Biochar effects on soil physicochemical properties and on maize yields (Zea mays L.) in tropical soils of Burkina Faso

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VICTOR BURGEON

TRAVAIL DE FIN D'ÉTUDES PRÉSENTÉ EN VUE DE L'OBTENTION DU DIPLÔME DE MASTER BIOINGÉNIEUR EN SCIENCES ET TECHNOLOGIES DE L'ENVIRONNEMENT

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Quand le dernier arbre sera abattu,
la dernière rivière empoisonnée,
le dernier poisson capturé,
alors le visage pâle s'apercevra
que l'argent ne se mange pas…
-SITTING BULL- 1831-1890

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Abbreviations

ANOVA - Analysis of variance

AV1 - Analysis of Variance with one variable

AV2 - Analysis of Variance with two variables

BC - Black Carbon

C_e - Carbon equivalent

CEC - Cation exchange capacity

CH_4 - Methane

CO_2 - Carbon Dioxide

COP 21 - Conference of Parties 21

EBC - European Biochar Certificate

FAO - Food and Agriculture Organization of the UN

GHG - Green House Gases

GxABT-ULg - Gembloux Agro-Bio Tech Université de Liège

IBI - International Biochar Initiative

IPCC - Intergovernmental Panel on Climate Change

LOC - Labile Organic Carbon

LSD - Least Significant Difference

N_2O - Nitrous Oxide

NPK - Nitrogen, Phosphorus and Potassium fertilizer

NW - North West

OC - Organic Carbon

OM - Organic Matter

S&B - Slash and Burn

SOC - Soil Organic Carbon

SW - South West

TLUD - Top lit updraft

UN - United Nations

UPB - Université Polytechnique de Bobo-Dioulasso

WHC - Water Holding Capacity

WHO - World Health Organization of the UN

WRB - World Reference Base

Foreword

This master thesis was partly written in the form of a scientific paper in the goal of being published. Very few works studying biochar effects on soil properties have been published in West Africa and it is hoped this study will.

The structure of this paper is presented in two sections as follows. To start off with, **section one** is written as a scientific paper. In the **second section** an in-depth state of the art is presented as well as additional information describing the scientific procedure needed to establish the paper.

THE ARTICLE

SECTION ONE

Abstract

Biochar is a recalcitrant carbon rich product obtained through the pyrolysis of biomass and used in soils as an amendment. It is commonly known that tropical soils are highly weathered soils and thus where biochar influence on the fertility of agricultural systems can be the most substantial. Herein we aim at filling the missing data for the application of biochar in *in situ* experiments. To do so we study the effects of biochar, produced from cotton branch residues, on maize biomass production (*Zea mays* L.) in a field trial in Koumbia, province of Tuy, Burkina Faso. The effect of biochar application rate (0 $t.ha^{-1}$, 10 $t.ha^{-1}$, 30 $t.ha^{-1}$) and its combination with conventional fertilizer quantities (0 $kg.ha^{-1}$, 100 $kg.ha^{-1}$, 150 $kg.ha^{-1}$) have been investigated. Soil physico-chemical characteristics and plant tissue nutrient concentrations were analyzed. The content of bioavailable phosphorus (P) and potassium (K), pH values and organic carbon concentration increased with biochar application in soil. In parallel, we observed a significant growth of P content in plant tissue. Our results show an increase in total aboveground biomass but no significant variation of yield in response to biochar. We conclude that higher concentrations of bioavailable nutrients could lead to a reduced fertilizer use and reduced production costs for farmers.

Keywords:

Biochar, Tropical soils, Plant nutrient uptake, *Zea mays L.*, *in situ* field experiment, Burkina Faso

Résumé

Le biochar est un produit riche en carbone obtenu lors de la pyrolyse de biomasse végétale et utilisé dans les sols comme amendement. Les sols tropicaux étant connus pour être hautement altérés, l'utilisation de biochar y a le plus haut potentiel d'amélioration de leur fertilité. Dans cette étude nous visons à combler le manque de données sur l'application du biochar *in situ.* Pour ce faire, nous mettons en œuvre des essais sur un champ de maïs (*Zea mays* L.) à Koumbia dans la province de Tuy, Burkina Faso et étudions les effets du biochar fait à partir de résidus de coton. La quantité de biochar appliquée (0 $t.ha^{-1}$, 10 $t.ha^{-1}$, 30 $t.ha^{-1}$) et sa combinaison avec différentes quantités conventionnelles de fertilisants (0 $kg.ha^{-1}$, 100 $kg.ha^{-1}$, 150 $kg.ha^{-1}$) ont été étudiées. On observe que, suite à l'application de biochar, la quantité de phosphore (P) et de potassium (K) biodisponibles, les valeurs de pH et la concentration en carbone organique du sol augmentent. En parallèle, on remarque un accroissement significatif de la concentration en P dans les tissus végétaux. Les résultats montrent également une augmentation en biomasse aérienne, mais aucune variation significative en termes de rendement en grains. On peut donc en conclure que le biochar pourrait permettre une diminution des besoins en fertilisants ce qui impliquerait alors des moindres coûts pour l'agriculteur.

Mots clefs:

Biochar, Sols tropicaux, absorption de nutriments par la plante, Zea mays L., expérimentation in situ, Burkina Faso

I. Introduction

In the light of a global change in climate, the scientific community is searching for solutions to mitigate the human impact. A reduction of greenhouse gas emissions is essential to avoid the maximum upper boundary of a 2 °C increase agreed upon at the 21st Conference of Parties (COP-21). However, global warming scenarios presented by the United Nations (UN) group of experts (IPCC, 2014) do not all agree this target value is reachable. As a result, other ways of reducing global change must therefore be found. The scientific community is focusing on ways towards climate change mitigation and in particular through the sequestration of greenhouse gases (GHG), notably carbon dioxide (CO_2) from the atmosphere.

Soils play an essential role in the carbon cycle and account for more than two-thirds of the carbon stocks on terrestrial ecosystems (Lal, 2004). However, Soil Organic Carbon (SOC) stocks are fast depleting and the fertility of their systems along with it. This is particularly true for wet tropical soils (Ogle et al., 2005). Bationo et al. (2007) estimated that fertility issues alone could represent the biggest threat to the state of food security in West Africa. Furthermore, organic carbon is responsible for soil quality and the formation of aggregates in soils (An et al., 2010). When these are absent the soil clogs up and loses its structure leading to increased erosion and worsening fertility issues. Erosion has been held responsible for the loss of between 65 $kg.ha^{-1}$ and 1801 $kg.ha^{-1}$ of carbon stocks (Bationo et al., 2007) per year in these tropical soils.

As a solution to both the catastrophic state of carbon contents in soils and as a climate mitigator, the scientific community holds good hopes in biochar (Lehmann, 2007). Biochar is defined as a carbon-rich product issued from the pyrolysis of biomass. Because of its high carbon content and a recalcitrant chemical composition (Cheng et al., 2008) biochar holds a great potential as a climate change mitigation tool (Woolf and Lehmann, 2012). This material is often referred to as a win-win-win scenario in which energy is produced from a renewable matter, carbon is sequestered on a long-term basis whilst improving soil fertility parameters (Laird, 2008). An analysis by Woolf et al. (2010) estimates that overall, biochar has a potential to sequester 12% of human CO_2-C_e emissions.

As biochar production processes are relatively simple and cheap their use can be popularized to local communities. Furthermore, biochar ovens can be fitted for household purposes. By using a combination of waste biomass as biochar feedstock and pyrolysis ovens for household purposes, mitigation potential is enhanced by a decreased deforestation for firewood. Similarly, more efficient stoves also further enhance this mitigation potential by reducing fuel consumption. Crop residues if unused are generally burnt by the farmers on the fields. It was estimated that burning these residues results in a 21% decrease of organic carbon (OC) additions to soil (Parker et al., 2010, cited in Mekuria and Noble, 2013, p.2).

Interests in biochar amendments are partly related to its high agricultural potential (Glaser et al., 2002). It has been shown that biochar substantially improves soil properties and crop yields for acidic and sandy soils (Jeffery et al., 2011; Biederman et Harpole, 2013). Its retention potential also allows for a decrease in fertilizer use (Laird et al., 2010). However this biochar potential varies greatly depending on soil texture (Jeffery et al., 2011), feedstock type, production temperatures (Novak et al., 2009) and general environment to such an extent that findings are often site-specific.

Hereby we address this need for site specific information in order to tackle the call for *in situ* experiments in West Africa. To our knowledge no literature exists on the application of biochar on maize crops in Burkina-Faso. In the present paper, we first study the impact of biochar and fertilizer application rate on soil physico-chemical properties. Secondly, we correlate these findings to understand the effect of biochar on the maize crop itself and on its yield.

II. Material & Methods

1. Experimental site

The trials were set up as a field experiment in Koumbia, province of Tuy, Burkina-Faso (11°14'27.4"N 3°42'28.2"W; 290 m alt.) in June 2016 on Maize (*Zea mays* L. - variety SR21). Burkina Faso has a tropical climate but the annual rainfall varies strongly throughout the country. In Bobo-Dioulasso, 67 km from the study site, the climate is defined as a Sudano-Sahelian and as an *Aw* (Tropical Savannah) in the Köppen-Geiger classification system (Peel et al., 2006). The mean annual precipitation ranges between 800 mm and 1100 mm (Vall et al., 2006). The rainy season starts in May/June and ends in September. The mean annual temperature is 27 °C. The sandy loam in place is relatively thin and shows a lateritic endurement at a 20 cm depth or above. This soil is categorised as a ferric plinthosol as defined by the World Reference Base (WRB, IUSS 2014) and developed on a granitic/granodioritic parent material (Annex 2; Annex 3) (Hottin and Ouedraogo, 1976; Schlutter, 2014). The field has been used since 1985 for maize crops with only a few growing seasons dedicated to cotton.

2. Biochar production

Two types of ovens were used for the production of the biochar from dried up cotton branches crop residues. The first was a conventional Top-Lit UpDraft (TLUD - Figure 10) oven (Roth, 2014) and the second a Kon-Tiki (Figure 17) flame curtain pyrolyser (Schmidt and Taylor, 2014). The TLUD oven allowed for input loads ranging between 14 kg and 19 kg maximum. Its yield is approximately 30% dry weight and the pyrolysis time per batch lasts approximately 20 minutes. The final goal was to produce 450 kg of biochar in one week. Considering the drying time per batch of approximately two days in the sun, the Kon-tiki flame curtain pyrolyser was built to upscale the production (Schmidt and Taylor, 2014). Oven temperatures were recorded using a pyrometer. Although the Kon-tiki oven working temperature (650-700 °C) is higher (Schmidt and Taylor, 2014) than the TLUD (500-600 °C) oven (Roth, 2014), it allowed a greater yield per batch and the targeted production was met quite easily. Out of the 450 kg of biochar produced, 150 kg came from the Kon-tiki oven. To counter the effect of different pyrolysis temperatures the two biochar types were mixed up before being amended.

3. Experiment set up and measurements

The aim of this trial was to study the effect of two main variables: biochar concentration (0 $t.ha^{-1}$, 10 $t.ha^{-1}$ and 30 $t.ha^{-1}$) combined with two traditional fertilizer NPK (15-15-15) doses (0 $kg.ha^{-1}$, 100 $kg.ha^{-1}$ and 150 $kg.ha^{-1}$ (Table 1). Urea (46% N) was applied all over the field as well as sheep dung as is conventionally done in Koumbia. Seven treatments with five replicates each were set up (Table 1). Treatment G, the unamended control treatment, received no biochar nor NPK amendment as input. In total 35 plots of 8 m² (4 m*2 m) were allocated randomly across the study area. Around each plot a buffer zone of 1 m was left untouched to limit interactions between plots (Annex 7). Because the trial site was surrounded by a maize field, treated with conventional phytosanitary practices, 2 m wide buffer zone was set out on the outer limit of the trial site.

To begin with, the experimental site was ploughed with a single sided ploughshare by animal traction. The limits of each plot were then drawn out and assigned a tag for recognition. The biochar was then incorporated manually with a *daba* (hand plough). The sheep dung was then added before planting three seeds per seed hole. The fertilizer was applied all at once on the same day. The urea, on the other hand, was applied 30 days after planting.

From June to October, the experimental site was managed by our local partners from the Polytechnic University of Bobo-Dioulasso (UPB). During this time the germination rate, plant height and weed coverage were monitored. After 10 growing days, the germination rate was determined (number of seedlings/number of seeds planted) and had an average value of 96%. Two weeks after germination only one seedling was selected per seed hole. Soil humidity, weed coverage and plant height were all three measured 15, 30 and 60 days after seeding. Soil humidity was measured by weight difference between the fresh sample and that of the dried sample at 105 °C for 24 h. The average plant height was measured with decameter. Lastly weed coverage was estimated using Marnottes' (1984) notation and quantified through the use of a metre squared quadrant.

Table 1 - Treatment characteristics. The reference name addresses the "treatment-biochar quantity- fertilizer (NPK) quantity". e.g: A-10-150 refers to treatment A, 10 $t.ha^{-1}$ of biochar and 150 $kg.ha^{-1}$ of fertilizer

Treatment	Biochar ($t.ha^{-1}$)	NPK ($kg.ha^{-1}$)	Urea ($kg.ha^{-1}$)	Reference name
A	10	150	50	A- 10-150
B	10	100	50	B- 10-100
C	30	150	50	C- 30-150
D	30	100	50	D-30-100
E	0	150	50	E - 0 -150
F	0	100	50	F - 0 -100
G	0	0	0	G - 0 - 0

4. Harvest and Sampling

For baseline information about the soil, thirteen soil samples were collected using a manual auger prior to the implementation of the trials at a depth range between 0-20 cm. Below this depth drilling was complicated due to the laterite endurement.

At the end of the rainy season and after 130 days the trial site was harvested. All the buffer zones were cut-down first in order to highlight the limits of each plot. For each plot the cobs were then harvested counted and weighed. The plants were then ripped out with their roots system and the total biomass per plot was weighed. Using a corn-sheller the kernel was then separated from the cob and both were weighed. For each plot, plants and kernel subsamples (300 g) were kept for analysis. The plants subsamples were obtained by crushing two plants selected at random in the center of the plot where the effect of the treatments are supposedly the greatest. The organic subsamples were then dried in ovens at 40 °C before being crushed with a hammer mill to a fraction inferior to 2 mm. Subsequently, soil samples were collected between 0-20 cm. For each plot five drills were gathered and homogenised in a basket to assure the representativeness of our samples. Subsamples were then collected from the baskets for laboratory analysis.

5. Laboratory analysis

A 2 g sample of each, plant and kernel subsamples, were digested in a 50/50 mix of nitric (HNO_3-60%) and perchloric ($HCLO_4$-70%) acid for 16 hours. The extract was then heated till complete evaporation. The residue was recovered in chloridric acid (HCl-10%). Lastly after being dissolved in distilled water the sample was filtered and ready for element quantification. A total of 70 samples (35 plant & 35 for the kernel samples) were analyzed by atomic absorption spectrometry for calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), manganese (Mn), copper (Cu), iron (Fe) and zinc (Zn) concentrations. Phosphorus (P) was determined by spectrophotometry. For nitrogen (N), samples were first mineralised in sulfuric acid (95%). After cooling, distilled water was added before the quantification by titration with chloridric acid (HCl - 0.01 N) according to the Kjeldahl method (1883).

For the baseline soil samples only, soil texture was determined using the "Robinson's pipette" method based on gravimetric sedimentation speed in liquids (norm: NF-X-31-107) and after removal of carbonates in dry soil samples. Soil pH values were analysed in a 1/5, volume to volume ratio either in distilled water (pH-H_2O) or in potassium chloride (KCl - 1 N) (pH-KCl) using a pH-meter.

The following analysis were undertaken for the thirteen baseline samples and the thirty-five samples (one per plot). Organic carbon contents were determined through dry combustion after removal of carbonates with HCl. Using an atomic absorption spectrometer, after extraction in ammonium acetate (0.5 N) and EDTA (0.02 M - pH=4.65), we determined the same bioavailable elements (K, Mg, Ca, Na, Cu, Zn, Al, Mn, Fe) as we studied for kernel and plant tissue concentration. P was analysed using a spectrophotometer and total N according to the Kjeldahl method (1883). Soil exchangeable bases (Mg, K, Na, Ca) were extracted from soils with ammonium acetate and analyzed using the atomic absorption spectrometer. After extraction of bases the samples were first rinsed thrice with ethanol (Technisolv 96%), then mixed with 50 ml sodium hydroxide (NaOH - 50%) and diluted in distilled water. The following day, samples from this mix were distilled and titrated with HCl (0.1N) to determine the cation exchange capacity (CEC) of soils (Metson 1956). Soil pH corresponding to plot samples were determined only in potassium chloride for pH-KCl (1 N, 1/5 volume/volume ratio).

Biochar characteristics have been determined according to the European Biochar Certificate (EBC)

6. Data analysis

All the data was statistically analyzed for mean difference by an analysis of variance. The interaction between the two factors, biochar application rate and fertilizer application rate, were analysed through ANOVAs with two factors (AV2). When no interaction was found ANOVAs with one factor (AV1) were used to study factors independently. AV2 were performed using the program minitab® 17 statistical software and AV1s with R-studio. The means were determined and used for comparison between the treatments and a p-value<0.05 was the threshold for considering significant differences between means. Fishers least-significant difference (LSD) test was used to determine groups of equal mean. Before undertaking the ANOVAs, the "Shapiro-Wilk normality test" and the "Fligner-Killeen Test of Homogeneity of Variances", allowed us to ensure a normal distribution and equality of variances between plots within a treatment. Correlation tests were led by Pearson comparison with the threshold value set a p-value<0.05. The following R packages were used; "agricolae" (De Mendiburu, 2009), "car" (Fox and Weisberg, 2011),"ggplot2" (Wickham, 2009), "plyr" (Wickham, 2011), "gridExtra" (Murrell, 2005).

III. Results

1. Baseline plot data

Results for soil samples collected before starting the experiment are shown in Table 2. They show a typical tropical soil with a dominant sandy texture and poor in nutrient contents.

Table 2 - Baseline for soil physico-chemical properties

Parameter	Unit	mean 0-20 cm	STD
clay	[%]	5,48	1,31
silt	[%]	24,22	5,72
sand	[%]	70,30	6,68
pH (H2O)	[Units]	6,30	0,36
pH (KCl)	[Units]	5,59	0,36
organic carbon	[g/kg]	5,29	1,21
bioavailable P	[mg/100g]	0,53	0,26
bioavailable K	[mg/100g]	3,45	1,27
bioavailable Mg	[mg/100g]	4,07	1,03
bioavailable Ca	[mg/100g]	43,05	12,93
bioavailable Na	[mg/100g]	2,29	0,39
bioavailable Cu	[ppm]	0,45	0,10
bioavailable Zn	[ppm]	0,45	0,27
bioavailable Al	[ppm]	5,04	1,23
bioavailable Mn	[ppm]	31,73	6,29
bioavailable Fe	[ppm]	35,02	7,05
total N	[%]	0,04	0,01
C/N	[-]	11,81	1,58
C.E.C	[meq/100g]	3,31	0,96
exch.bases Ca	[meq/100g]	1,94	0,66
exch.bases K	[meq/100g]	0,14	0,05
exch.bases Mg	[meq/100g]	0,45	0,09
exch.bases Na	[meq/100g]	0,01	0,04
Base saturation	[%]	79,32	20,86

2. Soil physico-chemical properties

The bioavailability of potassium (K) and phosphorus (P) showed a very significant increase in concentration in response to the biochar input ($p<0.001$) (Table 3).

There was a significant increase in bioavailable P for all treatments with biochar with respect to treatments without. Firstly treatments A-10-150 and B-10-100 increased by 99% and 39% with respect to treatments E-0-150 and F-0-100. For treatments C-30-150 and D-30-100 the increase in P bioavailability was of 215% and 205% with respect to E-0-150 and F-0-100.

The K bioavailability also significantly increased ($p<0.001$) in plot with biochar. Treatments A-10-150 and B-10-100 showed 82% and 52% increases with respect to treatments E-0-150 and F-0-100 respectively. The increase for plots C-30-150 and D-30-100 was of 345% and by 155% with respects to E-0-150 and F-0-100.

Table 3 - Bioavailablity of nutrients in the soil. Letters refer to treatments with statistically ($p<0.05$) equal means according to Fisher's LSD test. Only total nitrogen was determined for N.

		A-10-150	B-10-100	C-30-150	D-30-100	E-0-150	F-0-100	G-0-0
P [mg/100g]	mean	1,28	0,91	2,02	2,00	0,64	0,66	0,69
	std	0,22	0,08	0,40	0,24	0,27	0,28	0,39
	group	b	bc	a	a	c	c	c
K [mg/100g]	mean	11,86	10,11	23,52	18,48	5,28	7,24	7,00
	std	2,08	1,74	7,63	4,90	1,52	1,52	2,09
	group	c	cd	a	b	d	cd	cd
Mg [mg/100g]	mean	5,86	4,11	5,91	5,71	4,76	5,31	6,79
	std	0,70	0,66	1,28	0,46	1,01	1,06	3,04
	group	ab	b	ab	ab	b	ab	a
Ca [mg/100g]	mean	67,55	43,67	67,41	59,12	47,66	57,72	73,13
	std	12,09	12,47	11,55	7,30	14,84	14,86	31,72
	group	ab	c	ab	abc	bc	abc	a
Cu [mg/100g]	mean	0,05	0,04	0,05	0,05	0,05	0,05	0,06
	std	0,01	0,01	0,01	0,01	0,01	0,01	0,02
	group	ab	b	a	ab	ab	ab	a
Na [mg/100g]	mean	2,04	1,92	2,04	2,37	2,04	1,88	2,16
	std	0,32	0,36	0,28	0,91	0,30	0,13	0,22
	group	a	a	a	a	a	a	a
Zn [mg/100g]	mean	0,08	0,05	0,09	0,10	0,07	0,08	0,09
	std	0,02	0,01	0,06	0,05	0,03	0,03	0,07
	group	a	a	a	a	a	a	a
Al [mg/100g]	mean	0,47	0,41	0,44	0,44	0,52	0,43	0,53
	std	0,07	0,05	0,12	0,11	0,21	0,14	0,08
	group	a	a	a	a	a	a	a
Mn [mg/100g]	mean	3,23	2,82	3,29	3,03	3,78	3,60	3,96
	Std	0,55	0,64	0,51	0,29	1,30	0,88	0,94
	group	a	a	a	a	a	a	a
Fe [mg/100g]	mean	3,39	2,99	3,63	3,30	4,19	4,12	4,58
	std	0,53	0,50	0,75	0,50	1,27	0,90	1,03
	group	bc	c	abc	bc	ab	abc	a
N total [mg/100g]	mean	62,40	41,75	56,00	49,80	51,80	50,20	52,50
	std	6,58	7,80	11,70	9,58	12,87	9,20	13,58
	group	a	b	ab	ab	ab	ab	ab

For the rest of the major elements (Ca and Mg) quantified, as well as the minor elements (Cu, Na, Zn, Al, Mn, Fe), no significant difference has been observed from the ANOVAs analysis. Particular attention must nevertheless be paid to Fe and Mn which seem to be more available on plots with no biochar than the contrary, this difference remains nevertheless non-significant.

The initial soil pH (KCl) of the plot had an average value of 5.59 units (Table 4). Baseline measures on the trial site showed important heterogeneity as measures oscillated by more or less half a unit around the mean. pH (KCl) values were very strongly correlated (Pearson R=0.807) to the input of biochar. Treatments with 30 $t.ha^{-1}$ of biochar increased the soil pH by 1.52 units and 1.49 for D-30-100 and C-30-150 respectively whereas they increased by 0.89 units and 0.48 units of pH for A-10-150 and B-10-100 all with respect to the initial conditions of the trial site. Soil pH values in plots with no biochar are not significantly different to the initial conditions on the trial site.

The OC content (Table 4) also increases very significantly ($p<0.0001$). Starting from an average of 0.5% the carbon content at the end of the trials increased for all treatments. The OC content increases by 61%, 23%, 113% and 110% for treatments A-10-150, B-10-100,C-30-150 and D-30-100 respectively with respect to initial conditions. OC contents also increased by 18%, 28% and 57% for treatments E-0-150, F-0-100 and G-0-0 with respect to baseline OC contents. Groups according to Fisher's LSD test are shown in Table 4. Total N contents did not vary significantly with treatments ($p >0.05$). As a result C/N ratio increased very significantly ($p<0.001$) with the quantity of biochar applied (Pearson R=0.789). Treatments C-30-150 and D-30-100 show similar increases in C/N ratio of 66% and 69% with respect to E-0-150 and F-0-100. C/N values for treatments with 10 $t.ha^{-1}$ of biochar input did not significantly differ from treatments with no biochar.

Table 4 - Soil physico-chemical parameters under different treatments, letters show groups of equal means according to Fisher's LSD test ($p<0.05$)

		A-10-150	B-10-100	C-30-150	D-30-100	E-0-150	F-0-100	G-0-0
pH (KCl)	mean	6,39	5,99	6,99	7,02	5,56	5,90	6,20
	std	0,28	0,24	0,17	0,33	0,36	0,15	0,69
	group	b	bcd	a	a	d	cd	bc
C org [g/kg]	mean	8,52	6,50	11,28	11,09	6,25	6,77	8,31
	std	1,20	1,47	2,86	1,13	1,78	1,65	3,25
	group	bc	c	a	ab	c	c	c
C/N	mean	13,6	15,5	20,0	22,7	12,0	13,4	16,0
	std	0,7	0,8	1,2	3,3	0,5	1,5	5,2
	group	bc	b	a	a	c	bc	b
Base saturation [%]	mean	101,9	63,7	90,5	92,5	48,0	72,2	98,8
	std	27,6	7,5	17,4	31,1	8,7	7,9	19,8
	group	a	cd	abc	ab	d	bcd	ab
CEC [meq/100g]	mean	4,3	4,7	4,8	4,1	4,9	4,3	4,8
	std	0,8	0,4	1,0	0,5	1,2	0,9	1,5
	group	a	a	a	a	a	a	a

There was no significant difference in CEC between the treatments. The exchange capacity was however significantly greater than the CEC of the baseline situation (Table 4). Addition of biochar seemed to have no effect on the CEC (Pearson R= -0.071) . Nevertheless the treatments led to significant differences in terms of base saturation particularly for calcium and potassium. The highest concentrations of calcium were found in treatments G-0-0, A-10-150, C-30-150 and D-30-100 with no apparent relation to biochar (Table 5). On the contrary for magnesium the concentration was much related to the treatments (Table 5) (Pearson R= 0.719). As a result base saturation on the trial site does vary significantly (p-value<0.01) with treatment types (Table 4).

Table 5 - Base concentration under different treatments, letters show treatments of equal means according to Fisher's LSD (p<0.05)

base		**A-10-150**	**B-10-100**	**C-30-150**	**D-30-100**	**E-0-150**	**F-0-100**	**G-0-0**
Ca [meq/100g]	**mean**	3,251	2,219	3,288	2,726	1,602	2,293	3,901
	std	0,660	0,600	1,070	1,337	0,611	0,682	1,155
	group	ab	bc	ab	abc	c	bc	a
K [meq/100g]	**mean**	0,356	0,312	0,550	0,559	0,163	0,214	0,181
	std	0,054	0,060	0,373	0,173	0,041	0,036	0,051
	group	ab	b	a	a	b	b	b
Mg [meq/100g]	**mean**	0,562	0,439	0,546	0,529	0,498	0,567	0,583
	std	0,093	0,055	0,128	0,048	0,068	0,116	0,150
	group	a	a	a	a	a	a	a
Na [meq/100g]	**mean**	0,068	0,060	0,037	0,048	0,042	0,047	0,022
	std	0,045	0,024	0,012	0,027	0,036	0,025	0,031
	group	a	a	a	a	a	a	a
Sum of bases [meq/100g]	**mean**	4,237	3,030	4,421	3,862	2,305	3,120	4,687
	std	0,800	0,607	1,493	1,502	0,626	0,748	1,322
	group	ab	bc	ab	ab	c	bc	a

3. Elemental concentration in maize

The concentration of Ca, K, Mg, Mn, P, Na, Cu, Fe, Zn and N were measured in kernel tissue (Table 6) and plant tissue (Table 7) from the composite samples taken from each plot. For both types of samples very little to no effect of the treatments were noticed. Significant differences in grain tissues between treatments (Table 6) were observed only for K for which concentrations for treatment A-10-100 are significantly lower than for other treatments (p-value<0.01).

Table 6 - Nutrient concentration in **grain**. Parameters with letters show statistically different treatments. Letters show treatments of equal means according to Fisher's LSD (p<0.05)

	grain	A-10-150	B-10-100	C-30-150	D-30-100	E-0-150	F-0-100	G-0-0
Ca [mg/100g]	**means**	0	1,63	1,27	1,25	6,44	4,17	1,93
	std	2,49	1,84	4,23	3,64	5,17	0,88	3,68
	group	c	abc	abc	bc	a	ab	abc
K [mg/100g]	**means**	263,90	319,99	306,92	318,51	331,00	306,73	331,84
	std	20,02	25,55	11,40	20,12	29,88	10,62	18,02
	group	b	a	a	a	a	a	a
Mg [mg/100g]	**means**	85,87	89,65	92,12	92,69	93,85	94,42	96,68
	std	9,22	7,42	10,43	18,11	3,51	6,57	13,08
	group	a	a	a	a	a	a	a
P [mg/100g]	**means**	252,23	257,70	243,81	258,94	292,69	248,60	265,30
	std	29,57	7,18	12,51	11,33	18,40	44,08	8,20
	group	b	b	b	b	a	ab	b
Mn [mg/100g]	**means**	0,04	0,04	0,04	0,04	0,05	0,03	0,04
	std	0,01	0,00	0,00	0,00	0,01	0,01	0,01
	group	ab	ab	bc	ab	a	c	ab
Cu [mg/100g]	**means**	0,16	0,16	0,35	0,18	0,26	0,16	0,24
	std	0,03	0,02	0,18	0,02	0,20	0,05	0,11
	group	b	b	b	b	b	b	a
Fe [mg/100g]	**means**	0,16	0,16	0,35	0,18	0,26	0,16	0,24
	std	0,03	0,02	0,18	0,02	0,20	0,05	0,11
	group	b	b	a	b	ab	b	ab
Zn [mg/100g]	**means**	0,55	0,28	0,35	0,26	0,16	0,21	0,24
	std	0,43	0,08	0,09	0,08	0,04	0,02	0,07
	group	a	b	ab	b	b	b	b
N [mg/100g]	**means**	1338,34	1347,12	1272,53	1236,35	1356,27	1373,04	1447,79
	std	49,57	74,21	98,53	38,32	131,38	122,01	86,18
	group	abc	abc	bc	c	abc	ab	a

For plant tissue (Table 7), phosphorus varied very significantly between treatments (ANOVA p-value < 0.05) and was strongly correlated to the bioavailability of phosphorus in the soil (Pearson R=0.573 and p-value< 0.01).

Table 7 - Nutrient concentration in **plant** tissue. Letters show treatments of equal means according to Fisher's LSD (p<0.05)

	plant	**A-10-150**	**B-10-100**	**C-30-150**	**D-30-100**	**E-0-150**	**F-0-100**	**G-0-0**
Ca [mg/100g]	**means**	145,36	135,07	210,21	133,67	178,34	192,68	176,20
	std	32,90	20,48	61,12	46,50	26,50	65,71	77,86
	group	ab	ab	a	b	ab	ab	ab
K [mg/100g]	**means**	1546,65	1377,49	1433,93	1549,54	1350,31	1344,13	1703,37
	std	175,47	143,47	334,95	251,19	266,14	592,55	382,98
	group	a	a	a	a	a	a	a
Mg [mg/100g]	**means**	138,51	109,42	148,43	126,97	142,04	182,46	138,18
	std	7,82	10,84	43,39	23,10	10,02	68,41	36,46
	group	ab	b	ab	b	ab	a	ab
Na [mg/100g]	**means**	1,54	1,72	2,68	2,10	1,66	0,04	2,64
	std	0,57	0,33	0,48	1,59	0,77	1,69	1,63
	group	ab	a	a	a	ab	b	c
P [mg/100g]	**means**	123,38	81,33	96,03	166,08	66,86	60,18	123,30
	std	63,25	39,36	32,96	39,17	24,21	22,67	54,52
	group	ab	bc	bc	a	bc	c	abc
Mn [mg/100g]	**means**	0,33	0,34	0,28	0,24	0,42	0,37	0,35
	std	0,12	0,05	0,12	0,05	0,13	0,12	0,28
	group	a	a	a	a	a	a	a
Cu [mg/100g]	**means**	0,02	0,03	0,02	0,02	0,03	0,03	0,02
	std	0,00	0,01	0,00	0,00	0,01	0,01	0,01
	group	a	a	a	a	a	a	a
Fe [mg/100g]	**means**	17,32	13,68	10,72	13,87	8,95	5,90	14,19
	std	20,85	18,91	11,39	7,67	9,13	5,00	14,94
	group	a	a	a	a	a	a	a
Zn [mg/100g]	**means**	0,49	0,17	0,24	0,29	0,12	0,25	0,35
	std	0,30	0,04	0,08	0,13	0,04	0,20	0,32
	group	a	b	ab	ab	b	ab	ab
N [mg/100g]	**means**	473,71	360,93	407,25	471,83	450,09	462,34	442,66
	std	89,34	42,51	52,10	139,72	68,05	103,53	36,75
	group	a	a	a	a	a	a	a

4. Maize biomass production

The treatments applied led to a significant increase in the total aboveground biomass (Figure 1) produced per plot (p<0.05). Treatments with 30 $t.ha^{-1}$ of biochar (C-30-150 and D-30-100) on average showed a higher total biomass than treatments with 10 $t.ha^{-1}$ of biochar (A-10-150 and B-10-100) which in turn produced more than treatments with no biochar. These yields were increased by 43%, 53%, 39% and 25% (C-30-150, D-30-100, A-10-150, B-10-100) in comparison to the corresponding treatments in terms of fertilizer added but without biochar (E-0-150 and F-0-100). Although the total biomass increased there was no significant difference in grain yield (p>0.05).

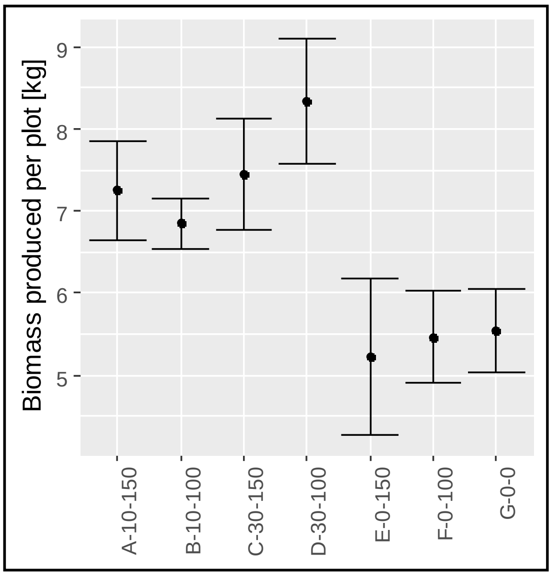

Figure 1 -Total aboveground production of biomass per plot with respect to treatment type and standard errors**.**

Table 8 - Yield characteristics with respect to treatments. Letters show treatments of equal means according to Fisher's LSD (p<0.05)

Measure per plot		**A-10-150**	**B-10-100**	**C-30-150**	**D-30-100**	**E-0-150**	**F-0-100**	**G-0-0**
	mean	56	57	58	58	37	48	52
plant [unit]	**std**	7,50	3,30	4,98	7,89	19,25	14,78	10,58
	group	a	a	a	a	b	ab	ab
	mean	48	49	47	50	33	39	41
cob [unit]	**std**	6,50	8,85	4,15	4,82	12,05	11,90	2,45
	group	ab	ab	ab	a	c	bc	abc
	mean	7,25	6,85	7,45	8,33	5,22	5,46	5,55
yield [kg]	**std**	1,34	0,61	1,50	1,71	2,13	1,25	1,02
	group	abc	abcd	ab	a	d	cd	bcd
	mean	4,12	3,18	3,47	3,21	3,36	3,89	3,25
grain weight [kg]	**std**	0,35	0,52	0,68	0,94	0,96	0,55	0,87
	group	a	a	a	a	a	a	a

5. Element uptake by maize

The addition of biochar to the soil increased the total aboveground mineral uptake per plot. This increase is statistically significant for K ($p<0.05$) and P ($p<0.01$) uptakes (Figure 2). For potassium, treatments with 10 $t.ha^{-1}$ of biochar increased the uptake by 55% and 37% (A-10-150 and B-10-100) both with respect to E-0-150 and F-0-100.Treatments C-30-150 and D-30-100 increased total uptake by 61% and 83% with respect to E-0-150 and F-0-100. For phosphorus, treatments A-10-150 and C-30-150 increased total uptakes by 56% and 32% with respect to G-0-150. Similarly B-10-100 and D-30-100 increased uptakes by 9% and 74% with respect to F-0-100. Sodium concentrations were however small and although an increase is noticeable on the graph, values are very close to the sensitivity limit of the spectrometer.

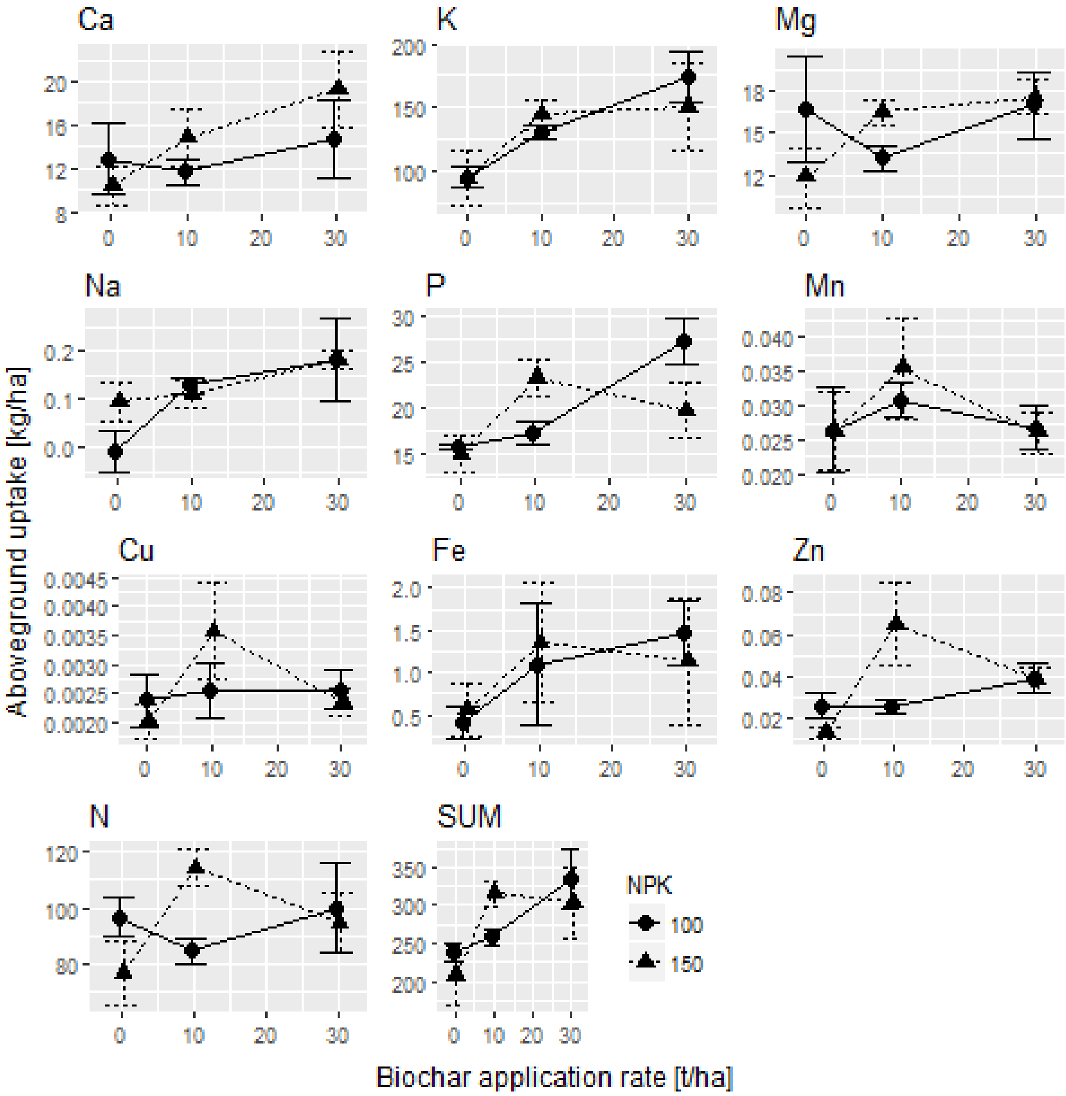

Figure 2 - Above ground uptake of nutrients per plot with respect to biochar application rates. Different lines and shape style differentiate the two fertilizer concentrations used in $kg.ha^{-1}$. Error bars correspond to the standard error on recordings.

6. Biochar characteristics

Biochar characteristics have been determined according to the EBC and indicate a premium quality char in terms of recalcitrance and according to EBC standards. Hereby we present results needed in the discussion. Complete information is available in additional information of this document.

Table 9 - Biochar characteristics. "A*s received*" refers to the fresh matter, "*Dry basis*" refers to dry matter

	Units	As received	Dry basis
Water holding capacity (WHC)	% w/w	-	363.0
Ash content 550°C	%w/w	17.1	18.1
Total C	%w/w	71.8	75.8
Total N	%w/w	0.87	0.92
Ratio H/C (molar)	-	0.18	0.18
Ratio O/C	-	0.07	0.068
pH ($CaCl_2$)	-	9.2	-
Iron calculated as Fe2O3	%w/w	-	2.0
Postassium calculated as K2O	%w/w	-	27.6
Phosphorus calculated as P2O5	%w/w	-	4.1

IV. Discussion:

1. Effect of biochar amendment on soil physico-chemical properties

1.1. Baseline plot state

Baseline soil samples were analysed to understand and characterise the variability of our results. The inconsistency in nutrient contents and pH values were mainly noted for samples Z2, Z5, Z10, Z11, Z12 and Z13 (Figure 3).This variability may be explained by the effect of slash and burn (S&B) practices on one part and by variability in soil texture on another.

Residues of S&B practices were found mainly in two areas. The first area corresponded to a plot under treatment G-0-0 South-West (SW) of the trial site, and the second area was located between plots under treatments G-0-0 and F-0-100 North-West (NW) of the trial area. GPS coordinates of the sample points allowed matching S&B affected areas to baseline samples Z1 and Z2 SW of the site and sample Z10 NW. The S&B effects were mainly visible for sampling sites Z2 and Z10, where the overall nutrient content was significantly higher from the rest (Figure 3).

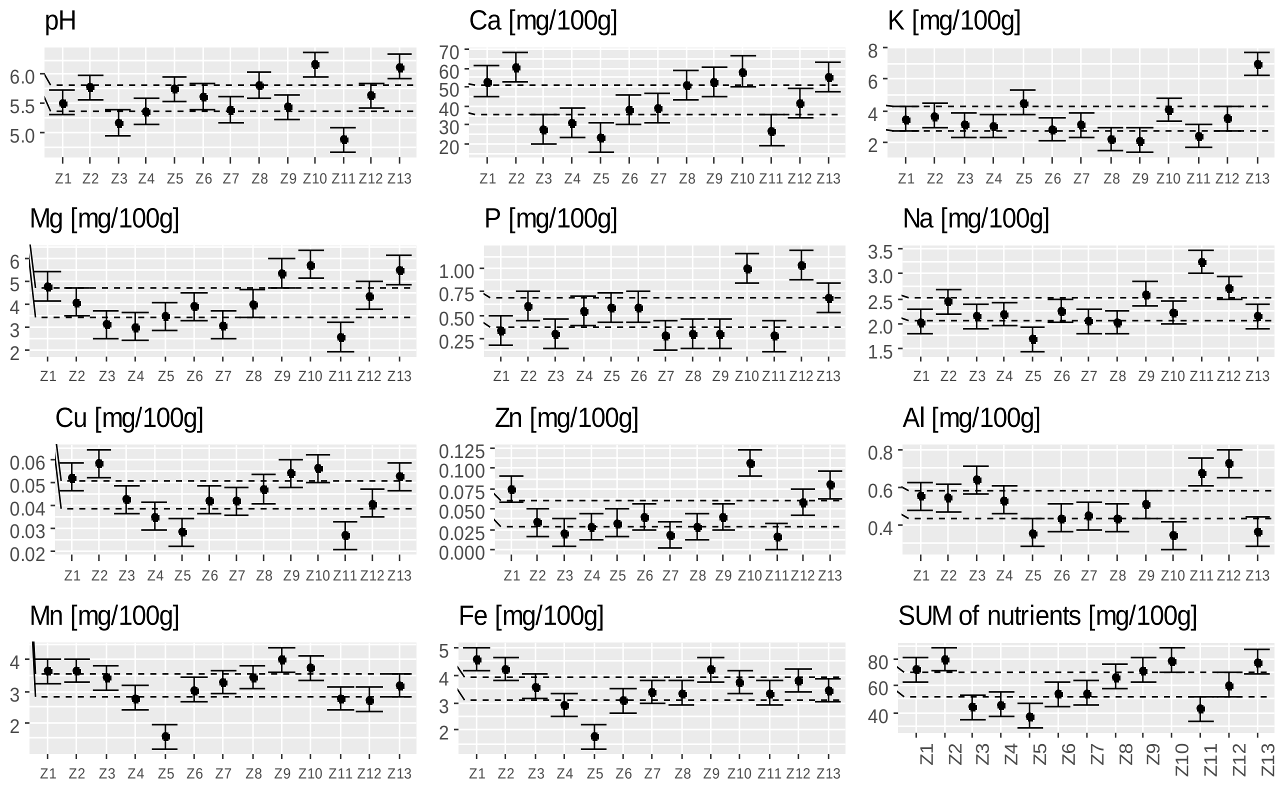

Figure 3 - Baseline characteristics of the plot. Dotted lines indicate the 95% confidence interval (CI) around the mean value. Z1 to Z13 correspond to samples taken across the plot and referenced by GPS coordinates. Error-bars correspond to the same 95% CI for the mean containing all 13 sub-samples.

The variability of baseline soil nutrients values could be also related to the soil pH. Values of pH were relatively heterogeneous on the study area. At Z10 and Z13 pH values were significantly higher than the average, while at Z11 they were significantly lower. Pearson correlation between pH values and nutrients showed that pH is mainly correlated to P, K, Mg, Ca, Zn and Cu (Table 10). It is likely that the pH variability could in turn be related to the S&B practice. To this regard, pH value could be the reference variable for S&B affected areas since not all S&B residues could still be apparent on soil surface one or two years after the fire. For instance, at Z13, pH values, as well as P and Mg availability, were significantly higher than at the other sampling points but no *in situ* observations could explain this result other than hypothetic S&B residues from the 2015 season.

Table 10 - Pearson R correlation between bioavailable nutrients in the soils and pH (KCl) values

	P [mg/100g]	K [mg/100g]	Mg [mg/100g]	Ca [mg/100g]	Na [mg/100g]	Zn [mg/100g]	Al [mg/100g]	Fe [mg/100g]	Mn [mg/100g]	Cu [mg/100g]
pH (KCl)	0,637	0,628	0,744	0,653	-0,475	0,72	-0,704	-0,005	0,103	0,585

In addition, the variability in texture in our study area could have played a role in soil nutrient contents. It is well known in fact that leaching, which causes loss of nutrients through the soil, is favoured by a coarse texture (Figure 4). Nonetheless, S&B residues might have played a role also in this regard. For instance, at plot Z10, which showed both a larger sand fraction and S&B residues, nutrient availability were high. This observation is in accordance with general acceptance that S&B practices increases nutrient availability also in coarse textured soils (Juo and Manu., 1996).

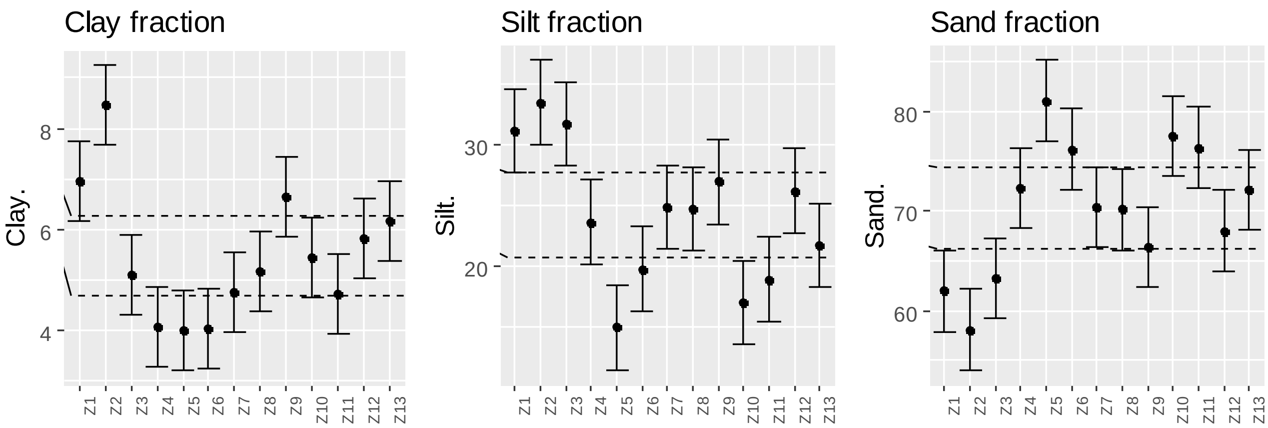

Figure 4 - Granulometry for baseline samples. Dotted lines correspond to the 95% CI around the mean. Error bars for each sample correspond to the same 95% CI.

1.2. Plot response to biochar amendments

The difference in total bioavailable elements in our soil is significant between treatments ($p<0.05$) and somehow related to the biochar inputs (Pearson P-value<0.05 and R=0.37). If plots where S&B residues were noticed are removed from the statistical analysis, the correlation between bioavailable elements and treatment type are further increased (Pearson p-value=0.001 and r=0.56). Benefits resulting from these practices are well documented as they are common in tropical soils, although their effects are only short lived (Juo and Manu., 1996). In this study the influence of slash and burn residues were apparent in the initial parameters for Z10 (between G-0-0 and F-0-100 plots NW), Z2 (SW of the site plot G-0-0), sampling points and resulted mainly in an increase in Ca, Mg, P and pH.

Regardless of baseline values, biochar additions surpassed this initial heterogeneity and increased pH to almost neutral values. Jeffery et al., (2011) found that the increase in crop productivity was greatest for soils with initial pH values ranging between 5≤pH≤6, which corresponds to our mean range of initial values. A liming effect after biochar addition is often obtained in field results and is particularly visible for biochar produced at high temperatures (Novak et al., 2009) and in sandy soils (Tryon, 1948). Feedstock type very much influences the initial pH of biochar with observed values ranging from 6.2 for green waste to 9.9 for poultry litter (Chan and Xu, 2009). In our case, the pyrolysed cotton branches had a pH ($CaCl_2$) of 9.2 (Table 9). This alkaline pH for our feedstock is in line with most of the literature for different feedstock types (Chan et al., 2009; Novak et al., 2009; Major et al., 2010).

The bioavailability of P and K was significantly greater where biochar was applied compared to the reference plots (Table 5). Firstly, this difference was mainly attributed to the addition of ash with biochar. The bigger increase in K than in P is mainly explained by the 6.7 times higher K than P contents (Table 9) in biochar ash (Glaser et al., 2002; Laird et al., 2010; Gao et al., 2016). Biederman and Harpole (2013) in their meta-analysis showed that increases in soil P and K were very often significant compared to non-amended soils. This effect is larger as pyrolysis temperatures increases or are at least higher than 500 °C. In fact, with higher temperatures the higher the ash content and, hence, the nutrients content in ash (Novak et al, 2009).

Within the distribution of bioavailable phosphorus (Figure 5) there is no significant difference between treatments C-30-150 and D-30-100 regardless of the fertilizer quantity amended. This is less the case for treatments receiving the lowest biochar application rate of 10 t ha^{-1} for which the addition of an extra 50 kg of NPK made a difference in P bioavailability. Conversely, the effect of different fertilizer quantities on available K was still remarkable for both application rates of biochar. The difference is less evident between treatments A-10-150 and B-10-100 than for treatments C-30-150 and D-30-100. What is however genuinely true is that even the smallest application rate of biochar, with either 100 kg or 150 kg of NPK fertilizer, will render P and K significantly more available than in reference plots. This finding demonstrates that fertilizer use could be reduced. This would diminish costs for farmers, lower depletion of inorganic fertilizers stocks and reduce water table pollution through less leaching (Laird et al., 2010). However, caution must be kept as this effect could only be temporary, as it is mainly related to ash addition along with biochar.

The ash retained onto biochar resulted also in pH increase, which in turn have an impact on the bioavailability of elements. At higher pH, for instance, P and K are made more readily available to plants (Cui et al., 2011). On the other hand, availability of other elements could be lowered. In our study, available Fe and Mn content seemed to be higher in plots with no biochar (Figure 5), although the results were not statistically significant. In fact, they are usually unavailable when pH values are close to neutrality. According to Kishimoto and Sugiura (1985) the decrease in these micronutrients could negatively affect crop yields.

The effect of soil baseline characteristics also affected the bioavailability of phosphorus in soils. This is particularly true for treatment G-0-0 (Figure 5) for which the standard deviation is the greatest for treatment G-0-0. This effect was however surpassed by the addition of biochar which significantly increased P bioavailability.

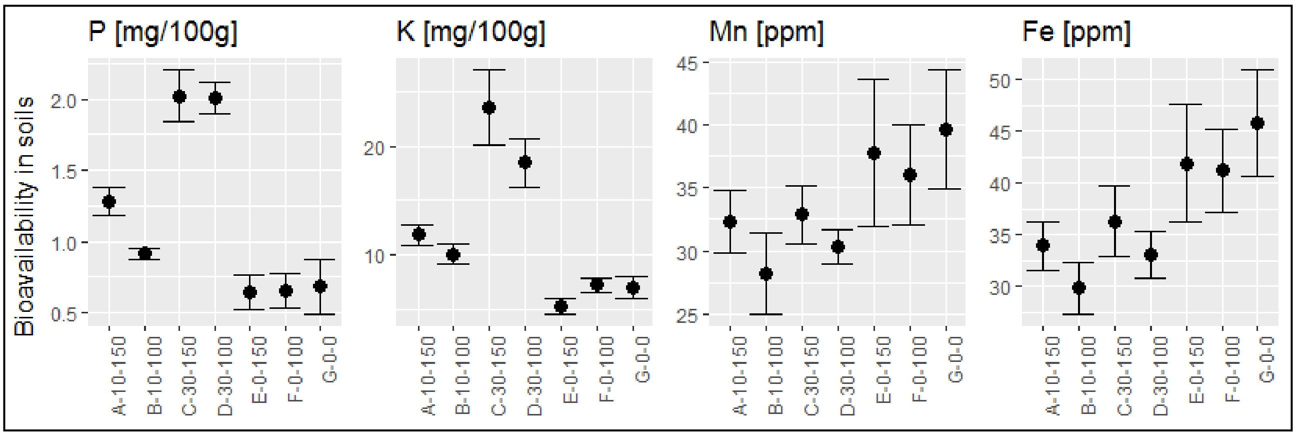

Figure 5 - Bioavailable nutrients in soils with respect to treatment and standard error of measurements.

Most of the time when biochar is applied to soils, cation exchange capacity (CEC) increases (Liang et al., 2006) as a result of negative charges on the biochars surface. In our study, baseline values of CEC were low because of poor OC and clay content. The CEC did not increase after the biochar input. An increase may however be noticed over time as the biochar amended here was probably too young and its surface not oxidized enough for significant differences to be noticeable (Cheng et al., 2008). As a mean of comparison Hardy et al. (2017) studied the effect of ageing on black carbon (BC) now incorporated in the Belgian landscape and agricultural fields and dated back to the pre-industrial period. Although ploughing homogenised the fields and decreased BC stock from where the kiln was first located, results showed that after more than 150 years the CEC was almost double as high for charcoal rich soils than for the adjacent soils.

Biochar CEC is also affected by pyrolisis temperature. With heat, carboxylic groups are partly broken down into carbon dioxide and as a result negative charges are lost and cation exchange capacity reduced (Novak et al., 2009). This decarboxylation typically occurs at temperatures between 400 °C and 700 °C (Novak et al., 2009). On the other hand, carbon content of biochar tends to increase at higher pyrolysis temperatures (Glaser et al., 2002; Novak et al., 2009) alongside biochar recalcitrance (Glaser et al., 2002; Guo and Chen, 2014).

The reason for biochar recalcitrance still deserves further research; however, Schmidt and Noack (2000) have found strong contents of charred biomass in deeper soils supporting long term recalcitrance of charred materials. Similarly, *Terra Preta*, a very common "dark earth" soil found in South America, also proves long term recalcitrance of charred organic matter (Glaser et al., 2001; Glaser and Birk, 2012). The recalcitrant nature of biochar has been attributed to the aromatic rings on its structure (Cheng et al., 2008) protecting it from chemical or biotic decomposition (Cheng et al., 2006). Very low H/C (aromaticity) and O/C (maturity) ratios (Table 9) suggest that our biochar retains a very recalcitrant nature. In fact, the biochar temperatures formation reached in this study are superior to 500°C.

Therefore, an equilibrium must be found between a biochar purposed for carbon sequestration, formed at higher temperatures, and a biochar with ideal characteristics for soil fertility. OC contents result directly from the biochar addition and therefore give better estimates for the true end amount remaining on the plots. A strong correlation between OC contents and bioavailable nutrients (Figure 6) still justifies the use of a not much active biochar, thanks to the higher ash load of biochar formed at high temperatures. Furthermore, it must be expected that even a material as recalcitrant as biochar will be oxidised over time, therefore offering negative charges on its surface, increasing soil CEC and, thus, improving soil fertility (Liang et al., 2006).

As a result of biochar addition, SOC significantly increased in all plots with respects to initial conditions. In fact, the biochar used in this study was mainly composed of C (Table 9 -75.8%). Where no biochar was added, C increase was mainly caused by the addition of organic amendment and fallen biomass. This C pool, however, will be likely prone to fast mineralization in tropical zones such as Burkina Faso (Tiessen et al., 1994). Even if biochar storage time is supposed to be lower in warm and humid zones compared to other climatic conditions (Cheng et al., 2008) its recalcitrant nature gives it a long turnover time (Glaser et al., 2000; Glaser et al.,2002).

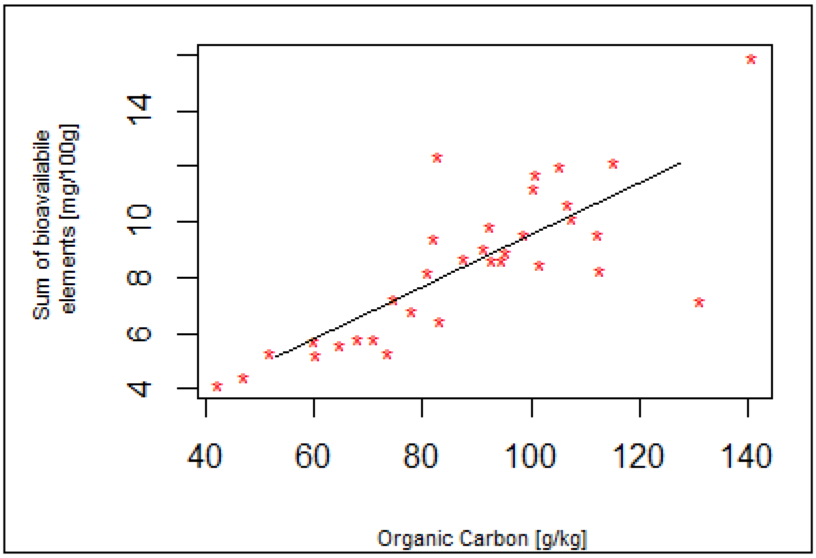

Figure 6 - Relationship between OC and the sum of all bioavailable elements in the soils - R=0.80 Pearson correlation

2. Effect of biochar amendment on element uptake by maize and on yield

The increased bioavailability of phosphorus and potassium is positively correlated to their direct uptake by the plant. As a result nutrients loss should be reduced and the fertilizer used more efficiently. P and K are two major elements in the plant and better uptakes will lead to a better crop health. In accordance to our study, Major et al. (2010) found that total nutrient uptake increased with biochar amendments. Increases in bioavailability had some effects on the concentrations in the plant tissue but none in grains (Figure 7).

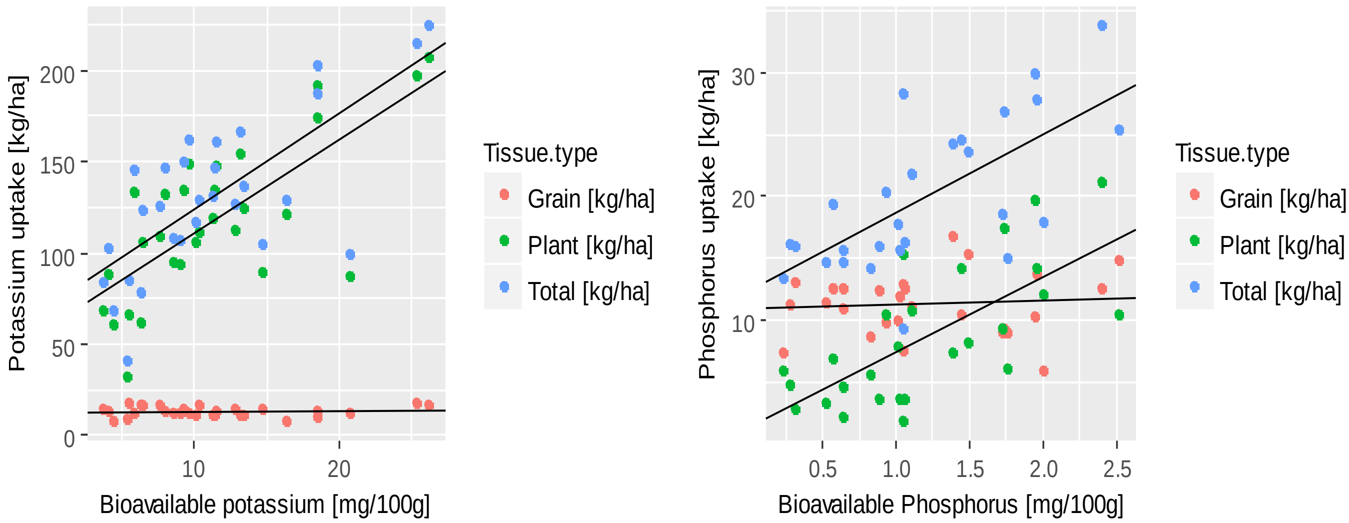

Figure 7 -Relationship between the bioavailable nutrient and the total plant uptake for this nutrient as explained by either the plant or the grain. Total uptake corresponds to the sum of these two tissue types. Correlation are for grain, plant and total respectively; 0.072 - 0.720 - 0.723 for potassium and 0.083 - 0.701 - 0.674 for phosphorus.

P concentration in plants also increased from 85.41 [$mg.100g^{-1}$] to 102.36 [$mg.100g^{-1}$] and 131.055 [$mg.100g^{-1}$], in response to 0 $t.ha^{-1}$, 10$t.ha^{-1}$and 30 $t.ha^{-1}$ of biochar addition respectively. In their review, Biederman and Harpole (2013) also found a positive increase in tissue P concentration after biochar addition. However due to numerous different findings amongst the studies used for their review, their results showed that overall no increase in P concentrations exists.

P and K are two major elements for plants, related to the regulation of energy balance, photosynthesis activity and synthesis of proteins and starch (Hopkins, 2003). The present study shows an increase in aboveground biomass production (Figure 8) related to biochar addition. The increase in P and K content could in part justify the increase in biomass production we noticed. As proof, Pearson's correlation was significant between total biomass yield and P and K bioavailability (R=0.56 and 0.58, respectively).

However, the increase in biomass production was not significant enough for a difference in grain yield to be noticeable for this first growing season. Various studies show immediate crop response to biochar. In neighbouring Ghana, Yeboah et al., (2016) found a significant increase in grain yield with application rates of 5 $t.ha^{-1}$ on an ultisol (FAO WRB: acrisols). On the other hand Major et al. (2010) found that there was no significant increase in yield during the first growing season in Amazonian oxisols (FAO WRB: ferralsol). Although not immediate, the effects of biochar on grain yield could be cumulated over multiple growing seasons (Steiner et al., 2007). Modelisation and meta-analysis suggest that the region studied holds the most potential for increased crop productivity (Crane-Droesch et al., 2013). Liu et al. (2013) and Jeffery et al. (2011) also show that biochar has the most potential on sandy, acidic and weathered soils. In fact although on average bioavailable nutrient contents increased with biochar, some micronutrients such as Fe and Mn decreased when close to neutral pH values (Mielki et al., 2016).

Total biomass yield could be in part also explained with the greater plant survival rate occurred in biochar amended plots. In fact, on average ten plants died after thinning in plots with no biochar addition in comparison to only one or two for plots with biochar. Biochar is known to increase the water holding capacity (WHC) and nutrient bioavailability (Laird et al., 2010; Deng et al., 2016). As a result, plots under biochar may have been more resistant to drought and nutrient deficiency, thus explaining a better fitness of plants with biochar when harsh environmental conditions occurred. Furthermore, Sun and al. (2017) found that maize biochar has an effect on germination through the action of bioactive molecules. He also found, however, that wheat biochar inhibits germination and further research should prove the effect of cotton biochar on germination to confirm our hypothesis.

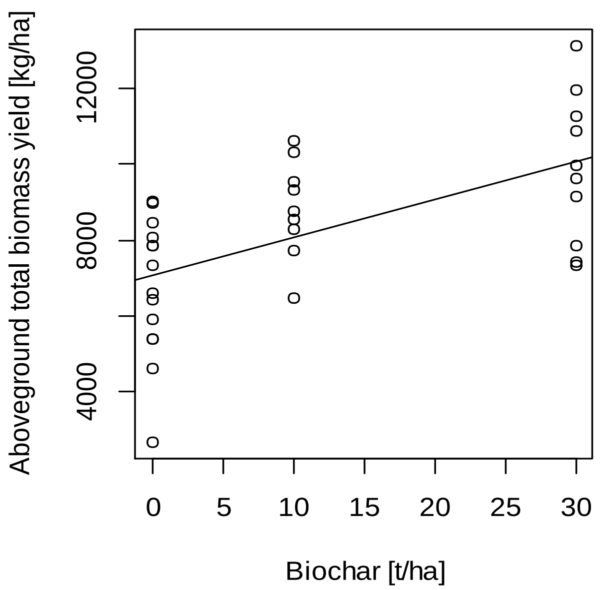

Figure 8 - Total aboveground biomass produced, extrapolated to the hectare scale with respect to biochar inputs (R=0.59)

Based on the groups obtained from the ANOVAs on total biomass per plot (Table 8) there was some correlation effect (Pearson $R=0.591$ and $p\text{-value}<0.001$) between biochar application rate and total biomass produced (Figure 8). In Ghana, Yeboah et al. (2016) found that the biochar application rate did have an effect on crop production. This is not the general trend however as Biederman and Harpole (2013) report "no clear relationship between productivity and biochar application rate" (Biederman and Harpole, 2013, p.205). The variability in findings relating productivity and application rate is however high and our results are therefore not surprising.

V. Conclusions

Hereby the increase in total aboveground biomass is mainly accredited to increased nutrient availability in soils, most probably through the addition of ash along with biochar and the pH increase in soil solution.

Total biomass production was increased by the application of biochar. However, this increase was not visible in crop yield. Nonetheless, biochar improved the uptake efficiency of nutrients by plants. It can therefore be concluded that fertilizer amendment could be reduced thanks to biochar.

This trial was the first set out in Burkina Faso according to available literature. Biochar has often been found to be a promising amendment in tropical soils and accordingly, benefits were noticeable in our trials. Nonetheless, longer term studies in these environments are needed to observe the reaction of biochar in time and the adaptation of the environment to its addition in soil.

Soil carbon contents increased after biochar addition. Furthermore, biochar produced from cotton by-products by a low-tech pyrolyser showed a high condensation degree and recalcitrance, hence possibly representing a very stable carbon pool in soil. However, in Burkina Faso this is not the major issue and biochar must still prove its potential to improve grain yield.

VI. Perspectives

For further research in the region, we suggest activating the biochar especially if a young product is used. In fact, many studies have shown improved biochar characteristics through activation (Lin et al., 2012; Khan et al., 2014). Schmidt et al. (2015) showed a pumpkin yield four times higher as a result of urine-enhanced biochar. The feasibility of various activation processes must be looked into for it to be adapted on a large scale. In Koumbia livestock is readily available and co-composting trials of manure or urine from sheep, goat or cow with biochar could be carried out.

Soil microorganisms have a great impact on the biochar and dictate its longevity in soils particularly in tropical regions. Further studies on this interaction are therefore needed to ensure amending biochar in Koumbian soils is interesting in terms of improving fertility. Moreover, as peanut fields are also commonly grown in Koumbia, it would be interesting to study the effect of biochar on nodulations.

There are three main types of crops in Koumbia: maize, cotton and sorghum. To allow for the greatest potential of biochar in the region, the study of feedstock type used for pyrolysis, and potentially the combination of different types, is also essential and should be explored. Furthermore the effect of biochar on these crops could also be investigated.

Based on the yield per hectare of cotton bolls (1.4 $t.ha^{-1}$ to 1.8 $t.ha^{-1}$), an harvest index (HI) of 33 % (used biomass/total crop biomass) and pyrolysis batch yields of 30% of dry weight, it has been estimated that only between 1.3 $t.ha^{-1}yr^{-1}$ and 1.6 $t.ha^{-1}yr^{-1}$of biochar could realistically and optimistically be produced annually from cotton. Similarly, using maize as feedstock (HI =0.5), there is a slightly smaller biochar production potential ranging between 0.7 $t.ha^{-1}$ and 1 $t.ha^{-1}$ of biochar. As a result, to ensure a more realistic research, we would recommend focusing on smaller biochar amendment quantities. Similarly focusing on the effect of year after year addition of biochar to the same plots would allow to understand the effects of and on additional biochar to a soil with already modified physico-chemical and biological activity.

Lastly, the behaviour of biochar on the long term is possibly the biggest and most important source of uncertainty in biochar science. For future research in the region, we suggest setting up trial plots on a larger scale and on multiple years. In fact in the present study total aboveground biomass is higher for all treatments compared to usual yields in Koumbia. Studying the effect of biochar on bigger plots and in different fields would allow better extrapolation to the hectare scale.

STATE OF THE ART

AND ADDITIONAL INFORMATION

SECTION TWO

I. State of the art

1. The carbon question worldwide

Greenhouse gas (GHG) emissions are as high as they have ever been (IPCC, 2014). Human activity, demographic growth and more demanding lifestyles are causing a catastrophic change in climate (IPCC, 2014). In the wake of this climate change, the scientific community has been searching for alternatives aiming at mitigating the impacts of different sectors.

The Intergovernmental Panel on Climate Change (IPCC, 2014) has estimated that agriculture, forestry and a changing land use combined are responsible for a quarter of human emissions of greenhouse gases to the environment. Approximately 14% of these are caused by the agricultural sector (FAO, 2010) and of these 14%, 74% of the GHG emitted come from emerging countries (FAO, 2010). It seems however that trends are inverting suggesting that these three sectors combined may well become a carbon sink before the end of the century (IPCC, 2014). This would happen mainly through a decrease in deforestation and forest degradation, an increase in reforestation rates, better agricultural land management and in result increased organic contents of soils (IPCC, 2014). Slowing down polluting human activity is essential to achieve the targets all nations agreed to meet at the climate conference in Paris (COP 21). Climate change has a certain inertia (IPCC, 2014) and although scenarios suggest temperature will have risen by more than 1.5°C by the end of the century the maximum 2°C increase agreed in the Paris Agreement is still within reach (IPCC, 2014). However not only do we need to cut down on emissions but sequestration of GHG from the atmosphere is also essential. A change in agricultural practices, mainly by maintaining or increasing the soil organic carbon contents has often been brought up as a solution (Lal, 2004)

According to Lal (2004), the carbon stock of soils is 3.3 times greater than that of the atmosphere and 4.5 times greater than that of the biotic stock. Combined, soil organic carbon (SOC) and inorganic carbon account for more than two-thirds of the total terrestrial ecosystems carbon pools. However, pressure caused by agricultural practices is reducing the stocking capacity and thus decreasing soil fertility (Ogle et al., 2005). Through the conversion of natural to agricultural lands, carbon stocks are diminished by 60% for soils under temperate climate and 75% for tropical soils (Lal, 2004). The stock potential of soils for storing carbon dioxide can be increased through improved land management (FAO, 2010) such as reduced tillage, better residue management and the restoration of degraded land. The potential for carbon sequestration is the highest in places where the SOC has been run down the most. In their meta-analysis, Ogle et al. (2005) found that the biggest depletion of SOC stocks was noticed in wet tropical soils and least in dry temperate regions. This depletion is naturally fast in dry and wet environmental conditions due to the ideal combination of warmth and humidity for soil microorganisms. In these conditions mineralization of organic matter is speeded up. In addition, the SOC depletion is also explained by the excessive exportation of matter through grazing and an insufficient amendment of organic matter (OM). Nevertheless, Ogle et al. (2005) further showed that the tropical soils under wet conditions responded the fastest to a change in land management such as limited tillage and thus can be restored faster.

Improved land management has a high potential for sequestering carbon. However, if not chemically bonded in the soil, the labile organic carbon (LOC) will always be prone to faster mineralization and hence only sequester carbon temporarily (Mekuria and Noble, 2013). A long-term solution to carbon sequestration is biochar (Schmidt and Noack, 2000; Lehmann, 2007) a product issued from the pyrolysis (a low oxygen carbonization process) of biomass. During this process, organic matter is turned into a recalcitrant (resistant to degradation and stable over time) charcoal. As a result, carbon is sequestered on the long term (International Biochar Initiative (IBI) - cited in Lehmann and Joseph, 2009 p.108). When this charcoal is intended to be used as an amendment in soils it is called biochar(Lehmann and Joseph, 2009).

With regards to the decrease in carbon stocks and the decline of soil fertility it engenders, the "maximum sustainable technical potential" of biochar to mitigate climate change has been estimated by Woolf et al., (2010). Biochar could contribute to the sequestration of 1.8 Gt of CO_{2}-C_{e} or in other terms 12% of the annual GHG emissions by cutting down on CO_2, N_2O, and CH_4 gases. The reaction of an ecosystem to the application of biochar depends on many factors. Mean annual temperatures (Cheng et al., 2008), soil texture, cation exchange capacity (CEC), feedstock type, soil pH increase and others parameters will play a role in determining the effects of biochar on crop production and carbon sequestration potential (Jeffery et al., 2011). Crane-Droesch et al. (2013) combined data from 84 studies to produce a world map (Figure 9) modelling the effects of biochar on crop yields.

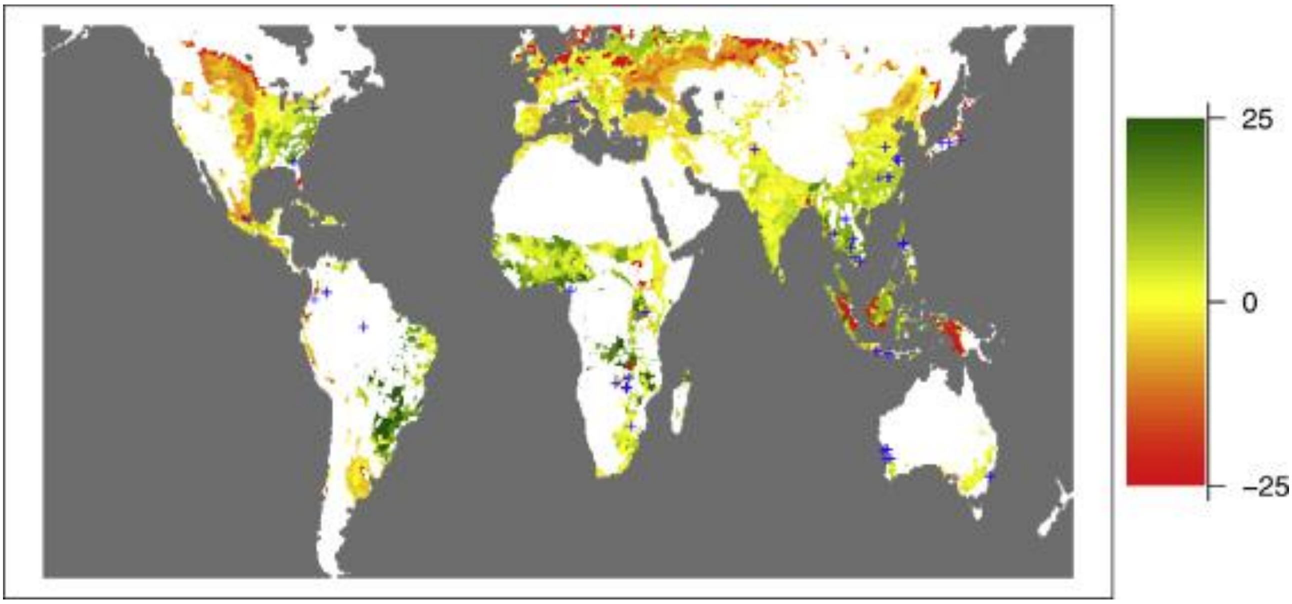

Figure 9 - Predictions for the relative increase in maize production across the globe resulting from biochar use. The coloured legend correspond to percentage of relative production of biomass increase in green and decrease in red. Blue crosses correspond to studies used as input data. Source: Crane-Droesch et al. (2013)

Results show that the biggest potential occurs in regions with tropical climates and where the soils are considered as highly weathered (Crane-Droesch et al., 2013). A comparison with FAO's world hunger map (2014) is obvious (Annex 4) particularly around the equator which further enhances the interest in biochar.

2. Biochar

2.1. The carbon cycle modifier

Biochar has been referred to by Laird (2008) as the perfect "Win-Win-Win Scenario" as it could be the solution for three major issues: producing energy from a renewable material, storing carbon in soils whilst increasing its long-term fertility and preventing the leaching of inorganic fertilizer resources.

The concept of using biochar as a soil amendment emerged from South America where black earth also known as *"terra preta de Indios"* was discovered. These soils were reported as incredibly fertile (Glaser and Birk, 2012) as opposed to other ferralsols, acrisols and arenosols found in the region (FAO-UNESCO, 1970). This "*terra preta de Indios",* was supposedly first reported by the American geologist James Orton in 1870 during an expedition to South America. Black soils resulted from the accumulation of organic and inorganic matter between 500 and 2500 years ago by pre-Colombian Indian tribes (Petersen et al., 2001, cited in Lehmann et al., 2003.p.343). Various household residues such as manure, food residues, bones, biochar and much more were thrown away in big pits hence forming *terra preta* anthrosols (Glaser and Birk, 2012). Nutrient availability is very high in these anthrosols and although soils are subject to strong leaching in the Amazon the fertility of these soils remains stable over time (Lehman et al., 2003; Glaser and Birk, 2012). Such man-made soils are very promising to counter-balance the lack of fertility in the tropics. From the residues found, biochar has been retained as an easily and relatively fast way of obtaining similar soils.

The following figure illustrates how biochar modifies the carbon cycle and sequesters carbon (Figure 10).

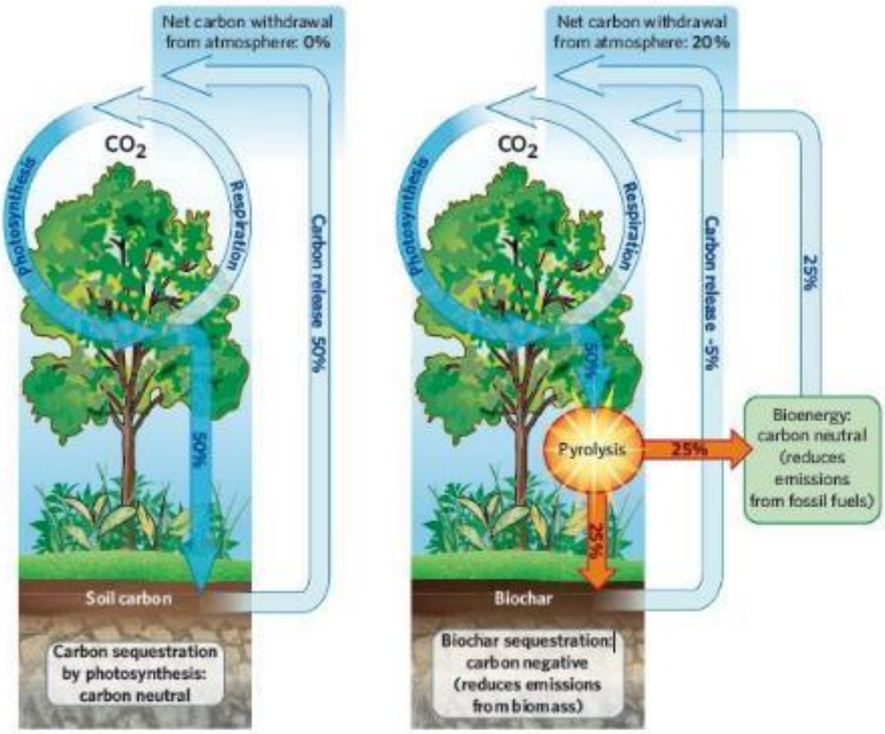

Figure 10 - The impact of biochar on the carbon cycle. Source: Lehmann (2007)

Carbon is fixed from the atmosphere through photosynthesis by biological activity and stored as fresh biomass (Hopkins, 2003). When the plant has finished its natural cycle and after harvesting in the case of agricultural systems, waste material of any kind, hardwood, crop residues or even waste water sludge can be used as input in the carbonization process (Woolf et al., 2010). To produce biochar, the biomass may undergo numerous different kinds of processes, presented later in the document, notably pyrolysis the process used in this study. As a result, the main products issued for the pyrolysis are bio-oil, heat, synthetic gas (Syngas) and biochar in different proportions (Woolf et al., 2010) depending on the treatment time, temperature and level of oxygen. These conditions will be regulated depending on the purpose of the pyrolysis. Additionally to these products, the final output of the process is CO_2 emitted back to the atmosphere. The clear advantage of this process is that it postpones part of the emissions of GHG in two ways. Firstly part of the biochar is stabilized on the longer term (Figure 10- right diagram) in the soil. While it is stored this biochar creates a positive feedback loop by enhancing the primary productivity of crops through better physicochemical properties (Woolf et al., 2010; Biederman and Harpole, 2013). Secondly, through a clean pyrolysis in a controlled environment, this process reduces the emission of GHG such as methane, nitrous oxide and carbon dioxide (Woolf et al., 2010).

2.2. Production

2.2.1. The technology

Many different technologies exist for the production of charcoal as potential biochar. One of the main advantages of biochar is that the production technology needed is relatively simple and that industrial processes are not always needed. Its relatively cheap price and the process allow the production at minimal cost making it accessible to anyone with minimal experience.

Common carbonization procedures are torrefaction, gasification, hydrothermal carbonization, flash carbonization and pyrolysis to name a few (Meyer et al., 2011). These differ mainly by the carbonization temperature needed for the process and the time for carbonization to occur (Novak et al., 2009). Of all these technologies and different processes the most common production method for biochar remains low or medium temperatures pyrolysis as for now few to no biochar produced from other methods have shown an increase crop production (Meyer et al., 2011).

Different pyrolysing processes exist but their principle remains the same. Here a top lid up draft pyrolyser (Figure 11) and its *modus operandi* will be described. To start off biomass fuel is stacked in the oven in which the amount of oxygen is controlled and limited. A fire is then lit on the top of the fuel stock (Figure 11 & Figure 15). As Schmidt and Taylor (2014) explain, the biomass itself doesn't burn, it is the gas emitted from a heated material that causes the combustion. As the biomass on top is being pyrolysed, the biomass just under is heated and emits gases who in turn ignite (Schmidt and Taylor., 2014) making the pyrolytic front migrate downwards. The advantage of this enclosed system is that the combustion is as complete as can be. All the gases emitted from the biomass pass through the flame before exiting the oven through the top chimney ensuring that we avoid the production of harmful gases such as carbon monoxide (Roth, 2014). The heat produced during the process can also be harvested. As a result, biochar producing ovens such as the top lit updraft (TLUD) oven can be designed to fit household cooking needs (Roth, 2014)

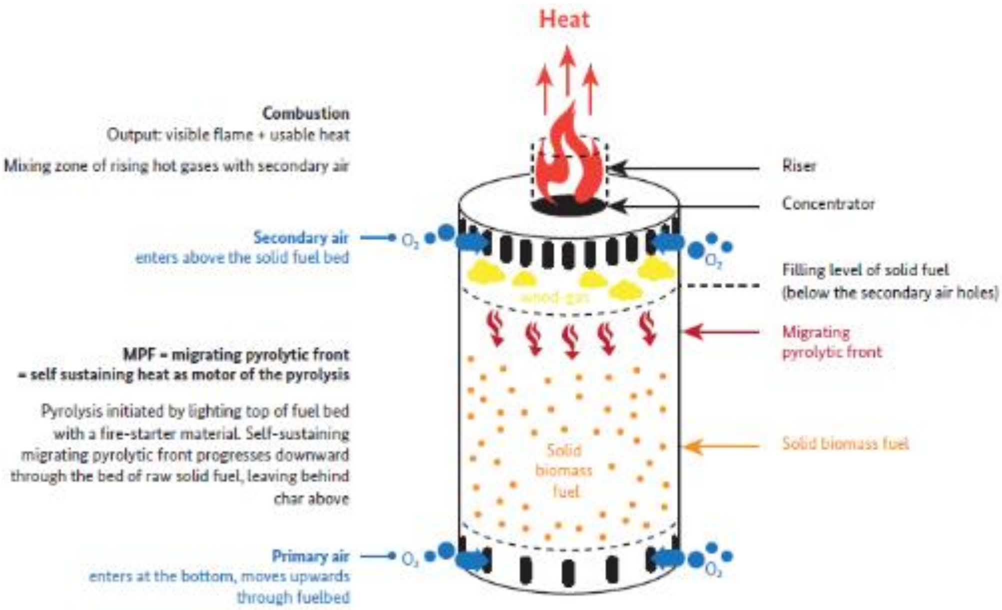

Figure 11 - Top Lit UpDraft pyrolyser**.** Source: Roth (2014)

Feedstock type had a significant effect on the characteristics of biochar and as a result on the productivity of the plot. Poultry litter, paper pulp and wood chips, as well as wood for example have a significant positive effect on crop production (Jeffery et al., 2011). Pyrolysis temperature also had an important effect on the characteristics of biochar. With higher temperatures biochar gain in overall carbon concentrations as its pores and surface are cleared from minerals and most functional groups. Greater surface area result from higher temperature pyrolysis. Furthermore higher temperatures also induce higher pH values and higher ash contents (Novak et al., 2009). Comparing the two effects, Rajkovich et al. (2012) showed that the effects of feedstock type on plant growth were eight times more important than pyrolysis temperatures.

2.3. Effects on soil

2.3.1. Yield increase

In most studies where it has been applied and particularly in tropical soils, biochar has increased the crop productivity (Blackwell et al., 2009). In this section we look into the effects of biochar on the soil physico-chemical properties and on soil biota. Furthermore, we analyze what makes this form of organic carbon so recalcitrant.

2.3.2. Chemical properties

The addition of biochar to soil shows an overall reduction in nutrient leaching (Steiner et al., 2007; Laird et al., 2010; Cornelissen et al., 2013). In their meta-analysis Biederman and Harpole (2013) review a clear increase in soil P and K availability, a total N increase as well as an increase in carbon contents in soils. In some other cases the nutrient availability of Ca (Rondon et al., 2007) and Mg is also increased (Major et al., 2010).

The cation exchange capacity of soils is also positively increased by the addition of biochar in soils (Liang et al., 2006; Agegnehu et al., 2016) and significantly increases over time (Hardy et al., 2017). This increase in CEC is explained by Cheng et al. (2006) as the result of biotic or abiotic processes on the oxidation of the biochar surface. This oxidation results in an increase in negative charges on the surface or the biochar (Cheng et al., 2008). As a result of its porous structure, the surface/volume ratio is high. Biochar in itself can also act as a fertilizer through the addition of nutrients to the soil mainly through the ash that is amended along with it (Glaser et al., 2002).

The pH of soils is also commonly increased by the addition of biochar (Rondon et al., 2007; Major et al., 2010; Biederman and Harpole, 2013). The decrease in acidity is generally linked to the type of biochar added (Chan and Xu, 2009) and the response to this increase in pH varies. If the initial pH is very acidic, the effect of biochar is not always profitable (Jeffery et al., 2011). However if the values are neutral (pH>6) or moderately acid (5<pH<6) then an addition of biochar generally leads to an increase in crop productivity (Jeffery et al., 2011). The pH values have a clear role on the bioavailability of nutrients in soil. Whereas in some cases it increases the bioavailability, notably for P, K, Ca and others, in other cases bioavailability is decreased, especially for Fe, Mn, Cu Zn and other. This is often the case for Al (Rondon et al., 2007; Steiner et al., 2007) which is found mainly as aluminium hydroxides around neutral pH values. The nutrient cycle of other minerals can also be altered by biochar. Recent research has shown that heavy metals can be immobilized by the action of biochar (Venegas et al., 2016).

2.3.3. Physical properties

Biochar increases the availability of water (Jeffery et al., 2011) through a very porous structure (Kishimoto and Sugiura, 1985) that acts as a sponge. Tryon (1948) showed that coarse textured soils had the most to gain from the addition of biochar as the water availability could increase by 18%. More recently, Cornelissen et al. (2013) partly correlated their increase in yield with an increased availability of water for the plant. Xiao et al. (2016) also showed an increase in "readily available water content" well correlated to the biochar application rate.

Aggregates formation in the soil are formed and maintained by organic matter (An et al., 2010). With biochar, Mbagwu and Piccolo (1997) have shown that humic acids derived from coal products have a significant impact on the formation of aggregates in soils. As a direct consequence erosion is usually decreased thanks to better infiltration (An et al., 2010). Soil bulk density is also linearly decreased by the application of biochar as a function of application rate (Glaser et al., 2002). On the contrary soil total porosity logically increases with application rates (Xiao et al., 2016) which also improves water penetration in soil and decreases the run-off effect.

Although many promising characteristics may be attributed to biochar one of its negative aspects concern its albedo. Genesio et al., 2012 showed a decrease in albedo of up to 80% (Annex 5). This implies that carbon mitigation is in part diminished by a lowered reflectance of the surface of biochar amended fields as soils absorb more heat. Although this significant decrease in albedo is only temporary and brought down to a decrease of less than 20% after tillage, further research is needed to hold this aspect into consideration when quantifying the benefits of biochar (Genesio et al., 2012). A darker soil could, however, increase soil temperature and in turn improve germination depending on latitude.

2.3.4. Effects on soil microorganisms.

Correctly understanding the response of soil biota to the application of biochar is crucial to ensure its longevity in soils. In fact in the event biochar decays faster than expected, through biotic or abiotic means, efforts to mitigate climate change would turn out to speed up global warming instead of slowing it down (Lehman et al., 2011). Soil microorganisms are a major contributor to the emissions of GHG and the addition of biochar could modify these patterns (Zhang et al., 2010; Lehmann et al., 2011; Bamminger et al., 2014).

Although quite a few studies have already been undertaken on the effect of biochar on soil biota, these effects are as numerous as the number of combinations between soil type, biochar feedstock type, production processes and climatic conditions. The size of the micro-organic pool generally increases as a result of the biochar application (Lehmann et al., 2011). This variable was measured by soil respiration rate by O'Neill et al. (2009) which also proved a higher activity in soils. An activity he explained was mainly due to bacteria populations. Makoto et al. (2010) similarly showed a significant increase in total biomass and yield in his pot experiments. This increase was due to an ectomycorrhizal community which developed on the biochar amended layer in the pots, colonizing the biochar pores.

In other cases when different biochar feedstock type is applied, biodiversity can however significantly decrease. Khodadad et al. (2011) show a decrease in total biodiversity whilst some specialized species became dominant. It has already been discussed that biochar increases nutrient bioavailability and water contents. Its dark colour also has a certain impact on soil dynamics (Sun et al., 2016) and as a result, moist and hot conditions are ideal for microorganisms to develop. For t*erra preta* soils many more studies are available on soil biota, Kim et al. (2007) found that there was a 25% greater species diversity in *terra preta* soils than in adjacent natural soils.

In their review, Biederman and Harpole (2013) found a significant increase in rhizobia nodulations. This was explained by the fact that nitrogen fixing conditions were improved (Rondon et al., 2007). In this study, N-fixation was increased by 72% as a result of biochar addition.

Concerning mycorrhizal fungi, Biederman and Harpole (2013) found that no general statement regarding either an increase or a decrease could be stated. In fact, the variability in results suggests that the system's response is very dependent on the environmental conditions. Lehmann et al. (2011) argue that the occasional decrease in nitrogen fixation in mycorrhizal colonies could be explained by a decrease in the need for symbionts by the plant, as nutrients are naturally more bioavailable when biochar is applied (Raznikiewicz et al., 1994).

Although some information is already available concerning the effect of biochar on soil organisms, the amount of published data is still negligible with respect to the variability within the organic pool (Lehmann et al., 2011).

As is the case for aboveground ecosystems and ecological patterns studies, it is important to consider the soil living organisms as a whole. The relationship between species dictates the soils composition and "health". The soil macrofauna is the least documented domain related to biochar (Lehmann et al., 2011).

Of this fauna, earthworms were amongst the better-studied species. They have been shown to feed on carbon-rich soils and in some cases earthworms preferred these soils over others (van Zwieten et al., 2010). Bamminger et al. (2014) also showed a positive interaction between earthworms and biochar but no direct uptake of the biochar by the fauna in temperate regions on a stagnic Luvisol.

The ingestion of biochar by earthworms although not systematic could be explained in different ways. Firstly biochar could be used as a grinder in the worm's gizzard to improve degradation of the ingested particles (Lehmann et al., 2011). Furthermore, as earthworms partly feed on soil microorganisms (Lavelle, 1988), the hunt is facilitated when microorganisms develop on the char, as a result biochar is ingested alongside organisms attached to biochar. Some bioturbation was also noticed on sites with biochar, Major et al. (2010) noted darker traces in earthworm's tunnels which further suggest that biochar was ingested.

2.3.5. Biochar stability in soils

Biochar gains its recalcitrance from the condensed aromatic structures that are obtained during pyrolysis (Lehmann and Joseph 2009) whilst cellulose and lignin are completely destroyed (Paris et al., 2005). Because its mitigation potential directly relies on the recalcitrance of the carbon, quite a lot of studies exist on the oxidation process of these aromatic structures. Lau et al. (1986) showed that the oxidation process would form mainly carboxylic groups alongside hydroxyl, carbonyl and others functional groups that would also be found in non-negligible quantities. This is in accordance with Cheng et al. (2006) who compared biotic and abiotic oxidation and found that when oxidation occurred, some acid functional groups would be created mainly as carboxylic groups.

Furthermore, biochar can bind to organic carbon or minerals (Annex 6) by its functional groups (Kaiser and Guggenberger, 2000; Lehmann and Joseph, 2009) which further stabilises biochar. In fact when this link happens, biochar's functional groups are uncharged and oxidation is harder. Lin et al. (2012) suggested through microscopic evidence that the mineral phase linked to biochar in part through the porous structure available (Annex 6)

2.3.6. Priming effect

Through the application of pyrolysed black carbon, some studies have reported an increase in the labile organic carbon (LOC) mineralization rates in soils. This positive priming (LOC mineralization speeds up as a result of biochar application) effect would challenge biochar's mitigation capacity and is therefore much debated (Wardle et al., 2008).

Woolf and Lehmann (2012) argued that even if LOC is in fact mineralized faster with the application of biochar the loss would be minimal implying a decrease by only 4% of LOC in soils over 100 years. Pyrolysis temperatures also have an important effect on this priming effect (Zimmerman et al., 2011). Biomass pyrolysed at lower temperatures tend to show a higher positive priming effect soon after the amendment of biochar. The opposite is true for high temperatures which show a negative priming effect (LOC is stabilized by the addition of biochar) (Zimmerman et al., 2011) as a result of biochar application. Zimmerman et al. (2011) and Woolf and Lehmann (2012) agree however that the priming effect would only have small consequences on the global biochar mitigation cycle. Not only would the quantity mineralized be negligible with respect to the potential of biochar, but complexation would, in turn, increase the stability of further added organic material through a negative priming effect.

In the following figure (Figure 12) Lehmann et al. (2009) summarise on the one hand the factors we have discussed in this section which influence the stability of biochar in the soil and on the other hand the moment when their effect is the most important. To avoid repetition of already discussed material we will simply point out the factors that have not been discussed yet. Erosion will affect biochar directly after apllication and will decrease as the biochar stabilizes in soils. Lastly, leaching/eluviations and bio/pedoturbation are depicted as minor transport mechanisms within the soil profile that affect biochar throughout its lifespan.

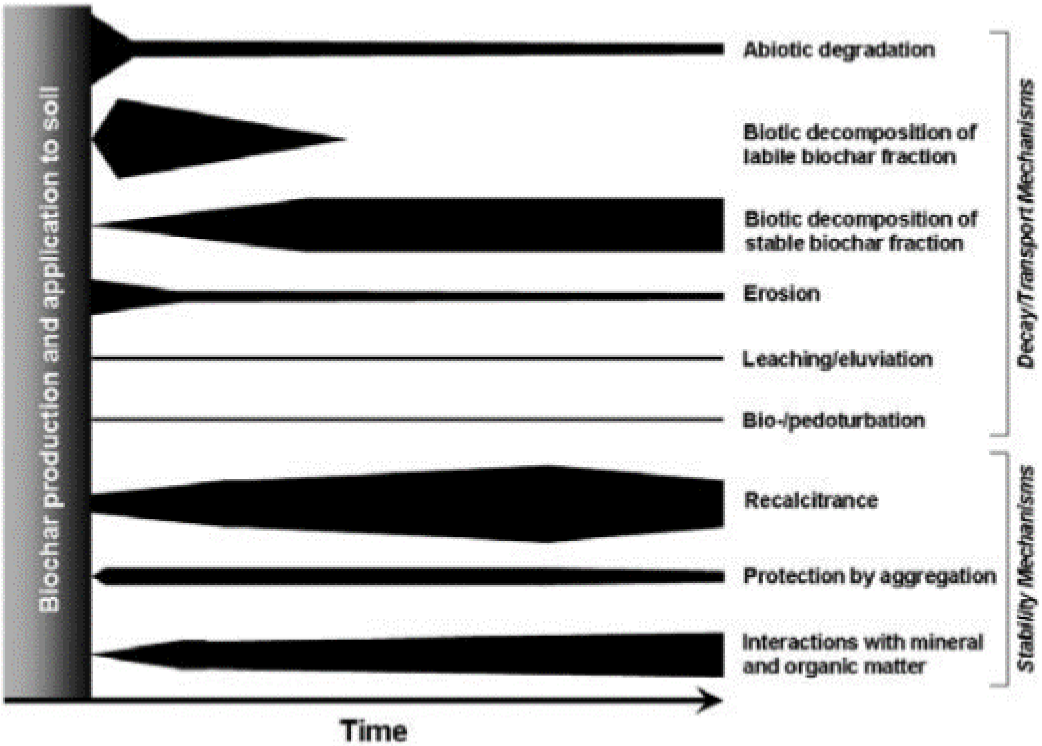

Figure 12- Summary of factors influencing the recalcitrance of biochar in soils and the transport mechanisms that will affect it. Source: Lehmann et al. (2009)

We have seen in this section that biochar can have numerous positive impacts on soil fertility. This gain nevertheless depends on many factors such as soil texture, climate, production technology and others. These factors must be considered when using biochar.

In the following part of this state of the art, we will focus on the case of biochar application to West Africa and in particular to its application in Burkina Faso.

3. The case of Burkina Faso

There is a common consensus that sub-Saharan tropical soils are degrading fast as a result of non-sustainable agricultural systems (Mekuria and Noble., 2013; FAO, 2016). This decrease in soil fertility alone is the most significant restriction to the state of food security and resilience of West African countries (Bationo et al., 2007). Soil erosion alone could contribute to between 65 and 1801 $kg.ha^{-1}$ of lost SOC (Bationo et al., 2007) per year in these tropical soils.

This decrease in SOC is explained by two main factors: exportation of biomass through grazing and the burning of crop residues on fields (Mekuria and Noble., 2013). Human pressure coupled with naturally higher turn-over in the tropics and naturally poor clay contents lead to readily degraded soils. For sandy soils mean loss can reach 4.7% of SOC loss per year (Bationo et al., 2007)

In Burkina Faso, as is the case in many African countries crop residues are often burnt on the field (Figure 13). Although this may have a slash and burn effect and temporarily enrich soils in nutrient contents, mainly soluble salts, crop preparation through burning in general (not only crop residues) was estimated to contribute to a 21% reduction in SOC and add up to emit 1.4 t $CO_2.ha^{-1}$ (Parker et al., 2010 cited in Mekuria and Noble, 2013. p.2)

Figure 13 - Crop residues burnt on fields near Koumbia. Source: Victor Burgeon - June 2016

However biomass has the potential to become a carbon sink instead of a source when turned to biochar. In fact, crop residues are often burned and considered as waste material. By pyrolizing the unused biomass from crops it is possible to use it first as cooking fuel and then as a field amendment. The obvious benefits of this combination are numerous (Roth, 2014). Firstly the housekeepers, often women in small villages of Burkina Faso, will not need to travel far from the house to harvest burning fuel often collected in the forest. With fuel efficient stoves the risk of inhaling toxic smoke, which is the primary cause for 50% deaths related to pneumonia for children under 5 worldwide, is decreased (WHO, 2016). As a result of these ovens, deforestation is decreased and less GHG are emitted thanks to cleaner combustion of organic resources (Roth, 2014).

Duku et al. (2011) have determined that there is a very high potential for biochar production in neighbouring Ghana. Waste products such as agricultural and logging residues as well as municipal solid waste and animal dung show that biochar could easily fit in. A similar study could be undertaken in Burkina Faso, however, it seems fair to believe the two biochar producing potentials would be similar.

II. Material and methods

(Additional information)

1. Location of the site

Experiments were set out 67 km east of Bobo-Dioulasso in Koumbia, a village along the main national route joining Bobo-dioulasso and Ouagadougou. Koumbia is a district located in the province of Tuy, the village of Koumbia (Figure 14) itself has a population of 5300 individuals equally divided between genders.

Overall 3 447 ha are dedicated to agricultural practices with the majority dedicated to cotton crops, 1 841 ha and maize 1 185ha (Vall et al., 2006). Sorgho is also an important crop and represents 421 ha of arable land. Livestock represents a significant source of income in the region and livestock distribution varies according to the ethnical groups. *Peuhl* and *Mossis* ethnies are historically the migrant populations and account for more than 80% of total livestock (cattle, sheep and goats). The small livestock generally grazes as it pleases, unlike cattle which are taken care of. In Burkina Faso, and particularly in Koumbia, 85% of the active population relies on agricultural practices as a source of income (MECV, 2011). This shows the importance of a productive and resilient agro-pastoral systems.

Pedogenetic factors have been further presented in the article section of this document. We however wish to point out that regardless of a poorer production potential, sandy soils are usually preferred by the local farmers than other soils with finer textures (Vall et al.,2006). In fact these are easier to plough with animal traction and water stagnates less during the rainy season.

Figure 14 - Map of Burkina Faso illustrating the sites mentioned in the present thesis. Source: www.diva-gis.org/ accessed on 01/08/2016)

This masters' thesis will be used as a preliminary study for a project elaborated between the Faculty of Gembloux Agro-Bio Tech (GxABT-ULg) and the *Université Polytechnique de Bobo-dioulasso* (UPB) aiming to study and develop the use of biochar for improving OM management and soil fertility parameters in the West region of Burkina Faso.

2. Experimental set-up and factors studied

Three biochar application rates were studied: 0 $t.ha^{-1}$, 10 $t.ha^{-1}$ and 30 $t.ha^{-1}$. To these rates were added either 0 $kg.ha^{-1}$, 100 $kg.ha^{-1}$ or 150 $kg.ha^{-1}$ of NPK fertilizer in equal quantities (Table 11). Furthermore urea and sheep dung were applied to every plot in equal proportions as is conventionally done in Koumbia. Each treatment type was repeated 5 times to ensure the validity of our results. Plots were distributed in a completely randomized manner on the trial site (Annex 7)

Table 11- Treatments installed on the plot

Treatment	Type OM	Crop type	Biochar dose [$kg.m^{-2}$]	NPK [$g.m^{-2}$]	Urea (g/m^2)	Total biochar needed [kg]
A	Cotton	Maize	1	15	5	40
B	Cotton	Maize	1	10	5	40
C	Cotton	Maize	3	15	5	120
D	Cotton	Maize	3	10	5	120
E	Reference	Maize	0	15	5	0
F	Reference	Maize	0	10	5	0
G	reference	Maize	0	0	0	0
					Total	320

For the total biochar quantity to be produced, 320 kg, two TLUD ovens were built using local material, in collaboration with Mr. David Lefebvre. It was first estimated that production of these ovens would cost between 110 € and 170 € using Belgian materials and not accounting for labour. In Burkina Faso the material being cheaper the construction of an oven costs more or less 40 €. Labour must then be accounted for. It is estimated that such ovens could be used for more or less 250 to 300 batches. To reach our target quantity we used them for approximately 4 batches a day for a week and no signs of degradation of the oven were noticeable.

On average 18kg of dried and cut down to pieces, biomass could be added to the ovens and resulted in on average 6 kg of biochar per batch. A total time of one hour was needed for the whole process which took place as follows. First of all dry biomass was cut down to smaller pieces with a machete in order to fit in the oven. After this, a small fire was lit on top of the biomass (Figure 15) and the oven was closed with a lid equipped with a chimney (Figure 16). The heat front was visible on the outside of the metal surface and when it reached the bottom of the oven the biomass was cooled down with water as fast as possible to avoid over-combustion.

Figure 15 - Top lit updraft oven without chimney

Figure 16 - Top lit updraft oven with chimney

Figure 17 - Kon-tiki oven

Due to a lack of time and a need for more biochar, the Kon-tiki oven as presented by Schmidt and Taylor (2014) was built in collaboration with Mr. David Lefebvre (Figure 17). The idea behind the Kon-tiki is based on the finding that biochar was first obtained by burning biomass in cone shaped pits. Here a fire is lit at the bottom of the cone and fresh biomass is added as the fire burns. Before biochar turns to ash at the bottom of the cone extra biomass is added and so on till the cone is full. No lid is needed for this oven due to the shape of the cone. When it is heated a convection movement is created along the oven's walls. When air reaches the top it "pushes" gases towards the center of the cone where flames alight these bio-gases (Schmidt and Taylor, 2014). As a result a product very similar to the one obtained with TLUD ovens is created through a simpler manner and with a greater total biomass production at the end of approximately 50 kg per batch (similar yield of 30% biochar to fresh biomass ratio).

3. Potential biochar production

In the western part of Burkina Faso (zone of Koumbia) maize (37% of arable land) and cotton (51%) are the two main crop types (Vall et al., 2006). Harvest index (useful biomass/ total biomass) very much depends on the variety of each species used but is generally higher for maize (Grain HI ±0.52) than for cotton (Bolls HI ±0.33). In 2004 cotton yielded between 1.4 $t.ha^{-1}$ and 1.8 $t.ha^{-1}$, corresponding to a total biomass yield ranging between 4.2 $t.ha^{-1}$ and 5.4 $t.ha^{-1}$.

Knowing that our ovens yield approximately 30% (biochar/fresh biomass ratio) depending on pyrolysis temperature, there is a potential to produce between 1.2 $t.ha^{-1}$ and 1.6 $t.ha^{-1}$ of biochar per growing season for cotton. Similarly, for maize, there is a potential to produce a bit less biochar, between 0.7 $t.ha^{-1}$ and 1 $t.ha^{-1}$ (Vall et al., 2006).

Bibliography

Agegnehu, G. et al., 2016. Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of the Total Environment*, **543**, pp.295–306.

An, S. et al., 2010. Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest and shrub vegetation on the Loess Plateau, China. *Catena*, **81**(3), pp.226–233.

Bamminger, C. et al., 2014. Effects of biochar, earthworms, and litter addition on soil microbial activity and abundance in a temperate agricultural soil. *Biology and Fertility of Soils*, **50**(8), pp.1189–1200.

Bationo, A. et al., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems*, **94**(1), pp.13–25.

Biederman, L.A. & Harpole, S.W., 2013. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy*, **5**(2), pp.202–214.

Blackwell, P. et al., 2009. Biochar application for soil. In: Lehmann J. & Joseph S. (eds.): *Biochar for environmental management science and technology*. London: Earthscan, pp. 207–226.

Chan K.Y, and Xu, Z., 2009. Biochar: Nutrient Properties and Their Enhancement. In Lehmann J. & Joseph S. (eds.): *Biochar for environmental management science and technology*. London: Earthscan, p. 69

Cheng, C.H. et al., 2006. Oxidation of black carbon by biotic and abiotic processes. *Organic Geochemistry*, **37**(11), pp.1477–1488.

Cheng, C.H. et al., 2008. Stability of black carbon in soils across a climatic gradient. *Journal of Geophysical Research: Biogeosciences*, **113**(2), pp.1–10.

Cornelissen, G. et al., 2013. Biochar Effect on Maize Yield and Soil Characteristics in Five Conservation Farming Sites in Zambia. *Agronomy*, **3**, pp.256–274.

Crane-Droesch, A. et al. 2013. Heterogeneous Global Crop Yield Response to Biochar: A Meta-Regression Analysis. *Environmental Research Letters,* **8**.4 : 44049.

Cui, H.J. et al., 2011. Enhancing phosphorus availability in phosphorus-fertilized zones by reducing phosphate adsorbed on ferrihydrite using rice straw-derived biochar. *Journal of Soils and Sediments*, **11**(7), pp.1135–1141.

De Mendiburu, F., 2009. *Una herramienta de analisis estadistico para la investigacion agricola*. Tesis : Universidad Nacional de Ingenieria (UNI-PERU).

Deng, B. et al., 2016. Effects of Acacia seyal and biochar on soil properties and sorghum yield in agroforestry systems in South Sudan. *Agroforestry Systems*, **91**, pp.137–148.

Duku, M.H. et al., 2011. Biochar production potential in Ghana - A review. *Renewable and Sustainable Energy Reviews*, **15**(8), pp.3539–3551.

FAO, 2010. Enabling Agriculture to contribute to climate change mitigation. The Food and Agriculture Organization of the United Nation, Rome, Italy.

FAO, 2014. World Hunger map 2014. http://www.fao.org/3/a-i4033e.pdf, Consulted on the 02/06/2017

FAO, 2016. Boosting Africa's soils, From the Abuja Declaration on Fertilizers to a sustainable soil management framework for food and nutrition security in Africa by 2030. Land and Water Division (AGL) The Food and Agriculture Organization of the United Nations, Accra, Ghana.

FAO-Unesco, 1970. South America In: Soil map of the World IV.1-1 .1:5 000 000. Compiled by: FAO, Rome. Published by: Unesco, Paris, 1970.

Fox J. & Weisberg S., 2011. *An {R} Companion to Applied Regression*. 2nd ed. Thousand Oaks CA: Sage.

Gao, S. et al., 2016. Locally produced wood biochar increases nutrient retention and availability in agricultural soils of the San Juan Islands, USA. *Agriculture, Ecosystems and Environment*, **233**, pp.43–54.

Genesio, L. et al., 2012. Surface albedo following biochar application in durum wheat. *Environmental Research Letters*, **7**(1), p.14025.

Glaser, B. et al., 2000. Black carbon in density fractions of anthropogenic soils of the Brazilian Amazon region. *Organic Geochemistry*, **31**(7–8), pp.669–678.

Glaser, B., et al., 2001. The Terra Preta phenomenon – A model for sustainable agriculture in the humid tropic. *Naturwissenschaften,* **88**, 37-41.

Glaser, B. et al., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - A review. *Biology and Fertility of Soils*, **35**(4), pp.219–230.

Glaser, B. & Birk, J.J., 2012. State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (Terra preta de Indio). *Geochimica et Cosmochimica Acta*, **82**, pp.39–51.

Guo, J. & Chen, B., 2014. Insights on the molecular mechanism for the recalcitrance of biochars: interactive effects of carbon and silicon components. *Environmental Science & Technology*, **48**(16), pp.9103–9112.

Hardy, B. et al., 2016. Evaluation of the long-term effect of biochar on properties of temperate agricultural soil at pre-industrial charcoal kiln sites in Wallonia, Belgium. *European Journal of Soil Science*, **68**, pp.80-89.

Hopkins, W. G., 2003. *Physiologie Végétale*. 1st ed. Bruxelles: De Boeck.

Hottin, G. & Ouedraogo, O.F., 1976*Carte géologique de la république de Haute-Volta. . 1:1 000 000*. Boulogne, France : Direction général de la Géologie et des mines.

IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von

Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014, International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jeffery, S. et al., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems and Environment*, **144**(1), pp.175–187.

Jin, H., 2010. *Characterization of microbial life colonizing biochar and biochar amended soils*. Thesis: Cornell University, Ithaca, NY.

Juo, A.S.R. & Manu, A., 1996. Chemical dynamics in slash-and-burn agriculture. *Agriculture, Ecosystems and Environment*, **58**(1), pp.49–60.

Kaiser, K. & Guggenberger, G., 2000. The role of DOM sorption to mineral surfaces in the preservation of organic matter in soils. *Organic Geochemistry*, **31**(7–8), pp.711–725.

Khan, N. et al., 2014. Maturity indices in co-composting of chicken manure and sawdust with biochar. *Bioresource Technology*, **168**, pp.245–251.

Khodadad, C.L.M. et al., 2011. Taxa-specific changes in soil microbial community composition induced by pyrogenic carbon amendments. *Soil Biology and Biochemistry*, **43**(2), pp.385–392.

Kishimoto, S., & Sugiura, G., 1985. Charcoal as a soil conditioner. In: *Symposium on Forest Products Research, International Achievements for the Future*,**5**,pp.12-15

Kim, J.S. et al., 2007. Bacterial diversity of terra preta and pristine forest soil from the Western Amazon. *Soil Biology and Biochemistry*, **39**(2), pp.684–690.

Kjeldahl, J. 1883. Neue Methode zur Bestimmung des Stickstoffs in organischen Körpern, Z. *Anal. Chem*. 22, 366-382

Laird, D., 2008. The Charcoal Vision: A Win-Win-Win Scenario for Simultaneously Producing Bioeneger, Permanently Sequestering Carbon, while Improving Soil and Water Quality. *Agronomy Journal*, **100**(1), p.178.

Laird, D. et al., 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, **158**(3–4), pp.436–442.

Lal, R., 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science,* **304**, pp.1623-1627

Lau, A.C., et al., 1986. The electrokinetic properties of carbon black and graphitized carbon black aqueous colloids. *Colloids and Surfaces*, **18**, 93–104.

Lavelle, P., 1988. Earthworm activities and the soil system. *Biology and Fertility of Soils*, **6**(3), pp.237–251.

Lehman, J., Joseph., S., 2009. Biochar for Environmental Management: an introduction. In: Lehmann J. & Joseph S. (eds.): *Biochar for environmental management science and technology.* London: Earthscan, pp1-9

Lehmann, J. et al., 2009. Stability of Biochar in the Soil. In: Lehmann J. & Joseph S. (eds.): *Biochar for environmental management science and technology.* London: Earthscan, p 189

Lehmann, J. et al., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil*, **249**, pp.343–357.

Lehmann, J. et al., 2011. Biochar effects on soil biota - A review. *Soil Biology and Biochemistry*, **43**(9), pp.1812–1836.

Lehmann, J., 2007. A handful of carbon. *Nature*, **447**(7141), pp.143–144.

Liang, B. et al., 2006. Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal*, **70**(5), pp.1719–1730.

Liu, X. et al., 2013. Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data. *Plant and Soil*, **373**(1–2), pp.583–594.

Lin, Y. et al., 2012. Migration of dissolved organic carbon in biochars and biochar-mineral complexes. *Pesquisa Agropecuaria Brasileira*, **47**(5), pp.677–686.

Major, J. et al., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil*, **333**(1), pp.117–128.

Makoto, K. et al., 2010. Buried Charcoal Layer and Ectomycorrhizae Cooperatively Promote the Growth of Larix Gmelinii Seedlings. *Plant and Soil,* **327**(1), pp. 143–152.

Marnotte, P., 1984. Influence des facteurs agroécologiques sur le développement des mauvaises herbes en climat tropical humide . 7ème Coll. Int. Ecol. Biol.et Syst. des Mauvaises Herbes, Paris, France, COLUMA-EWRS

Mbagwu, J .S.C, & Piccolo, A., 1997. Effects of Humic Substances from Oxidized Coal on Soil Chemical Properties and Maize Yield *The Role of Humic Substances in the Ecosystems and in Environmental Protection*, **53**, pp.921–925.

MECV, 2011. Rapport final: Analyse Economique du secteur du cotton Lien Pauvreté et Environnement. Ministère de l'Environnement et du Cadre de Vie (MECV) du Burkina Faso

Mekuria, W. & Noble, A., 2013. The role of biochar in ameliorating disturbed soils and sequestering soil carbon in tropical agricultural production systems. *Applied and Environmental Soil Science*.

Metson, A.J., 1956. Methods of chemical analysis for soil survey samples. N.Z. Soil Bureau Scientific Report 10B

Meyer, S., et al., 2011. Technical, economical, and climate-related aspects of biochar production technologies: A literature review. *Environmental Science and Technology*, **45**(22), pp.9473–9483.

Mielki, G.F. et al., 2016. Iron availability in tropical soils and iron uptake by plants. *Revista Brasileira de Ciencia do Solo*, **40**, pp.1–14.

Murrell, P. 2005. *R Graphics*. Chapman & Hall/CRC Press.

Novak, J.M. et al., 2009. Characterization of Designer Biochar Produced At Different Temperatures and Their Effects on a Loamy Sand. *Annals of Environmental Science*, **3**(843), pp.195–206.

O'Neill, B. et al., 2009. Bacterial Community Composition in Brazilian Anthrosols and Adjacent Soils Characterized Using Culturing and Molecular Identification. *Microbial Ecology,* **58**(1), pp. 23–35.

Ogle, S.M. et al., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry*, **72**(1), pp.87–121

Peel, M.C. et al., 2006. Updated world map of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift*, **15**, pp.259–263.

Paris,O., et al., 2005. Decomposition and carbonisation of wood biopolymers – a microstructural study of softwood pyrolysis, *Carbon*, **43**, pp53–66

Rajkovich, S. et al., 2012. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biology and Fertility of Soils*, **48**(3), pp.271–284.

Raznikiewicz, H., et al., 1994. Impact of phosphorus fertilization and liming on the presence of arbuscular mycorrhizal spores in a Swedish long-term field experiment. *Swedish Journal of Agricultural Research*, **24**, 157–164.

Roth, C., 2014. *Micro-gasification: Cooking with gas from dry biomass, an introduction to concepts and application of wood-gas burning technologies for cooking*. 2nd ed. Obrigheim: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, pp.23-26

Rondon, M.A. et al., 2007. Biological nitrogen fixation by common beans (Phaseolus vulgaris L.) increases with bio-char additions. *Biology and Fertility of Soils*, **43**(6), pp.699–708.

Schlutter, T., 2014. *Geological Atlas of Africa: With Notes On Stratigraphy, Tectonics, Economic Geology, Geohazards and Geosites of Each Country*. 2nd ed. Berlin: Springer.

Schmidt, H. et al., 2014. Kon-Tiki flame curtain pyrolysis for the democratization of biochar production. *The Biochar Journal*, pp.14–24.

Schmidt, H. et al., 2015. Fourfold Increase in Pumpkin Yield in Response to Low-Dosage Root Zone Application of Urine-Enhanced Biochar to a Fertile Tropical Soil. Agriculture, **5**(3), pp.723–741.

Schmidt, M.W.I. & Noack, A.G., 2000. Black carbon in soils and sediments: Analysis, distribution, implications and current challenges. *Global Biogeochemical Cycles*, **14**(3), pp.777–793.

Steiner, C. et al., 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil*, **291**(1–2), pp.275–290.

Sun, J. et al., 2017. The molecular properties of biochar carbon released in dilute acidic solution and its effects on maize seed germination. *Science of the Total Environment*, **576**, pp.858–867.

Tiessen, H. et al., 1994. The role of soil organic matter in sustaining soil fertility. *Nature,* **371**,pp.783–785.

Tryon, E.H., 1948. Effect of charcoal on certain physical, chemical and biological properties of forest soils. *Ecological Monographs,* **18**, 81-115

Vall, E. et al., 2006. Rapport de projet: Situation agropastorale des villages de Koumbia et Waly (Burkina Faso) : diversité et pratiques. In: *Valoriser les savoirs locaux sur l'intégration agriculture élevage pour une gestion durable des écosystèmes des savanes subhumides de l'Afrique* - Centre International de Recherche-Développement sur l'Elevage en Zone Subhumide (Burkina-Faso) CIDRES.

Van Zwieten, L. et al., 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil*, **327**(1), pp.235–246.

Venegas, A., et al., 2016. Effect of ageing on the availability of heavy metals in soils amended with compost and biochar: evaluation of changes in soil and amendment properties. *Environmental Science and Pollution Research*, **23**(20), pp.20619–20627.

Wardle, D.A., et al., 2008. Response to Comment on “Fire-Derived Charcoal Causes Loss of Forest Humus.” *Science*, **321**(5894), pp.1295–1295.

WHO, 2016. Household air pollution and health- Fact sheet N°292 World Health organisation of the United Nations.

Wickham, H., 2009. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York

Wickham, H., 2011. The Split-Apply-Combine Strategy for Data Analysis. *Journal of Statistical Software*, **40**(1), 1-29.

Woolf, D. & Lehmann, J., 2012. Modelling the long-term response to positive and negative priming of soil organic carbon by black carbon. *Biogeochemistry*, **111**(1–3), pp.83–95.

Woolf, D. et al., 2010. Sustainable biochar to mitigate global climate change. *Nat. Commun*. 1:56 doi: 10.1038 / ncomms1053

Xiao, Q. et al., 2016. Sensitivity of soil water retention and availability to biochar addition in rainfed semi-arid farmland during a three-year field experiment. *Field Crops Research*, **196**, pp.284–293.

Yeboah, E. et al., 2016. Effect of Biochar Type and Rate of Application on Maize Yield Indices and Water Use Efficiency on an Ultisol in Ghana. *Energy Procedia*, **93**, pp.14–18.

Zhang, A. et al., 2010. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture, Ecosystems and Environment*, **139**(4), pp.469–475.

Zimmerman, A.R., et al., 2011. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry*, **43**(6), pp.1169–1179.

Annexes

Annex 1: European Biochar Certificate

Test report to order 11710993
No. 1020811001 page 1 / 3

eurofins | Umwelt

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Title:	**Test report to order 11710993**
Test report:	**No. 1020811001**
Project:	**No. 1020811**
Title of project:	**analysis of biochar**
Number of samples:	**1 sample**
Sample type:	**biochar**
Sampler:	**client**
Receipt of samples:	**2017-05-11**
Test period:	**2017-05-11 - 2017-05-29**
Annex:	**thermogravimetry**

The test results refer solely to the analysed test specimen. Unless the sampling was done by our laboratory or in our sub-order the responsibility for the correctness of the sampling is disclaimed. This test report is only valid with signature and may only be further published completely and unchanged. Extracts or changes require the authorisation of the EUROFINS UMWELT in each individual case.

Our General Terms & Conditions of Sale (GTCS) are applicable, as far as no specific agreements do exist. The GTCS are available on http://www.eurofins.de/umwelt/avb.aspx.

Accredited test laboratory according to DIN EN ISO/IEC 17025 notification under the DAkkS German Accreditation System for Testing. The accreditation shall apply for the tests listed in the certificate.

Freiberg, 2017-05-29

Hr. W. Homilius
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Annex 1- Test report from Eurofin laboratory of biochar according to EBC standards

Project: analysis of biochar

Analysis according to Biochar according to European Biochar Certificate

Parameter	Unit	LOQ	limits GW 1	limits GW 2	Method	ar	db
Sample designation						Biochar	
Lab-ID#						117040724	
water holding capacity (WHC)	% w/w				DIN EN ISO 14238, Anhang A (SB99 /f)	-	363,0
bulk density	kg/m³				DIN 51705 (FR-JE02)	130	-
specific surface area (BET)	m²/g				DIN 66137 / DIN ISO 9277 (SUIB /f)	-	287,2
true density	g/cm³				DIN 66137 / DIN ISO 9277 (SUIB /f)	-	1,75
total water	% w/w	0,1			DIN 51718 (FR-JE02)	5,3	-
ash content at 550°C	% w/w	0,1			analogue DIN 51719 (FR-JE02)	17,1	18,1
hydrogen	% w/w	0,1			DIN 51732 (FR-JE02)	1,11	1,17
carbon, total	% w/w	0,2	> 50	> 50	DIN 51732 (FR-JE02)	71,8	75,8
nitrogen, total	% w/w	0,05			DIN 51732 (FR-JE02)	0,87	0,92
oxygen, diff.	% w/w				DIN 51733, calculated (FR-JE02)	6,5	6,9
carbonate as CO2	% w/w	0,4			DIN 51726 (FR-JE02)	2,94	3,11
carbon, organic	% w/w				calculated (FR-JE02)	71,0	75,0
ratio H/C (molar)			< 0,6	< 0,6	calculated (FR-JE02)	0,18	0,18
ratio H/Corganic (molar)			< 0,7	< 0,7	calculated (FR-JE02)	0,19	0,19
ratio O/C (molar)			< 0,4	< 0,4	calculated (FR-JE02)	0,07	0,068
sulfur, total	% w/w	0,03			DIN 51724-3 (FR-JE02)	0,11	0,12
pH value (CaCl2)			≤ 10	≤ 10	DIN ISO 10390 (FR-JE02)	9,2	-
electrical conductivity	µS/cm	5			BGK Kapitel III. C2 (FR-JE02)	11100	-
salt content	g/kg	0,005			BGK Kapitel III. C2 (FR-JE02)	58,3	61,6
salt content calc. with bulkdensity	g/l	0,005			BGK Kapitel III. C2 (FR-JE02)	7,58	8,01
thermogravimetry TGA 950°C by N-Atm.					TGA 701 D4C (FR)	see annex	-
total inorganic carbon (TIC)	% w/w	0,1			DIN 51726 (FR-JE02)	0,8	0,8
Determination from the microwave digestion according to DIN 22022-1 (FR-JE02)							
arsenic (As)	g/t	0,8	< 13	< 13	DIN EN ISO 17294-2 (FR-JE02)	-	< 0,8
lead (Pb)	g/t	2	< 150	< 120	DIN EN ISO 17294-2 (FR-JE02)	-	<2
cadmium (Cd)	g/t	0,2	< 1,5	< 1	DIN EN ISO 17294-2 (FR-JE02)	-	<0,2
copper (Cu)	g/t	1	< 100	< 100	DIN EN ISO 17294-2 (FR-JE02)	-	21
nickel (Ni)	g/t	1	< 50	< 30	DIN EN ISO 17294-2 (FR-JE02)	-	2
mercury (Hg)	g/t	0,07	< 1	< 1	DIN 22022-4 (FR-JE02)	-	<0,07
zinc (Zn)	g/t	1	< 400	< 400	DIN EN ISO 17294-2 (FR-JE02)	-	12
chromium total (Cr)	g/t	1	< 90	< 80	DIN EN ISO 17294-2 (FR-JE02)	-	2
boron (B)	mg/kg	1			DIN EN ISO 17294-2 (FR-JE02)	-	30
manganese (Mn)	mg/kg	1			DIN EN ISO 17294-2 (FR-JE02)	-	44
Determination from the melting digestion on ash 550°C according to DIN 51729-1/ -11 - referred to ash (FR-JE02)							
iron calculated as Fe2O3	% w/w	0,1			DIN EN ISO 11885 (FR-JE02)	-	2,0
calcium calculated as CaO	% w/w	0,1			DIN EN ISO 11885 (FR-JE02)	-	19,4
potassium calculated as K2O	% w/w	0,1			DIN EN ISO 11885 (FR-JE02)	-	27,6
magnesium calculated as MgO	% w/w	0,1			DIN EN ISO 11885 (FR-JE02)	-	3,9
sodium calculated as Na2O	% w/w	0,1			DIN EN ISO 11885 (FR-JE02)	-	0,7
phosphorus calculated as P2O5	% w/w	0,1			DIN EN ISO 11885 (FR-JE02)	-	4,1
sulfur calculated as SO3	% w/w	0,1			DIN EN ISO 11885 (FR-JE02)	-	1,7
silicon calculated as SiO2	% w/w	0,1			DIN EN ISO 11885 (FR-JE02)	-	21,9

Project: analysis of biochar

Analysis according to Biochar according to European Biochar Certificate			limits		Sample designation	Biochar	
					Lab-ID#	117040724	
Parameter	Unit	LOQ	GW 1	GW 2	Method	ar	db
Determination from the melting digestion on ash 550°C according to DIN 51729-1/ -11 - referred to original substance (FR-JE02)							
phosphorus	mg/kg				DIN EN ISO 11885 (FR-JE02)	-	3200
magnesium	mg/kg				DIN EN ISO 11885 (FR-JE02)	-	4200
calcium	mg/kg				DIN EN ISO 11885 (FR-JE02)	-	25000
potassium	mg/kg				DIN EN ISO 11885 (FR-JE02)	-	41000
sodium	mg/kg				DIN EN ISO 11885 (FR-JE02)	-	940
iron	mg/kg				DIN EN ISO 11885 (FR-JE02)	-	2500
silicon	mg/kg				DIN EN ISO 11885 (FR-JE02)	-	18000
sulfur	mg/kg				DIN EN ISO 11885 (FR-JE02)	-	1300
Determination from the toluene extract							
naphthalene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	1,0
acenaphthylene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	< 0,1
acenaphthene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	< 0,1
fluorene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	< 0,1
phenanthrene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	0,5
anthracene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	0,1
fluoranthene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	0,1
pyrene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	0,1
benz(a)anthracene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	< 0,1
chrysene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	< 0,1
benzo(b)fluoranthene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	0,1
benzo(k)fluoranthene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	0,1
benzo(a)pyrene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	< 0,1
indeno(1,2,3-cd)pyrene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	0,1
dibenz(a,h)anthracene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	0,2
benzo(g,h,i)perylene (toluene extr.)	mg/kg	0,1			analogue DIN EN 15527 (FR-JE02)	-	< 0,1
sum PAH (EPA) (toluene extr.)	mg/kg		< 12	< 4	calculated (FR-JE02)	-	2,30

Annotation:
GW 1: basic quality grade (refered to dry basis)
GW 2 : premium quality grade (refered to dry basis)

ar - as received = fresh matter
db - dry basis = dry matter

EUROFINS UMWELT is not liable for acuracy of the cited limits.

Explanations on Locations and Accreditations
The parameters identified by SB99 have been performed by the laboratory GEOS Freiberg (Halsbrücke).

The parameters identified by FR have been performed by the laboratory EUROFINS Umwelt Ost GmbH (Bobritzsch-Hilbersdorf).
The accreditation code JE02 identifies the parameters accredited according to DIN EN ISO/IEC 17025:2005 D-PL-14081-01-00.

The parameters identified by SUIB have been performed by the laboratory TU Bergakademie Freiberg (Freiberg).

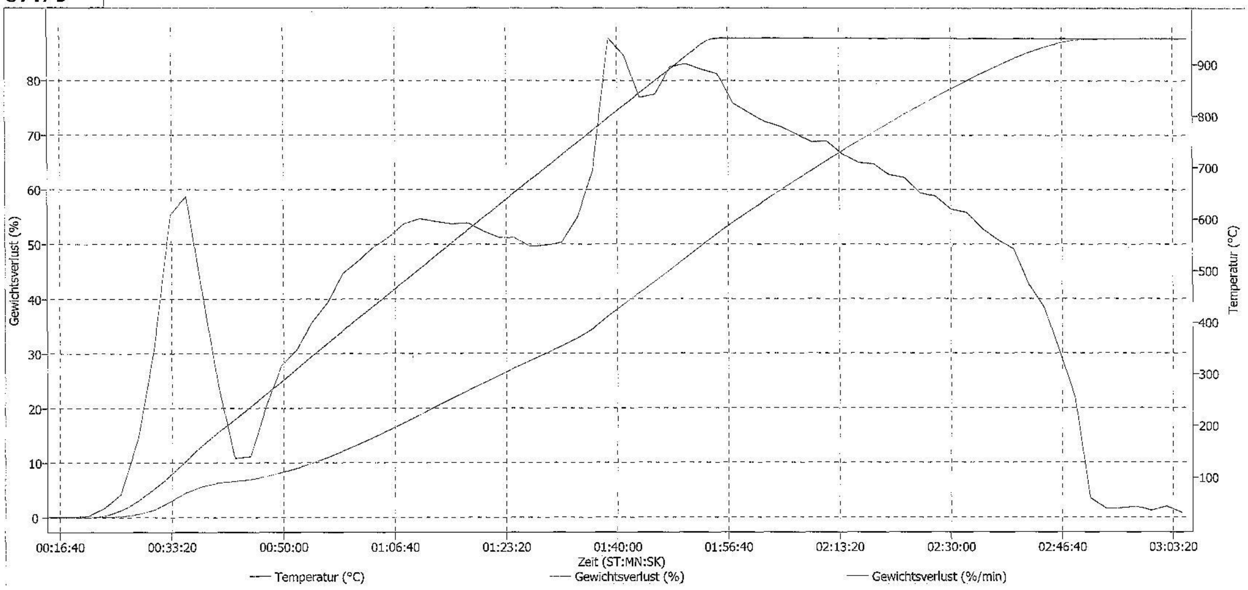
f: The analysis of this parameter was subcontracted externally (own accreditation not applicable).

TGA 701

5/24/2017 10:49:40 AM

Name	Position	Kommentar	Methode	Ausgangsgewicht	Wasser	Asche 550	Asche 775	Asche 815	Asche 975	W 40	GV 200	GV 450	GV 360	GV 850	TGA 950	Datum der Analyse
117040724	2	gd6s	TGA 950 N (Pflanzenkohl	0.9791											87.79	Abgebroche

TGA 950
87.79

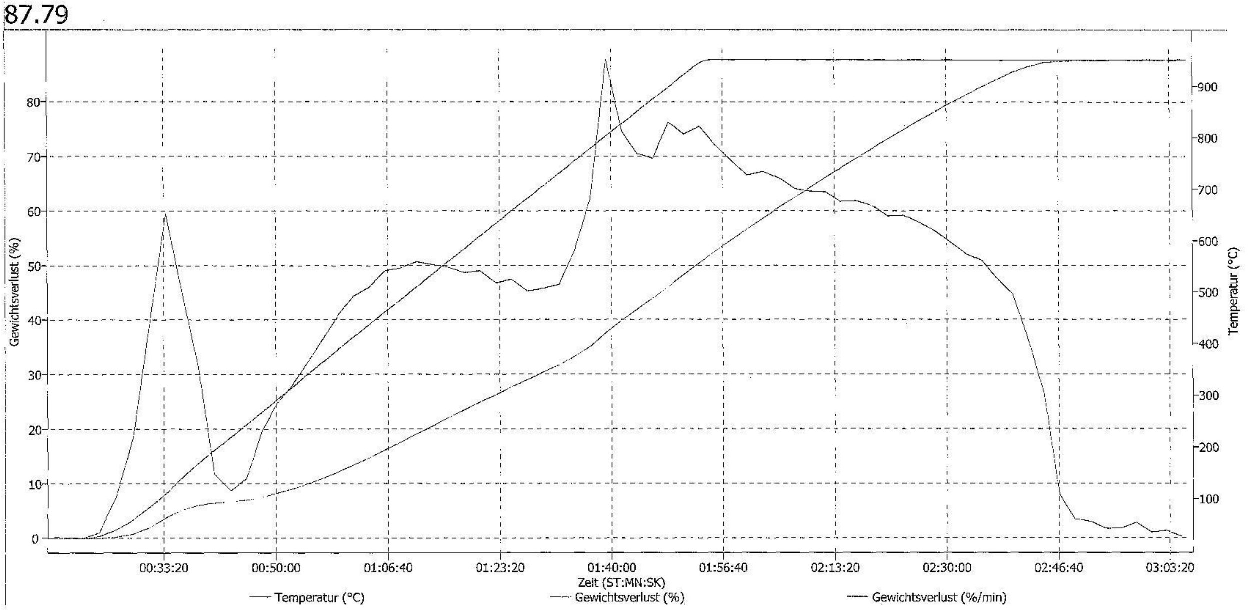


TGA 701

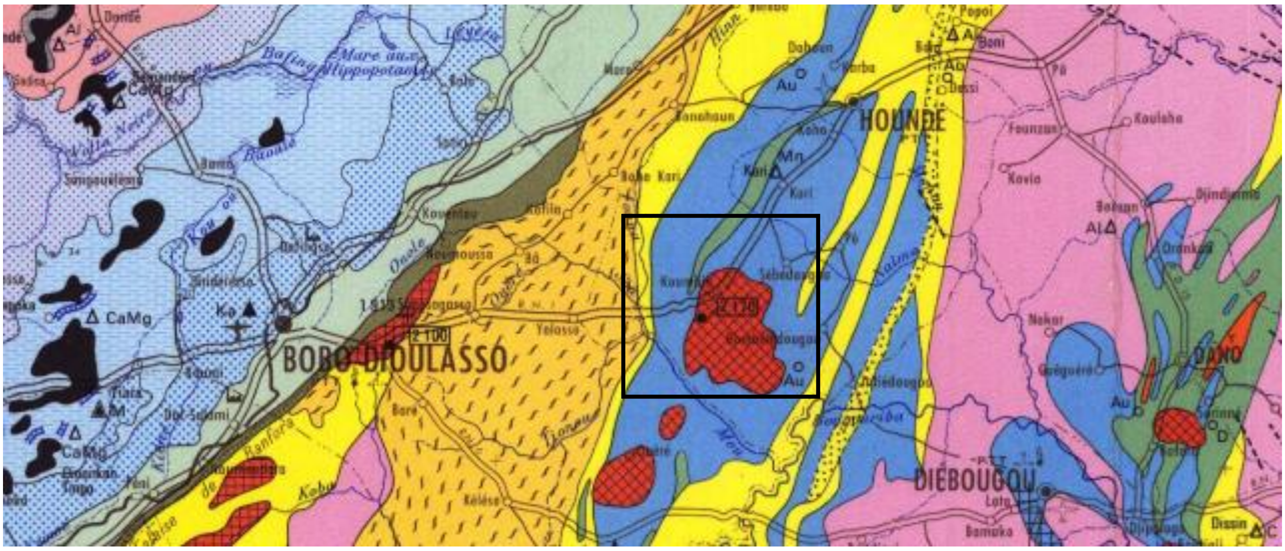
5/24/2017 10:50:15 AM

Name	Position	Kommentar	Methode	Ausgangsgewicht	Wasser	Asche 550	Asche 775	Asche 815	Asche 975	W 40	GV 200	GV 450	GV 360	GV 850	TGA 950	Datum der Analyse
117040724	6	gd6s	TGA 950 N (Pflanzenkohl	0.9397											87.79	Abgebroche

TGA 950
87.79

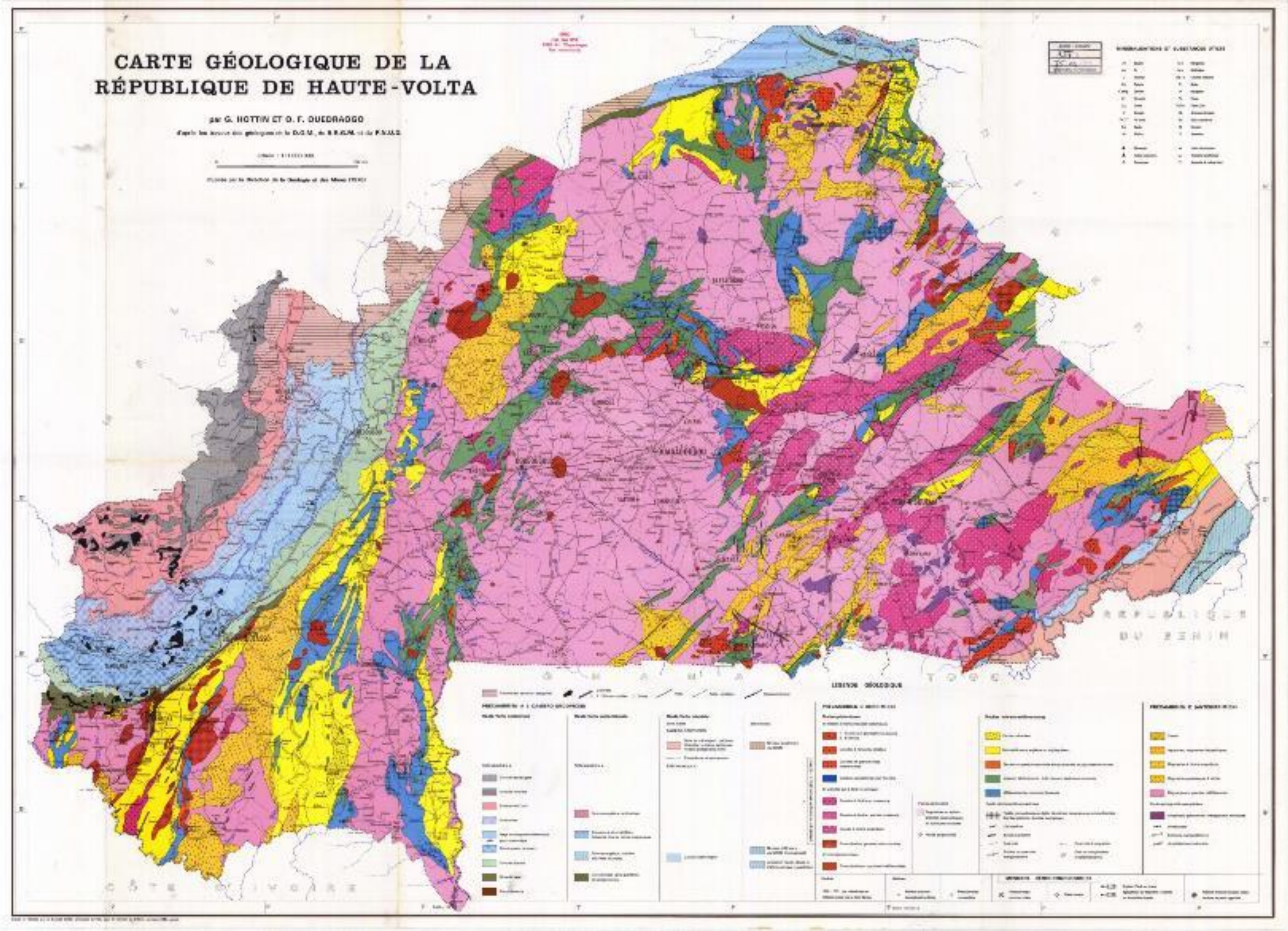


Annex 2: Zoom on the geological map of Burkina Faso: Koumbia



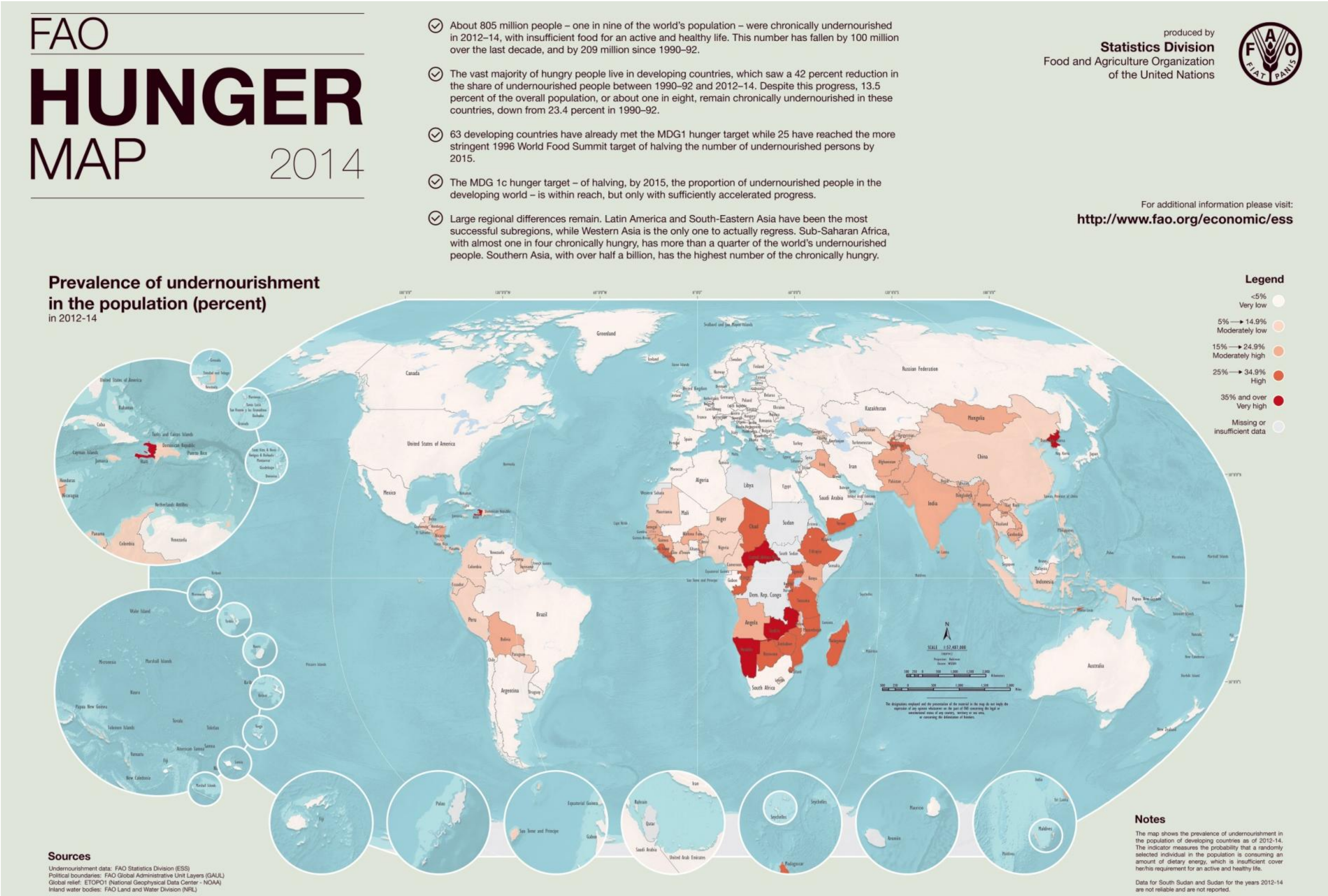
Annex 2 - Geological map of the "République de Haute-Volta". Source: Hottin et Ouedraogo (1976) - Legend and overall map available in Annex 3.

Annex 3: Geological map of Burkina Faso



Annex 3 - Overall geological map of Burkina Faso. Source: Hottin et Ouedraogo (1976)

Annex 4: World Hunger Map of the FAO

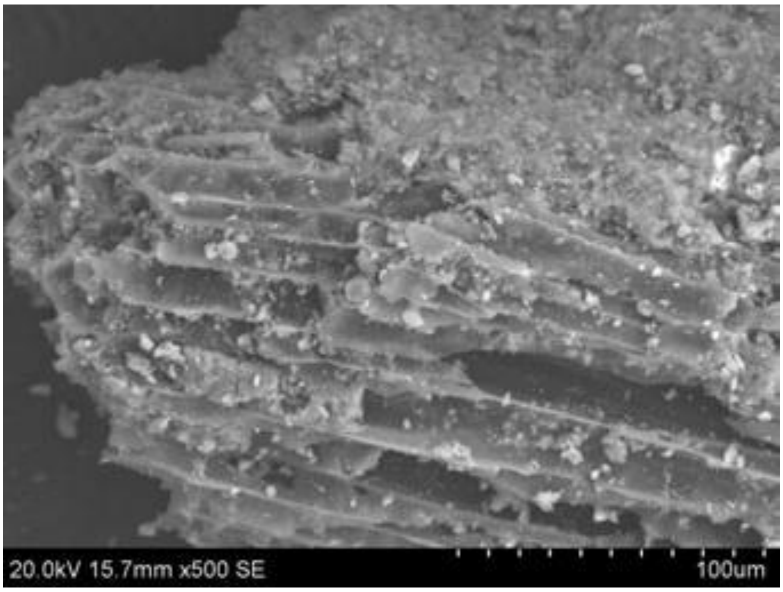


Annex 4 - World hunger map. Source: FAO (2014)

Annex 5: Picture of plot distribution and their albedo

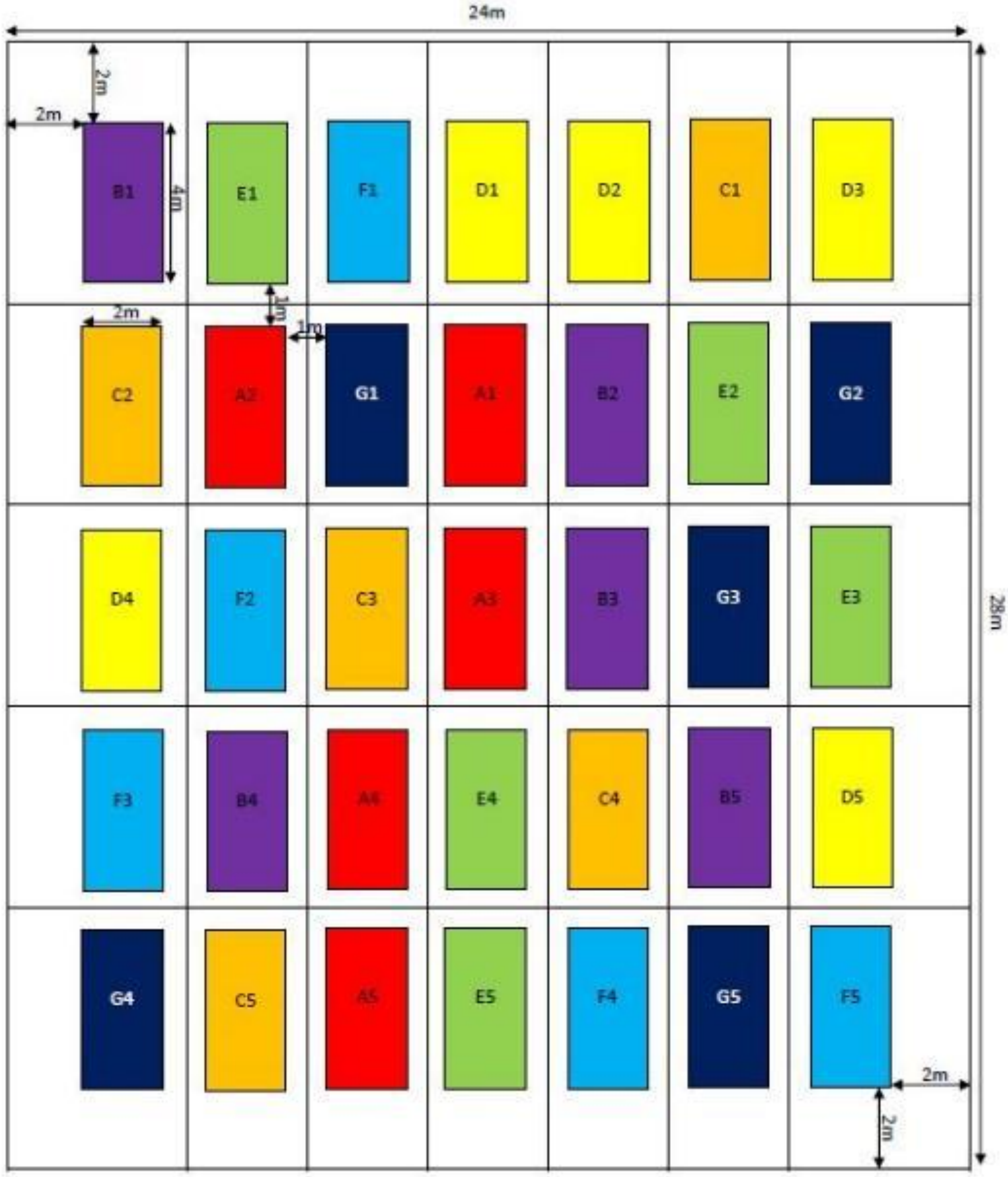
Annex 5 - Plot appearance with the addition of biochar and modified albedo. Source: David Lefebvre

Annex 6: Microscopic view of biochar and its interaction with the mineral phase



Annex 6 - Microscopic view of the biochar structure. Pores are particularly visible. Lighter toned spots potentially correspond to the mineral phase. Source: Lin et al., 2012

Annex 7: Plot distribution on the trial site



Annex 7 - Completely randomized plot distribution on the trial site. Source: Victor Burgeon protocol

Annex 8: Detailed experimental protocol

Protocole expérimental: Etude de l'impact du biochar comme amendement dans les sols tropicaux du Burkina Faso

Introduction :

Le but du document ci présenté est de décrire le procédé expérimental nécessaire à l'étude de l'effet du biochar comme amendement dans les sols tropicaux du Burkina Faso. Cette étude s'inscrira dans le cadre de mon travail de fin d'études dans le but d'obtenir le titre de bioingénieur. Il permettra également de fournir des données préliminaires dans le cadre du projet BIOPROTECHSOL mené en collaboration entre l'université polytechnique de Bobo-Dioulasso (UPB) et la faculté de Gembloux Agro Bio Tech (ULg).

Objectifs des essais :

L'objectif des essais qui seront menés au sud de Houndé (province de Tuy) est de prouver l'intérêt tant agronomique, en termes de rendement en biomasse d'une culture, que pédologique en termes de fixation des éléments lors d'un amendement en biochar. Pour ce faire, les variables étudiées sont les suivantes :

- La quantité de biochar amendé
- La quantité de fertilisant de type NPK amendé

Pour permettre d'étudier l'effet de ces variables, les analyses suivantes seront effectuées sur des échantillons de sols récoltés avant et après la culture :

- Le dosage des éléments biodisponibles par extraction à l'EDTA
- Le dosage de la MO (COT)
- Acidité/Bases échangeables

En ce qui concerne la culture en elle-même, le rendement de celle-ci sera étudié en fonction du traitement qui lui sera appliqué. Par la suite afin de connaitre la raison d'une éventuelle augmentation du rendement tout en faisant le lien avec le contenu en éléments disponibles de la matrice du sol, une analyse chimique de la constitution de la plante pourra être mené.

- Quantification des éléments en présences: Échantillon de plantes (Ca, Mg, K, N, P, Zn, Fe, Mn)
- Quantification des éléments en présences: Échantillon de maïs fruit (Ca, Mg, K, N, P, Zn, Fe, Mn)

Matériel nécessaire:

Matériel pour échantillonnage:

- Tarière pédologique
- Sac de récolte de terre en plastique (+ de quoi nommer les échantillons)
- GPS
- Couteau pédologique
- Brouette

- Seau
- Pelle

Matériel pour traitements du champ et pyrolyse:

- 5 kg d'amendement NPK
- Quantité de compost suffisante pour amender 400 m²
- Quantité d'urée suffisante pour amender 400 m²
- 2 tonnes de MS de tige de coton
- Balance (1-100Kg)

L'accès à un point d'eau courante est également crucial pour permettre un refroidissement rapide des fours à charbon et l'enchainement des fournées.

Calendrier de la recherche :

Les essais auront lieu en champ sur des parcelles expérimentales de huit mètres carrés (2m x 4m) de surface et sous une culture de coton. Le semis de celui-ci ayant lieu mi-juin, un premier voyage sera effectué dans le but de pyrolyser la matière organique d'intérêt en quantité suffisante et de l'amender selon différents traitements au sol. Lors de ce premier voyage, une première série d'échantillons de sols sera également prélevée ce qui permettra de déterminer une *baseline* pédologique des caractéristiques des sols étudiés.

Lors des mois de juin, juillet, août et début septembre, la gestion de la culture sera exécutée par les gestionnaires de la ferme expérimentale de l'UPB. Certains relevés d'humidité du sol pourraient également être effectués par l'étudiant partenaire de l'université de Bodo-Dioulasso permettant de la sorte d'étudier la capacité de rétention en eau du charbon. Un suivi de l'évolution de la croissance végétative serait également souhaitable tant en termes qualitatifs (photos) que quantitatif (mesures de la hauteur moyenne de la culture par parcelle, taux de levée etc.).

A la fin de la culture, fin septembre/mi-octobre en fonction de l'avancement de la culture, un nouveau voyage sera organisé. Plusieurs mesures devront alors être effectuées, à savoir :

- Le rendement en biomasse (totale)
- Le rendement en termes de récolte

Les échantillons récoltés seront les suivants:

- Échantillon composite de la biomasse non utile (plante)
- Échantillon composite de la biomasse utile (grain de maïs)

Par la suite les échantillons de sols rapportés au laboratoire de pédologie seront analysés à partir de janvier 2017.

Facteurs étudiés :

Avant le semis, la terre sera travaillée selon les habitudes des fermiers locaux et de la même manière. Il conviendra alors de trouver sur place une manière d'incorporer selon les quantités choisies le biochar au sol. Deux quantités différentes de biochar seront étudiées, 10 tonnes/ha et 30 tonnes/ha. Par la suite, des engrais NPK, de l'urée et de la MO fraiche seront également apportés. Un minimum de 5 répétitions par traitement sera mis en place. Des parcelles témoins seront également mises en place afin de permettre une quantification réelle de l'effet des traitements. Le tableau ci-dessous reprend une synthèse des différents traitements réalisés.

traitement	Type M.O	Culture	Dose Biocharbon (Kg/m²)	Dose de NPK (g/m²)	Dose d'urée (g/m²)	Nombre de répétitions	Surface totale des parcelles par traitement (m²)	Quantité totale de NPK (g)	Quantité totale d'Urée (g)	Quantité totale de biochar (Kg)
A	Coton	Mais	1	15	5	5	40	600	200	40
B	Coton	Mais	1	10	5	5	40	400	200	40
C	Coton	Mais	3	15	5	5	40	600	200	120
D	Coton	Mais	3	10	5	5	40	400	200	120
E	TEMOINS	Mais	0	15	5	5	40	600	200	0
F	TEMOINS	Mais	0	10	5	5	40	400	200	0
G	TEMOINS	Mais	0	0	0	5	40	0	0	0
					Somme	35	280	3000	1200	320

La quantité totale de biochar nécessaire est de 320 kg. D'après la littérature avec le type de four que nous utilisons, nous pouvons nous attendre à un rendement en masse de 15% à 22%. Obtenir une telle quantité de biochar est donc faisable pour autant que trois fours soient disponibles et fonctionnels. Deux fournées seront également nécessaires par jour. Les calculs de coûts ci-dessous sont estimés pour des prix belges. Au Burkina Faso la construction de tels fours sera sans doute moins coûteuse:

	Prix par four (€)	Nombre de fours	Coût total (€)
Prix max (Std. Belge)	170	3	510
Prix min (Std. Belge)	110	3	330

Dispositif expérimental :

L'espace entre les parcelles permettra de limiter l'influence que les parcelles peuvent avoir les unes sur les autres. La distance d'un mètre est importante, par ailleurs, les parcelles étant déjà petites, cette distance permettra de ne pas devoir éliminer une bande tampon autour de chaque parcelle (ce qui est de coutume en statistique pour éviter les effets de bord). Cette distance facilitera aussi la distinction des parcelles lors de l'application des traitements. À défaut d'hétérogénéité du champ notable (effet de pente, vent dominant, types de sols, etc.), auquel cas ce protocole sera revisité, les parcelles seront placées de manière complètement aléatoire.

Conclusion

Ce protocole expérimental vise à mettre en place l'expérimentation précédant la culture. Par la suite un deuxième protocole sera établi pour ce qui concerne la visite en fin de culture. Ce deuxième protocole sera alors établi avec une meilleure connaissance du terrain permettant une approche expérimentale plus fondée.