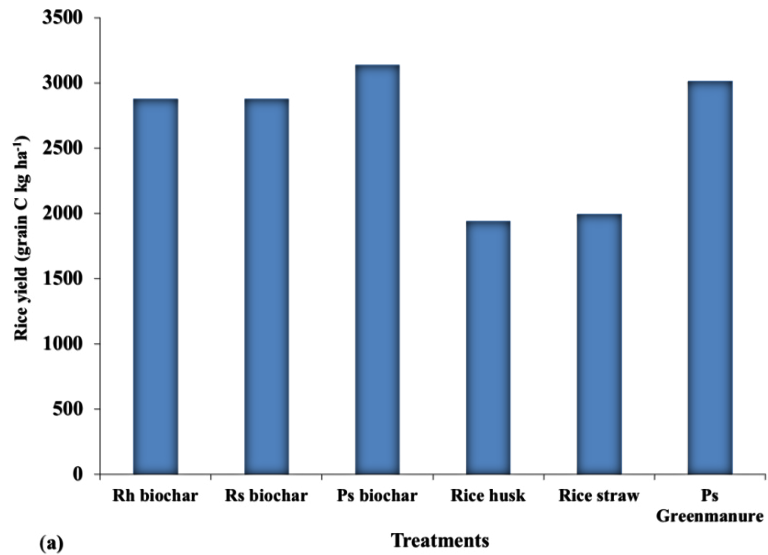
### **5.2.6 Simulating crop yields obtained from biochar applications compared to fresh biomass application**

Crop yields from the application of raw biomass of rice husk, rice straw and pigeon pea stem compared to the yields of biochar soil additions were estimated by DNDC. Simulated rice yields from biomass applications were rice husk application, 33%, rice straw application, 31%, and pigeon pea stem green manure application, 4%, respectively lower than the respective biochar applications (Fig. 5.15 (a)).

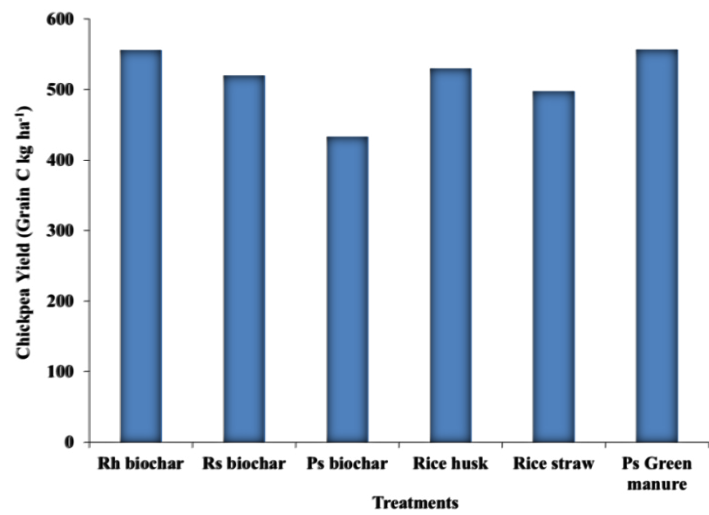
Chickpea yields were simulated as the second crop cultivated after rice. No fertilizer or manure input was added to chickpea simulation. Simulated chickpea yields from rice-husk biomass application and rice straw biomass application were 5% and 4% respectively lower than that of rice husk biochar application and rice straw biochar application. Simulated yield from pigeon pea stem green manure application was 29% higher than that of pigeon pea stem biochar application (Fig. 5.15 (b)).

Simulated cotton yields from biomass applications were rice-husk biomass application, 21%, rice straw biomass application, 24%, and pigeon pea green manure application, 10%, respectively lower than the respective biochar applications (Fig. 5.15 (c)).

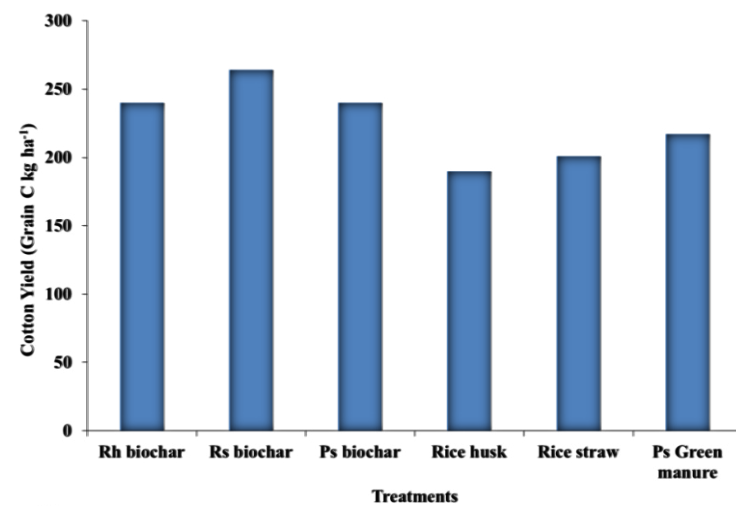




(a)



(b)



(c)

Figure 5.15: Simulated crop yields obtained from the biochar applications compared to the application of raw biomass (a) rice yields (b) chickpea yields (c) cotton yield

In estimating the future yields, all crop yields from rice husk and rice straw raw biomass applications were lower than their biochar applications in the initial year of simulation (Fig. 5.16, 5.17, and 5.18). However, in the following years, the yields remained at the same level up to the end of simulations. In pigeon pea stem green manure application, crop yields were higher since the initial year up to the end of simulation. Simulated SOC (0-0.2 m) was lower in fresh biomass applications compared to biochar applications (Fig. 5.19).

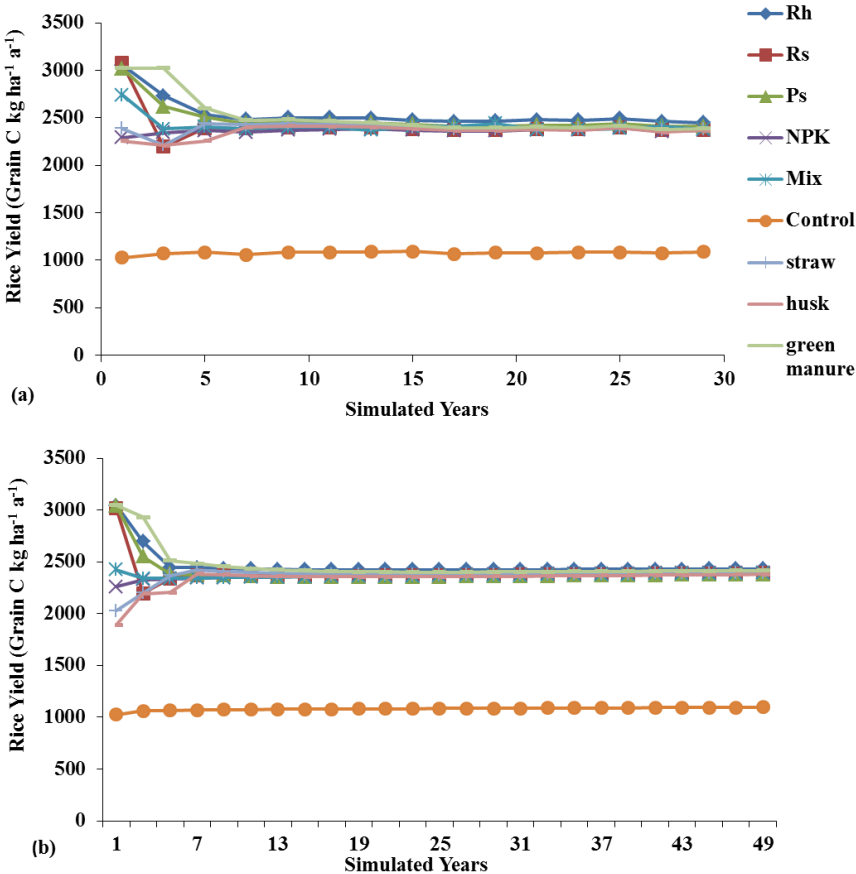


Figure 5.16: Simulated rice yields comparing the effects of biochar applications, rice straw-, rice husk- and pigeon pea stem biomass applications, NPK fertilizer application, and the control (a) 30-year simulation by using the climate data from 1984 to 2013 (b) 50-year simulation by using a single year climate data, from 2012, with the lowest rainfall (532 mm mean annual rainfall)

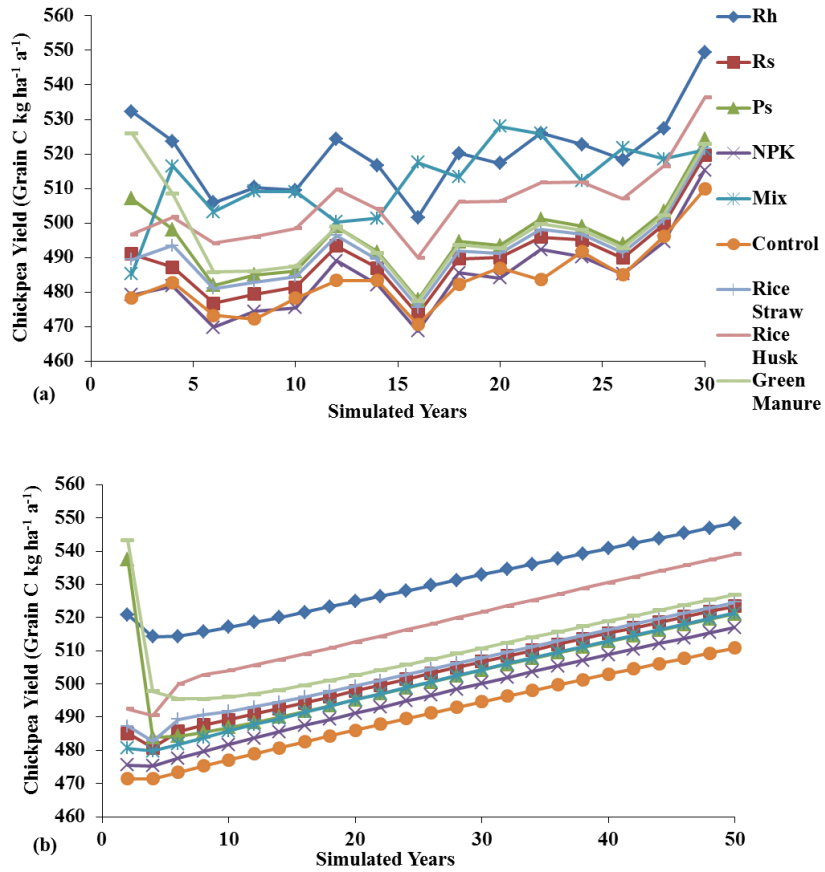


Figure 5.17: Simulated chickpea yields comparing the effects of biochar applications, rice straw-, rice husk- and pigeon pea stem biomass applications, NPK fertilizer application, and the control (a) 30-year simulation by using the climate data from 1984 to 2013 (b) 50-year simulation by using a single year climate data, from 2012, with the lowest rainfall (532 mm mean annual rainfall)

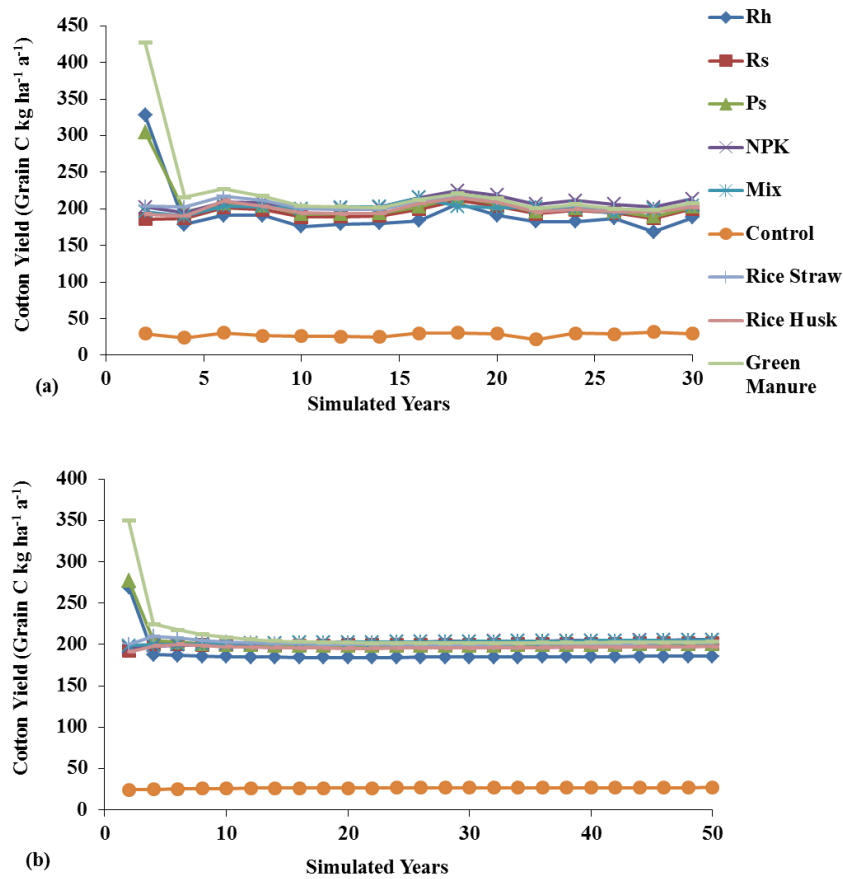


Figure 5.18: Simulated cotton yields comparing the effects of biochar applications, rice straw-, rice husk- and pigeon pea stem biomass applications, NPK fertilizer application, and the control (a) 30-year simulation by using different climate data (1984-2013) (b) 50-year simulation by using a single year climate data from 2012 with the lowest rainfall (532 mm mean annual rainfall)

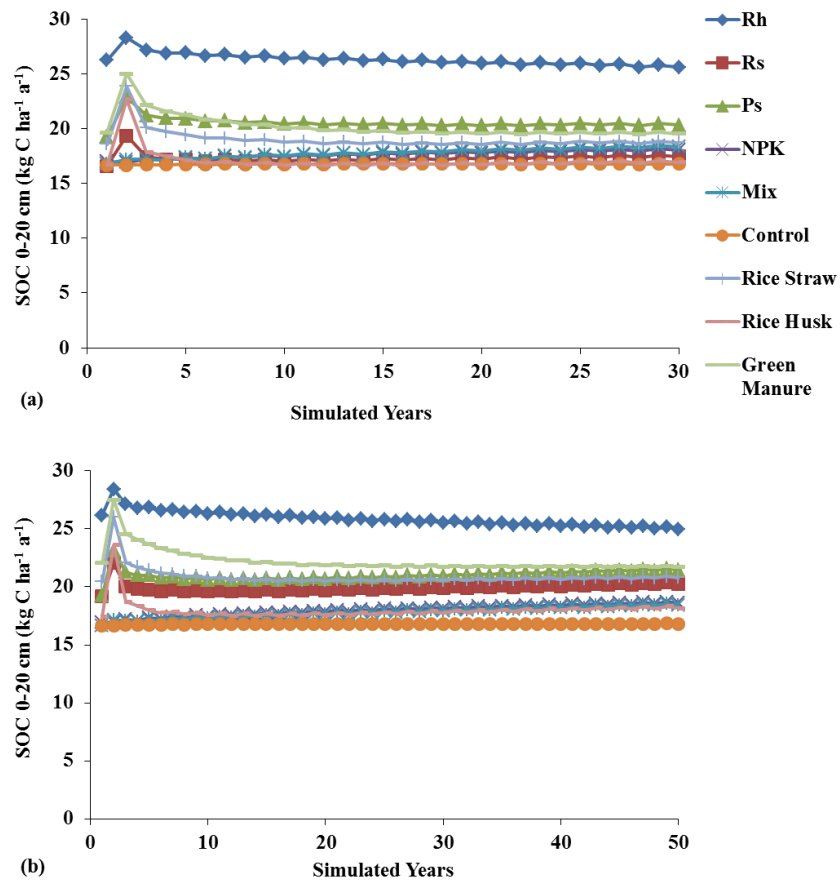


Figure 5.19: Simulated SOC in topsoil (0-0.2 m) after the applications of rice straw-, rice husk-, and pigeon pea stem biochars, rice straw-, rice husk-, and pigeon pea stem biomass, NPK fertilizers, and the control, after harvesting cotton (a) 30-year simulation by using the climate data from 1984 to 2013 (b) 50-year simulation by using a single year climate data from the year 2012, with the lowest rainfall (532 mm mean annual rainfall)

## Chapter 6: General Discussion

### 6.1 Changes of Soil Properties after Biochar Applications in Combination with NPK Fertilizers compared to Control and NPK Fertilizer Sole Application

To assess the changes of soil properties after biochar applications in combination with NPK fertilizers to agricultural soils, soil samples from the experimental plots before and after running the experiments were analysed and changes of their properties were observed. Findings from laboratory observations showed that biochar soil applications improved soil quality by decreasing bulk density, increasing soil organic carbon, water holding capacity, total exchangeable cations, and the rate of soil microbial respiration.

#### 6.1.1 Initial soil properties

According to laboratory analyses of soil properties, soil type of experimental site can be assigned as alkaline sandy loam soil with fine textured sands. Soil nutritional status has never been measured in the study area and therefore, nutrient deficiency or toxicity cannot be known. Since 1994, medium staple cotton (*G.hirsutum*) has sown every year by irrigation at the experimental site. Removal of aboveground portions of the crops at harvesting time is a habit in Myanmar. Cotton stems and roots were also removed during land preparation for the next cropping season. In growing cotton, chemical fertilizers were applied at average application rate of 70 kg N ha<sup>-1</sup>, 28 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, 39 kg K<sub>2</sub>O ha<sup>-1</sup>. When the ignition loss of organic matters from soil samples taken before conducting the field experiments were measured in the laboratory, 2% humus content was detected. At this value, humus content of experimental site can be classified as slightly humid (Table 1.1 in Appendix). Soils of the arid tropics are highly variable and organic matter production is slow due to low rainfall and reduced plant growth. In the other mean, because they receive less rainfall, existing organic matter degradation will also be slow (Creswell and Martin, 1993). However, the problem with low rainfall is the accumulation of easily soluble salts that is very common in arid and semi-arid climates (Geißler, 2007). Soil at the experimental site also has the problem of salt accumulation on the surface layer, as it is located in semi-arid region.

#### 6.1.2 Biochar properties

The major factors that affect the characteristics of the produced biochar are the composition of the original organic materials, the pyrolysis temperature, and residence time at the target temperature and, the heating rate (Brownsort, 2009).

Total carbon in biochars were rice husk biochar 44%, rice straw biochar 76%, rice husk biochar and farmyard manure mixture 23%, and pigeon pea stem biochar 50% respectively. Ash content of biochar (percentage dry wt.) was rice husk biochar 38%, rice straw biochar 62%, pigeon pea stem biochar 8%, and rice husk biochar and farmyard manure mixture 12%, respectively. According to biochar characterisation by European Biochar Certificate, pyrolysed char with carbon content below 50% of the dry mass were not classified as biochar. It was classified as Bio-Carbon-Minerals (BCM) and that have high nutrient content. Rice husk biochar and rice husk biochar + farmyard manure mixture used in the present research could be taken as BCM as their carbon content was lower than 50% of the dry mass.

Ash content of rice husk and rice straw biochar were in agreement with the proximate analysis results of ash content of rice husk and rice straw biochars that were produced at 650°C by Crombie et al. (2013). Total carbon, total nitrogen and pH of rice husk biochar was consistent with those of rice husk biochar used in the experiment that tested the effect of charcoal amendments on soil fertility and rice production in NE Thailand by Hemwong et al. (2012). They recorded its chemical properties as having a pH 6.78, total carbon content of 307 g kg<sup>-1</sup>, total nitrogen amounts of 10.4 g kg<sup>-1</sup>, and C/N ratio of about 30. Total carbon content of rice husk biochar was consistent with that of rice husk biochar produced at 1000°C by Paethanom (2012). Paethanom (2012) studied rice husk biochar produced at 600, 800 and 1000°C pyrolysis temperatures and stated that the higher the pyrolysis temperature, the more volatile matters were removed and resulted more fixed carbon. In that production process, carbon in the char particle was 38.88% (wt. /wt.) at 1000°C.

Rice straw biochar properties differ depending on biochar production methods. Rice straw biochar investigated by Ghoneim and Ebid (2013) was produced by using tubular furnace under oxygen absence environment with the temperature range 300-700°C. Rice straw biochar used in the present research was produced under partially oxygen-limited condition. In that case, rice straw seemed already reached to ash stage after pyrolysis because there was only 48% weight loss when rice straw biochar was heated in muffle furnace at 550°C for ash analysis. Higher pyrolysis temperatures will result lower biochar mass recovery, greater surface areas, elevated pH, higher ash contents, and minimal total surface charge (Novak et al., 2009). When rice straw biochar produced under oxygen absence condition (Ghoneim and Ebid, 2013) and rice straw biochar produced under partially oxygen controlled condition (present research) were compared, the former one yielded two times higher biochar, two times higher total carbon and total nitrogen, two times lower ash content and, lower pH. Relative high ash content of biochar that was produced by using low-tech kiln could be traced back to

the initial burning of raw materials due to the higher amount of oxygen flow during burning process (Gangil and Wakudkar, 2013).

Gangil and Wakudkar (2013) observed the generation of biochar from crop residues and investigated the effect of temperature on the yield and stability of char. In that research, pigeon pea stem biochar was produced under temperatures ranging between 250°C and 450°C. Ash content of pigeon pea stem biochar produced through the internal heating using CIAE charring kiln (developed by the Central Institute of Agricultural Engineering, Bhopal Madhya Pradesh, India) was 15.5% and pH ranged from 9.44 to 9.85. Biochar yield varied from 21 to 40%. These properties were consistent with the properties of pigeon pea stem biochar produced for the present research, having a pH of 9.14, a biochar yield of 34% and an ash content of 10%. Under the same production condition, a higher ash content of rice straw biochar compared to rice husk and pigeon pea stem biochar could be due to different chemical compositions of biomass materials such as different lignin and cellulose compositions. During the pyrolysis or oxidation process that generates biochar, heating causes some nutrients to volatilize, individual elements are lost to the atmosphere, fixed into recalcitrant forms or liberated as soluble oxides (Deluca, et al., 2009).

### **6.1.3 Effects of biochar applications on soil bulk density and porosity**

When soil physical properties after biochar applications were measured, bulk density changes of biochar-applied soils were not statistically significant from that of NPK fertilizer application and the control. However, soil bulk density reduced slightly in biochar-applied soils compared to the control and NPK fertilizer-applied soils. Bulk density of sands and sandy loams usually showed variations between about 1.20 g cm<sup>-3</sup> and 1.80 g cm<sup>-3</sup> (Landon, 1991). Bulk densities of the soils from experimental plots were between 1.60 g cm<sup>-3</sup> and 1.80 g cm<sup>-3</sup> in the upper 0-0.2 m soil horizon.

The lowest bulk density of 1.6 g cm<sup>-3</sup> resulted from Rh biochar application among the treatments. That was in agreement with the findings of Jeon et.al (2010). They found that carbonised rice husk application improved soil physical properties such as bulk density and porosity although rice yields were not significantly different between biochar application and non-biochar application. Zhang et al. (2012) stated 40 Mg ha<sup>-1</sup> rate of biochar application reduced soil bulk density consistently by 0.10 g cm<sup>-3</sup> within one year and 0.06 g cm<sup>-3</sup> in the second year. It was in agreement with the present research findings. After 40 Mg ha<sup>-1</sup> application of rice straw biochar, pigeon pea stem biochar and 20 Mg ha<sup>-1</sup> application of Rh biochar + FYM mixture, soil bulk densities of these treatments reduced by 0.10 g cm<sup>-3</sup> than



the initial soil bulk density. After 40 Mg ha<sup>-1</sup> Rh biochar application, soil bulk density decreased by 0.20 g cm<sup>-3</sup> compared to the initial values. Bulk densities of NPK fertilizer application and control remained the same as the initial bulk density.

In the Rh biochar applied soils, bulk density was decreased by 0.20 g cm<sup>-3</sup> compared to initial values, control and NPK sole application. In Rh biochar + FYM mixture applied soils, although 20 Mg ha<sup>-1</sup> rate of biochar was applied (total application rate of two year biochar applications), reduction of soil bulk density was the same level as that of Rs and Ps biochar total 40 Mg ha<sup>-1</sup> applications. That could be due to the properties of Rh biochar contained in Rh biochar + FYM mixture.

Biochar additions to the soil have the potential to reduce soil bulk density (Gundale and DeLuca, 2006) and bulk density is closely relating to porosity (Joseph et al., 2009). When soil physical properties of all treatments were compared, Rh biochar applied soils showed the lowest bulk density and highest porosity, highest maximum water holding capacity and the second highest water content at field capacity next to Ps biochar treated soils. Depending on the particle sizes and ash contents, surface area and porosity of these three biochars would differ and that would attribute to different impacts on the changes of soil bulk density. The density of biochar depends upon the nature of starting material and pyrolysis process (Pandolfo et al., 1994). Bulk density is that of the material consisting of multiple particles and includes the macro-porosity within each particle and the inter-particle voids (Downie et al., 2009). In the present research, since all of the biomass received the same pyrolysis condition, differences in densities might be due to the different properties of starting biomass. Changes of physical structure of biochar will depend on the chemical composition of each biomass material (Downie et al., 2009). Therefore, physical properties of rice husk, rice straw and pigeon pea stem biochars modified after pyrolysis process would vary with respect to the chemical composition of rice husk, rice straw and pigeon pea stem. In a long-term soil column incubation study of Laird et al. (2010), biochar less than 1 cm size was mixed with fine loamy soil with the rates 0, 5, 10 and 20 g kg<sup>-1</sup> and significant increase of the specific surface was found at the rate of 20 g kg<sup>-1</sup> biochar soil mixture (15% higher than control). At 5 g kg<sup>-1</sup> rate, there was 1% increase of specific surface area compared to the control. In the present research, size of Rh biochar particles (around 2 mm) was in the middle of those of Rs (smaller than 1 mm) and Ps (larger than 0.001 m) biochars, whereas soil from rice husk biochar treated plots showed the highest porosity. This change of specific soil surface area after mixing with biochar can help explain the changes of porosity since the surface area improvement is relating to the improvement of the porosity of soils. Significant improvement of the specific

soil surface area of soil particles and total porosity could vary with soil type, biochar type and the rate of biochar application. Biochar produced at temperatures ranging between 600°C to 750°C have a surface area of approximately 400 m<sup>2</sup> g<sup>-1</sup> (Brown et al., 2006; Downie et al., 2009).

In the present research, porosity percentages among the treatments were not statistically significant. However, certain differences of porosity values among the treatments were observed. Porosity of soils from control and NPK plots showed the lowest values compared to biochar applications. Jeon et al. (2010) studied the effect of rice-husk biochar application on rice yield and soil properties compared to chemical fertilizer application in a field experiment. Biochar was applied 2 Mg ha<sup>-1</sup> rate and soil of the experimental site was a fine loamy paddy soil. The results showed that although rice growth and yield from biochar application did not significantly differ from conventional chemical fertilizer application, rice husk biochar application increased soil porosity.

Porosity of biochars with high ash content will increase gradually over time because ash will leach out as the time passes (Thies and Rilig, 2009). In contrast to this statement, although Rs biochar had the highest ash content (64%), porosity of Rs biochar treated soils was lower than the other biochars with low ash content. High ash content in rice straw biochar could be due to the higher cellulose content of rice straw, 37.74% cellulose and 26.03% hemicelluloses (Rahnama et al., 2013). Temperature range lower than 600°C will require for proper biochar production from rice straw because volatilisation rate, degradation of anhydrosugars present in tar and biochar yield will decrease at 300°C-600°C temperature range (Amonette and Joseph, 2009). Cellulose of biomass that transformed to tar during pyrolysis is chiefly composed of anhydrosugars such as laevoglucose (Shafizadeh, 1982; Amonette and Joseph, 2009). Therefore, rice straw biomass will transform to ash with the less number of pore space.

In the present research, although porosity of biochar treated soils was higher than control and NPK fertilizer application, this porosity level was still lower than the level that is favourable for root penetration. Total porosity of soils usually lies between 30% and 70% and was used as a very general indicator of the degree of compaction in a soil (Landon, J.R. (1991). For example, sands with a total pore space less than about 40% are liable to restrict root growth due to excessive strength (Harrod, 1975 cited by Landon 1991). In the here presented field experiments, biochar and soil mixing rate was 5.6 g biochar per kilogram resulting in an increase of porosity of 11.46% compared to the control in Rh biochar applied soils, 5.03% in Rs biochar applied soil, 1.73% in Ps biochar applied soils and 1.73% in Rh biochar + FYM

mixture applied soils, respectively. In the NPK fertilizer application, porosity was 2.10% less than that of the control. 5.6 g kg<sup>-1</sup> biochar soil mixing rate might not large enough for significantly changing the soil surface area within one year after biochar application. Long-term study of more than one year would require in order getting more precise information of biochar effects on the changes of soil porosity because biochar has the potential of improving porosity.

#### **6.1.4 Effects of biochar applications on maximum water holding capacity and water retention**

In water retention measurements, although the results were not statistically significant, water retention improved in biochar treated soils compared to NPK fertilizer application and control. Soils of Rh biochar treatment and Rh biochar + FYM mixture treatment had the same water content at field capacity. Although soils from Ps biochar application contained the same percent of water filled pore space as the soils of NPK and rice straw biochar applications, Ps biochar treated soils had the highest percent of plant available water among all treatments. Ps biochar applied soils held fewer amount of water at permanent wilting point than the other soils. This showed that Ps biochar could store more water that was available for the cultivated crops. That could be due to macro-pore content of pigeon pea stem biochar as macro-pores are very relevant to vital soil functions as aeration and hydrology (Troch and Thompson, 2005; Downie et al., 2009). Biochar soil amendment can increase the total soil-specific surfaces through its micro-, meso- and macro-pore contents (Downie et al., 2009). At permanent wilting point, NPK fertilizer applied soils held the highest amount of water in its pore space and in consequence, crops sown in NPK fertilizer applied soils would face more water stress than the plants of the other treatments under water scarcity conditions and would have less nutrient uptake ability influencing the crop yields.

Results showed that significant improvement of water retention capacity of biochar applied soils could vary with biochar type, initial soil property and biochar application rate. Yu et al. (2013) stated that by addition of each 1% by mass of biochar, water-holding capacity of loamy sand soil increased by 1.7% compared to the control. In their research, biochar application rate was 0.56% by mass of biochar, and, water-holding capacity of sandy loam soils increased by 0.1-3.5% depending on different biochar feedstock. Soil surface area is an important characteristic as it influences soil physical functions. Limited water holding capacity of sandy soils is relating to the small surface area of soil particles (Troech and Thompson, 2005; Downie et al., 2009). In the former studies of biochar application to sandy

soils, water retention in those soils increased when 80 to 900 Mg ha<sup>-1</sup> rate of biochar was applied (Tyron, 1948; Gaskin et al 2007; Novak et al., 2009). In the present research, biochar application rate was lower than those rates that showed significant improvement of water retention and its effect on the improvement of water retention capacity was not significant although some level of changes occurred compared to control and conventional NPK fertilizer application.

#### **6.1.5 Effects of biochar applications on total soil organic carbon**

In both years, total soil organic carbon (SOC) changed significantly due to treatments. The highest SOC was detected in Rh biochar applied soils. After harvesting rice and after harvesting cotton, SOC in NPK fertilizer-applied soils was lower than that of the control and SOC in biochar-applied soils was higher than control. Increased SOC of soils after biochar applications were already stated in the former biochar research, both in incubation and field experiments (Glaser et al., 2002; Lehmann and Joseph 2009; Lentz and Ippolito, 2011; Nigussie et al., 2012; Zhang et al., 2012; Ghoneim and Ebid 2013; Schulz et al., 2013). In the present research, after first time biochar application in 2012, total carbon in topsoil 0-0.2 m increased by 53% in Rh biochar application, 12% in Ps biochar application, and 8% in Rs biochar application, respectively compared to the control and initial condition as well. After second time biochar-application in cotton growing season, total carbon in biochar treated soils increased and that in NPK and control soils decreased. In that season, total carbon in Rh biochar applied soil increased by 169% compared to control. Between first and second cropping seasons, total carbon increased by 31.36% in Rs biochar applied soils, 27% in Rh biochar applied soils, and 13% in Rh biochar + FYM mixture applied soils, respectively.

The highest SOC measured in Rh biochar treated soils among all treatments in the end of the field experiments could be due to total carbon content and the texture of biochar materials. Rs biochar contained the highest SOC (76%) compared to the other three biochars. However, Rh biochar contained higher stable carbon (15%) than Rs biochar (2.18%). Therefore, stable carbon of Rh biochar might remain in the soil longer than that of Rs biochar. Although Ps biochar contained higher total carbon (50%) and higher stable carbon (23.5%) than Rh biochar (44% total carbon and 15% stable carbon), measured SOC in Ps biochar applied soil was 42% lower than that of Rh biochar applied soils. That difference might be due to higher mobile carbon content of Ps biochar. Its carbon might easily be consumed by the cultivated crops or by soil microorganisms during the growing season and finally, in the end of the growing season less amount of carbon from Ps biochar would remain in the soil. Another

factor could be the nature of less homogeneity of Ps biochar particles with soil due to its size. In consequence, it would move in the plot through cultivation practices, that would affect the sample collection, and measurement of carbon content of Ps biochar applied soils.

SOC values obtained from DNDC model simulation, SOC values obtained from soil analysis and calculated SOC values were compared to assess how much SOC was left in the soil at the time of harvesting. Calculated SOC was the amount of SOC that should be in the soil with respect to total carbon content of biochar and biochar application rate. It was found that calculated SOC was always higher than the measured SOC (from soil analysis) and simulated SOC (by DNDC model) in both years in all treatments except Rh biochar treatment. Despite the significant changes of SOC among the treatments in both years, the amount of SOC detected in biochar-applied soils appeared lower, relative to biochar application rate and organic carbon content of biochars. This low amount of detected organic carbon could be due to the sampling depth and the distribution of applied biochars in the soil profile, losses of biochars through irrigation water and cultivation practices, and due to different mechanisms that enhanced carbon and biochar degradation. According to Zimmerman and Gao (2013), black carbon and biochar can be lost by biotic degradation due to soil microbial activities, abiotic oxidative degradation due to the oxidation of both on biochar surfaces and in bulk, non-oxidative abiotic losses through desorption of CO<sub>2</sub> or volatilisation of organic compounds, leaching, erosion or translocation, and volatilisation and decomposition by later fires.

Biochar can be mobilised at different scales in the landscape, ranging from fractions of meters in the soil profile that mainly involve tillage, turbation and dissolution, up to hundreds of meters through erosion of biochar from the soil (Hammes and Schmidt, 2009). According to Major et al. (2010) and Zimmerman and Gao (2013), black carbon losses from biochar amended soils due to leaching, downward movement and mineralisation was less than 3% and 20-53% of the applied black carbon must have been lost by surface erosion.

Although water or other cultural practices can bring biochar particles to downstream, that might happen rarely in present research since experimental plots were separated with double bunds and biochars applied to each plot were maintained in the respective plots. As an exception, uneven scattering of biochars due to lateral movement in the subplots and accumulation of biochars in a certain corner of the plots could have happened. Zimmerman and Gao (2013) stated that in levelled agricultural systems, since biochar is initially mixed with soil, losses by erosion could be less.

Environmental conditions and land use will affect the degradation rate of biochar in soils (Lehmann et al., 2009). The resistance of biochar to degradation will vary with different properties of biochars such as macro- and micro-pore structure, solubility, surface affinity for other soil components and environmental factors such as pH, oxidant concentration, moisture level and soil compaction and structure (Zimmerman and Gao, 2013). In the present research, since the treatments received the same management and environmental conditions, the rate of degradation among biochars would differ with respect to the properties of raw biomass, size of biochars, dispersion and location of biochar particles in the soil, and solubility and homogeneity of biochars in the soil.

When applied to soil, rice straw biochar could have physically degraded and been transported faster than rice husk biochar by irrigated water and tillage operation horizontally and vertically in the soil due to its chemical composition and physical structure. Rice straw biochar contained more ash than rice husk and pigeon pea stem biochars. The proportion of inorganic (ash) components also has implications on physical structure (Downie et al., 2009). Size of rice straw biochar was smaller than that of rice husk biochar (< 2mm) and rice straw originally contained lower lignin (9%-12.3%) (Rahnama et al., 2013; She et al., 2011) compared to the lignin content of rice husk (26-31%) (Ludueña et al., 2011) and that of pigeon pea stem (25%) (Elzaki et al., 2012).

Zimmerman and Gao (2013) reviewed the observation of biochar stability in short-term laboratory incubation experiments and they made a general assumption that biochars made from grasses are more labile than those made from woody materials. Xie et al. (2013) stated that 15.5% of wheat straw biochar was lost in the sandy loam Inceptisol soils over the 117 days experimental period. Knoblauch et al. (2011) found that under aerobic and anaerobic conditions, 4.4% and 8.5% respectively of rice husk biochar was lost after 2.9 years of incubation. Pigeon pea stem biochar size was larger than rice husk biochar and it could not mix homogeneously with the soil like rice husk biochar and could easily move by tillage or water.

Before growing cotton for cotton experiment, the land of experimental plots was disc harrowed and ploughed by moldboard plough. Biochars applied in the previous season could have been crushed by those tillage operations and moved to the deeper soil layer. Withstanding to wear and tear during the use of biochars will be relating to the quality of activated carbon. This quality of activated carbon is characterized by the mechanical strength. Mechanical strength of biochar is relating to its solid density (Downie et al., 2009). Properties

such as mechanical strength and hardness can be explained by high lignin and low ash contents (Aygün et al., 2003; Downie et al. 2009).

Haefele et al. (2011) discussed the influence of sampling depth on soil organic matter measurements. Haefele et al. observed the organic carbon storage of rice soils after rice husk biochar and fresh rice husk application at three locations in two rice-growing seasons. Half of applied carbon from rice husk biochar was detected in the first rice season and all of applied carbon was detected in the second season. They found carbon from rice husk biochar moved to the next soil layer, 0.15-0.30 m, in the locations with high percolation rate. This vertical movement was possible for rice husk and rice straw biochars as their sizes were less than 0.001 m, and the texture of the soil of experimental site was a sandy loam and had fair rates of percolation. In the present research, soil samples were taken from topsoil 0-0.20 m. If the samples could have been taken from the next horizon depth, like 0.20-0.40 m, a more complete and stronger figure of total carbon content from biochar-applied soils could be obtained.

Higher total carbon detected in Rh biochar treated soils was consistent with the ecological quotient of respired carbon per unit of organic carbon. The rate of substrate induced respiration (SIR) per unit of organic carbon was the highest in NPK, Rh biochar + FYM mixture and Rs biochar treated soils and the lowest in Rh biochar treated soils although the highest amount of organic carbon was found in Rh biochar treated soils. That lower microbial respiration rate might lead to the slower rate of degradation of carbon and as well as Rh biochar. In consequence, higher amount of organic carbon might have been detected in Rh biochar treated soils.

#### **6.1.6 Effects of biochar applications on total nitrogen**

In the present research, inorganic fertilizers were applied together with biochars. Despite organic and inorganic fertilizer applications, less amount of total nitrogen was detected in Rh-, Rs- and Ps biochar applied soils after harvesting rice crop. Total N in Rh biochar + FYM mixture applied soil was higher than that of the control and NPK fertilizer applied soils. That could be due to the impact of biochar surface properties that retain nitrogen contained in manure, nutrient transformation, and initial soil properties. Biochar may act as a habitat for soil microorganisms (Pietikäinen et al., 2000; Deluca et al., 2009). Biochar certainly has the capacity to support the presence of adsorbed bacteria (Pietikäinen et al., 2000; Rivera-Utrilla et al., 2001, Deluca et al., 2009) from which the organisms may influence soil processes. Total nitrogen losses will be higher during first growing period after biochar application due

to bigger protein demand of soil biota (Schulz et al 2013). After harvesting cotton, total nitrogen in all biochar applied soils increased to around 20-40% higher than the control and NPK fertilizer applied soils. Total nitrogen content in NPK fertilizer applied soil was the same level as that of control soil. Overall level of total N after harvesting cotton in all treatments was lower than previous year. That might be due to different nutrient uptake of cultivated crops and the effects of the nature of upland and lowland cropping practices on soil chemical and biological properties. Cotton was sown after harvesting chickpea and field was irrigated according to crop's water requirement. Those conditions would favour the biological nitrogen fixation. Sufficient nitrogen might have been stored in biochar treated soils because of the symbiosis reaction of biochar and soil microorganisms. It is possible total N detected in biochar-applied soils was higher than that of non-biochar applied soils at the time of soil sampling because of adequate nitrogen storage in soils throughout the cropping season.

Higher amount of total N in Rh biochar + FYM mixture application after harvesting rice could be due to the combined effects of biochar, manure and inorganic nitrogen fertilizer. Denitrification process requires available carbon and a terminal electron acceptor, such as  $\text{NO}_3^-$  (Stevenson and Cole, 1999; Deluca et al., 2009). Adding biochar and manure would potentially increase the bioavailable C in the soil solution (Lehmann et al., 2003; Steiner et al., 2007) and this will enhance the denitrification potential in mineral soils under anaerobic condition (Deluca et al., 2009).

Biochar is more important as soil conditioner and less important as a primary source of nutrients (Glaser et al., 2002; Lehmann et al., 2003; Deluca et al., 2009). Haeferle et al. (2011) studied the effects of rice husk biochar on rice yields and soil properties on three different soils having different soil properties and receiving different amount of irrigation water. In that research, response of rice yield to biochar application was significant under poor soil conditions than under full irrigation and fertile soil conditions. It was assumed that under poor soil conditions, the crops will consume all applied inorganic fertilizers and nutrients from organic amendments since there are originally not enough nutrients in the soil. In addition, the effects of biochar on soil quality such as increasing nutrient efficiency and increasing CEC was apparent when it was applied to nutrient deficient soils.

In contrast to this situation, biochar additions to fertile agricultural soils may show slight decline in net ammonification due to  $\text{NH}_4^+$  adsorption or enhanced ammonification (Deluca et al., 2009). The next reason of low level of total N in soil could be nitrogen immobilisation. When fresh biochar having high C/N ratio is applied to soil, some decomposition will occur (Schneour, 1996; Liang et al., 2006; Deluca et al., 2009). That will induce the net



immobilisation of inorganic N already present in the soil solution or in applied fertilizer and organic nitrogen will temporarily be maintained and in consequence, inorganic N leaching will be reduced (Steiner et al., 2007; Deluca et al., 2009). Another reason for low level of total organic nitrogen in the soil after harvesting the crops could be the increased rate of ammonia volatilisation due to biochar application (Xie et al., 2013) during the cropping season. Xie et al found ammonia volatilisation after the application of alkaline wheat straw biochar (pH=10.12) to alkaline Inceptisol soil (pH=7.6).

### **6.1.7 Effects of biochar applications on soil microbial respiration**

Effects of biochar applications on soil microbial respiration were measured in the laboratory through the observations on basal respiration (BR) and substrate induced respiration (SIR). There were differences in the rate of respiration between control, NPK fertilizer application and biochar applications. In 2012 after harvesting rice, Ps biochar applied soils showed the lowest rate of respired carbon dioxide in both BR and SIR among all treatments. That amount was higher in Rh biochar, Rs biochar and Rh biochar + FYM mixture applied soils compared to the control. In 2013 after harvesting cotton, all biochar treatments showed higher respiration rate than control and NPK fertilizer application. The growth of soil microbial community is normally limited by a lack of easily available C (Demoling et al., 2007), and thus addition of biochar as well as C will induce a positive growth response of the microbial community (Rousk et al., 2013) and in consequence microbial respiration rate will be higher. Among biochar treatments, the highest rate of respiration was found in Rs biochar applied soil and the second highest was found in Rh biochar applied soils and the third was in the Rh biochar + FYM mixture and Ps biochar applied soils, respectively. That finding was consistent with the ash content and total carbon content of biochar materials. Rs biochar contained highest ash content followed by Rh biochar, Rh biochar + FYM mixture and Ps biochar, respectively. Those ashes could easily be soluble in water and available for microbial consumption and have enhanced the rate of microbial respiration. In biochar pores microbial activity occur under both aerobic and anaerobic conditions (Thies and Rillig 2009). Residues remaining on biochar surfaces after pyrolysis like ash can include water-soluble compounds that have bactericidal or fungicidal activity (Painter, 2001; Thies and Rillig, 2009). Rice straw biochar applied soils might have created more favourable conditions for microbial colonisation than the other biochars due to its high ash content (62% wt./wt.), higher water holding capacity (553% dry wt. basics), provided surface area for colonisation of microbes and the particle size (less than 1cm) that could mix more homogenously with the soils.

In 2012, the amount of 20 Mg ha<sup>-1</sup> each of rice husk-, rice straw- and pigeon pea stem biochars and 10 Mg ha<sup>-1</sup> of Rh biochar + FYM mixture were applied before rice cultivation. Soil microbes might have started to colonise during rice growing season. After harvesting rice, only rice roots were remained in the soil as rice leaves and stems were harvested and removed out of the field. Chickpea was sown between rice and cotton crops. Chickpea crop might have functioned as soil cover that could slow down soil nutrient losses and fixed atmospheric nitrogen to soils through its nitrogen-fixing bacteria. When biochars were added second time before growing cotton, the amount of organic carbon that was available for soil microbes might increase during the cotton-growing season. During cotton-growing season, cotton leaves and other unfertilised reproductive organs would fall onto the ground throughout the season. Canopy of cotton crops and drying and rewetting of cotton fields might favour the decomposition of organic matters. There could be organic substances, not only applied biochars but also organic matters from cotton fields that were available for the multiplication of soil microorganisms. Therefore, soil samples that collected after harvesting cotton showed the higher rate of microbial respiration.

The ratio of microbial respired carbon to soil organic carbon (C<sub>mic</sub>:C<sub>org</sub>), ecological quotient, reflects the contribution of microbial biomass to soil organic carbon (Anderson and Domsch, 1989). It also represents the substrate availability to soil microorganisms. In the present research, C<sub>mic</sub>:C<sub>org</sub> values were significantly different responding to the treatments and responding to the cropping seasons. There were no significant interaction effects of treatments and seasons on soil microbial respiration.

In 2012 after harvesting rice, ecological quotient was the highest in Rh biochar + FYM application, followed by NPK sole application, Rs biochar application, Ps biochar application, control and Rh biochar application, respectively. In 2013 after harvesting cotton, ecological quotient was the highest in Rh biochar + FYM mixture application, Rs biochar application and NPK sole application, followed by Ps biochar application, control and Rh biochar application. It showed that substrate availability was higher in Rh biochar + FYM mixture + NPK fertilizer treated soils compared to that in the biochars + NPK fertilizer treated soils. That could be assumed that mixing farmyard manure with biochar could promote the soil microbial activities. Bhattacharyya et al. (2005) studied the suitability of municipal solid waste compost application with and without urea fertilizer to submerge rice paddies compared to decomposed cow manure application with and without urea fertilizer, chemical fertilizer applications and the control. They found the highest microbial biomass carbon in decomposed cow manure + urea treated soils.

Higher substrate availability in Rs biochar treated soils could be due to the higher ash content (62%) and higher mobile carbon content (67%) that might provide enough food for microorganisms. Ps biochar and Rh biochar treated soils also showed the lower substrate availability compared to Rh biochar + FYM mixture, Rs biochar and NPK treated soils. That could be due to the more recalcitrant nature of Rh and Ps biochars. Rh biochar contained 15% fixed carbon and Ps biochar contained 23.5% fixed carbon, respectively.

When the percent changes of ecological quotient between two seasons were compared, ecological quotient of Rs biochar application in 2013 increased by 107% compared to 2012, followed by Rh biochar application, control, NPK sole application, Rh biochar + FYM mixture, and Ps biochar application, respectively. Although Rh biochar application showed lower value in general, the rate of increase of substrate availability was highest among the treatments. Different increasing rates of substrate availability among the treatments in the two seasons also followed the level of chickpea yields. Chickpea crops sown on the Rh biochar applied plots yielded the highest and they would have larger accumulation of root biomass. That must be due to the impact of chickpea root biomass on the substrate availability of organic matter in the following season. Soil systems receiving larger amount of organic matters tend to harbour higher level of microbial organic carbon with greater microbial activity (Sparling, 1985; Bhattacharyya et al., 2005).

#### **6.1.8 Effects of biochar applications on soil pH**

pH of biochars produced for this research were 8.2 in Rh biochar, 10.28 in Rs biochar, 9.14 in Ps biochar and 7.62 in Rh biochar + FYM mixture respectively. Initial soil pH was 7.9. pH of Rh-, Rs- and Ps biochars were higher than that of initial soil pH. pH values of soils from all input applied treatments did not show significant differences from the control. Soil pH of all treatments was lower than pH of the soil before running the field experiment. After experiment, pH value dropped from 8.0 to 7.6-7.7. pH of the control decreased compared to initial soil pH as well. That could be due to the changes of cultivation practices such as changing cropping practices from successive upland cropping to lowland cropping with permanent presence of water in the fields.

Rice straw (Rs) biochar had the highest pH value of 10.3. When it was applied to the soil, soil pH did not increase. Although pH values of all biochar types were high, (higher than 8) soil pH did not increase and it remained under 8.0.

Rh biochar had lower pH than Rs and Ps biochars and Rh biochar applied soils showed lower pH value than Rs and Ps biochar applications. Most of biochar researches were conducted on

acid soils and results showed that biochar application elevated the soil pH due to the presence of oxidised functional groups (Mbagwu 1989; Matsubara et al., 2002; Lehmann et al., 2003; DeLuca et al., 2009). Scholz et al., 2013 studied biochar compost application to sandy and loamy soil substrates. They stated that soil texture could affect pH changes after biochar application. In their experiment pH values of biochar compost, sandy soil substrate and loamy soil substrate were nearly the same. The results showed that by applying biochar compost to a sandy soil substrate, soil pH did not change. However, pH of loamy soil increased with respect to the proportion of biochar in biochar compost. This could be due to the reaction of basic cations on the biochar surfaces with the negatively charged clay particles in loamy soils. Lentz, R.D., and Ippolito, J.A. (2011) studied the effects of manure single application, hardwood-derived biochar single application and hardwood-derived biochar together with manure application. The results showed that biochar did not alter pH of calcareous soils. Van Zweiten et al. (2010) also found the same result after application of biochar with pH 8.2 to a Calcarosol having initial pH of 7.7. Liu and Zhang (2012) studied the effect of biochar on pH of five alkaline soils in the Loess Plateau, China. Results from incubation experiments showed that application of alkaline biochar (pH 8.4) did not increase soil pH. Soil pH was decreasing especially with higher biochar application rates of 8 g kg<sup>-1</sup> and 16 g kg<sup>-1</sup> wt. /wt. of biochar soil mixture and this decreasing rate was significant in the 0.10 m - 0.20 m deep layer. The reason of pH reduction could be due to the formation of soluble carbonates from the combination biochar cations and carbonate of calcareous soil. That soluble carbonate would restrict the hydrolysis of carbonates and decrease the hydroxyl amount in soil and in consequence, soil pH would be reduced (Liu and Zhang, 2012).

### **6.1.9 Effects of biochar applications on carbonate content**

Carbonate content of biochar applied soils were the same as that of control and NPK applied soils in 2012 after harvesting rice. The level of carbonate content in the soils of every treatment did not exceed the threshold level that could affect crop production (less than 2%). In 2013, carbonate content was lower than the previous year in all treatments; reduced by 65% in Rh biochar application, 58% in Rs biochar application, 39% in control, 36% in NPK fertilizer application, 19% in Rh biochar + FYM mixture application, and 8% in Ps biochar application, respectively. In both years, carbonate content of biochar-applied soils was the same as that of control and NPK fertilizer applied soils except Rh biochar application. Carbonate content in Rh biochar applied soil was 50% lower than the control. Zimmerman and Gao (2013) stated the release of carbonate C from biochar by citing the observation of

Zimmerman (2010) that carbonate C from biochar desorption would require the acidification by strong acid. Zimmerman (2010) used 10% phosphoric acid to measure the CO<sub>2</sub> evolved and the range of 0.01-0.6% CaCO<sub>3</sub>-C (wt. %) was detected after 72 hour acidification. Jones et al. (2011) found that when biochar was incubated in soil after rinsing with water, CO<sub>2</sub> release was 50% decreased and after treated with acid, CO<sub>2</sub> release was decreased to 5-fold. In the present research, biochars were applied under flooded condition in 2012 and in 2013, biochar stood in alkaline soil under drying and rewetting condition. Those conditions could have affected CO<sub>2</sub> release from carbonate fraction of biochar treated soils when the samples were analysed for carbonate content.

#### **6.1.10 Effects of biochar applications on soluble salt content**

Soluble salt content was getting higher after application of 40 Mg ha<sup>-1</sup> of Rh-, Rs- and Ps biochar and 20 Mg ha<sup>-1</sup> of Rh biochar + FYM mixture. Although soluble salt was increased, the level of soluble salt content, ranged between 0.04-0.06, was still lower than 0.65% which is the threshold level for crop growth (Table 6.4). Regarding the crops that were tested in the present research, rice is moderately tolerant to soil salinity, and threshold salinity for rice is about 3 dS m<sup>-1</sup> (1.6% soluble salt content) (Maas and Hoffman, 1977; Fageria et al., 1997). Cotton is also tolerant to salinity having a threshold salinity value of 7.7 dS m<sup>-1</sup> (4.07% soluble salt content) (Fageria et al., 1997). Chickpea is highly susceptible to salinity, its root growth was affected at 2 dS m<sup>-1</sup> (1.1% soluble salt content) and growth and yield were inhibited at 4 dS m<sup>-1</sup> (2.1% soluble salt content) (Richter et al., 1999).

Increased EC values in 2013 compared to 2012 has not only found in biochar treated soils but also in the control and NPK fertilizer applied soils. Maximum conductivity value was found in soils of rice straw biochar and NPK fertilizer applied plots. Highest soluble salt content of Rs biochar treated soils compared to the other three biochars could be due to the higher soluble salt content of rice straw biochar (15.3%).

#### **6.1.11 Effects of biochar applications on exchangeable cations, ESP and SAR in soil**

In the present research exchangeable cations of the soils of all treatments, including control was higher than the initial amount of exchangeable cations of the soil before experiment.

After harvesting rice in the first year of biochar application, total exchangeable cations of biochar-applied soils were lower than that of the control. Total exchangeable cations in the soil after conducting rice experiment were higher than that of initial soil. That could be due to land management changes at the time of experimentation that differed from the cultivation

practices in the past. During the last 20 years, only upland crops were cultivated. At the time of conducting field experiment, land use was changed to flooded rice cultivation. Short-term ponding conditions may affect the aggregation state of upland soils through changes in chemical conditions, such as the redox state of the soil. When soils are flooded, aerobic microbial respiration consumes  $O_2$  in the saturated soil and a shift from aerobic to anaerobic respiration occurs (Rowell, 1981; De-Ceampos, 2009). After  $O_2$  depletion, minerals ( $NO_3$ , Mn, Fe, S, and organic substrates) will occur in the reduction form and in consequence of the reducing conditions, CEC in soil will change together with the changes of mineralogy and structure of the soils (Ponnamperuma, 1981; Patrick and Jugsujinda, 1992; Shen et al., 1992; Fieldler and Kalbitz, 2003; and De-Ceampos, 2009).

After harvesting cotton, total exchangeable cations of biochar-applied soils were higher than the previous year and higher than that of the control and NPK fertilizer applied soils. Total exchangeable cations of the control remained the same as the previous year. Addition of biochar to soil has shown definite increases in the availability of major cations (Glaser et al., 2002; Lehmann et al., 2003). It is indirect nutrient value of biochar to retain exchangeable cations to replenish the nutrients in soil solution for plant uptake (Chan and Xu, 2009). The greater amount of cation exchange capacity per unit C found in the soils with high amount of biochars such as the Amazonian Dark Earths (Sombroek, 1966) may be the result of a greater surface area of biochar and a higher charge density per unit surface area. Once biochar is exposed to  $O_2$  and water, spontaneous oxidation reactions occur resulting very high CEC (Cheng et al., 2006, 2008; Chan and Xu, 2009; Liang et al., 2006).

The highest total exchangeable cations were found in Rh biochar applied soils and Rs biochar applied soils. Exchangeable cations in soils after biochar applications did not follow that of respective biochar materials applied to the soils. Although total exchangeable cations of rice husk biochar was lower than that of Ps- and Rh biochar + FYM mixture, total exchangeable cations of Rh biochar applied soils was higher than that of Ps biochar and Rh biochar + FYM mixture. When the proportions of exchangeable cations of each treated soil were analysed, it could be stated that the high total exchangeable cations values of control and NPK fertilizer applied soils were due to the higher exchangeable sodium content (7% of all major cations). Biochar applied soils contained higher composition of exchangeable Ca, Mg and K and less amount of exchangeable sodium, (3% of all major cations in Rh biochar, Rs biochar, Ps biochar and NPK applied soils).

In 2013 after harvesting cotton, in all treatments, major cation in soils was Ca and the second was Mg. This proportion of exchangeable bases did not follow the proportion in biochars

except the case of exchangeable potassium content of Rs biochar. Proportion of exchangeable K was the highest in Rs biochar applied soils and the second highest exchangeable K was found in Ps biochar applied soils. Before pyrolysis, 90% of K in rice straw was occurred as a water-soluble form and after pyrolysis with the temperatures  $> 600^{\circ}\text{C}$ , 48% was lost by vaporisation and a greater proportion of the remaining K was therefore found as exchangeable K (Chan and Xu, 2009). When rice straw biochar was applied to the soil, plant available K level would be higher with respect to the higher level of exchangeable K that contained in rice straw biochar.

Before the experiment, exchangeable sodium in the soil was undetectable. Exchangeable sodium percent (ESP) in 2012 was not significantly different among the treatments. In control and NPK fertilizer sole application, exchangeable sodium showed an increasing trend. In 2013 in upland cropping season, ESP had increased in all treatments. Increased ESP in all treatments could be due to continuous conventional tillage in all cropping seasons. Fando and Pardo (2009) studied the effect of different tillage practices on soil chemical properties and found that ESP in topsoil 0-0.30 m under conventional tillage was higher than that under minimum tillage and no-tillage. When ESP of input applied soils were compared with the control, their ESP values were lower than that of the control. Maximum ESP was found in control soils however that was lower than the threshold limit of 15% ESP (Table 6.5) for sensitive crop and 35% ESP for tolerant crops (Havlin et al., 2014).

A soil with ESP value less than 15, EC higher than  $4 \text{ mS cm}^{-1}$  and pH lower than 8.5 is regarded as non-sodic soil containing sufficient soluble salts to interfere with the growth of most crops (Havlin et al., 2014). Although the soil in the study area had, ESP less than 15 and pH lower than 8.5, soluble salt content was not as high as  $4 \text{ mS cm}^{-1}$ , and this soil cannot be regarded as sodic or saline soil. However, if the ESP value continues to increase, necessary care should be taken to protect the soil from becoming saline soil. Although increment of ESP value was not as high as the control plot, biochar treated soil also showed an increase of ESP. After harvesting cotton in 2013 ESP in control was significantly higher than the other treatments and compared to the previous year.

Sodium adsorption ratio (SAR) also tended to increase in all treatments in 2012. In 2012 after harvesting rice, SAR of all treatments was higher than the control except Ps biochar treatment. Soils of the control and Rh biochar + FYM mixture treatments showed the highest rate of increase of SAR. SAR of biochar-applied soils was lower than that of the control in 2013 after harvesting cotton. SAR of all treatments in 2013 after harvesting cotton was higher than the SAR of previous year after rice harvest. The highest SAR after cotton harvest was

observed in the control soils and the lowest was found in soils of Ps biochar applied soils.  $\text{*mmho cm}^{-1} = \text{dS m}^{-1}$  in SI units, where ds= decisiemen.

### **6.1.12 Effects of biochar applications on available K**

Plant available K in biochar applied soils showed significant differences in both years compared to non-biochar applied soils. Although there were significant differences of plant available K among the treatments, differences were not so high in 2012 after harvesting rice. In 2013, available K in rice straw biochar applied soils increased and there was a big difference of available K level between rice straw biochar applied soil and soil of the other treatments. That could be due to originally higher level of exchangeable potassium content in rice straw biochar compared to the other three biochars. About 90% of total K in rice straw was in water-soluble form before pyrolysis and this K was lost when heating up to 673°C. With the temperatures above 600°C, a greater proportion of the remaining K was found in exchangeable and acid extractable form (Yu et al., 2005; Chan and Xu, 2009). As exchangeable K of rice straw biochar applied soils was the highest among the treatments, available K concentration of rice straw biochar applied soils was also the highest among the treatments. Exchangeable potassium in rice straw biochar was 100%, 80%, and 57%, respectively higher than that of rice husk biochar, pigeon pea stem biochar and rice husk biochar and farmyard manure mixture. That hierarchy of exchangeable potassium content in biochar materials was consistent with the exchangeable potassium of biochar treated soils. According to the measurements of exchangeable potassium in biochar treated soils after harvesting cotton in 2013, exchangeable potassium of rice husk biochar, pigeon pea stem biochar, rice husk biochar and farmyard manure mixture applied soils were 5 times, 3 times and, 1 time, respectively lower than that of rice straw biochar applied soils. Since the initial soil was a low fertile soil and the nature of cotton crop required potassium for cotton lint and bolls, this amount of available potassium did not affect cotton crop growth and yield. Crop growth and yield of rice straw biochar applied plots were comparable with those of Rh biochar + FYM mixture applied plots.

### **6.1.13 General discussion on the results of soil property analyses**

Although the trend of total nitrogen level in biochar applied soils and non-biochar applied soils was consistent with the level of total carbon and nitrogen content of biochar materials, total nitrogen content was not consistent with the total carbon content measured from the same soils. Not only total nitrogen, but also the results obtained from the laboratory



measurements such as total amount of exchangeable cations, soluble salt content and total nitrogen content of soil samples were not statistically significant. Soluble salt contents were much lower than the range for normal soil conditions. Total nitrogen contents were much lower, compared to total organic carbon content of the same soil. To find the reason of such results might need further research as the problem could be the actual properties of biochar and could be due to the artifact in sample handling and sample measurements. Non-significant differences in the changes of soil physical properties such as soil bulk density and water retention capacity could be due to the time required for the improvement of soil physical properties and the amount and type of biochars applied to the plots. The next possibility of the slow response of soil properties to the treatments could be due to the problem with original soil quality such as organic matter content, clay mineral content, bulk density and pH. Poor soils will need time to respond to soil amendment application since they originally are weak to be able to transform applied nutrients to plant available form. They have low level of organic matter and low number of microorganisms that could facilitate soil functions and properties that in turn supports the crop productivity with the favourable conditions for nutrient uptakes by the crops from the soil solutions.

## **6.2 Effects of Biochar Applications in Combination with NPK Fertilizers on Crop Yields**

### **6.2.1 Biochar effects on rice crop growth and yield**

World average yield of rice is about 3.50 Mgha<sup>-1</sup> (FAO, 1992). According to the data reported by World Bank, current yield of monsoon paddy is 2.5 Mgha<sup>-1</sup>. According to FAO (2009), average rice yield of Myanmar is 3.51 Mgha<sup>-1</sup>. In the present research the highest rice yield was obtained from Ps biochar application (6.61 Mgha<sup>-1</sup>) and that yield was significantly different from control (56% > control) and NPK fertilizer application (44% > NPK).

In rice experiment, better crop growth and highest yield resulted from Ps biochar treatment compared to the other treatments. Among biochar treatments, yield of Rh biochar, Rs biochar and Ps biochar treatments were not significantly different ( $p \geq 0.05$ ). Slight differences of rice yields between Ps biochar treated plots and Rh- and Rs biochar treated plots could be due to the differences in the number of spikelet per panicle. "Panicle number is influenced by the number of tillers that develop during the vegetative stage, while spikelet number and number of filled spikelet are determined in the reproductive stage." (DeDatta, 1981; Walker, 2006). Rice yield was significantly relating to spikelet sterility, thousand grain weight, and harvest index.

Highest harvest index was found in Ps biochar and Rh biochar treatments. Harvest index of Ps biochar treatment was lower than that of Rh biochar treatment because rice plants from Ps biochar applied plots had higher number of spikelet per panicle and higher straw yield as well. That could be due to the effect of Ps biochar on rice crop's nutrient availability. Biochar has the potential to increase nutrient availability for plants. Nutrient availability can be affected by increasing cation exchange capacity, altering soil pH, or direct nutrient contributions from biochar (Lehmann et al., 2003). Ps biochar had total exchangeable cations of 8.19 and the dominant cation was exchangeable K, which is major nutrient for crop growth and high yield. To obtain 1000 kg of rice yield 15 kg N, 2.6 kg P and 15 kg K will be needed for crop uptake (IRRI, 2007). Although Rs biochar and Rh biochar + FYM mixture had higher total exchangeable cations than Ps biochar, Rs biochar contained higher exchangeable Na and Rh biochar + FYM mixture had higher proportion of exchangeable Ca compared to Ps biochar. The next factor providing the nutrient availability for the crops is nutrient retention in biochar pores. Under lowland condition, porosity of pigeon pea stem biochar would have favourable conditions to retain the available nutrients in its pores and crops would receive required nutrients without suffering nutrient deficiency. Ps biochar had low ash content (9%) compared to Rh biochar, Rs biochar and Rh biochar + FYM mixture. Macro pores cleared from blockage of ash can prevent nutrient leaching (Thies and Rilig, 2009). Ps biochar also had higher total nitrogen content and lower C/N ratio compared to the other three biochars (Rh, Rs and Rh biochar + FYM mixture). Hemwong and Cadisch (2011) observed the effects of three charcoal amendments on rice yield. They found that rice plants treated with charcoal having high C/N ratio (117.3) needed supplemental nitrogen fertilizer application at the time of panicle initiation to improve rice grain yield.

Among insect pests, stem borers (*Chilo suppressalis*, *C. polychrysus*, *Scirpophaga incertulas*, *S. innotata* and *Sesamia inferens*) are important pests of rice in Asia. They cause damage and reduction of rice yields by reducing the tiller number or grain growth. Young larvae feed on leaves and leaf sheaths, later they penetrate the stem and feed inside the stem near the base (Veragara, 1992). During vegetative growth stage, rice plots were infested by stem borer *Chilo suppressalis* and resulted empty panicles in some rice plants. Since pest infestation was controlled by insecticide application (carbofuran 3G), and flooding the field to destroy the eggs, rice yield was not severely affected by insect pest infestation. There occurred some so called "White head" and resulted spikelet sterility. When spikelet sterility was compared among the treatments, higher number of spikelet sterility were found in Ps biochar treated plots since its vegetative growth might have attracted the *Chilo suppressalis* caterpillars.

Although it had higher spikelet sterility, Ps biochar applied plots maintained the highest rice yield among all treatments due to higher total number of spikelet.

In the present research, crop growth and yields from biochar application treatments were higher than the yields of the control and NPK fertilizer application with the application rate of 20 Mg ha<sup>-1</sup> pure biochar and 10 Mg ha<sup>-1</sup> biochar + manure in combination with NPK fertilizer. Zhang et al. (2012) studied three different biochar rates 10 Mg ha<sup>-1</sup>, 20 Mg ha<sup>-1</sup> and 40 Mg ha<sup>-1</sup> on rice yields in two rice growing seasons and found that higher rice yield was resulted by biochar applications compared to control and rice yield was not affected by biochar rates. Jones et al. (2012) suggested that it is possible to apply 25 or 50 Mg ha<sup>-1</sup> rate of biochar without negative effect on productivity. Glaser et al. (2002) discussed that 1-3 Mg ha<sup>-1</sup> rate of biochar soil application is sufficient for increased crop production to apply to 0-0.3 m soil layer. Economic feasibility of biochar application will need to be analysed with respect to the cultivated crops and socioeconomic condition of the specific region.

In rice field experiments, biochar to soil ratio was 5.6 g biochar kg<sup>-1</sup> soil for Rh-, Rs- and Ps biochars and 2.8 g Rh biochar + FYM mixture kg<sup>-1</sup> soil. NPK fertilizer application rate in this experiment was 100:50:50 kg N: P: K ha<sup>-1</sup>. Ghoneim and Ebid (2013) studied the effect of rice straw biochar on rice yield and soil properties compared to recommended NPK fertilizer application. In their experiment, two rice straw biochar rates, 15 g kg<sup>-1</sup> dry soil and 30 g kg<sup>-1</sup> dry soil, were used to observe the effects of biochar applications on rice yields. Information regarding the chemical fertilizer application rate was not stated in that research. That could possibly mean that the effect of rice straw biochar addition on rice yield was tested solely rice straw biochar addition without chemical fertilizers. They found significant increase of rice yield over NPK treatment of 12.7% with biochar rate 15 g kg<sup>-1</sup> dry soil and 49.3% with biochar rate 30 g kg<sup>-1</sup> dry soil. By comparing the results of observation by Ghoneim and Ebid and current research findings, it can be accounted that optimum combination of biochar and chemical fertilizers should be adjusted depending on the objective of biochar soil application. By applying 5.6 kg biochar kg<sup>-1</sup> dry soil + NPK fertilizer, 28% higher yield was achieved compared to NPK fertilizer sole application in current research. By applying 30 kg biochar kg<sup>-1</sup> dry soil, 49.3% higher rice yield can be obtained compared to NPK fertilizer sole application (Ghoneim and Ebid, 2013). If biochar application intended to improve soil quality, higher biochar rate should be applied. If the farming objective was for economic profitability and getting high crop yield, organic and inorganic fertilizer combination should be adjusted depending on the availability of organic fertilizers and affordability of farmers for chemical fertilizers.

### **6.2.2 Biochar effects on chickpea crop growth and yield**

Due to the *R. solani* infection of seedlings, uneven seedling growth occurred in chickpea cultivation. Under such condition, biochar applied plots yielded higher than control and NPK fertilizer applied plots except Rh biochar + FYM mixture application. Chickpea crop growth was not significantly different among the treatments. Simulated chickpea yield from Rh biochar application was the most stable yield and highest among the treatments in both 30- and 50-year simulations. These results agreed with the results of field experiments.

### **6.2.3 Biochar effects on cotton crop growth and yield**

Average seed-cotton yield of Myanmar (*G. hirsutum*) in 2005/2006 growing season was 717 kg ha<sup>-1</sup>, around 30% of world average seed cotton yield (Myanma Cotton and Sericulture Enterprise, 2006). In the present research, seed cotton yield of control exceeded the average seed-cotton yield of Myanmar. The highest yield was obtained from Rh biochar + FYM mixture treatment and the lowest yield was obtained from the control plots. Cotton yield increased respectively by 75.39% in Rh biochar + FYM mixture application, 72.33% in Rs biochar application, 69.30% in Rh biochar application, 68.26% in Ps biochar application, and 62% in NPK fertilizer application, compared to control.

In the present research, by comparing the effects of pigeon pea stem biochar and Rh biochar + FYM mixture on rice yield and cotton yield, it could be assumed that the effects of biochars could vary with respect to the nature of biochars and the nature of crops as well. Rice has fibrous root system and cotton has tap root system. Rice root rhizosphere could be able to extend only to nearby soil and biochar and it would have received nutrients from surface layer. For cotton, its roots could extend to the deeper soil layers and they could have absorbed the nutrients from the deeper soil layers than rice crop can. Cotton plant has a deep taproot system with unusually low root density in the surface soil layer where available nutrient levels are greatest (Cassman, 1993).

Water, nutrients, insects, and diseases are major constraints of cotton productivity in major cotton-growing regions (Fageria et al., 1997). Since management practices including pest and disease control were given equally to all treatments, decisive factors for cotton yield could be the impact of nutrients and applied biochars to the plots. Fertilizer rate for cotton field experiment was 100:30:117 kg ha<sup>-1</sup> N: P: K. Nitrogen fertilizer was Urea, P was triple super phosphate and K fertilizer was muriate of potash. Although irrigation water was equally supplied for all treatments, the amount of available water might have been affected by soil water holding capacity depending on the type of biochar applied to the soil. According to the

results obtained from water retention analyses, water holding capacity of biochars were Rh biochar 320%, Rs biochar 553%, Ps biochar 568% and Rh biochar + FYM mixture 261%, respectively. The data showed that Ps biochar had highest water holding capacity among four biochars and Rh biochar + FYM mixture had the lowest water holding capacity. According to the results of water retention analysis, available water capacity was the highest in Ps biochar treated soils and available water capacity of Rh biochar + FYM mixture was the lowest compared to the other treatments except control. In comparing the percent of water filled pore space at field capacity, Rs and Ps biochar treated soils held larger amount of water than the other soils. These data showed that Ps biochar could retain available water better than the other biochars, NPK and control. This ability of retaining water was beneficial for the roots to absorb water and nutrients from soil solution when large amount of water was available. However, for seedlings under upland condition, since their root systems could not extend to reach to the Ps biochar particles, they would have competed with Ps biochar to absorb moisture directly from nearby soil and the seedlings would feel water stress. Contrastingly, Rh biochar + FYM mixture had finer pores than Ps biochar. The mixture would have mixed homogeneously with the soils, and they would have shared the moisture together with nearby soils and seedlings. Nutrient retention of biochar and manure mixture could also have helped the cotton plants for better access to required nutrients.

During earlier stages of cotton cultivation, around 7-5 days after germination, damping off symptoms due to collar rot (*Rhizoctonia solani*) were found in cotton seedlings and seedling mortality occurred. Soil was treated with fungicides and missing holes were replaced during the first week after germination of cotton plants. Due to this reason, there were different plant heights even within the same treatment during the first time of data collection on plant height. Plant height became the same at the time of peak flowering since the older plants reached reproductive phase and their vegetative growth was slower. Plant height was not significantly different among the treatments except control. Apparently, since there was neither organic nor inorganic additional nutrient supply for control, cotton plants from control plots had poor crop growth compared to the plants of other treatments that received organic and inorganic fertilizers.

Plant height is an important growth parameter for cotton plants with respect to the yield of the crop (Saleem et al., 2010). The higher the cotton plant, the higher the number of main stem node and there will be higher numbers of fruiting branches. In cotton, height node (H/N) ratio indicates the growth balance of the crop. This ratio was calculated by dividing the plant height by the number of main stem nodes. At pre blooming stage, H/N ratio should be in the range 1-

1.5 (measurement in inches) (Guthrie et al., 1993). H/N ratio was within this range in all treatments. At this stage, the crop was in the vegetative stage and that level of plant height was at its optimal growth. If H/N ratio was higher than this range, the growth of cotton plants should be regulated by using crop growth regulators or by mechanical topping. Excessive vegetative growth of cotton will delay the boll setting and in consequence delay harvesting. Although there are not large number of branches, its growth and number of bolls per sympodial branch is the influence factor on yield (Fageria et al., 1997).

Schulz et al. (2013) tested the effects of composted biochar made from woodchip with different biochar proportions on the growth of cereal oat (*Avena stiva* L.) in sandy and loamy soil substrates in greenhouse condition. The results indicated that crop growth increased in both substrates. Plant growth and soil fertility improvement was higher in composts that contained higher proportion of biochar. That could be due to increased total organic carbon in soils providing favourable conditions for the cultivated crops to access available nutrients and in consequence resulting higher crop growth. In this greenhouse experiment, the results also revealed that both biochar and compost supplied nutrients to the crops in the first cropping season. In the second cropping season, only composts could supply plant available nutrients to the crops. They assumed that in the second cropping season, only composts continued mineralisation and biochar controlled the mineralisation rate since they found that the higher the biochar content in compost, the lower the rate of mineralisation. In the present research, similar effects were observed in the cotton-growing season. The highest cotton yield was obtained from Rh biochar + FYM mixture applications. It seemed biochar and manure mixture applied to rice fields could continue its nutrient supply for the next crop, due to the combined effect of nutrient supply from manure, and NPK fertilizers that applied in combination with Rh biochar + FYM mixture and the ability of biochar that retain the nutrients from leaching losses.

Yield components of cotton are number of bolls per plant, number of seeds per boll, boll weight, and lint yield. Lint yield was defined as a function of components including plant density, bolls per plant, and average boll size. The number of bolls per plant is the most important yield variable (Fageria et al., 1997). In the present research, number of mature bolls and boll weights differed significantly among the treatments. The lowest number of bolls per plant was found in the control and the second lowest was found in NPK fertilizer sole application. Initially, the number of flowers per plant was not significantly different from one treatment to another. Significant difference was found in the number of open bolls per plant at the time of harvesting. That could be due to the differences in the availability of moisture and

nutrients required for boll setting and boll maturity. If there were no sufficient nutrition, small boll shedding could be occurred. There were significant differences in the proportion of harvested seed cotton among the treatments. At the first time of cotton picking, the largest proportion of seed cotton was obtained from control plots and harvested cotton from control plots gradually decreased in the second and third cotton pickings. Harvested seed cotton of the other treatments gradually increased from first to third cotton picking reflecting the response of cotton plant to the nutrient supply from the soil. In control, since nutrient supply was not sufficient for both vegetative and reproductive developments, the crop could not provide enough food for all of the fertilised bolls. It maintained the bolls that set during its early development stage and shed the additional squares and small bolls that were out of its capability to supply food and in consequence, crop yield was reduced.

Single boll weight of the control was significantly lower than that of the other treatments, boll weight from Rh biochar + FYM mixture application was 31.73%, NPK fertilizer application 30.61%, Rh biochar application 26.17%, Rs biochar application 24.59%, and Ps biochar application 24.07%, respectively, higher than control. Compared to NPK fertilizer application, only Rh biochar + FYM mixture treated plants showed higher single boll weight (1.61%). Between biochar treatments and non-biochar treatments, decision factors for yield differences were number of bolls per plant and boll weights. Among biochar treatments, the decision factor of yield differences was single boll weights as there was no significant difference in the number of bolls per plant. It was apparent in Rs biochar application that had even higher boll number per plant than Rh biochar + FYM mixture.

### **6.3 Estimation of the Effect of Biochar Applications on Future Crop Yields, Soil Organic Carbon Dynamics, and Greenhouse Gas Emissions by Using DNDC Model**

#### **6.3.1 Estimating crop yields**

When measured- and simulated rice yields were compared, model overestimated rice grain-C yield in all biochar applications. The highest difference of modelled rice yields and simulated rice yields were found in Rh biochar application and the control. This overestimation was obviously due to the higher nitrogen content of Rh biochars compared to other treatments and low level of nutrient input to control.

When measured chickpea and simulated chickpea yields were compared, model underestimated the yields. It was found that modelled crop yields followed the order of nutrient content of biochar materials that were applied to the previous rice crop. Model would have taken into account only on that initial nutrient level of soil for chickpea nutrition. Since

there was no additional fertilizer input to chickpea cultivation, modelled yield will be low with respect to its nutrient input amount. Except the slight underestimation of PBIAS (6.56%), model fitness in simulating chickpea yield appeared strong enough in terms of correlation analysis and relative root mean square error.

In simulating cotton yields, the reason for the weakness of model fitness could be due to the large difference between measured and simulated yield of the control. Since the control received neither chemical nor organic fertilizer input, in model simulation, cotton crops from control would have suffered nitrogen stress and in consequence, crop growth and yield would be underestimated. Under actual field condition, cotton yield from control was not as low as modelled yield because the crop could still maintain its growth in a given environmental condition and produce its minimum attainable yield according to its nature. Overestimation of cotton yields from Rh biochar and Ps biochar applications could be due to higher nitrogen content of these two biochars compared to the other biochars and NPK fertilizers. There might be some differences of nitrogen available for the cultivated crops and nitrogen losses between actual field condition and modelling due to unpredictable climatic and management factors.

In estimating future crop yields, in both 30-year and 50-year simulations, crop yields were higher in biochar treatments compared to control and NPK fertilizer application treatments in the year of biochar application. In the next year after biochar application, crop yields dropped around 1-20% in rice and chickpea and 4-45% in cotton. Although simulated rice and chickpea yields from biochar treatments were reduced, those yields were higher than the yield of control and NPK fertilizer application treatments. Simulated cotton yields of the following years after biochar application were the same as the yields of NPK fertilizer application. In crop model of DNDC, the major processes are crop developments, leaf area index (LAI), photosynthesis and respiration, assimilate allocation, rooting processes and water and nitrogen uptake. The phenological stages and stress factors (water and nitrogen) influence carbon allocation and nitrogen demand. The model-simulated crop yields by using soil and climate data of the experimental site, crop parameters, and management practices as inputs. During simulation, crop growth and development interact with climate and soil biogeochemical processes (Zhang et al., 2002).

### **6.3.2 Comparing simulated crop yields obtained from biochar soil additions and raw biomass addition**

Simulated rice yields of rice husk and rice straw biomass applications were lower than that of pigeon pea green manure application and the yield from Rh- and Rs biochar applications. Pigeon pea stem biochar provided the highest rice yield in actual field conditions. Simulated



rice yield from pigeon pea green manure application was the highest compared to rice husk and rice straw biomass applications. Moreover, simulated rice yield obtained from pigeon pea stem green manure application was the same as those of pigeon pea stem biochar application. That could be due to higher nitrogen content and lower carbon to nitrogen ratio of pigeon pea biomass compared to rice husk and rice straw. It can be assumed that pigeon pea stem green manure application, unconverted to biochar, was also suitable for rice crop. In 30-year and 50-year projections after raw biomass applications, pigeon pea green manure application also showed higher yield than pigeon pea stem biochar application throughout the simulated years. Crop yields from rice husk and rice straw biomass applications were lower than rice husk biochar and rice straw biochar applications in the first year of simulations. In the following years of simulations, crop yields were at the same level up to the end of simulations. According to the present model simulation, it can be concluded that application of raw biomass can provide the same crop yield as biochar application when long-term trends were observed. Hafele et al. (2011) studied the effect of rice husk application compared to rice-husk biochar application. It was suggested that rice-husk biochar application helped to increase crop yield by improving soil quality of poor soils and increasing soil organic carbon storage. To promote the use of biochars, more consistent products with higher nutrient values and nutrient retention are desirable (Chan and Xu, 2009). For the profitable crop production with less damage to environment, different input combinations should be considered not only biochar sole application but also combination with green manures, fertilizers and composts, as well.

### **6.3.3 Simulation of the effects of biochar applications on soil organic carbon in topsoil (0-0.2 m)**

When the simulation results of SOC by DNDC model were quantified by statistical indices, PBIAS and RMSE values showed that DNDC model fit well for simulating SOC. When measured- simulated- and calculated-SOC (0-0.2 m) after harvesting rice and after harvesting cotton were compared, calculated SOC (0-0.2 m) was higher than measured and simulated SOC (0-0.2 m) in all treatments in both years, except Rh biochar application. Calculated SOC was SOC obtained by multiplying total carbon content of biochar and per hectare biochar-application rate. In actual condition, that SOC will not exist in the soil due to different losses such as, microbial degradation, leaching, and movements out of the experimental plots by irrigation water or tillage operations. In the present study, we compared calculated- measured- and simulated-SOC to estimate the carbon losses between the time of biochar addition and the time of soil sampling.

In Rh biochar application, higher amount of measured SOC were found in 2013 after harvesting cotton. That could be due to remaining SOC of Rh biochar in the topsoil (0-0.2 m) that applied during the previous year. In the other treatments, simulated SOC and measured SOC were consistent.

Simulated SOC was lower than both calculated and measured SOC. In cotton cropping season, drying and rewetting of soil happened very often due to rainfall events and supplemental irrigations during cropping season. Since carbon- and nitrogen-mineralisation rates are highly susceptible to changes of soil moisture and drying rewetting cycles (Fierer and Schimel, 2002) DNDC would simulate SOC dynamics following the impacts of land management practices and environmental conditions. Due to the lack of organic matter input in control and NPK fertilizer applied plots, simulated SOC storage in those low input soils would be lower than that of biochar-applied soils. To reduce the gap between measured and simulated SOC values in model validation, field measurement of SOC content should be done not only from top soil layer but also from deeper layer of soil profile.

In 50-year projections of SOC after biochar application by using single year climate data, SOC in Rh biochar application was the highest in the first year of simulation and decreasing in the following years. SOC from Rs biochar and Ps biochar applications were the second highest, compared to the control, NPK sole application, and Rh biochar + FYM mixture application. SOC level in the control remained at the same level from the first simulated year up to the end of simulation. SOC levels from Rs-, Ps-, Rh biochar + FYM mixture and NPK applications were increasing. For Rh biochar treatment, higher simulated SOC in the first year could be due to the input soil properties such as lower bulk density, highest porosity and the second highest total organic carbon content. Decreasing simulated SOC in Rh biochar treatment in the following years could be due to the losses through carbon mineralisation as the simulated CO<sub>2</sub> and CH<sub>4</sub> emissions, and biomass production from the Rh biochar treatment were the highest among the treatments. Increasing trends of SOC in Rh biochar + FYM mixture treatment, Rs biochar treatment and NPK fertilizer treatment in the later years of simulation might be due to increase accumulation of organic carbon compared to mineralisation rate. In 30-year simulation, since climate conditions were different among the simulated years, some fluctuation of SOC occurred. Despite that SOC fluctuation, the trend was the same as that of 50-year simulation that used single year climate data. Those trends might represent the changes of SOC in soils according to input soil properties and biochar properties such as initial soil SOC at surface soil (0-0.1) m, fixed- and mobile carbon fractions of biochars, and the degradability of biochar.

**6.3.4 Simulation of the effects of biochar applications on GHGs emissions by DNDC**

Total GHGs emissions in the year 2000 including Land Use, Land Use Change and Forestry (LULUCF) of Myanmar is currently low compared to the other neighbouring countries (Table 6.1). Total greenhouse gas emission was negative due to the reduction of CO<sub>2</sub> emission because of carbon sequestration of land use, land use change and forestry exceeds the country’s greenhouse gas emissions (IGES, 2012) ( Fig. 6.1 (a) and (b)). Under this low GHG emission condition, agriculture sector contributes the largest proportion of GHGs emission (Figure 6.1 (c)) (Table 6.3). In agriculture sector, emission from rice cultivation was the largest contributor (Table 6.2). There are potentials for increasing GHGs emission in Myanmar due to decreased forest area by 20% from 1975 to 2006, and increased economic activities (IGES, 2012). Increases of carbon sequestration at farm level and application of low-carbon development technologies will have the potentials in maintaining the existing balance of GHGs emission.

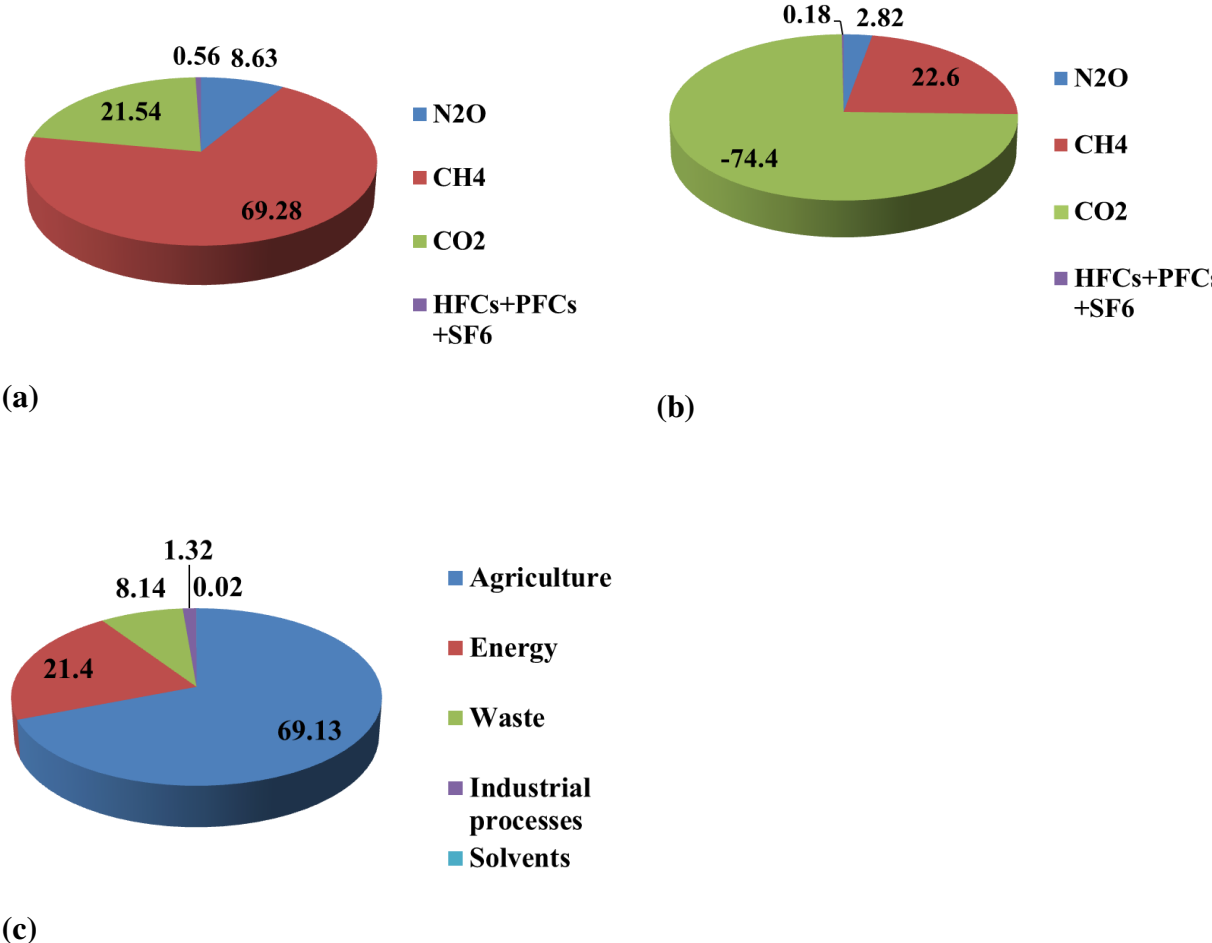


Figure 6.1: Greenhouse gas emissions in Myanmar in 2005, showing (a) emissions by gas without Land Use Change and Forestry (LUCF), (b) emissions by gas including LUCF, and (c) emissions by sector in 2005 without LUCF (source: “Emission summary for Myanmar” United Nations, Climate Change Secretariat, online information, retrieved on 26.01.2015, <http://unfccc.int/di/DetailedByGas>)

Table 6.1: GHGs emissions CO<sub>2</sub> equivalent in 2000 comparing the emissions of Myanmar and neighbouring Asian countries

Gas	Myanmar	Malaysia	Indonesia	Thailand	Laos	India	China
CO <sub>2</sub>	-100,657.44	-82,510.14	1,110,700.52	157,857.10	41,763.97	788,515.43	5,554,038.00
CH <sub>4</sub>	26,224.61	52,416.21	236,388.18	58,830.26	6,440.70	418,841.01	933,508.80
N <sub>2</sub> O	4,011.59	2,976.00	28,499.23	12,369.01	2,613.30	81,893.75	394,165.00
HFCs	143.00	143.00	-	-	-	5,200.00	147,286.89
PFCs	-	-	-	-	-	6,455.40	5,608.90
SF <sub>6</sub>	71.70	6.21	-	-	-	298.75	10,437.13
Total	-70,206.55	-26,797.58	1,375,587.93	229,056.37	50,817.97	1,301,204.34	7,045,044.72
Difference in total emission (%)		-61.8	-2,059.3	-426.3	-172.4	-1,953.4	-12,373.6

Source: <http://unfccc.int/di/DetailedByGas>

In the present research, DNDC model was used to estimate the effects of biochar soil applications on CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> emissions from the experiments. Simulated CO<sub>2</sub> emission was higher in rice growing seasons than cotton growing seasons in both 30-year and 50-year simulations. Under both upland and lowland conditions, simulated CO<sub>2</sub> emissions from biochar treatments were higher than that of control and NPK fertilizer application. Under upland condition, CO<sub>2</sub> emission was the highest from Rh biochar + FYM mixture application. In both 30-year and 50-year projections under lowland condition, in the first year of simulation, CO<sub>2</sub> emissions from biochar treatments were higher than that from NPK fertilizer application and control. CO<sub>2</sub> emissions from biochar treatments in the first year of simulation were higher than the following simulated years since biochars were applied in the first year. Application of biochar together with nitrogen fertilizer increases CO<sub>2</sub> emission during rice growing season (Wang et al., 2012). Higher CO<sub>2</sub> emission from biochar treatments could be due to higher organic carbon content or of carbon lability of biochar amended soils (Kimetu and Lehmann, 2010; Cross and Sohi, 2011, Zhang et al., 2012).

Simulated N<sub>2</sub>O emission was higher in 30-year simulation that used multi-year climate data than 50-year simulation that used single year climate data. The amount of emission changed according to the changes of climatic conditions and nitrogen input. In both of 30-year and 50-year simulations, N<sub>2</sub>O emission from control was the lowest among the treatments. The second lowest emission was in NPK fertilizer application and N<sub>2</sub>O emissions from biochar treatments were higher than both control and NPK fertilizer application. N<sub>2</sub>O emission from agricultural soils in Myanmar in 2005 was 0.84 kg N<sub>2</sub>O ha<sup>-1</sup>a<sup>-1</sup> (Table 6.2). Although simulated N<sub>2</sub>O emissions from Rh and Ps biochar applications were high in the year of biochar application (around 50%), compared to following years, average emission amounts for all simulated years agreed with the actual emission.

Table 6.2: Estimation of GHG emissions from agriculture sector of Myanmar\*

Years	1990	1995	2000	2001	2002	2003	2004	2005
Emissions from rice cultivation (Gg)								
CH <sub>4</sub>	349.33	485.18	507.23	514.06	511.32	523.69	540.09	589.81
Emissions from agricultural soils (Gg)								
N <sub>2</sub> O	5.53	7.07	8.2	8.53	8.67	9.05	9.49	10.19
Emissions from field burning of agricultural residues (Gg)								
CH <sub>4</sub>	0.0174	0.0214	0.024	0.0249	0.0247	0.0255	0.0264	0.0282
N <sub>2</sub> O	0.0004	0.0006	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007
NO <sub>x</sub>	0.0161	0.0198	0.022	0.0231	0.0229	0.0236	0.0245	0.0262
CO	0.5913	0.729	0.81	0.8488	0.843	0.8696	0.9003	0.9623
Total	9,051.	12,381.	13,195.	13,441.2	13,427.	13,804.	14,285.	15,546.
(Gg CO <sub>2</sub> e)	4	9	4		1	7	6	8

\*Source: A report of the Ministry of Environmental Conservation and Forestry, The Republic of The Union of Myanmar, 2012, Myanmar's Initial National Communication under The United Nations Framework Convention on Climate Change (UNFCCC)

Table 6.3: National greenhouse gas inventory of Myanmar (2010)

Source/Sink	CO <sub>2</sub> removal (Gg)	CO <sub>2</sub> e total emissions (Gg)	CO <sub>2</sub> e net emissions (Gg)
Energy sector		7863.47	7863.47
Industrial sector		463.29	463.29
Agricultural sector including livestock		22, 843.25	22, 843.25
Land use change and Forestry sector	142, 221.20	40, 404.73	-101, 816.50
Waste sector		2825.97	2, 825.97
Total	142, 221.40	74, 400.71	-67, 820.50

Source: National GHG Inventory of INC project Myanmar

Although simulated N<sub>2</sub>O fluxes agreed with the actual emission in general, higher N<sub>2</sub>O emission from soils with biochar addition compared to the soils without biochar addition was contrasting to some of former research findings of the effect of biochar applications on N<sub>2</sub>O emission. N<sub>2</sub>O emission decreased by 10.7% and 41.8% after 20 Mg ha<sup>-1</sup> and 40 Mg ha<sup>-1</sup> of biochar was applied to maize fields in calcareous loamy soil together with 300 kg N ha<sup>-1</sup> compared to solely nitrogen fertilizer application (Zhang et al., 2012). Jia et al. (2012) stated that 30 Mg ha<sup>-1</sup> of maize straw biochar application together with manure and urea fertilizer greatly reduced N<sub>2</sub>O emissions and maintained vegetable yields compared to control, manure + urea, manure + biochar (20 Mg ha<sup>-1</sup> and 40 Mg ha<sup>-1</sup> rates) + urea applications. That experiment was conducted on acidic soils.

Wang et al. (2012) tested the effect of rice-husk biochar application (with and without chemical fertilizers) on crop yields and GHG emissions in rice-wheat systems. The experiments were conducted on a clayey loamy Orthic Antrosols upland soil and a silty loamy Stagnic Anthrosols lowland soil. The results showed that biochar addition, without nitrogen fertilizer to both upland and paddy soils caused the decreased  $N_2O$  emissions during the flooded rice and drained wheat seasons. Biochar application with nitrogen fertilizer caused the increased  $N_2O$  emissions from wheat fields. That meant that applying biochar together with nitrogen fertilizer could lead to decreased  $N_2O$  emission under lowland condition and increase the emission under upland condition. That was consistent with the simulated DNDC model simulation of  $N_2O$  emission in the current research.  $N_2O$  emission was higher in cotton growing seasons (ranging  $0.51-1.80 \text{ kg N ha}^{-1}\text{a}^{-1}$ ) and lower in rice growing seasons (ranging  $0.15-0.81 \text{ kg N ha}^{-1}\text{a}^{-1}$ ). In contrast to these, Xie et al. (2013) studied the effects of wheat straw biochar ( $12 \text{ Mg ha}^{-1}$ ) and corn stalk biochar ( $12 \text{ Mg ha}^{-1}$ ) on rice nitrogen nutrition and GHG emissions in a slightly alkaline sandy loamy Inceptisol and an acidic clayey loamy Ultisol. They found  $N_2O$  emissions from biochar application treatments similar to the control in the acidic Ultisol and significantly higher in the alkaline Inceptisol.  $N_2O$  emission of the soils without biochar addition is governed by 1) nitrification, 2) nitrifier denitrification, and 3) denitrification (Wrage et al., 2005; Van Zwiiten et al., 2009). These pathways are relating to soil physical properties such as moisture content and aeration (Mukherjee and Lal, 2013). In biochar applied soils, the mechanisms controlling  $N_2O$  emission by biochar application are attributed to increased soil aeration (Yanai et al., 2007; Van Zwiiten et al., 2010), sorption of  $NH_4^+$  or  $NO_3^-$  (Singh, B. P. et al., 2010; Van Zwiiten et al., 2010) or presence of microbial inhibitor compounds such as ethylene (Spokas et al., 2010). Rondon et al. (2006) found out the facts that biochar application reduced  $N_2O$  emission;  $NH_4^+$  - N in soil incubated with biochar was lower than that of the control and; biochar application did not add  $NH_4^+$  - N that supports nitrifier activity. Under anaerobic condition, biochar reduces  $N_2O$  emission by suppressing the activities of denitrifying enzymes, that convert  $NO_3^-$  to  $N_2O$ , and by enhancing the activities of denitrifying enzymes that involves in the conversion of  $N_2O$  to  $N_2$  (Van Zwiiten et al., 2009). Model might not take into account  $NH_4^+$  or  $NO_3^-$  sorption properties of biochars and  $N_2O$  emission from biochar-applied soils might have been overestimated due to the biochars that contained higher amount of nitrogen.

Simulated  $CH_4$  emissions of biochar applications during rice growing seasons were higher than that of NPK fertilizer application and the control in both 30-year and 50-year simulations.  $CH_4$  emissions from the control and NPK fertilizer application were at a



comparable level as the emissions from rice fields of Myanmar. According to the literatures, CH<sub>4</sub> emission from irrigated rice fields in Myanmar in the year 2000 was 120 kg ha<sup>-1</sup>a<sup>-1</sup> (Table 6.4). In the review of Mukherjee and Lal (2013), CH<sub>4</sub> emissions from wheat straw biochar (0.7 g g<sup>-1</sup> rate) applied rice fields ranged from 78-215 kg CH<sub>4</sub> ha<sup>-1</sup>a<sup>-1</sup>.

Table 6.4: CH<sub>4</sub> emissions from flooded rice fields of different rice ecosystems in Myanmar in the year 2000 \*

No.	Rice ecosystems	Harvested area (ha)	CH <sub>4</sub> (Gg yr <sup>-1</sup> )	% of total emission
1	Irrigated Rice	1,842,691	220.46	43.46
2	Regular rain-fed rice	2,432,690	134.62	26.54
3	Drought-prone rain-fed rice	756,276	34.75	6.85
4	Deep water rice	1,071,392	117.4	23.15
	Total	6,302,306	507.23	100

Xie et al (2013) observed the effects of wheat straw biochar and corn stalk biochar on CH<sub>4</sub> emission. They found that CH<sub>4</sub> emissions from biochar applications were similar to the controls. In the present study in biochar treatments and control, simulated CH<sub>4</sub> emissions were higher (40-80%) in the initial year of simulation and decreased in the following years. In NPK fertilizer application, CH<sub>4</sub> emission was getting higher in the following years of simulation compared to the first year of simulation. In a 2-year field study by Knoblauch et al. (2010), a rice paddy amended with carbonised rice husks at the rate of 41Mg ha<sup>-1</sup>, CH<sub>4</sub> emission significantly increased in the first rice crop cycle. Wang et al., 2012 stated that both pure biochar application and application of biochar together with nitrogen fertilizer to rice fields increase CH<sub>4</sub> emissions.

In 2013 during cotton growing season, the simulated CH<sub>4</sub> emission was zero. Jia et al. (2012) studied the effect of different combination of biochar, manure and urea fertilizer applications on vegetable yields and CH<sub>4</sub> emissions under upland condition. Although CH<sub>4</sub> emission was not significantly different among the treatments, emission from biochar treatments were 43-60% lower than non-biochar treatments. Under upland condition, CH<sub>4</sub> emission would have been completely suppressed because of aerobic condition and high rate of CH<sub>4</sub> diffusion into the soil. Biochar applications would also make soil conditions favourable for methanotrophs and unfavourable for methanogenic activities (Lehmann et al., 2011).

Substrates for methane production are acetate, formate, CO<sub>2</sub>, and H<sub>2</sub> that are produced during the anaerobic decomposition of organic matter in soil (Dalal et al., 2008; Van Zweiten et al., 2009). Under flooded conditions, redox potential will decrease, soil pH will reduce in alkaline

soils, nitrogen and phosphorus availability will increase, and carbon dioxide and methane gases will be generated (Vergara, 1992). DNDC model simulates CH<sub>4</sub> emission based on soil redox potential, soil SOC sources (DOC and CO<sub>2</sub>) available for the methanogens, soil temperature and CH<sub>4</sub> diffusion rate, and soil texture (Li, 2000). Anaerobic conditions of rice fields, warm temperatures of the experimental site, high bulk density, fine textured soils, pH value 7-8, and input carbon amounts of biochar application treatments in the present research were supporting the high activities of methanogenic organisms (Dalal et al., 2008; Van Zveiten et al., 2009). DNDC simulated CH<sub>4</sub> emission based on these inputs. Some of those mechanisms were counted in model simulation such as biological mechanisms and soil physical properties. Some were out of the range of model simulation such as biochar surface properties that carry out the chemical reactions and reduce soil N<sub>2</sub>O and CH<sub>4</sub> emissions. The effects of biochar amendments on non-CO<sub>2</sub> GHGs emission could also vary with the soil and site condition as well as biochar properties (Spokas and Reicosky, 2009). Simulated CH<sub>4</sub> emission was the highest in Rh biochar + FYM mixture application. Compared to NPK sole application and the control, Rh biochar + FYM mixture application showed better crop growth and higher biomass production and in consequence, the model might have overestimated the CH<sub>4</sub> emission from rice crops. The model would have taken into account the texture of this treatment as unfavorable factor for CH<sub>4</sub> diffusion. For the other biochars, although they produced the same amount of biomass as Rh biochar + FYM mixture application, those treatments had lower bulk densities and in consequence, simulated CH<sub>4</sub> emissions from Rh, Rs and Ps biochar applications were lower than that of Rh biochar + FYM mixture application. Lower simulated CH<sub>4</sub> emissions from NPK fertilizer application and control might be due to lower DOC values in soils of these treatments compared to biochar treatments. Since N<sub>2</sub>O and CH<sub>4</sub> emissions were not measured in actual field condition, it could not be completely assumed as the model overestimated the CH<sub>4</sub> emission. Further measurements and validations might require for assessing the model performance on greenhouse gas emission.

## 6.4 Conclusion

By summarising the results of the present research, the following effects of biochar applications under upland and lowland conditions to a sandy loamy soil can be assumed as:

- Biochar application increased crop yields compared to conventional NPK fertilizer application and non-fertilizer application. According to the results of field experiments, crop yields from biochar-applied plots exceeded the yields of NPK fertilizer applied plots and the control. All biochars tested in the field experiments showed different impacts on crop growths, yields and soil properties compared to NPK fertilizer applications and the control. Among biochars, it was found that Ps biochar is suitable to apply to rice fields due to its superiority compared to Rh biochar and Rs biochar in retaining nutrients, gas exchange through better ventilation of its pore spaces under submerged condition and, possible direct nitrogen supply to rice crop. Rh biochar and Rh Biochar + FYM mixture were suitable for upland conditions due to their effects on improving soil physical properties such as reducing soil bulk density, increased water holding capacity and nutrient retention.
- Biochar improved soil quality in alkaline sandy loam soil of semi-arid region of Myanmar by decreasing soil bulk density, regulating soil pH at the level that was not harmful for the cultivated crops, and increasing water holding capacity after one-year application. Although there were improvements in both soil physical and chemical properties, some improvements such as bulk density and soil water retention were not significantly different from control and NPK fertilizer application in current research findings. That could be due to low biochar application rates compared to organic carbon requirement of the soil, initial soil properties and due to short experimental period, being not long enough estimating a significant improvement of soil physical properties.
- Generally, simulated results of the DNDC model were in agreement with the actual values from field measurements and from laboratory analyses. Model fitness testing showed that DNDC model was sensitive to nutrient inputs in simulating crop yields such as underestimation of crop yields from controls. That was due to crop input data and some biogeochemical processes such as root interaction with soils, microbial activities and nitrogen fixations, instead of management, or climate data. Simulated rice yields showed more consistency with field measurements compared to simulated chickpea and cotton yields. That could be due to the following reasons. (1) DNDC was

widely validated and applied in tropical lowland rice conditions especially in China. (2) Rice cultivar used in the present research was originated from China. (3) Carbon and nitrogen of rice grains, leaves and stems used as model inputs were the actual values obtained from the experimental findings and. (4) Rice experiments did not experience any biotic or abiotic stresses during the growing season. In simulating cotton and chickpea yields, carbon and nitrogen content of cotton and chickpea stems were obtained from the literatures and other research findings. Moreover, some variations could have occurred in the biogeochemical processes that control the growth and yields such as photosynthesis, leaf area index, root exudation and nitrogen fixation since there are wide range of cotton cultivars and chickpea cultivars.

- By using DNDC model, potential crop yields and soil organic carbon storage for future 30 years and 50 years were projected. Except slight differences of soil organic carbon and crop yields due to climate differences in 30-year simulations, simulated results of the effects of biochars on crop yields and soil organic carbon storage were in the same situation in both 30-year simulations and 50-year simulations. Simulated soil organic carbon dynamics and crop yields were in agreement with the field measurements except underestimation of cotton yields of control plot.
- Simulations of GHG emissions showed higher emissions from biochar applied soils compared to the control and NPK fertilizer application. Simulated GHG emissions from control plots and NPK sole applications were consistent with the emissions of Myanmar agricultural soils. Since emissions from biochar applied rice fields was not measured in Myanmar so far, model validation for GHG emissions from biochar-applied soils could not perform. When simulated GHG emissions were compared with the research findings of international researchers conducted under similar crops, soils and biochar types, GHG emissions simulated by DNDC model were consistent with those findings. Therefore, it can be assumed that DNDC model is compatible for simulating the effect of land management practices on crop yields, soil organic carbon and nitrogen dynamics and greenhouse gas emissions.

## **Chapter 7: Recommendations**

### **7.1 Suitability of Biochar Technology for the Central Dry Zone of Myanmar**

Effects of biochar on soils and crop productivity cannot be generalised, as they are biochar-, plant- and site-specific (Lorenz et al., 2014). In present research, effects of four types of biochars produced from different substrates were tested in rice-chickpea-cotton cropping system on an alkaline sandy loamy soil under semi-arid climatic condition. Even on the same soil, each biochar responded differently to cultivation practices, weather and cultivated crops. Crop yields showed a positive response to biochar applications compared to the unsupplied control and chemical fertilizer sole application.

When we consider both of increasing crop yield and improvement of soil quality, rice husk biochar in combination with farmyard manure will be the most suitable organic soil amendment for the semi-arid Dry Zone area of Myanmar. Although the highest rice yield was obtained from pigeon pea stem biochar application, rice yield obtained from the other biochar treatments were not significantly lower than that of pigeon pea stem biochar treatment. Regarding soil quality responses to Rh biochar + FYM mixture application, using rice husk biochar in combination with farmyard manure will be the most suitable amendment for the soil types of experimental site and the cultivated crops of the study area. A mixture of biochar and manure is more suitable as it reduces the possibility of the dispersal of biochar by wind during the process of field application. Furthermore, crops can benefit the effects of manure more sufficiently by combining the manure with biochar than manure sole application since biochar has the properties to control nutrient leaching from the manures. Although this amendment will not show sudden improvement of soil properties, a stable improvement of soil properties can be retained. At last, farmyard manure is available for the farmers and less amount of biochar is needed compared to the application of biochar solely. Pigeon pea stem biochar can also preferably be used as soil amendment solely or as biochar compost next to rice husk biochar. If farmers are willing to produce or other commercial suppliers are available, pigeon pea stem biochar is beneficial for crop nutrition and soil quality improvement due to its physical and chemical properties. The size of pigeon pea stem biochar should be taken into consideration for soil application because the larger biochar particles can have side effects on the seedlings especially for upland crops such as competing for moisture or hindering root penetration of seedlings. Rice straw biochar application under upland condition also showed positive yield responses next to Rh Biochar + FYM mixture. That could be due to higher carbon content and higher level of total exchangeable cations of Rs

biochar. Since Rs biochar has fine texture, it will easily mix with the soil and will not disturb young seedlings. Challenges of using rice straw as biochar could be raw biomass availability, as it is also useful as fodder; cost for efficient production technology by optimising biochar yield and nutrient composition; and efficient field application method with fewer losses to environment due to its particle size.

Rice yields from biochar treatments were not significantly different although they are higher than the yields from control. The same situation was found in cotton experiments. Crop growth and yields from all biochar treatments were significantly higher than that of control. Higher than 200% more yields were obtained from biochar treated plots compared to the control. However, when cotton yields from biochar treatments were compared to NPK sole application, yield difference was not significant (19-53%). When simulated crop yields from the application of raw biomass of biochar materials were compared with the simulated yields of biochar applications, yields from biochar applications were 4-33% higher in rice, 5-29% higher in chickpea and 10-24% higher in cotton, respectively than raw biomass application. In the present research, 20 Mg ha<sup>-1</sup> of each kind of biochar was applied in each of rice and cotton cropping season. There was total of 40 Mg ha<sup>-1</sup> of each kind of biochar applied in two cropping seasons. Therefore, economic profit obtained from increased crop yields due to biochar application should be considered. It should be considered compared to investment and profit obtained from the other inorganic and organic fertilizer applications if soil reclamation and carbon sequestration are not the main issues in the respective region because farm income is a priority factor for the farm families.

## **7.2 Recommendation for Biochar Production and Technology Adoption by Farmers**

In Myanmar, black ash of rice husks, obtained from rice mills and other small-scale industries that use rice husks as fuel, are being used in agriculture especially as the growing medium for nurseries of ornamental plants, and seedbed preparations for vegetables and rice. Application of rice husk biochar, produced under oxygen-limited condition, for soil fertility improvement has not yet been widely known up to current time. Myanmar farmers need to be informed about the usefulness of biochar as soil amendment because production and application of biochars from farm wastes is a new technology for them. Therefore, many steps are needed to carry out for the dissemination and adoption of biochar technology among Myanmar farmers. This could be achieved by informing research results to the farmers' fields, demonstrating biochar field applications for crop production, and the distribution of biochar for farmers.

Concerning small-scale productions, rural farmers can use biochar stoves and collect the charcoals obtained from these stoves, since most of rural population is using firewood as fuel for cooking although the amount collected could be small. Substituting conventional cooking stoves by biochar cooking stoves is also beneficial way of reducing risk of health problems related to smokes and GHG emissions to environment. This is a way of saving fuel wood consumption, reducing GHG emissions and protecting deforestation on a basic level (Ministry of Forestry, 2005).

Although obtaining biochar by using stoves and low-tech charcoal kilns is an option of biochar production through cheap methods of proper waste disposal for smallholder farmers, for long term and extensive application of biochar as soil amendment, large scale production will require. This technology of using low-tech charcoal kilns will not be sustainable both economically and environmentally due to its low biochar yields and emission of CH<sub>4</sub>, N<sub>2</sub>O, soot or volatile organic compounds (Woolf et al., 2010). However, substitution of the stoves that use electricity or gas in the place of fuel wood cooking-stoves will not easy for rural households. Therefore, low-tech stoves are still necessary for the households compared to the use of traditional stone stoves for protecting the health of households and for saving fuel wood consumption. Moreover, low-tech charcoal kilns can reduce GHG emission compared to field burning of agro-residues. Biomass burning is the second largest source of trace gases and the largest source of primary fine carbonaceous particles in the global atmosphere (Akagi et al 2011). Agricultural burning releases other gases in addition to CO<sub>2</sub>, which are by-products of incomplete combustion such as methane, carbon monoxide, nitrous oxide, and oxides of nitrogen. These non-CO<sub>2</sub> trace gas emissions from biomass burning are net transfers from the biosphere to the atmosphere (IPCC, 2006). Conversion of biomass from agricultural residues by using low-tech kilns and using low-tech efficient cooking stoves can reduce the trace gas emissions to a certain level compared to biomass field burning and fuel wood burning by using traditional cooking stoves.

Most of the farmers will also be interested in getting instant access to the required amount of finished products instead of collecting it from their kitchen since the application of soil amendments will also require to be harmonised with the time of land preparation and crop cultivation together with a proper application rate. In Myanmar's situation, since there are already some small-scale energy production plants and small industries at government managed farms and private sectors that utilise rice husks as power source, rice husk biochars are already available at these places. Biochars produced at high pyrolysis temperature (450°C–650°C) have more stable carbon and a larger surface area. Those properties of

biochar will enhance soil carbon sequestration and increase crop yields by improving soil physical properties. It will be very effective as both energy and biochar can be produced at the same time by large-scale production plants. If large-scale production is available, biochar production from the diverse sources of feedstocks will be possible. Biochars produced from different biomass will have different properties and those biochars can be used extensively for diverse crop varieties.

### **7.3 Recommendation for Future Research**

According to the findings of field experiments, laboratory analyses and estimation of future impacts on crop yields and soil properties, biochar soil application in combination with chemical fertilizers showed certain beneficial impacts on the rice-based cropping systems in the Dry Zone area of Myanmar.

The effect of long-term biochar soil application on crop growth and yields are still needed to observe under the specific climatic, crop and soil conditions. Research activities that observe the impacts of biochars on drought tolerance, pest and disease tolerance and nutrient efficiency under low rainfall conditions for all upland crops are needed to conduct under field conditions. By knowing these impacts, we can apply farm wastes beneficially without harming the environment and crop productivity as well.

Present research was conducted in the dry zone area and it was tested on organic matter poor sandy loam soil under irrigation. There was no moisture stress in both seasons. There was an exception for chickpea crops sown on pigeon pea stem biochar applied plot. Those chickpea plants faced with moisture stress during seedling stage because they competed available moisture with pigeon pea stem biochar. Biochar water use efficiency in semi-arid regions under rain-fed condition and impact of biochar application on crops' drought tolerance will also be needed to observe.

The fact that biochar creates the place for microorganisms is a favourable situation for soil quality improvement and crop production. In the present research, a fungal infestation to chickpea seedlings and cotton seedlings happened although crops survived after receiving a pesticide treatment and the seedlings overcome the age of susceptible stage. Causal organisms of most cotton diseases are soil borne pathogens (Hodges, 1992). *Rhizoctonia solani* is also the causal organism of sheath blight disease in rice. Sheath blight symptoms were found in the rice experiment. It was not affecting the rice yield since it happened late in the rice season. The fungus must have remained in the soil together with rice residues and they would infect the following chickpea crop since the viability of the sclerotia of *R.solani* can last for the next



cropping season if they have the place to detach (Hodges, 1992). In the current research, since the fungus was remained in the soil together with rice straws of the previous season, it would easily attack the following crops. Biochars was already in soil for one cropping season and it might need more time to interact with the beneficial soil microorganisms like mycorrhizal fungi. More research will be needed to observe the impacts of biochars on the crop's resistance to pest and diseases. The study of biochar and insect pest relation will also be required under different soils, climatic conditions and cropping systems.

Fine grain biochar and its moisture holding capacity can affect the cultivated crops during germination and early crop growth by competing for moisture uptake with the crop. In the present research, compared to the other fine textured biochars, pigeon pea stem biochar had larger pore size and the plots with Ps biochar application used up the moisture faster than the other biochar applied plots. Under upland condition, water from larger pores will evaporate faster than that from finer pores and they will absorb moisture from the nearby soils and in consequence, cultivated crops will suffer water stress if supplementary irrigation is not available. Therefore, particle size of biochar for efficient field application and the appropriate time of field application with less harmful effect on the crops should also be studied.

Effects of biochars on crop production, soil properties and impacts on environmental quality can vary depending on the type of crops, biochar application rates, site properties, biochar application methods, and land management practices. Therefore, further research about biochar soil application will be needed to study the above-mentioned issues.

Regarding with biochar application rates, different research results revealed the effects of different biochar application rates. Since biochar can be produced from different raw material and having different properties, it will not be easy to set the most appropriate biochar application rate. It will be better to decide the biochar application rate depending on the crop type, soil type and the purpose of biochar use: whether to improve soil properties or to remediate the toxicity effects of agrochemicals or for the improvement of crop yields, etc.

For practical field application, not only positive impacts of biochar on crop production and soil quality, but also economic profitability should be considered because farming objectives of the majority of farmers are food security and economic profitability. Research on biochar type, production method, and economically feasible biochar application rates will therefore be required.

Research and demonstrations are also needed to inform the farmers about the effectiveness of organic soil amendments other than inorganic fertilizers as those organic soil amendments are within the reach of smallholder farmers.

## Chapter 8: Bibliography

ACIAR 1996: (1996) In: Kirchhof, G., Und So, H.B (Eds.), Management of Clay Soils for Rain-fed Lowland Rice-Based Cropping Systems. Proceedings of Australian Centre for International Agricultural Research (ACIAR) International Workshop Held at the Bureau of Soil and Water Management, Quezon City, Manila. ACIAR, Canberra.

Ad-Hoc-Arbeitsgruppe-Boden, (2005): Bodenkundliche Kartieranleitung, 5. Auflage, 438. Schweizerbart'Sche Verlagsbuchhandlung, Stuttgart.

Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., Reid, J.S., Karl, T., Crouse, J.D., and Wennberg, P.O. (2011): Emission Factors for Open and Domestic Biomass Burning for Use in Atmospheric Models. *Atoms. Chem. Phys.* 11:4039-4072.

Allen, R.L. (1846): A Brief Compendium of American Agriculture. Sexton & Miles, New York. USA.

Amonette, J.E., and Joseph, S. (2009): Characteristics of Biochar: Microchemical Properties. In: Lehmann, J., and Joseph, S. (Eds.), *Biochar for Environmental Management, Science and Technology*, Earthscan, London pp, 33-43.

Anderson, T.H., Domsch, K.H. (1989): Ratios of microbial biomass carbon to total organic-C in arable soils. *Soil Biol. Biochem.* 21:471-479.

Andreae, M.O., and Merlet, P. (2001): Emission of Trace Gases and Aerosols from Biomass Burning. *Global Biological Cycles*, 15 (4):955-966.

Asai, H., Samson, B.K., Stephan, H.M., Songyikhangauthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., Horie, T. (2009): Biochar Amendment Techniques for Upland Rice Production in Northern Laos 1. Soil Physical Properties, Leaf SPAD and Grain Yield, *Field Crops Research*, 111:81-84.

Asian Development Bank (2013): Myanmar: Agriculture, Natural Resources, and Environment Initial Sector Assessment, Strategy, and Road Map. Pp, 1-48. Asian Development Bank, Philippine.

Åslund, I. (2012): Effects Of Applying Biochar To Soils From Embu, Kenya - Effects on Crop Residue Decomposition and Soil Fertility Under Varying Soil Moisture Levels. Bachelor Project. Swedish University of Agricultural Sciences (SLU).

Atkinson, C.J., Fitzgerald, J.D., and Hips, N.A. (2010): Potential Mechanisms for Achieving Agricultural Benefits from Biochar Application to Temperate Soils: A Review. *Plant Soil*, 337: 1-18.

Aygun, A., Yenisoy-Karakas, S., And Duman, I. (2003): Production of Granular Activated Carbon From Fruit Stones and Nutshells and Evaluation of Their Physical, Chemical and Adsorption Properties. *Microporous and Mesoporous Materials*, 66: 189-195.

Bhattacharyya, P., Chakrabarti, K., Chakraborty, A. (2005): Microbial Biomass and Enzyme Activities in Submerged Rice Soil Amended With Municipal Solid Waste Compost and Decomposed Cow Manure. *Chemosphere* 60: 310-318.

- Boumann, B.A.M., Kropff, M.J., Tuong, T.P., Wopereis, M.C.S., ten Berge, H.F.M., and van Laar, H.H. (2001): *ORYZA 2000: Modelling Lowland Rice*. Los Baños (Philippines): International Rice Research Institute, and Wageningen: Wageningen University and Research Centre. 235 pages.
- Bouyoucos, G.J. (1936): Directions for Making Mechanical Analysis of Soils by the Hydrometer Method. *Soil Science* 4:225 – 228
- Brown, R.A. (2009): Biochar Production Technology. In: Lehmann, J., and Joseph, S. (Eds), *Biochar for Environmental Management, Science and Technology*. Pp, 127-139. Earthscan, UK.
- Brown, R.A., Kercher, A.K., Nguyen, T.H., Nagle, D.C., and Ball, W.P. (2006): Production and Characterization of Synthetic Wood Chars for Use as Surrogates for Natural Sorbents. *Organic Geochemistry*, 37:321-333.
- Brownsort, P.A. (2009): Biomass Pyrolysis Processes: Review of Scope, Control and Variability. UKBRC (UK Biochar Research Centre) Working Paper 5.
- Brownsort, P.A. (2010): Second Annual Conference: Advancing the Science and Evaluating Biochar Systems. UKBRC Working Paper 6.
- Bruun, E.W., Ambus, P., Egsgaard, H., and Hauggaard-Nielson, H. (2012): Effects of Slow and Fast Pyrolysis Biochar on Soil C and N Turnover Dynamics. *Soil Biology and Biochemistry*, 46: 73-79.
- Bundesgütegemeinschaft Kompost E.V (BGK), (2003): *Methods Book for the Analysis of Compost*. 20 (1), Method III.
- Buringh, P. (1979): *Introduction to the Study of Soils in Tropical and Subtropical Regions*. Third Edition. Centre for Agricultural Publishing and Documentation, Wageningen, Netherlands. 124 pages.
- Cai, Z., Sawamoto, T., Li, C., Kang, G., Boonjawat, J., Mosier, A., Wassmann, R., and Tsuruta, H. (2003): Field Validation of the DNDC Model for Greenhouse Gas Emissions in East Asian Cropping Systems. *Global Biogeochemical Cycles*, 17 (4).
- Cassman, K. G. (1993): Cotton. In: Bennett, W. F. (Ed.) *Nutrient Deficiencies and Toxicities in Crop Plants*. APS Press, St. Paul, MN, pp, 111-119.
- Chan, K.Y., And Xu, Z. (2009): Biochar: Nutrient Properties and Their Enhancement. In: Lehmann, J., and Joseph, S. (Eds), *Biochar for Environmental Management, Science and Technology*. Earthscan, London, pp, 67-81.
- Chan, K.Y., Zweiten, L. V., Meszaros, I., Downie, A., Joseph, S. (2007): Agronomic Values of Green waste Biochar as a Soil Amendment. *Australian J. Soil Res.*, 45:629-634.
- Chan, K.Y., Zweiten, L.V., Meszaros, I., Downie, A., And Joseph, S. (2008): Using Poultry Litter Biochars as Soil Amendments. *Australian J. Soil Res.*, 46:437-444.
- Cheng, C.H., Lehmann, J., and Engelhard, M. (2008): Natural Oxidation of Black Carbon in Soils: Changes in Molecular Form and Surface Charge along a Cli-Mosequence. *Geochimica Et Cosmochimica Acta* 72:1598–1610.

- Cheng, C.H., Lehmann, J., Thies, E., Burton, S.D., and Engelhard, M.H. (2006): Oxidation of Black Carbon by Biotic and Abiotic Processes. *Organic Geochemistry*, 37:1477–1488.
- Creswell, R., And Martin, F.W. Dr. (1993, 1998): *Dryland Farming: Crops & Techniques for Arid Regions*. Educational Concerns For Hunger Organization (ECHO) Technical Note, U.S.A.
- Crombie, K., Mašek, O., Sohi, S.P., Brownsort, P., Cross, A. (2013): The Effect of Pyrolysis Conditions on Biochar Stability as Determined by Three Methods. *Global Change Biology and Bioenergy*, 5: 122–131.
- Cross, A., and Sohi, S.P. (2013): A Method for Screening the Relative Long-Term Stability of Biochar. *GCB Bioenergy*, 5:215-220.
- Dalal, R. C., Allen, D. E., Livesley, S. J., & Richards, G. (2008): Magnitude and Biophysical Regulators of Methane Emission and Consumption in the Australian Agricultural, Forest, and Submerged Landscapes: A Review. *Plant and Soil*, 309: 43-76.
- De-Campos, A.B, Mamedov, A.I, and Huang, C. (2009): Short-Term Reducing Conditions Decrease Soil Aggregation. *Soil Sci. Soc. Am. J.*, 73:550-559.
- De-Datta, S.K. (1981): Morphology, Growth and Development of the Rice Plant. In: *Principles and Practices of Rice Production*. Wiley-Interscience, New York, pp, 146-172.
- Deluca, T.H., Mackenzie M.D., and Gundale, M.J. (2009): Biochar Effects on Soil Nutrient Transformations. In: Lehmann, J. and Joseph, S. (Eds). *Biochar for Environmental Management, Science and Technology*, Earthscan, London, pp, 251-265.
- Demoling, F., Figueroa, D., And Murphy, D.V. (2007): Comparison of Factors Limiting Bacterial Growth in Different Soils. *Soil Biology & Biochemistry*, 39:2485-2495.
- DNDC (2012): User's Guide for the Denitrification Decomposition (DNDC) Model, Version 9.5. Institute for the Study of Earth, Oceans and Space. University of New Hampshire.
- Downie, A., Crosky, A., and Munroe, P. (2009): Physical Properties of Biochar. In: Lehmann, J. and Joseph, S. (Eds). *Biochar for Environmental Management, Science and Technology*, Earthscan, London, pp, 13-29.
- Elad, Y., David, D.R., Harel, Y.M., Borenshtein, M., Kalifa, H.B., Silber, A. and Graber, E.R. (2010): Introduction of Systemic Resistance in Plants By Biochar, a Soil-Applied Carbon Sequestering Agent. *Phytopath.* 100: 913-921.
- Elmer, W.H. and J.J. Pignatello (2011): Effect of Biochar Amendments on Mycorrhizal Associations and Fusarium Crown and Root Rot of Asparagus in Replant Soil. *Plant Disease*, 95: 960-966.
- Elzaki, O.T., Khider, T.O., And Omer, S.H. (2012): Pulp And Paper Making Characteristics of *Cajanus Cajan* Stems From Sudan. *American-Eurasian J. Agric. & Environ. Sci.*, 12 (2): 159-163.
- Fageria, N.K., Baligar, V.C., and Jones, C.A. (1997): *Growth and Mineral Nutrition of Field Crops*, Second Edition, New York.

- Fageria, N.K., Moreira, A., and Coelho, A.M. (2011): Yield and Yield Components of Upland Rice as Influenced by Nitrogen Sources. *Journal of Plant Nutrition*, 34:361-370.
- Fando, C.L., Pardo, M.T. (2009): Changes in Soil Chemical Characteristics with Different Tillage Practices in a Semi-Arid Environment. *Soil & Tillage Research*, 104: 278-284.
- FAO (1998): World reference base for soil resources. 84 World Soil Resources Reports. International Society of Soil Science, ISSS-AISS-IBG, International Soil Reference and Information Centre, ISRIC, Food and Agriculture Organization of the United Nations, Rome.
- FAO (2004): Carbon Sequestration in Dryland Soils. World Soils Resources Reports 102, Natural Resources Management and Environment Department, FAO, Rome.
- FAO (2005): Management of Irrigation-Induced Salt-Affected Soils. FAO, Rome.
- FAO (2009): FAOSTAT Database (Online Information).
- FAO (2011): Case Studies on Policies and Strategies for Sustainable Soil Fertility and Fertilizer Management in South Asia, 2011, FAO, Bangkok.
- Fiedler, S., and Kalbitz, K. (2003): Concentrations and Properties of Dissolved Organic Matter in Forest Soils as Affected by the Redox Regime. *Soil Science*, 168: 793-801.
- Fierer, N., and Schimel, J. P. (2002): Effects of Drying-Rewetting Frequency on Soil Carbon and Nitrogen Transformations. *Soil Biology & Biochemistry*, 34: 777-787.
- Gallup, J.L And Sachs, J.D. (2000): Agriculture, Climate And Technology: Why Are The Tropics Falling Behind? *Amer. J. Agr. Econ*, 82: 731/737.
- Gangil, S., and Wakudkar H.M. (2013): Generation of Biochar from Crop Residues. *International Journal of Emerging Technology and Advanced Engineering*, 3 (3): 566-570.
- Gardner, C. M.K., Laryea, K.B., and Unger, P.W. (1999): Soil Physical Constraints to Plant Growth and Crop Production. Land and Water Development Division, FAO, Rome.
- Gaskin, J.W., Speir, A., Morris, L.M., Ogden, L., Harris, K., Lee, D., and Das, K.C. (2007): Potential for Pyrolysis Char to Affect Soil Moisture and Nutrient Status of a Loamy Sand Soil. Proceedings of the 2007 Georgia Water Resources Conference, March 27-29, 2007, Athens, Georgia.
- Geißler, V. (2007): Classification and Geochemistry of Arid and Semi-arid Paleosols. Paper Submitted to Oberseminar Winter Semester 2006/2007, TU Bergakademie Freiberg, Germany.
- Ghoneim, A.M., and Ebid, A.I. (2013): Impact of Rice-Straw Biochar on Some Selected Properties and Rice (*Oryza Sativa* L.) Grain Yield. *International Journal of Agronomy and Agricultural Research (IJAAR)*, 3 (4):14-22.
- Gilhespy, S.L, Anthony, S., Cardenas, L., Chadwick, D., Del Prado, A., Li, C., Misselbrook, T., Rees, R.M., Salas, W., Sanz-Cobena, A., Smith, P., Tilston, E.L., Topp, C.F.E., Vetter, S., And Yeluripati, J.B. (2014): First 20 Years Of DNDC (Denitrification Decomposition): Model Evolution. *Ecological Modelling* 292:51-62.

Glaser, B., Lehmann, J., and Zech, W. (2002): Ameliorating Physical and Chemical Properties of Highly Weathered Soils in the Tropics with Charcoal - A Review, *Biol. Fertil. Soils*, 35: 219-230.

GRDC (2013): Nitrogen Fixation And Benefits of Chickpeas And Faba Beans In Northern Farming Systems, Nitrogen Fixation Fact Sheet, Grains Research & Development Corporation, Australia. (Online Accessed On 15.07.2014)

Gundale, M.J., And Deluca, T.H. (2006): Temperature and Source Material Influence the Chemical Properties of Charcoal in The Ponderosa Pine/Douglas-Fir Ecosystem. *Forest Ecology and Management*, 231:86-93.

Günther, F. (2012): Small and Intermediate Charring Devices: Examples and Projects. Power Point Presentation. Research Institute on Small-Scale Charring, Hörby, Sweden.

Guthrie, D., Silvertooth, J., and Stichler, C. (1993): Monitoring Plant Vigour. Newsletter of the Cotton Physiology Education Program, National Cotton Council of America, 4(5):1-4.

Hadden, R.L. (2008): The Geology of Burma (Myanmar): An Annotated Bibliography of Burma's Geology, Geography and Earth Science. Topographic Engineering Centre, US Army Corps of Engineers, Alexandria, Virginia.

Haefele, S.M., Konboon, Y., Wongboon, W., Amarante, S., Maarifat, A.A, Pfeiffer, E.M., and Knoblauch, C. (2011): Effects and Fate of Biochar from Rice Residues in Rice-Based Systems. *Field Crop Research*, 121:430-440.

Haggblade, S., Denning, G., Kloeppinger-Todd, R., Khin Mar Cho, Wilson, S., And Wong. L. C.Y. (2013): A Strategic Agricultural Sector and Food Security Diagnostic for Myanmar. Myanmar Development Resource Institute, Michigan State University.

Hammes, K., and Schmidt, M.W.I. (2009): Changes of Biochar in Soil. In: Lehmann, J. and Joseph, S. (Eds). *Biochar for Environmental Management*, Earthscan, London, pp, 169-178.

Harrod, M.F. (1975): Field Behavior of Light Soils. In: *Soil Physical Conditions and Crop Production*. MAFF Tech. Bull. No. 29, HMSO, London, pp, 22-51.

Havlin, J.L., Samuel, L.T., Nelson, W.L., and Beaton, J.D. (2014): *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*, Eighth Edition, PHI Learning Ltd., India.

Hemwong, S., and Cadisch, G. (2011): Charcoal Amendments to Improve Soil Fertility and Rice Production in NE Thailand, FSC Brief No.3. Food Security Centre, Hohenheim University, Stuttgart, Germany.

Hillocks, R.J. (1992): Seedling Diseases. In: Hillocks, R.J. (Ed): *Cotton Diseases*. Pp, 1-389. C.A.B. International, Wallingford, UK.

Hodges, S.C. (1992): Nutrient Deficiency Disorders. In: Hillocks, R.J. (1992): *Cotton Diseases*, C.A.B. International, Wallingford, UK, pp, 355-403.

Huston, M.A. (1994): *Biological Diversity: The Coexistence of Species on Changing Landscapes*. Cambridge University Press, Cambridge, UK.

IGES (Institute for Global Environmental Strategies, Japan), (2012): Background Paper: Enabling Low-Carbon and Climate-Resilient Development in Myanmar. Prepared For Green Economy Green Growth Myanmar Conference, 13 November 2012, Nay Pyi Taw, Myanmar.

IPCC (2006): Houghton, J.T. (Ed.) 2006 IPCC Guidelines for National Greenhouse Inventories, IPCC National Greenhouse Gas Inventory Programme, Hayama, Japan.

IRRI (International Rice Research Institute), (2007): Fairhurst, T., Witt, C., Buresh, R., and Dovermann, A. (Eds.). Rice. A Practical Guide to Nutrient Management, Second Edition. International Rice Research Institute.

Izaurrealde, R.C., McGill, W.B., Robertson, J.A., Juma, N.G., and Thurston, J.J. (2001): Carbon Balance of the Breton Classical Plots over Half a Century. *Soil Sci. Soc. Am. J.* 65:431-441.

Izumi, T. Et Al. (2010): The Development Study on Sustainable Agricultural and Rural Development for Poverty Reduction Programme in the Central Dry Zone of the Union of Myanmar. Final Report. Japan International Cooperation Agency (JICA), Sanyu Consultants Inc., Tokyo, Japan.

Jeffery, S., Bezemer, T.M., Cornelissen, G., Kuyper, T.W., Lehmann, J., Mommer, L., Sohi, S. P., Voorde, T. F. J.V.D., Wardle, D.A., And Groenigen, J.W.V. (2014): The Way Forward in Biochar Research: Targeting Trade-Offs Between The Potential Wins. Pp 1-18. *Global Change Biology*.

Jenkinson, D.S., and Rayner, J.H. (1997): The Turnover of Soil Organic Matter in Some of the Rothamsted Classical Experiments. *Soil Science*, 123: 298-305.

Jeon, W.T., Seong, K.Y., Lee, J.K., Oh, I.S., Lee, Y.H., and Ok, Y.S. (2010): Effects of Green Manure and Carbonized Rice Husk On Soil Properties and Rice Growth. *Korean J. Soil Sci. Fert.* 43(4): 484-489.

Jia, J., Li, B., Chen, A., Xie, Z., and Xiong, Z. (2012): Effects of Biochar Application on Vegetable Production and Emissions of N<sub>2</sub>O and CH<sub>4</sub>. *Soil Science and Plant Nutrition*, 58: 503-509.

Jones, D.L., Edwards-Jones, G., And Murphy, D.V. (2011): Biochar Mediated Alterations in Herbicide Breakdown and Leaching in Soil. *Soil Biology & Biochemistry* 43:804-813.

Joseph, S., Peacocke, C., Lehmann, J., and Munroe, P., (2009): Developing a Biochar Classification and Test Methods. In: Lehmann, J. and Joseph, S. (Eds). *Biochar for Environmental Management, Science and Technology*, Earthscan, London, pp, 107-112.

Kimetu, J.M., and Lehmann, J. (2010): Stability and Stabilization of Biochar and Green Manure in Soil with Different Organic Carbon Contents. *Australian Journal of Soil Research*, 48: 577-585.

Kirchhof, G. Et Al. (2000): Growth And Yield Response of Grain Legumes to Different Soil Management Practices After Rain-Fed Lowland Rice. *Soil & Tillage Research*, 56:51-66

Kloss, S., Zehetner, F., Wimmer, B., Buecker, J., Rempt, F., Soja, G. (2014): Biochar Application to Temperate Soils. Effects on Soil Fertility and Crop Growth under Greenhouse Conditions, *Journal of Plant Nutrition and Soil Science*, 177 (1): 3-15.

Knoblauch, C., Maarifat, A.A., Pfeiffer, E.M., Haefele, S.M. (2011): Degradability of Black Carbon and Its Impact on Trace Gas Fluxes and Carbon Turnover in Paddy Soils. *Soil Biol. Biochem.*, 43: 1768–1778.

Krishnakumar S., Rajalakshmi, A.G., Balaganesh, B., Manikandan, P., Vinoth, C., and Rajendran, V. (2014): Impact of Biochar on Soil Health. Review Article. *International Journal of Advanced Research*, 2 (4): 933-950.

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., Karlen, D. L. (2010): Impact of Biochar Amendments on the Quality of a Typical Midwestern Agricultural Soil. *Geoderma*, 158:443-449.

Laird, D.A. (2008): The Charcoal Vision: A Win-Win-Win Scenario for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, While Improving Soil and Water Quality. *Agronomy Journal*, 100:178-181.

Lancashire, P.D., Bleiholder, H., Langelüddecke, P., Strauss. R., Van Den Boom, T., Weber, E., and Witzen-Berger, A. (1991): A Uniform Decimal Code for Growth Stages of Crops and Weeds. *Ann. Appl.Biol.* 119: 561-601. In: Uwe Meier (Ed.), *Growth Stages of Mono- and Dicotyledonous Plants*, BBCH Monograph, Second Edition, Federal Biological Research Centre for Agriculture and Forestry.

Landon, J.R. (1991): *Booker Tropical Soil Manual*. Longman Scientific & Technical, New York.

Lehmann, J. (2007): Bioenergy in the Black. *Frontiers in Ecology and the Environment*, 5:381-387.

Lehmann, J., And Joseph, S. (2009): Biochar Systems. In: Lehmann, J., and Joseph, S. (Eds.), *Biochar for Environmental Management: Science and Technology*. Earthscan, UK. Pp: 147-164.

Lehmann, J., and Rondon, M. (2006): Biochar Soil Management on Highly Weathered Soils in the Tropics. In: Uphoff, N., Ball. A.S., Fernandes, E., Herren, H., Husson, O., Laing, M., Palm, C., Pretty, J., Sanchez, P., Sanginga, N., and Thies, J. (Eds): *Biological Approaches To Sustainable Soil Systems*. Pp, 518-527. CRC Press.

Lehmann, J., Da Silva Jr., J. P.; Steiner, C., Nehls, T., Zech, W., And Glaser, B. (2003): Nutrient Availability and Leaching in an Archaeological Anthrosol and Ferralsol of the Central Amazon Basin: Fertilizer, Manure and Charcoal Amendments. *Plant Soil*. 249: 343-357.

Lehmann, J., Rillig, M., Thies, J., Masiello, C., Hockaday, W.C., and Crowley, D. (2011): Biochar Effects on Soil Biota: A Review. *Soil Biol. Biochem.*, 43: 1812-1836.

Lentz, R.D., And Ippolito, J.A. (2011): Biochar and Manure Affect Calcareous Soil and Corn Silage Nutrient Concentrations and Uptake. *Journal of Environmental Quality*, 41: 1033-1043.

Lewandowski, A., And Zumwinkle, M. (1999): *Assessing the Soil System, a Review of Soil Quality Literature*. Fish, A. (Ed.), Minnesota Department of Agriculture, Energy and Sustainable Agriculture Program, St. Paul.



- Li, C., Zhuang, Y., Frohking, S., Galloway, J., Harriss, R., Moore, B. III., Schimel, D., and Wang X. (2003): Modelling Soil Organic Carbon Change in Croplands of China. *Ecological Applications*, 13 (2):327-336.
- Li, C.S. (2000): Modelling Trace Gas Emissions from Agricultural Ecosystems. *Nutrient Cycling In Agroecosystems*, 58: 259-276.
- Li, F., Cao, X., Zhao, L., Yang, F., Wang, J., and Wang, S. (2013): Short-Term Effects of Raw Rice Straw and Its Derived Biochar on Greenhouse Gas Emission in Five Typical Soils in China. *Soil Science and Plant Nutrition*, 59:800-811.
- Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., and O'Neill, B. (2006): Black Carbon Increases Cation Exchange Capacity in Soils. *Soil Sci. Soc. Am. J.*, 70: 1719-1730.
- Liesch, A.M., Weyers, S.L., Gaskin, J.W., and Das, K.C. (2010): Impact of Two Different Biochars on Earthworm Growth and Survival. *Annals of Environmental Science*, 4:1-9.
- Liu, C., Lu, M., Cui, J., Li, B., and Fang, C. (2014): Effects of Straw Carbon Input on Carbon Dynamics in Agricultural Soils: A Meta-Analysis. *Global Change Biology*, 20:1366-1381.
- Liu, X.H., And Zhang, X.C. (2012): Effect of Biochar on pH of Alkaline Soils in the Loess Plateau: Results from Incubation Experiments. *International Journal of Agriculture & Biology*, 14: 745-750.
- Loague, K., And Green, R.E. (1991): Statistical and Graphical Methods for Evaluating Solute Transport Models: Overview And Application. *Journal of Contaminant Hydrology*, 7: 51-73.
- Lorenz, K., and Lal, R. (2014): Biochar Application to Soil for Climate Change Mitigation by Soil Organic Carbon Sequestration. *J. Plant Nutr. Soil Sci.*, 177: 651-670.
- Ludueña, L., Fasce, D., A. Alvarez, V., And M.Stefani, P. (2011): Nano cellulose From Rice Husk Following Alkaline Treatment to Remove Silica. *Bioresources*, 6 (2):1440-1453.
- Maas, E.V., and Hoffman, G.J. (1977): Crop Salt Tolerance-Current Assessment. *J. Irrigation and Drainage Division, Amer. Soc. Civil Eng.* 103:115-134.
- Major, J., J. Lehmann, M. Rondon, And C. Goodale (2010): Fate of Soil-Applied Black Carbon: Downward Migration, Leaching and Soil Respiration. *Global Change Biology*, 16:1366-1379.
- Mansur, C.P., Palled, Y.B., Salimath, P.M., and Halikatti, S.I. (2010): An Analysis of Dry Matter Production, Growth and Yield in Kabuli Chickpea as Influenced By Dates of Sowing and Irrigation Levels. *Karnataka J. Agri. Sci.*, 23 (3): 457-460.
- Maranan, (1987): Economic Performance of Cropping Patterns at Bantug, Guimba, Nueva Ecija CSR Site, 1986-87. Internal Report. Agricultural Economics Department, International Rice Research Institute, Los Baños, Philippines.
- Maranan, C.G. (1986): Agricultural Economic Research at Guimba Cropping Systems Site, Nueva Ecija, Philippines. Internal Report. Agricultural Economics Department, International Rice Research Institute, Los Banos, Philippines.

Martinsen, V., Mulder, J., Shitumbanuma, V., Sparrevik, M., Børresen, T., and Cornelissen, G. (2014): Farmer-Led Maize Biochar Trials: Effect on Crop Yield and Soil Nutrients under Conservation Farming. *J. Plant Nutr. Soil Sci.*, 177: 681-695.

Matsubara, Y., Hasegawa, N., and Fukui, H. (2002): Incidence of Fusarium Root Rot in Asparagus Seedlings Infected With Arbuscular Mycorrhizal Fungus As Affected By Several Soil Amendments. *J. Jap. Soc. Hortic. Sci.*, 71: 370-374.

Matsubara, Y., Tamura, H., and Harada, T. (1995): Effect of Inoculation Density of Vesicular-Arbuscular Mycorrhizal Fungal Spores and Addition of Carbonized Material to Bed Soil on Growth of Welsh Onion Seedlings. *Journal of the Japanese Society for Horticultural Science*, 64:549-554.

Matsuda, M. (2013): Upland Farming Systems Coping with Uncertain Rainfall in The Central Dry Zone of Myanmar: How Stable Is Indigenous Multiple Cropping Under Semi-Arid Conditions? *Hum Ecol.*, 41: 927-936.

Mbagwu, J.S.C. (1989): Effects of Organic Amendments on Some Physical Properties of a Tropical Ultisol. *Biological Wastes*, 28: 1-13.

McLaughlin, H., Anderson, P.S., Shields, F.E., And Reed, T.B. (2009): All Biochars Are Not Created Equal, and How To Tell Them Apart. Version 2 of the digital reprint issued at the North American Biochar Conference, Boulder, CO-August 2009.

Méndez, A., Gomez, A., Paz-Ferreiro, J., and Gasco, G. (2012): Effects of Sewage Sludge Biochar on Plant Metal Availability after Application to a Mediterranean Soil. *Chemosphere*, 89:1354-1359.

Micheni, A.N., Kihanda, F.M., Warren, G.P., and Probert, M.E. (2004): Testing the APSIM Model with Experimental Data from the Long-Term Manure Experiment at Machang'a (Embu), Kenya. In: Dolve, R.J., and Probert, M.E. (Eds). *Modelling Nutrient Management in Tropical Cropping Systems*, pp, 110-117.

Ministry Of Forestry, Myanmar (2005): National Action Programme of Myanmar to Combat Desertification in the Context of United Nations Convention to Combat Desertification (UNCCD) Yangon, Myanmar.

Moormann, E.R., And Van Breemen, N. (1978): *Rice: Soil, Water, Land*, International Rice Research Institute, Manila, Philippines.

Mori, S., and Marjenah, (1994): Effect of Charcoaled Rice Husks on the Growth of *Dipterocarpaceae* Seedlings in East Kalimantan with Special Reference to Ectomycorrhiza Formation. *Journal of the Japanese Forest Society*, 76: 462–464.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., and Veith, T.L. (2007): Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *American Society of Agricultural and Biological Engineers*, 50 (3): 885-900.

Morrow, M.R., and Krieg, D.R. (1990): Cotton Management Strategies for A Short Growing Season Environment: Water-Nitrogen Considerations. *Agron. J.* 82:52-56.

- Mousavi, S.F., Moazzeni, M., Mostafazadeh-Fard, B., and Yandani, M.R. (2012): Effects of Rice Straw Incorporation on Some Physical Characteristics of Paddy Soils. *J. Agr. Sci. Tech.*, 14:1173-1183.
- Mukherjee, A., and Lal, R. (2013): Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions. *Agronomy*, 3:313-339.
- Munger, P., Leiholder, H., Hack, H., Hess, M., Strauss, R., Van Den Boom, T., and Weber, E. (1998): Phenological Growth Stages and BBCH-Identification Keys of the Cotton (*Gossypium Hirsute L.*). In: Uwe Meier (Ed.), Growth Stages of Mono- and Dicotyledonous Plants, BBCH Monograph, Second Edition, Federal Biological Research Centre for Agriculture and Forestry.
- Myanma Cotton and Sericulture Enterprise (2006): Cotton in Myanmar, Ministry of Agriculture and Irrigation, Yangon, Myanmar, pp, 15.
- Nguyen, B.T., Lehmann, J., Kinyangi, J., Smernik, R., Riha, S.J., and Engelhard, M.H. (2008): Long Term Black Carbon Dynamics in Cultivated Soil. *Biogeochemistry*, 89: 295-308.
- Nigussie, A., Kissi, E., Misganaw, M., And Ambaw, G. (2012): Effect of Biochar Application on Soil Properties And Nutrient Uptake of Lettuces (*Lactuca Sativa*) Grown in Chromium Polluted Soils. *American-Eurasian J. Agric. & Environ. Sci.*, 12 (3): 369-376.
- Nishio, M. (1996): Microbial Fertilizers in Japan, FFTC Extension Bulletin. Food and Fertilizer Technology Centre, Taipei.
- Nishio, M., And Okano, S. (1991): Stimulation of the Growth of Alfalfa and Infection of Mycorrhizal Fungi by the Application of Charcoal, *Bull. Natl Grassland Res. Inst.*, 45: 61-71.
- Novak, J.M., Busscher, W.J., Watts, D.W., Amonette, J.E., Ippolito, J.A., Lima, I.M., Gaskin, J., Das, K.C., Steiner, C., Ahmedna, M., Rehrach, D., and Schomberg, H. (2012): Biochars Impact on Soil-Moisture Storage in an Ultisol and Two Aridisols, *Soil Science Journal*, 177:310-320.
- Novak, J.M., Lima, I., Xing, B., Gaskin, J.W., Steiner, C., Das, K.C., Ahmedna, M., Rehrach, D., Watts, D.W., Busscher, W.J., and Schomberg, H. (2009): Characterization of Designer Biochar Produced at Different Temperatures and Their Effects on Loamy Sand. *Annals of Environmental Science*, 3: 195-206.
- Nyalemegbe, K.K., Yangyuoru, M., Osei-Asare, Y., Ofosu-Budu, G.K., Mellon, S. and Tegbe, R.E. (2012): Enhancing Soil Productivity in The Rain-Fed Upland Ecology through Rotational Cropping of NERICA (New Rice For Africa) and Cowpea (*Vigna unguiculata*) *Agricultural Science Research Journal*, 2 (4):159– 166.
- Olmo, M., Albuquerque, J.A., Barròn, V., Campillo, M. C. Del., Gallardo, A., Fuentes, M., and Villar, R. (2014): Wheat Growth and Yield Responses to Biochar Addition under Mediterranean Climate Conditions. *Biol Fertil. Soils*, 50:1177-1187.
- Paethanom, A., and Yoshikawa, K. (2012): Influence of Pyrolysis Temperature on Rice Husk Char Characteristics and Its Tar Adsorption Capability. *Energies*, 5 (12):4941-4952.

- Painter, T.J. (2001): Carbohydrate Polymers In Food Preservation: An Integrated View of The Maillard Reaction with Special Reference to The Discoveries of Preserved Foods in Sphagnum Dominated Peat Bogs. *Carbohydrate Polymers*, 36: 335-347.
- Pandolfo, A.G., Amini-Amoli, M., and Killingley, J.S. (1994): Activated Carbons Prepared From Shells of Different Coconut Varieties. *Carbon* 32: 1015-1019.
- Parton, W.J., Anderson, D.W., Cole, C.V., and Stewart, J.W.B. (1983): Simulation of Soil Organic Matter Formations and Mineralisation in Semiarid Agroecosystems. In: Lowrance, R.R., Todd, R.L., Asmussen, L.E., And Leonard, R.A. (Eds.), *Nutrient Cycling In Agricultural Ecosystems*. Spec. Publ. 23, College Of Agriculture Exp. Stn., University Of Georgia, Athens, GA. Pp, 533-550.
- Parvage, Md. M., Ulén, B., Eriksson, J., Strock, Jeffery and Kirchmann, Holger (2013): Phosphorus Availability in Soils Amended With Wheat Residue Char. *Biology and Fertility of Soils*, 49 (2): 45-250.
- Pathak, H., Li, C., and Wassmann, R. (2005): GHG Emission from India Rice Fields: Calibration and Upscaling Using the DNDC Model. *Biogeosciences*, 2:113-123.
- Patrick, W. H., And Jugsujinda, A. (1992): Sequential Reduction and Oxidation of Inorganic Nitrogen, Manganese and Iron in Flooded Soil. *Soil Sci. Soc. Am. J.*, 56: 1071–1073.
- Paustian K. (2001): Modelling Soil Organic Matter Dynamics – Global Challenges. In: Rees R.M., Ball, B.C., Campbell and Watson C.A (Eds), *Sustainable Management of Soil Organic Matter*. Pp, 43-53. CAB International.
- Paz-Ferreiro, J., Lu, H., Fu, S., Méndez, A., And Gascó, G. (2014): Use Of Phytoremediation And Biochar To Remediate Heavy Metal Polluted Soils: A Review. *Soil Earth*, 5:65-75.
- Pietikäinen, J., Kiikkila, O., and Fritze, H. (2000): Charcoal as a Habitat for Microbes and Its Effect on the Microbial Community of the Underlying Humus, *Oikos*, 89:231-242.
- Poe, C.A. (2011): Food Security Assessment in The Dry Zone, Myanmar, Food Security Analysis Services (ODXF), World Food Program (Wfp.Org).
- Ponnamperuma, F.N. (1981): Properties of Tropical Rice Soils. Lecture Series Delivered to Graduate Students at The Tropical Agriculture College, H. Cardenas, Tabasco, Mexico.
- Powlson, D.S., Goulding, K.W.T., Willison. T.W., Webster, C.P., and Hütsch, B.W. (1997): The Effect of Agriculture on Methane Oxidation in Soil. *Nutrient Cycling in Agroecosystems*, 49(1-3):59-70.
- Powlson, D.S., Smith, P. & Smith, J.U. (Eds) (1996): Evaluation Of Soil Organic Matter Models Using Existing Long-Term Datasets, *NATO ASI*, 38 (1): 429. Springer.
- R Development Core Team (2008): A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0.
- Rahnama, N., Mamat, S., Shah, U.K.M., Ling, F.H., Rahman, N.A.A., and Ariff, A.B. (2013): Effect of Alkali Pretreatment of Rice on Cellulase and Xylanase Production by Local *Trichoderma Harzianum* SNRS3 under Solid State Fermentation. *Bioresources*, 8 (2): 2881-2896.

- Retan, G.A. (1915): Charcoal as a Means of Solving Some Nursery Problems. *Forestry Quaterly*, 13: 25-30.
- Richter, C., Heiligtag, B., Nagieb, M, and Mukhallalati, U. (1999): The Effects of Salinity on Growth and Ion Content of Chickpea (*Cicer Arietinum* L.), Eggfruit (*Solanum Melongena* L.) and Red Pepper (*Capsicum Annuum* L.) Varieties. *Der Tropenlandwirt, Beiträge Zur Tropischen Landwirtschaft Und Veterinärmedizin*, 100. Jahrgang. Pp, 3-16.
- Rivera-Utrilla, J., Bautilsta-Toledo, I., Ferro-Carcia, M.A., and Moreno-Catilla, C. (2001): Activated Carbon Surface Modifications by Adsorption of Bacteria and Their Effect on Aqueous Lead Adsorption. *Journal of Chemical Technology and Biotechnology*, 76: 1209-1215.
- Rogovska, N.P., Fleming, P., Laird, D.A., Cruse, R.M., Parkin, T., And Meek, D. (2010): Biochar Influences on Greenhouse Gas Emissions from a Midwestern Agricultural Soil. Submitted to *Soil Sci. Soc. Am. J.*
- Rohr, G.V. (2010): Arbeitshilfe der Arbeitsgruppe VBB/BSA Zur Anwendung und Interpretation Bodenbiologischer Parameter. *Bulletin BGS*, 30:63-67.
- Rondon, M. A., Lehmann, J., Ramírez, J. and Hurtado, M. (2006): Biological Nitrogen Fixation by Common Beans (*Phaseolus Vulgaris* L.) Increases with Biochar Additions, *Biol Fertil Soils*, 43: 699-708.
- Rousk, J., Dempster, D.N., and Jones, D.L. (2013): Transient Biochar Effects On Decomposer Microbial Growth Rates: Evidence from Two Agricultural Case Studies, *European Journal of Soil Science*, 64:770-776.
- Rowell, D.L. (1981): Oxidation and Reduction. In: Greenland, D.J., and Hayes, M.H.B. (Ed.) *the Chemistry of Soil Processes*. John Wiley & Sons, Chichester. P. 401–461.
- Sapkota, T.B., Jat, M. L., Kapoor, P., and Stirling, C., (2015, online): Yield Estimation of Food and Non-Food Crops in Smallholder Production Systems. In: *Measurement Methods: Guidelines for Field Measurements of Agricultural Greenhouse Gas Sources and Sinks*. Climate Change Agriculture and Food Security (CCAF), the Consultative Group for International Agricultural Research (CGIAR), Montpellier, France. pp, 1-14.
- Saito, M., and Marumoto, T. (1990): Charcoal as a Micro Habitat for VA Mycorrhizal Fungi, And Its Practical Application. *Agriculture, Ecosystems and Environment*, 29: 341-344.
- Saito, M., and Marumoto, T. (2002): Inoculation with Arbuscular Mycorrhizal Fungi: The Status Quo in Japan and the Future Prospects. *Plant and Soil*, 244: 273-279.
- Schneour, E.A. (1966): Oxidation of Graphite Carbon in Certain Soils. *Science*, 151:991-992.
- Schulz, H., and Glaser, B. (2012): Effects of Biochar Compared to Organic and Inorganic Fertilizers on Soil Quality and Plant Growth in a Greenhouse Experiment. *J. Plant Nutr. Soil Sci.*, 175: 410-422.
- Schulz, H., Dunst, G., Glaser, B. (2013): Positive Effects of Composted Biochar on Plant Growth and Soil Fertility. *Agronomy for Sustainable Development*, 33:817-827.

- Shafizadeh, F. (1982): Introduction to Pyrolysis of Biomass. *Journal of Analytical and applied Pyrolysis*, 3:283-305.
- She, D., Nie, X.N., Xu, F., Geng, Z.C., Jia, H.T., Jones, G.L., and Baird, M.S. (2011): Physio-Chemical Characterization of Different Alcohol Soluble Lignins from Rice Straw. *Cellulose Chem. Technol.*, 46 (3-4): 207-219.
- Shen, J., Tang, H., Liu, J., Li, Y., Ge, T., and Wu, J. (2013): A Comparison of Greenhouse Gas Emissions from a Paddy Field Following Incorporation of Rice Straw and Straw-Based Biochar. *Functions of Natural Organic Matter in Changing Environment*, pp, 1027-1031.
- Shen, S.Y., Stucki, J.W., and Boast, C.W. (1992): Effects of Structural Iron Reduction on the Hydraulic Conductivity of Na-smectite. *Clays Clay Miner*, 40: 381–386.
- Singh, B., Shan, Y.H., Johnson-Beebout, S.E., Singh, Y., and Buresh, R.J. (2008): Crop Residue Management for Lowland Rice-based Cropping Systems in Asia. *Advances in Agronomy*, 98:117-199.
- Singh, B.P., Hatton, B.J., Singh, B., Cowie, A.L., and Kthuria, A. (2010): Influence of Biochars on Nitrous Oxide Emission and Nitrogen Leaching from Two Contrasting Soils. *J. Environ. Qual*, 39: 1224-1235.
- Singh, F., and Diwakar (1995): Chickpea Botany and Production Practices. Skill Development Series Number 16. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Training and Fellowships Program, Andhra Pradesh, India.
- Skujins, J. (Ed.) (1991): *Semi-Arid Land and Deserts: Soil Resource and Reclamation*. New York, USA, Marcel Dekker Inc.
- Smith J.L., Collins, H.P., and Bailey V.L. (2010): The Effect of Young Biochar on Soil Respiration. *Soil Biology and Biochemistry*, 42 (12): 2345-2347
- Smith, P., Powlson, D.S., Smith, J.U., and Glendining, M.J., (1996a). The Global Change Mater Directory, Soil Organic Matter Network (GCTE SOMNET). A Global Network and Database of Soil Organic Matter Models and Long-Term Datasets. *Soil Use and Management* 12: 104
- Smith, P., Smith, J.U., and Powlson, D.S. (1996b): Soil Organic Matter Network (SOMNET). Model and Experimental Metadata. GCTE Report 7, GCTE Focus 3 Office, Wallingford, Oxon, 259 pages.
- Sohi, S.P., Krull, E., Lopez-Capel, E., and Bol, R. (2010): A Review of Biochar and Its Use and Function in Soil. *Advances in Agronomy*, 105: 47-82.
- Soil Science Glossary Terms Committee (2008): *Glossary of Soil Science Terms*. Soil Science Society of America. Madison, USA.
- Sombroek, W. G. (1966): *A Reconnaissance of the Soils of the Brazilian Amazon Region*. Centre for Agricultural Publications and Documentation, Wageningen.
- Sparling, G.P. (1985): The Soil Biomass. In: Vaughan, D., Malcolm, R.E. (Eds.), *Soil Organic Matter and Biological Activity*. Martinus Nijhoff /Dr. W. Junk. Dordrecht. Boston, Lanchester, pp, 223.

- Spokas, A.K., and Reicosky, D.C. (2009): Impacts of Sixteen Different Biochars on Soil Greenhouse Gas Production. *Ann. Environ. Sci.*, 3:179-193.
- Spokas, A.K., Baker, J., and Reicosky, D.C. (2010): Ethylene: Potential Key for Biochar Amendment Impacts. *Plant Soil*, 88: 133-143.
- Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R., Sumantha Kundu, Gajanan, G.N., and Ramachandrappa, B. (2012): Long-Term Effects of Crop residues and Fertility Management on Carbon sequestration and Agronomic Productivity of Groundnut-Finger millet Rotation on an Alfisol in Southern India. *International Journal of Agricultural Sustainability*, 10(3):1–15.
- Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., and Sumantha, K. (2013): Sustainable Management of Soils of Dryland Ecosystems of India for Enhancing Agronomic Productivity and Sequestering Carbon. *Advances in Agronomy*, 121:254-329.
- Steinbiss, S., Gleixner, G., and Antonietti, M. (2009): Effect of Biochar Amendment on Soil Carbon Balance and Soil Microbial Activity. *Soil Biology & Biochemistry*, 41(6): 1-10.
- Steiner, C., Teixeira, W.G., Lehmann, J., and Zech, W. (2004): Explorations in Space and Time. In: Glaser, B., and Woods, W.I., *Amazonian Dark Earths*. pp, 195-212.
- Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., and Vasconcelos de Macêdo, J.L. (2007): Long Term Effects of Manure, Charcoal and Mineral Fertilizer application on Crop Production and Fertility on a Highly Weathered Central Amazonian Upland Soil. *Plant and Soil*, 291: 275-290.
- Stevenson, F.J., and Cole, M.A., (1999): *Cycles of Soil: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients*, second Edition. Wiley-Interscience, New York.
- Sudo, K., and Akimoto, H. (2007): Global Source Attribution of Tropospheric Ozone: Long-Range Transport from Various Source Regions. *J. Geophys. Res.*, 112 D12302. DOI: 10.1029/2006JD007992.
- Sun, F., and Lu, S. (2014): Biochars Improve Aggregate Stability, Water Retention, and Pore-Space Properties Of Clayey Soil. *J. Plant Nutr. Soil Sci.*, 177:26-33.
- Tayyar, Ş., Egesel, C.Ö., Gül, K.M., and Turhan, H. (2008): The Effect of Autumn and Spring Planting Time on Seed Yield and Protein Content of Chickpea Genotypes. *African Journal of Biotechnology*, 7 (11): 1655-1661.
- Thies, J.E. and Rillig, M.C. (2009): Characteristics of Biochar: Biological Properties. In: *Biochar for Environmental Management, Science and Technology*, Lehmann, J. and Joseph, S. (Eds). pp, 85-102. Earthscan, London.
- Tin Aung Shein, U. (2008): *Improvement of Crop Production in the Dry Zone* Published in Myanmar Language, Department of Myanma Agriculture Service, Ministry of Agriculture and Irrigation, Myanmar. 99 pages.
- Troeh, F.R. and Thompson, L.M. (2005): *Soils and Soil Fertility*, Blackwell Publishing, Iowa, USA.

- Tyron, E.H., (1948): Effect of Charcoal on Certain Physical, Chemical and Biological Properties of Forest Soils. *Ecol. Monogr.*, 18:81-115.
- Urban, B. (2002): Manual For Analysis of Soils and Related Materials. In: Kunst, S., Kruse, T., Burmester, A., (Eds.), *Sustainable Water and Soil Management*. pp, 321-369. Springer.
- USDA (1999): Soil Taxonomy, a Basic System of Soil Classification for Making and Interpreting Soil Surveys, Second Edition. Agriculture handbook, Number 436, by soil survey staff, United States Department of Agriculture, natural Resources Conservation Service.
- User's guide for the DNDC model (version 9.5) (2012): Institute of the Study of Earth, Oceans and Space, University of Hampshire.
- Van Zweiten, L., Kimber, S., Morris, S., Downie, A., Berger, E., Rust, J., and Scheer, C. (2010): Influence of Biochars on Flux of N<sub>2</sub>O and CO<sub>2</sub> from Ferrosol. *Soil Res.* 48:555-568.
- Van Zweiten, L., Singh, B., Joseph, S., Kimber, S., Cowie, A., and Yin Chan, K. (2009): Biochar and Emissions of Non-CO<sub>2</sub> Greenhouse Gases from soil. In: Lehmann, J. and Joseph, S. (Eds). *Biochar for Environmental Management, Science and technology*, Earthscan Publishing London, pp, 227-243.
- VDLUFA 1991, (1991): German Agricultural Testing and Research Agency. Book of Methods. Vol. 1. Soil Exploration Method A 5.1.1.
- VDLUFA 1991, (1991): German Agricultural Testing and Research Agency. Book of Methods, Vol. 1, Soil Exploration Method A 5.3.1.
- Vergara, B.S. (1992): Tropical Wet Rice Systems. In: Pearson, C.J (Ed.), *Field-crop Ecosystems, Ecosystems of the World*, 18:167-182. Elsevier.
- Walker, T.W. (2006): Rice Grain Yield Response to Nitrogen Fertilization for Newly Released Cultivars and Hybrids. Research Report, Mississippi Agricultural & Forestry Experiment Station, 23(20): 1-5.
- Wang, J., pan, X., Liu, Y., Zhang, X., Xiong, Z. (2012): Effects of Biochar Amendment in Two Soils on Greenhouse Gas Emissions and Crop Production. *Plant Soil*, 360:287-298.
- Wang, J., Zhang, M., Xiong, Z., Liu, P., and Pan, G. (2011): Effects of Biochar Addition on N<sub>2</sub>O and CO<sub>2</sub> Emissions from Two Paddy Soils. *Bio Fertil. Soils*, 47:887-896.
- Warnock, D.D., Lehmann, J., Kuyper, T.W., and Rillig, M.C. (2007): Mycorrhizal Responses to Biochar in Soil - Concepts and Mechanisms. *Plant and soil*, 300 (1-2): 9-20.
- Weil, R.R., and Magdoff, F. (2004): Significance of Soil Organic Matter to Soil Quality and Health. In: Magdoff, F., and Weil, R.R. (Eds). *Soil Organic Matter in Sustainable Agriculture*. CRC Press, Boca Raton, FL, U.S.A. pp, 1-43.
- Wiedner, K., and Glaser, B. (2013): Biochar-Fungi Interactions in Soils. In: Ladygina, N., and Rineau, F. (Eds). *Biochar and Soil Biota*, CRC Press, Taylor & Francis Group, pp, 69-99.
- Wilding, L.P., and Puentes, R. (1988): Vertisols: Their Distribution, Properties, Classification and Management. Texas A & M University Printing Centre. College Station. TX, USA. pp, 55-79.



- Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., and Joseph, S. (2010): Sustainable Biochar to Mitigate Global Climate Change. *Nature Communications* 1, Article number: 56 (online journal).
- Wrage, N., Van Groenigen, J.W., Oenema, O., and Baggs, E.M., (2005). A Novel Dual-Isotope Labelling Method for Distinguishing Between Soil Sources of N<sub>2</sub>O. *Rapid Communications in Mass Spectrometry* 19:3298-3306.
- Xevi, E., Gilley, J., and Feyen, J. (1996): Comparative Study of Two Crop-Yield Simulation Models. *Agricultural Water Management*, 30: 155-173.
- Xie, Z., Xu, Y., Liu, G., Liu, Qi.,Zhu, J., Tu, C., Amonetter, J.E., Cadisch, G., Yong, J.W.H., Hu, S. (2013): Impact of Biochar Application on Nitrogen Nutrition of Rice, Greenhouse-Gas Emissions and Soil Organic Carbon Dynamics In Two Paddy Soils Of China, *Plant Soil*, 370:527-540.
- Yamato, M., Okimori, Y., Wibowo, I.F., Anshori, S., and Ogawa, M. (2006): Effects of The Application of Charred Bark of *Acacia Mangium* on the Yield of Maize, Cowpea and Peanut, and Soil Chemical Properties in South Sumatra Indonesia. *Soil Science and Plant Nutrition* 52: 489-495.
- Yanai, Y., Toyota, K., Okazaki, M. (2007): Effects of Charcoal Addition on N<sub>2</sub>O Emissions from Soil Resulting from Rewetting Air-Dried Soil in Short-Term Laboratory Experiments. *Soil Sci. Plant Nutr.*,53:181-188.
- Yu, C., Tang, Y., Fang, M., Luo, Z. and Cen, K. (2005): Experimental Study on Alkali Emission during Rice Straw Pyrolysis. *Journal of Zhejiang University (Engineering Science)*, 39: 1435-1444.
- Yu, O.Y., Brian, R., and Sink, S. (2013): Impact of Biochar on The Water Holding Capacity of Loamy Sand Soil. *International Journal of Energy and Environmental Engineering* 4:44.
- Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, Ji., Zheng, Ju., Ahang, X., Han, X., and Yu, X. (2012): Effects of Biochar Amendment on Soil Quality, Crop Yield and Greenhouse Gas Emission in a Chinese Rice Paddy: A Field Study of 2 Consecutive Rice Growing Cycles. *Field Crops Research*, 127: 153-160.
- Zhang, A., Liu, Y., Pan, G., Hussain, Q., Li, L., Zheng, J., and Zhang, X. (2012): Effect of Biochar Amendment on Maize Yield and Greenhouse Gas Emissions from a Soil Organic Carbon Poor Calcareous Loamy Soil from Central China Plain. *Plant Soil*, 351: 263-275.
- Zhang, Y., Li, C., Zhou, X., and Moore, B. III (2002): A Simulation Model Linking Crop Growth and Soil Biogeochemistry for Sustainable Agriculture. *Ecological Modelling*, 151 (1): 75-108.
- Zimmerman, A.R., and Ahn, M.Y. (2010): Organo-Mineral Enzyme Interactions and Influence on Soil Enzyme Activity. In: Shukla, G.C., and Varma, A. (Eds.). *Soil Enzymes*, Springer, Berlin Heidelberg.
- Zimmerman, A.R., and Gao, B. (2013): The Stability of Biochar in the Environment. In: Ladygina, N., and Rineau, F. (Eds.). *Biochar and Soil Biota*, CRC Press, Taylor and Francis Group, pp 1-40.

## Internet Web Pages

[ftp://ftp.fao.org/agl/agll/docs/salinity\\_brochure\\_eng.pdf](ftp://ftp.fao.org/agl/agll/docs/salinity_brochure_eng.pdf)

[http://adl.brs.gov.au/data/warehouse/biochar9abcm001/biochar9abcm00101/TR.2011.06\\_Biochar\\_v1.0.0.pdf](http://adl.brs.gov.au/data/warehouse/biochar9abcm001/biochar9abcm00101/TR.2011.06_Biochar_v1.0.0.pdf)

[http://ambiente.okayama-u.ac.jp/management/upload\\_files/gakkan/2012\\_en/2012\\_en\\_3-1.pdf](http://ambiente.okayama-u.ac.jp/management/upload_files/gakkan/2012_en/2012_en_3-1.pdf)

[http://ambiente.okayama-u.ac.jp/management/upload\\_files/gakkan/2012\\_en/2012\\_en\\_3-1.pdf](http://ambiente.okayama-u.ac.jp/management/upload_files/gakkan/2012_en/2012_en_3-1.pdf)

<http://faostat.fao.org/site/567/desktopdefault.aspx#ancor>

<http://grdc.com.au/Resources/Factsheets/2013/07/Nitrogen-fixation-and-N-benefits-of-chickpeas-and-faba-beans-in-northern-farming-systems>

<http://ies.jrc.ec.europa.eu/>

<http://journal-ijee.com/content/4/1/44>

<http://nates.psu.ac.th/Link/SoilCongress/bdd/symp26/708-t.pdf>

[http://people.umass.edu/psoil370/Syllabusfiles/Dryland\\_Farming\\_Crops\\_&\\_Tech\\_for\\_Arid\\_Regions.pdf](http://people.umass.edu/psoil370/Syllabusfiles/Dryland_Farming_Crops_&_Tech_for_Arid_Regions.pdf)

<http://samples.ccafs.cgiar.org/wp-content/uploads/2015/06/Chapter-8.pdf>

[http://stud.epsilon.slu.se/4008/1/aslund\\_i\\_120327.pdf](http://stud.epsilon.slu.se/4008/1/aslund_i_120327.pdf)

[http://vro.depi.vic.gov.au/dpi/vro/gbbreg.nsf/pages/soil\\_hydraulic\\_pdf/\\$FILE/TechReportch05.pdf](http://vro.depi.vic.gov.au/dpi/vro/gbbreg.nsf/pages/soil_hydraulic_pdf/$FILE/TechReportch05.pdf)

<http://www.biochar-international.org/node/1029>

<http://www.biochar-international.org/sites/default/files/All-Biochars--Version2--Oct2009.pdf>

<http://www.dpi.nsw.gov.au/agriculture/resources/soils/guides/soilpak/cotton>

<http://www.dpi.nsw.gov.au/agriculture/resources/soils/guides/soilpak/cotton>

<http://www.european-biochar.org/en/sownload>

<http://www.extension.org/sites/default/files/CausesSquareBollSheddingCotton%20CoPnew.pdf>

<http://www.fao.org/docrep/t0321e/t0321e-08.htm>

<http://www.fao.org/wairdocs/tac/x5756e/x5756e0j.htm>

[http://www.geo.tu-freiberg.de/oberseminar/os06\\_07/geissler.pdf](http://www.geo.tu-freiberg.de/oberseminar/os06_07/geissler.pdf)

[http://www.geog.bgu.ac.il/members/tal/pages/journals.files/svoray\\_karnieli.pdf](http://www.geog.bgu.ac.il/members/tal/pages/journals.files/svoray_karnieli.pdf)

[http://www.geo.tu-freiberg.de/oberseminar/os06\\_07/geissler.pdf](http://www.geo.tu-freiberg.de/oberseminar/os06_07/geissler.pdf)

<http://www.iges.or.jp/en/archive/cdm/pdf/regional/20121113/BackgroundPaper>

<http://www.myanmarfswg.org/image/data/pdf/Dry%20Zone%20Action%20Plan%2023%20July%202010.pdf>

[http://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/nrcs142p2\\_051232.pdf](http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051232.pdf)

<http://www.oilseedcrops.org/wp-content/uploads/2013/03/Myanmars-Forestry-Agricultural-and-Marine-Resources.pdf>

<http://www.resjournals.com/ARJ>

<http://www.R-project.org>

<http://www.unccd.int/ActionProgrammes/myanmar-eng2005.pdf>

[https://ew.uni-hohenheim.de/fileadmin/einrichtungen/fsc/FSC\\_Brief\\_No.3.pdf](https://ew.uni-hohenheim.de/fileadmin/einrichtungen/fsc/FSC_Brief_No.3.pdf)

<https://sites.google.com/a/irri.org/oryza2000/calibration-and-validation/experimental-data-collection-and-analysis/standard-procedure-for-determining-yield-components-at-harvest>

[https://unfccc.int/files/ghg\\_data/ghg\\_data\\_unfccc/ghg\\_profiles/application/pdf/mmr\\_ghg\\_profile.pdf](https://unfccc.int/files/ghg_data/ghg_data_unfccc/ghg_profiles/application/pdf/mmr_ghg_profile.pdf)

<https://www.slf.dep.no/no/miljo-og-okologisk/klima.../>

<https://www.slf.dep.no/no/miljo-og-okologisk/klima-og-miljoprogrammet/prosjektstotte/undersider/attachment/16333?ts=133a2700838&download=true>

<https://www.soils.org/publications/soils-glossary#>

[www.echonet.org](http://www.echonet.org)

[www.interscience.wiley.com](http://www.interscience.wiley.com)

[www.uidaho.edu/.../Laboratory%20Analysis%20Procedures/13Cation%20Exchange%20Capacity2.ashx](http://www.uidaho.edu/.../Laboratory%20Analysis%20Procedures/13Cation%20Exchange%20Capacity2.ashx)

[www.uidaho.edu/.../Laboratory%20Analysis%20Procedures/13Cation%20Exchange%20Capacity2.ashx](http://www.uidaho.edu/.../Laboratory%20Analysis%20Procedures/13Cation%20Exchange%20Capacity2.ashx)

[www.wepa-db.net/.../state/myanmar/myanmar.htm](http://www.wepa-db.net/.../state/myanmar/myanmar.htm)

## Appendix

Table 1.1: Evaluation of Humus content in soils (Pedological mapping instructions 1994) (Ad-hoc-Arbeitsgruppe-Boden, 2005)

Humus content %	Designation
<1	Very slightly humid
1-2	Slightly humid
2-4	Somewhat humid
4-8	Strongly humid
8-15	Very strongly humid
15-30	Extremely humid

Table 1.2: DNDC model input data about rice management

Date	Management practices	
18.5.12	Harrowing the filed with moldboard plough, (0.02 m)	
23.5.12	Ploughing with disk, 0.1 m	
24.5.12	Litter burying till	
25.5.12	Ploughing with chisel plough 0.1 m	
26.5.12	Ploughing slightly, 0.05 m	
22.5.12	Flooding the whole filed	
9.6.12	Nursery seeding	
21.6.12	First fertilizer application nursery (10 kg N ha <sup>-1</sup> )	
25.6.12	Second fertilizer application nursery (10 kg N ha <sup>-1</sup> )	
28.6.12	Land levelling, and plotting of experimental plots	
29.6.12	Biochar and fertilizer application into the experimental plots	75 kg N ha <sup>-1</sup> , 20 Mg Rh biochar ha <sup>-1</sup> , 20 Mg Rs biochar ha <sup>-1</sup> , 20 Mg Ps ha <sup>-1</sup> , 10 Mg Rh biochar+FYM mixture ha <sup>-1</sup>
1.7.12	Transplanting rice seedlings from nursery to experimental plots	
19.8.12	Second fertilizer application	25 kg N ha <sup>-1</sup>
9.10.12	Harvesting	Fraction of residues left in fields: 20%, cut fraction: 80%
22.5.12-29.6.12	Continuous flooding (depth 0.05-0.1 m)	
4.7.12 - 18.8.12	Continuous flooding	
21.8.12-27.9.12	Continuous flooding	

Table 1.3: DNDC model input data about chickpea management

Date	Management practices	
18.11.12	Ploughing and sowing	Chickpea was sown without fertilizer or manure input
7.3.13	Harvesting	

Table 1.4: Cotton Management data

Date	Management practices	Remarks
20.3.13	Planting and first irrigation	
14.3.13	Ploughing moldboard, 0.2 m	
15.3.13	Ploughing with chisel, 0.1 m	
28.3.13	Ploughing slightly, 0.05 m	
25.4.13	Ploughing slightly, 0.05 m	
7.5.13	Ploughing with chisel, 0.1 m	
14.5.13	Ploughing with chisel, 0.1 m	
17.3.13	Urea 50 kg N ha <sup>-1</sup>	75 kg N ha <sup>-1</sup> , 20 Mg Rh biochar ha <sup>-1</sup> , 20 Mg Rs biochar ha <sup>-1</sup> , 20 Mg Ps biochar ha <sup>-1</sup> , 10 Mg Rh biochar+FYM mixture ha <sup>-1</sup>
3.5.13	Urea 50 kg N ha <sup>-1</sup>	
20.3.13	30 cm water	
3.4.13	30 cm water	
29.6.13	30 cm water	
22.7.13	Harvesting	
7.8.13	Cut fraction 0.80	

Table 1.5: DNDC model input data about the treatments

Nr.	Treatment	Fertilizer application
1	Rice husk biochar, (20 Mg ha <sup>-1</sup> )	With NPK fertilizer 100:50:50 for rice and 100:30:117 for cotton
2	Rice straw biochar (20 Mg ha <sup>-1</sup> )	With NPK fertilizer 100:50:50 for rice and 100:30:117 for cotton
3	Pigeon pea stem biochar (20 Mg ha <sup>-1</sup> )	With NPK fertilizer 100:50:50 for rice and 100:30:117 for cotton
4	NPK fertilizer	100:50:50 for rice and 100:30:117 for cotton
5	Rice husk biochar+FYM mixture (10 Mg ha <sup>-1</sup> )	With NPK fertilizer 100:50:50 for rice and 100:30:117 for cotton
6	Without biochar	Without fertilizer

Table 1.6: DNDC model input data about the observed and simulated crop yields

Treatments	Rice yield (grain C kg ha <sup>-1</sup> )*		Chickpea (grain C kg ha <sup>-1</sup> )		Cotton (grain C kg ha <sup>-1</sup> )	
	Measured	Simulated	Measured	Simulated	Measured	Simulated
Rh biochar	2717	3016	584	548	242	268
Rs biochar	2330	3016	533	511	268	192
Ps biochar	3110	3305	448	536	234	290
NPK	1964	1867	479	483	196	195
Rh biochar+FYM	2325	2377	436	500	264	198
Control	1322	681	507	486	83	30
PBIAS (%)		-3.59		-2.58		8.86
RMSE(kg ha <sup>-1</sup> )		412.52		48.44		52.84
RRMSE of observed mean		18%		9.7%		24.6%

\*Grain C was calculated by multiplying carbon content of the grain to the crop yield.

Table 1.7: Testing model fitness by quantifying observed values from field experiments and simulated values from DNDC model of soil organic carbon in topsoil 0-0.2 m in biochar applied soils, NPK fertilizer applied soils and control after harvesting rice in 2012 and after harvesting cotton in 2013

Treatments	SOC 0-0.2 m 2012 (Mg ha <sup>-1</sup> )		SOC 0-0.2 m 2013 (Mg ha <sup>-1</sup> )	
	Measured	Simulated	Measured	Simulated
Rh biochar	30.00	26.16	38.16	28.23
Rs biochar	21.36	24.99	27.96	27.68
Ps biochar	22.08	19.27	22.08	22.96
NPK	17.88	14.00	13.92	14.00
Rh biochar+FYM mixture	19.08	19.82	21.48	20.26
Control	19.68	18.18	14.16	18.23
PBIAS (%)		5.89		4.65
RMSE (Mg ha <sup>-1</sup> )		0.99		4.43
RMSE% of observed mean		4.6		19

## Versicherung

Ich versichere, dass ich die eingereichte Dissertation

„Testing the Effects of Biochars on Soil Properties and Crop Yields in a Rice-Based Cropping System of Myanmar: Field Experiment and Modelling“ selbständig und ohne unerlaubte Hilfsmittel verfasst habe.

Anderer als der von mir angegebenen Hilfsmittel und Schriften habe ich mich nicht bedient. Alle wörtlich oder sinngemäß anderen Schriften entnommene Stellen habe ich kenntlich gemacht.

Datum: den 21 April 2015



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