Comparative study of biochar amendment effects on nutrient cycling in contrasting pedological context of Koumbia, Burkina Faso

Auteur : Maisonnier, Alexandre
Promoteur(s) : Cornelis, Jean-Thomas; Burgeon, Victor
Faculté : Gembloux Agro-Bio Tech (GxABT)
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List of abbreviations

AAS – Atomic Absorption Spectrometry
AEC – Anion Exchange Capacity
Al – Aluminium
AV1 – Analysis of Variance with one factor
AV2 – Analysis of Variance with two factors
AV3 – Analysis of Variance with three factors
BUNASOL – Bureau National des Sols (Burkina Faso)
Ca – Calcium
CEC – Cation Exchange Capacity
CH_4 – Methane
CO_2 – Carbon Dioxide
$CO_{2\text{-eq}}$ – Carbon Dioxide Equivalent
CSB – Cotton Stalks Biochar
EBC – European Biochar Certificate
FLC – Sol ferrugineux lessivé à concrétions
FLIPP – Sol ferrugineux lessivé induré peu profond
GHG – Greenhouse Gases
HPGS – Sol hydromorphe peu humifère à pseudogley de surface
K – Potassium
KUE – Potassium Use Efficiency
LSD – Least Significant Difference
Mg – Magnesium
Mn – Manganese
N – Nitrogen
N_2 – Dinitrogen
N_2O – Nitrous Oxide
Na – Sodium
NH_3 – Ammonia gas
NH_4^+ – Ammonium
$N\text{-}NH_4^+$ – Ammonium Nitrogen
$N\text{-}NO_3^-$ – Nitrate Nitrogen
NO_3^- – Nitrate
NPK – Nitrogen, Phosphorus and Potassium fertilizer
NUE – Nitrogen Use Efficiency
OM – Organic Matter
P – Phosphorus
PUE – Phosphorus Use Efficiency
RHB – Rice Husks Biochar
SDG – Sustainable Development Goals

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Section I: Article

Abstract

Interest in biochar in the scientific community is rising, both for its potential to mitigate climate change and for its agronomic properties. However, few studies focused on its impacts on nutrient cycling as a function of pedodiversity.

In this study, three contrasted soil types (FLIP: epipetric Plinthosol, FLC: ferric Lixisol, HPGS: eutric Gleysol) from the region of Koumbia in Burkina Faso were selected to conduct a pot experiment to determine the effects of a of urine-enhanced biochar amendment (2.5 t ha^{-1}) on N, P and K nutrient dynamics and their impact on biomass production in a maize crop (*Zea mays* L.). Three different biochar amendment modalities (cotton stalks biochar: C, rice husks: R, and control: T) and two NPK fertilization rates (100 and 150 kg ha^{-1}) were considered. The amounts of nutrients supplied by biochar, contained in soils, lost by leaching and uptaken by plants were assessed in order to determine the impacts of the different treatments on the N, P and K cycles in a tropical agroecosystem.

Results showed variable responses to the biochar amendment depending on the soil type. Biochar had the smallest effect on FLIPP soils, but still increased above-ground biomass up to 43% with treatment R-150. Treatment C-150 improved biomass production by 85% in FLC soil, and R-150 by 63% in HPGS soils, all compared to the reference pots with conventional farming practices (T-150). These findings were explained by the changing nutrient dynamics caused by biochar amendment, which shows that a moderate supply of biochar can lead to a substantial impact on yield and to an improved nutrient use efficiency.

Key words: Burkina Faso, enhanced biochar, nutrient cycling, pedodiversity, tropical soils.

Résumé

L'intérêt pour le biochar dans la communauté scientifique est croissant, à la fois pour son potentiel d'atténuation du changement climatique et pour ses propriétés agronomiques. Cependant, peu d'études se sont concentrées sur ses impacts sur les cycles des nutriments en fonction de la pédodiversité.

Dans cette études, trois types de sols contrastés (FLIPP : Plinthosol épipétrique, FLC : Lixisol ferrique, HPGS : Gleysol eutrique) de la région de Koumbia au Burkina Faso ont été utilisés afin de mener une expérience en pot visant à déterminer les effets d'un amendement en biochar activé à l'urine (2,5 t ha^{-1}) sur les cycles des nutriments N, P et K et leurs impacts sur la production de biomasse d'une culture de maïs (*Zea mays* L.). Trois différentes modalités d'amendement en biochar (biochar de tiges de coton : C, de balles de riz : R, et témoin : T) et deux taux de fertilisation en NPK (100 et 150 kg ha^{-1}) ont été considérées. Les quantités de nutriments apportées par le biochar, contenues dans le sol, perdues par lixiviation et absorbées par les plantes ont été déterminées afin d'évaluer l'impact des différents traitements sur les cycles des éléments N, P et K au sein d'un agroécosystème tropical.

Les résultats ont montré des réponses variables à l'amendement en biochar selon les types de sols. Le biochar a eu un impact plus faible sur les sols FLIPP, mais a tout de même augmenté la biomasse aérienne jusqu'à 43% avec le traitement R-150. Le traitement C-150 a amélioré la production de biomasse de 85% dans les sols FLC, et R-150 de 65% pour les sols HPGS, par rapport aux pots de référence amendés selon les pratiques agricoles conventionnelles (T-150). Ces résultats sont expliqués par un changement de dynamiques des nutriments engendré par l'amendement en biochar, ce qui montre qu'un apport raisonné en biochar peut avoir un impact important sur le rendement et sur l'efficacité de l'utilisation des nutriments.

Mots clefs : Burkina Faso, biochar activé, cycle des nutriments, pédodiversité, sols tropicaux.

I. Introduction

Global warming has already reached 1°C above pre-industrial levels (Allen *et al.*, 2018). Under the Paris Agreement on Climate Change in 2015 (COP 21), 195 countries committed to contain the global warming well below 2°C above pre-industrial levels. However, it seems that these goals are unlikely to be fulfilled. Indeed, Raftery et al. (2017) estimated that the probability to restrain the rise of global temperature to 2°C is only 5%. Therefore, strong actions and policies must be carried out in order to mitigate climate change.

In addition to this issue, world hunger has been on the rise again since 2014, after several decades of continuous decline. In fact, the number of undernourished people worldwide climbed back to 821 million in 2017, after falling to 784 in 2014 (FAO *et al.*, 2018). Regarding children under the age of 5, 50 million of them are facing emaciation. Moreover, 151 million are dealing with growth delay, in other words 22% of them.

Although these worldwide issues are highly concerning, they can be even more exacerbated at the local scale. Indeed, Burkina Faso in West Africa is facing severe food insecurity. Between 2015 and 2017, 21.3% of Burkinabe people suffered from undernourishment. In 2017, 27.3% of children under 5 years have been stunted in growth (FAO *et al.*, 2018). Though these prevalences tend to decline, they remain worrisome and far from the government's objectives (Ministère de la Santé du Burkina Faso, 2016). Moreover, West Africa is going to face with full force the impacts of climate change, notably with a mean temperature expected to rise by 1.7 to 4.7°C by 2090 (Roudier *et al.*, 2011). Agriculture will also be severely impacted. Besides the loss of arable lands, yields are expected to decrease by 18% in the Sudano-Sahelian zone and by 13% in the Guinean zone (Roudier *et al.*, 2011).

The recent interest in biochar, a product of biomass pyrolysis, stems from the fact that it is a potential response element to these two issues, which are climate change and food insecurity. Woolf et al. (2010) estimated that it has the potential to abate carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions up to 1.8 Gt CO_2-C equivalent annually, in other words 12% of current anthropogenic GHG emissions. Biochar is indeed enriched in aromatic carbon, which is highly recalcitrant and can thus enhance carbon sequestration in soils. In addition, biochar can significantly offset GHG emissions from soils, notably by absorbing ammonium, preventing its loss through volatilization and thus the release of nitrous oxide (N_2O), which has a global warming potential approximately 300 times greater than CO_2 (Lehmann, 2007; Cayuela *et al.*, 2013; Stavi and Lal, 2013).

Biochar is also known for improving crop yields, especially on sandy weathered soils of the tropics (Jeffery *et al.*, 2011; Spokas *et al.*, 2012; Biederman and Stanley Harpole, 2013). In fact, biochar can improve physico-chemical properties of soils in various ways, including increasing soil pH and thus nutrient availability in acidic soils, by enhancing water and nutrient retention, or as a nutrient provider (Glaser, Lehmann and Zech, 2002; Lehmann *et al.*, 2003; Verheijen *et al.*, 2009). In addition, it is commonly produced out of crop residues that would otherwise be burnt on field for a short-term effect only, while biochar's impact can last for several years (Lehmann *et al.*, 2002; Major, Rondon, *et al.*, 2010).

The fertility of west African soils tend to decline, notably due to their high annual nutrient depletion rates (Sanchez, 2002). Therefore, biochar shows a high potential in country such as Burkina Faso, where it could be an efficient way to improve crop yields in a sustainable way, by optimizing nutrient cycles and enhancing fertilizer efficiency. However, few or no studies focused the impact of biochar on nutrient cycles as a function of pedodiversity in West Africa. In addition, most studies are based on high biochar amendment rates, which could not be achievable by local farmers. Thus, this study aims to determine the effect of a reasoned amendment in biochar on N, P and K cycles in a contrasted pedological context in Burkina Faso, in order to understand more in-depth its impact on crop yields.

To do so, a pot experiment was conducted. The purpose was to ensure full control of the experimental conditions and to set up a leachate collection system. Thus, nutrient balances for the plant, soil and leaching compartments could be determined, in order to understand the impact of biochar and fertilization on the distribution of nutrient flows among them.

To allow the study of the effects of pedodiversity in combination with different biochars, three contrasted soil types from the Koumbia region in Burkina Faso where chosen. Maize (*Zea mays* L.) was used as it is a major food crop in Burkina Faso. In addition, its growth cycle is quite short, especially for the Barka variety which was used in this study (80 days). In addition, reasoned biochar amendments (2.5 t ha^{-1}) were chosen, in order remain within the ranges of what could be applied by local farmers.

Based on the current knowledge we hypothesize that biochar amendments will have the most positive effects on FLIPP soils. Indeed this type of soil is the most highly weathered among those studied and hence gives most room for improvement (Crane-Droesch *et al.*, 2013; Jeffery *et al.*, 2015).

Furthermore, we expect that biochar will reduce nutrient loss by leaching, thus optimizing the nutrient use efficiency, accordingly to literature (Major *et al.*, 2011; Biederman and Stanley Harpole, 2013; Laird and Rogovska, 2015).

II. Material & Methods

1. Soil sampling

1.1. Sampling sites

Soils were sampled at three different sampling sites on January 28 and 29, 2019, in Koumbia, province of Tuy, Burkina Faso, about 70 kilometers east of Bobo-Dioulasso. Koumbia is part of the Sudano-Sahelian climatic zone, within which mean annual rainfall varies from 600 to 900 mm. Precipitations are concentrated during the wet season, which lasts for four to five months, usually between May and September (Ouédraogo, 2012). The ecosystem in Koumbia is described as a shrub savannah or as a trees savannah, according to Aubréville's (1957) classification. Mean temperature in Koumbia is 28°C.

The three types of soil sampled are as follows:

- FLIPP, for *"sol ferrigineux lessivé peu profond"* as mentioned in the local soil classification BUNASOL which is based on CPCS (1967). In the FAO soil classification, it corresponds to an epipetric Plinthosol (WRB, 2015). This type of soil possesses a plinthic (cemented) horizon between 20 and 40 cm deep. It is extremely weathered and contains precipitated iron oxides. Superficial, sandy and poor, this soil is difficult to manage.
- FLC, for *"sol ferrigineux lessivé à concrétions"* according the BUNASOL classification, or ferric Lixisol in the WRB classification system. This type of soil, such as FLIPP, are formed with an acidic parent material enriched in quartz (Dabin and Maignien, 1979). Enriched in clay in its subsoil, it also contains iron concretions in a ferralic horizon governed by low activity clays and sand/silt fractions. It is usually acidic (pH between 5.5 and 6.5) with low CEC (Pallo and Thiombiano, 1989). It is also a poor soil which needs to be managed in order to grow crops.
- HPGS, for *"sol hydromorphe peu humifère à pseudogley de surface"*, or eutric Gleysol. This soil is influenced by the presence of excess water, leading to anaerobic or anoxic conditions, usually due to its topographic position downhill (Dabin and Maignien, 1979). This lack of oxygen results in reducing conditions, where soil can develop gleyic properties. This type of soil is usually richer than the ones mentioned above.

All soils were cultivated under the 2-year cotton-maize rotation. The soils physico-chemical properties of similar soils were described by Drissa Cissé and are shown in Annex 1 and Annex 2.

1.2. Sampling method

For each of the soil types, 4 sampling areas of about 1 m² were randomly selected in their respective fields. The crop mounds were removed prior to sampling because their nature is not precisely known. The surface was then levelled before the sampling began. For the FLC soil, two horizons were sampled: the E horizon from surface to a 15 cm depth, and the Bt horizon from 15 to 20 cm deep. Two horizons were also collected for the HPGS soil, from 0 to 10 cm deep and from 10 to 20 cm deep. For the FLIPP soil, only one horizon was sampled, from the surface to the plinthic horizon, at approximately 30 cm deep. For each of these soil types, the distinctions between the different horizons were always clear in the field.

2. Biochar production and enhancement

Biochar was produced from two different types of crop residues, namely rice husks and cotton stalks. A Top-Lit UpDraft (TLUD) furnace was used to pyrolyze the biomass. In this type of furnace, the temperature working temperature is between 500 and 600°C. Its biochar yield is about 30% of the dry biomass input. Both biochars were then enhanced by maceration in zebu urine for 48 hours under ambient conditions. They were then oven-dried at 40°C for 5 days.

3. Experiment set-up

3.1. Soil columns preparation

For each horizon, all the collected samples were first roughly crushed to break up the clods and were then homogenized. The samples were not screened to ensure that they remain representative of the field reality. For instance, the FLIPP soil contains a high proportion of large iron oxide concretions, which would have been removed.

9 L pots were used for cultivation. Their larger diameter was 27 cm, their height was 20 cm, and their base diameter was 15 cm. Prior to filling the pots, soil samples were crushed by hand with a traditional mortar, in order to break up the smaller clods. As the pots were filled, packing was carried out in order to achieve a density close to that under field conditions. The layout of in-situ horizons was maintained in the soil columns. Thus, FLC pots were first filled with 5 cm of Bt horizon, then covered with 15 cm of E horizon. For HPGS pots, samples from 10 to 20 cm deep were first introduced up to half of the pots, then the rest was filled with samples from 0 to 10 cm deep. For the FLIPP soil, only one horizon was collected, so the pots were entirely filled from it. Once completed, the soil columns were watered until they reached saturation.

3.2. Cultivation

The maize variety used was Barka. It is drought tolerant and has a very short growth cycle of 80 days (Sanou, 2007). Five seeds were sowed equidistantly at about 3 cm depth in each pot on February 14, 2019 (D+0). 11 days after sowing, 2 plants were selected based on their vigour, the other 3 were removed. On D+78, crops were harvested by cutting the stems just above the lower brace roots. The irrigation was controlled, measured, and identical for each of the pots. It was based on maize evapotranspiration. The evolution of watering volumes during the experiment is shown in Figure 1:

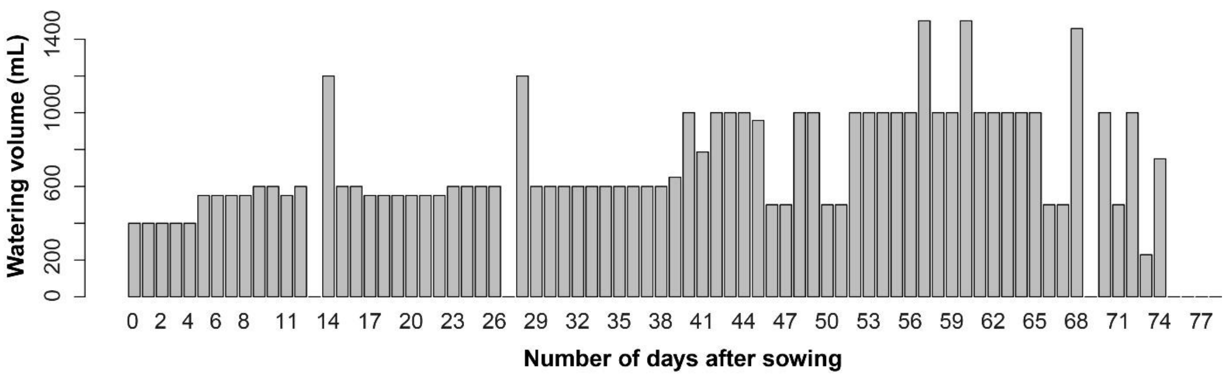

Figure 1: Evolution of watering volumes per pot during the experiment.

3.3. Fertilizers and biochar amendments

The different modalities were determined from the amount of mineral fertilizer (NPK) and the type of biochar applied. Concerning biochar, three different modalities have been defined. Soil columns were given either rice husks biochar, cotton stalks biochar, or no biochar (control). It was applied at a 2.5 t ha^{-1} rate, which corresponds to 14.3 g of biochar per pot, based on their surface. Biochar was applied at D+0 prior to sowing, and all soil columns surfaces were ploughed over 5 cm in order to incorporate it.

NPK 14-23-14 containing N in ureic form, P_2O_5 and K_2O, was applied on D+11 at two different rates (100 and 150 kg ha^{-1}, corresponding to 0.57 and 0.86 g per pot respectively). 150 kg ha^{-1} refers to the rate commonly applied by local farmers. 0.57 g (equivalent to 100 kg ha^{-1}) of urea (46% N) was added to each column on D+26, according to local practices. The columns were watered right after the additions of urea and NPK to their surfaces.

3.4. Pots layout

To sum up, the soil columns were filled from three types of soils, received 3 types of biochar inputs (including the control) and two doses of NPK fertilization, for a total of 18 combinations. The name for each combination is given in Table 1:

Table 1: Combinations names

Biochar	Control		Cotton stalks		Rice husks	
NPK rate (kg ha^{-1})	100	150	100	150	100	150
FLIPP	FLIPP-T-100	FLIPP-T-150	FLIPP-C-100	FLIPP-C-150	FLIPP-R-100	FLIPP-R-150
FLC	FLC-T-100	FLC-T-150	FLC-C-100	FLC-C-150	FLC-R-100	FLC-R-150
HPGS	HPGS-T-100	HPGS-T-150	HPGS-C-100	HPGS-C-150	HPGS-R-100	HPGS-R-150

All 18 combinations were repeated 6 times, for a total of 108 pots. The experiment took place at INERA's research station in Farako-Bâ, about 15 km South of Bobo Dioulasso, Burkina Faso. In the field intended for the conduct of the experiment, no heterogeneity factor was identified. Thus, the pots were arranged completely randomly in 9 rows of 12 pots. The experimental set-up is shown on Figure 2:

Figure 2: Experimental set-up.

3.5. Leachates collection

In order to recover the leachates from the soil columns, pots were elevated with supports. Each pot rested on a container fitted to its shape, pierced with a single hole that was sealingly connected to a closed bottle, serving as a container. Leachates could thus be collected continuously.

Leachates were harvested seven times during the experiment, on days 11, 19, 26, 33, 61 and 76. Leachate harvests were more frequent following fertilizer application, in order to determine the impact of biochar on the leaching of nutrients being provided. During each harvest, all leachates from each pot were homogenized, the total volume was measured, and a representative sample was taken for analysis. Samples were then filtered and placed in the refrigerator at 4°C until they were analyzed.

3.6. Crop phenological monitoring

Measurements were taken at different stages of the crop. On day 30, the height and the number of ligulated leaves of both plants in each pot were measured. The deficiency level was also assessed using a qualitative scale, ranging from 0 to 3 (0 = not deficient, 1 = slightly deficient, some reddening, especially in leaf margins, 2 = deficient, depigmentation of about half of leaves, 3 = very deficient, almost complete depigmentation of leaves). On day 55, the height and the level of tasseling (0 = no tasseling, 1 = emerging tassel, 2 = visible tassel, 3 = fully developed tassel) were recorded. Finally, the day before harvest (D+77), the height, the base diameter, and the development stage (0 = no tasseling, 1 = emerging tassel, 2 = visible tassel, 3 = fully developed tassel, 4 = emerging ears, 5 = visible ears) were assessed.

3.7. Experimental schedule

The schedule of the different events, measurements and leachate collections is shown on Figure 3:

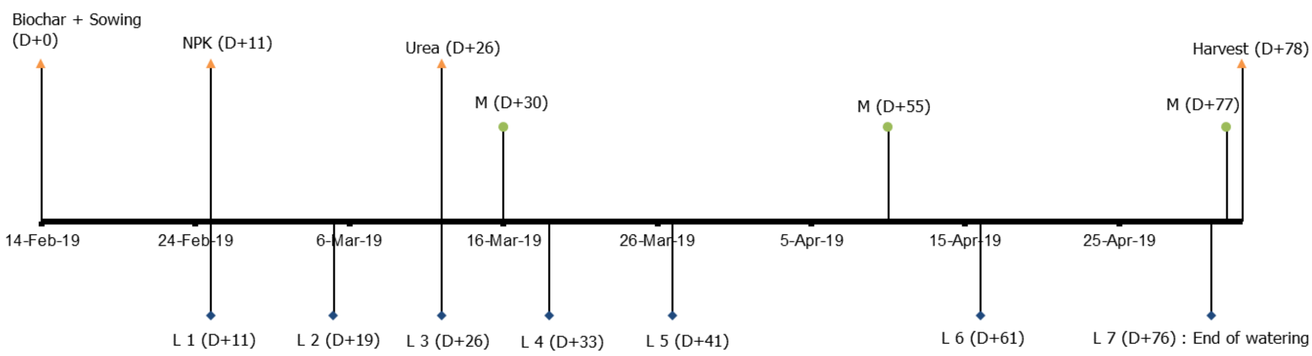

Figure 3: Experimental schedule. *(L: Leachates harvest, M: Crop measurements)*

4. End-of-experiment sampling

4.1. Soil columns

A representative soil sample was collected for each of the pots, without distinction between the different horizons. To do so, the content of each of the pots were crushed and then homogenized prior to sampling. Samples were then oven-dried at 40°C for 48 hours and sieved to 2 mm.

4.2. Biomass

Right after harvest, the basal leaves were removed to free the first node. Then, maize plants have been rinsed with water to avoid possible contamination by dust. They were hanged to dry for 5 days in a ventilated room. Finally, plants were oven-dried at 85°C for 12 h, as recommended by Campbell et al. (1998).

The ears were then separated from the plants before grinding, in order to be able to compare the plants with each other, since some plants did not produce ears. Plants and ears were then weighted. Subsequently, plants were mechanically grounded, while the ears were cut by hand. Representative samples of both plants and ears were then taken following homogenization in order to conduct the analyses at Gembloux Agro-Bio Tech, Liège University.

5. Laboratory analyses

5.1. Leachates and irrigation water

Leachates concentrations in P, $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$ were determined by spectrophotometry at wavelengths 720, 410, and 650 nm respectively. K concentrations were measured using a flame emission spectrophotometer at 766 nm. Irrigation water was also analyzed as indicated above.

5.2. Soils

The soil samples at the end of the experiment were sent to the La Hulpe laboratory (*Laboratoire d'analyses agricoles*), which determined the following characteristics: pH_{KCl}, bioavailable Phosphorous, Potassium, Magnesium, Calcium and Sodium, organic Nitrogen and total Carbon content.

5.3. Biomass

Biomass sub-samples from ears and plant tissues were first mineralized in a balanced mixture of concentrated perchloric and nitric acids ($HClO_4$ and HNO_3) for at least 16 h and were then heated until complete evaporation. The residue was then dissolved in hydrochloric acid (HCl) and diluted in distilled water before being filtered. Elemental concentrations in K, Ca, Mg and Mn were then determined by atomic absorption spectrometry (AAS) at respectively 404.4, 239 for plant tissues and 422.7 for ears, 285.2 and 279.5 nm. The P concentration was measured by spectrophotometry at 430 nm. Sub-samples were also sent to the La Hulpe laboratory, which determined their C et N content by dry combustion.

5.4. Biochar

Un-enhanced biochar samples were fully characterized by the Eurofins laboratory, which carried out the necessary analyses to issue the European Biochar Certificate (EBC). Total N, P, K, Ca, Mg and Mn contents of enhanced rice and cotton biochars were also assessed after mineralization of sub-samples.

Enhanced biochars nutrient contents were also determined. To do so, biochars were mineralized in the presence of sulphuric acid (H_2SO_4), salicylic acid ($C_7H_6O_3$), selenium and hydrogen peroxide (H_2O_2). N and P contents were measured by spectrophotometry at respectively 650 and 720 nm. K content was assessed by flame emission spectrometry at 766 nm. Ca, Mg and Mn contents were evaluated by AAS at 422.7, 285.2 and 279.5 nm respectively. Biochars carbon contents were determined by calcination at 550°C for 10 h. Their pH level was also measured.

6. Data analysis

Minitab ® 19 was used to perform statistical analysis of all data. First, outliers were identified and removed thanks to Grubbs' test. Analyses of variance with three factors (AV3; Soil, Biochar, NPK) were then conducted in order to determine potential interactions between the different factors. When no interaction was found, the dataset was split according to soil types, in order to do AV2. If no interaction had been found again, AV1 was performed. Then, Fisher's Least Significant Difference (LSD) test was used to highlight differences between means, by grouping means which showed no significant difference. A value $p < 0.05$ was considered as the significance threshold for all these analyses. When significant results were found, the same tests were conducted at lower p-values ($p<0.01$ and $p<0.001$) in order to assess the significance level.

III. Results

1. Nutrient content of inputs

The elemental composition of pristine and enhanced biochars and irrigation water are presented in Table 2:

Table 2: Elemental composition of the different inputs. *[1: pH-$CaCl_2$ for pristine biochars, and pH-H_2O for enhanced biochars; -: not measured; --: below detection level]*

	N (%)	**P (%)**	**K (%)**	**Ca (%)**	**Mg (%)**	**Mn (mg $100g^{-1}$)**	**C (%)**	**pH[1]**
Pristine cotton stalks biochar	1.49	0.10	0.90	1.40	0.20	6.1	74.5	8.2
Pristine rice husks biochar	0.75	0.20	0.70	0.20	0.20	43.5	42.2	7.4
Enhanced cotton stalks biochar	1.44	0.21	2.46	1.55	0.24	--	-	9.3
Enhanced rice husks Biochar	0.99	0.18	1.60	0.69	0.20	30.0	-	8.5
Irrigation water (mg L^{-1})	0.41	0.02	6.00	-	-	-	-	7.4
NPK	14	23	14	0	0	0	0	-
Urea	46	0	0	0	0	0	0	-

It contains the nutrient concentrations of the different inputs considered in this study. Both biochars had their K and Ca concentrations and pH increased as a result of urine enhancement. Biochar from cotton stalks had an overall higher nutrient content as opposed to rice husks biochar, except regarding Mn, and its pH was also higher. Results from the *Eurofins* analysis are available in Annex 3.

2. Soils chemical properties

Table 3 displays the results of the end-of-experiment soil analyses:

Table 3: Soils chemical properties at the end of the experiment. *[Yellow = control, Red / Green = significant decrease / increase compared to the corresponding control (according to Fisher's LSD test at *: p<0.05, **: p<0.01, ***: p<0.001)]. n=6.*

Soil type		FLIPP						FLC						HPGS					
Biochar type		Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks	
NPK (kg ha^{-1})		100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150
pH-KCl	mean	5.7	5.7	5.5***	5.7	5.7	5.7	5.9	5.8	5.9	5.9	5.9	5.8	6.0	6.0	6.1	6.2**	6.0	6.0
	std	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.0	0.1	0.2	0.2	0.1	0.2	0.1	0.1
Organic N (‰)	mean	0.36	0.36	0.32	0.37	0.34	0.35	0.57	0.55	0.58	0.60**	0.58	0.54	0.44	0.46	0.47	0.47	0.46	0.49
	std	0.04	0.02	0.03	0.05	0.05	0.02	0.02	0.06	0.03	0.03	0.03	0.05	0.03	0.03	0.04	0.02	0.02	0.02
Bioavailable P (mg 100g^{-1})	mean	0.15	0.15	0.16	0.17	0.20	0.23*	0.63	0.73	0.64	0.76	0.62	0.70	0.26	0.27	0.29	0.26	0.30	0.33
	std	0.01	0.02	0.02	0.01	0.02	0.06	0.10	0.07	0.06	0.11	0.10	0.10	0.01	0.06	0.05	0.06	0.07	0.09
Bioavailable K (mg 100g^{-1})	mean	5.10	4.62	5.07	5.01	5.17	4.97	5.91	6.13	6.40	5.84	5.72	5.65	7.69	7.63	8.36	7.39	7.29	7.25
	std	0.35	0.61	0.43	0.28	0.37	0.41	0.62	0.22	1.18	0.86	0.54	0.60	0.84	0.86	0.89	0.68	1.01	1.27
Bioavailable Ca (mg 100g^{-1})	mean	25.0	23.6	23.6	24.8	25.1	25.6	84.8	93.3	92.5**	97.7	90.9*	87.9*	47.2	47.7	48.0	48.7	47.6	46.5
	std	1.8	1.1	1.0	2.3	1.4	1.9	3.8	9.4	6.8	12.5	6.4	4.4	2.0	2.6	2.0	2.0	1.7	2.1
Bioavailable Mg (mg 100g^{-1})	mean	5.72	5.07	5.25	5.57	5.68	5.70	9.08	9.90	10.1**	10.4	9.88*	9.67	10.6	10.4	10.2	10.6	10.6	10.4
	std	0.36	0.37	0.25	0.51	0.35	0.59	0.45	1.22	1.0	1.0	0.49	0.44	0.5	0.5	0.51	0.6	0.9	0.7
Bioavailable Na (mg 100g^{-1})	mean	1.03	0.78	0.88	0.93	0.86	1.02	1.62	1.86	2.14*	2.14	2.22**	2.08	1.89	2.42	2.12	2.40	2.15	2.12
	std	0.69	0.11	0.13	0.19	0.14	0.11	0.16	0.31	0.23	0.28	0.15	0.16	0.16	1.18	0.21	0.23	0.18	0.23
Total C (%)	mean	0.40	0.40	0.42	0.44	0.45	0.48***	0.83	0.85	0.89*	0.95***	0.92**	0.85	0.52	0.51	0.55	0.55	0.58*	0.63*
	std	0.02	0.02	0.02	0.03	0.06	0.05	0.05	0.09	0.05	0.09	0.07	0.05	0.03	0.02	0.02	0.02	0.02	0.04

The three types of soil used in this study did not respond in the same way to the addition of biochar. FLIPP and HPGS soils have been less impacted than FLC soils, which showed strong responses to biochar amendments, especially when combined with a 100 kg ha^{-1} rate of NPK. In fact, in FLIPP soils, pH-KCl decreased for FLIPP-C-100 ($p<0.001$), bioavailable P increased by 53 % for FLIPP-R-150 ($p<0.05$), and total C rose by 20 % for FLIPP-R-150 ($p<0.001$), with respect to the corresponding controls.

For FLC soils, bioavailable Ca, Mg and Na increased significantly for FLC-C-100 and FLC-R-100 compared to FLC-T-100. Total C rose for FLC-C-100 ($p<0.05$), FLC-C-150 ($p<0.001$), and FLC-R-100 ($p<0.01$). Organic N content also increased by 9% for FLC-C-150 ($p<0.01$). However, bioavailable Ca decreased by 6 % compared to the corresponding control ($p<0.05$).

In HPGS soils, significant increases occurred for pH-KCl in HPGS-C-150 ($p<0.01$), and for total C contents of HPGS-R-100 and HPGS-R-150 ($p<0.05$ and $p<0.01$ respectively). All other results for these two soils were not significantly different from those of the corresponding controls.

In FLIPP soils no significant difference was induced by the NPK quantity applied between controls. In HPGS soils, only the bioavailable Na increased by 28 % between 100 to 150 kg ha^{-1} NPK without biochar addition ($p<0.05$). Regarding FLC soils, the differences between controls were more pronounced, with significant increases in bioavailable P, Ca and Mg as a function of the NPK rate.

3. Nutrient content in crop

The results of plant tissue nutrient analyses are shown in Table 4:

Table 4: Nutrient concentrations in plant tissues. *[Yellow = control, Red / Green = significant decrease / increase compared to the corresponding control (according to Fisher's LSD test at *: p<0.05, *: p<0.01, ***: p<0.001)]. n = 6, ^{1}: n = 5, ^{2}: n = 4.*

Soil type		FLIPP						FLC						HPGS					
Biochar type		Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks	
NPK (kg ha^{-1})		100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150
N (mg 100g^{-1})	mean	527^{2}	435	449	402^{1}	413^{1}	389	387	399	388	392^{1}	415	347	533^{1}	520	483	537	381^{**}	448
	std	44	48	119	77	78	61	42	52	93	111	74	42	141	170	98	81	27	129
P (mg 100g^{-1})	mean	91.0	53.2	86.4	93.4^{*}	71.3	76.0	54.9	59.4	99.8^{**}	106.8^{**}	99.0^{**}	110.3^{**}	79.1	64.1	90.1	100.1^{*}	81.6	93.0
	std	47.4	30.9	43.2	42.4	34.1	19.1	10.4	19.3	15.9	12.2	24.0	25.9	41.2	16.9	23.7	14.0	24.2	19.1
K (mg 100g^{-1})	mean	1879	1586	1906	2025^{**}	1674	1647	1313	1333	1463	1587	1558	1542	1354	1358	1477	1771^{**}	1443	1710^{*}
	std	451	251	457	143	325	364	103	291	247	305	195	220	240	208	220	123	222	16
Ca (mg 100g^{-1})	mean	294	193	221^{**}	251^{*}	251	208	231	283	327^{***}	321	327^{***}	287	256	281	268	287	299	303
	std	30	44	44	64	38	35	55	43	52	37	45	15	51	26	22	52	32	51
Mg (mg 100g^{-1})	mean	238^{1}	162	212	222	178^{***}	178	119	134	159^{*}	163	158^{*}	143	191	179	185	188	187	180
	std	27^{1}	26	51	29	30	30	12	20	25	23	41	12	31	19	32	19	16	22
Mn (mg 100g^{-1})	mean	33.3	36.5	39.2	27.3^{*}	40.1	29.1^{*}	35.4	40.9	32.0	30.2^{*}	28.7	28.0^{**}	31.0	40.2	27.9	21.7^{***}	25.8	28.9^{*}
	std	6.3	3.4	5.5	7.6	8.1	5.4	5.1	6.6	7.8	8.3	5.5	6.5	8.6	16.2	4.5	2.8	10.0	7.6
C (%)	mean	42.2^{1}	42.3	41.8	41.7^{1}	41.9^{1}	41.3^{**}	42.0	42.0	41.2^{**}	40.6^{*1}	41.6	40.9^{***}	42.7^{1}	41.9	41.7^{**}	41.6	41.3^{***}	41.4
	std	0.6	0.6	0.8	0.4	0.5	0.4	0.7	0.7	0.7	0.7	0.5	0.3	1.0	0.3	0.5	0.4	0.6	0.5

Regarding plant tissue N content, no significant trend could be identified, though biochar addition and fertilization seemed to reduce it slightly. However, biochar induced important increases in plant tissue P content, of 45 % on average. In crops on FLC soil, this trend was exacerbated, with an average increase of 82 % following biochar addition with respect to the corresponding controls ($p<0.01$).

The impact of biochar on K content did not show a clear trend, although some significant increases were identified. Regarding Ca, the same conclusions could be drawn. In FLC soils, biochar seemed to have a greater effect on Ca concentration in plant tissues, with a 41% increase for both FLC-C-100 and FLC-R-100 ($p<0.001$). Similarly, Mg concentration was increased following biochar application in FLC soils, while this was not observed in FLIPP and HPGS crops. Mn and C concentrations tended to decrease in crops amended with biochar for all soil types. Cotton stalks biochar was found to have a more positive impact on P and K concentrations in plant tissues grown on FLIPP and HPGS soils than rice husks biochar.

4. Nutrient losses by leaching

Figure 4 shows the evolution of cumulated nutrient loss according to treatment through leaching (K, N-NH_4^+, N-NO_3^- and P) and as a function of time and soil type. The evolution of leached nutrients as a function of time and the total amounts of nutrients leached can be found in Annex 4, Annex 5, Annex 6, Annex 7 and Annex 8.

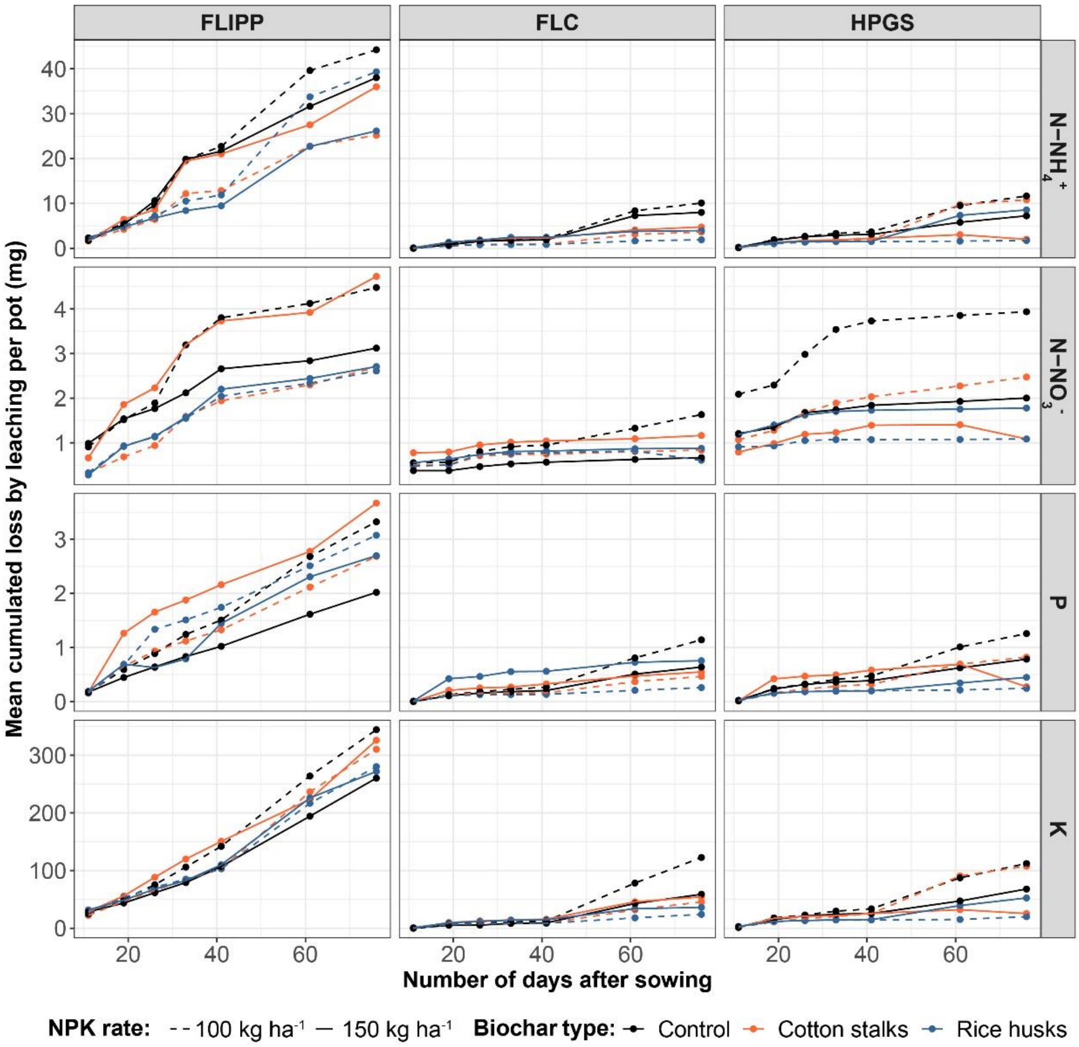

Figure 4: Evolution of cumulated losses by leaching of K, N-NH_4^+, N-NO_3^- and P during the experiment under the different treatments.

Losses by leaching were much higher in FLIPP soils than in HPGS and FLC soils, which show some similarities. In FLIPP soils, cumulated losses in the end of the experiment ranged from 260.3 to 344.2 mg for K, 25.2 to 44.2 mg for N-NH_4^+, 2.6 to 4.5 mg for N-NO_3^- and from 2.0 to 3.7 mg for P per pot. In contrast, nutrient losses in HPGS and FLC soils ranged from 20.1 to 122.2 mg for K, 1.9 to 11.7 mg N-NH_4^+, 0.7 to 3.9 mg N-NO_3^- and from 0.25 to 1.26 mg P per pot. In fact, losses by leaching in FLIPP soils were most of the time different than those of FLC and HPGS soils for corresponding modalities, for all four elements ($p<0.05$). On the other hand, losses by leaching in FLC and HPGS soils could not be statistically differentiated for corresponding modalities ($p>0.05$), except for N-NO_3^- losses in FLC-T-100 which were higher than those in HPGS-T-100 ($p<0.05$).

A general trend that emerges from Figure 4 is that N is mainly leached in the NH_4^+ form, with much lower N-NO_3^- losses for all soil types. It also appears that the addition of biochar seems to limit leaching losses compared to the corresponding controls, although this trend was only significant in few cases ($p<0.05$ for N-NH_4^+ in FLIPP-C-100, N-NO_3^- in HPGS-R-100 and K in FLC-R-100). On the opposite, P losses by leaching increased in FLIPP soils following the addition of cotton stalks biochar with an NPK application rate of 150 kg ha^{-1} ($p<0.05$). Rice husks and cotton stalks biochars have never shown a significant effect on the leaching of these nutrients. NPK losses by leaching in controls were always higher with lower application rates (100 kg ha^{-1}), though it was only significant for N-NO_3^- losses in HPGS soils. Nevertheless, this trend was reversed in the presence of biochar since losses by leaching were mostly greater in soils with higher application rates although never significant.

5. Crop performance

Table 5 summarizes crop performance indicators registered as the end of the normal growing phase of 77 days.

Table 5: Crop performance indicators. *[Yellow = control, Red / Green = significant decrease / increase compared to the corresponding control (according to Fisher's LSD test at *: p<0.05, **: p<0.01, ***: p<0.001)]. n = 6. [1]: Qualitative scale: 0 = no tasseling, 1 = emerging tassel, 2 = visible tassel, 3 = fully developed tassel, 4 = emerging ears, 5 = visible ears.*

Soil type		FLIPP						FLC						HPGS					
Biochar type		Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks	
NPK (kg ha^{-1})		100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150
Height (cm)	mean	45.4	65.0	63.3*	70.4	66.7*	80.4	71.7	71.7	94.2**	96.7**	93.8**	98.3**	75.0	85.0	92.1*	100.8	94.6*	107.9**
	std	16.3	12.3	9.8*	15.5	17.8*	15.4	11.8	15.9	12.5*	9.8*	7.2*	11.0*	15.3	19.8	20.9*	13.4	8.9*	13.5*
Diameter at the base (mm)	mean	3.3	5.9	5.8*	6.9	5.6*	7.3	7.5	9.7	10.8**	11.2	9.8*	10.9	8.3	9.5	10.3*	11.1	11.5**	11.6*
	std	0.5	1.8	2.0	2.2	1.7	2.6	1.6	2.6	1.7	0.8	0.8	1.3	1.8	2.1	2.4	1.3	1.0	1.7
Development stage[1] (mg)	mean	2.2	3.2	2.9*	2.8	3*	3.3	3.7	3	3.8	3.8	3.4	3.7	3.2	3.6	3.5	3.9	3.9*	4.3
	std	0.5	0.8	0.7	0.5	0.5	0.3	0.4	1.1	0.7	0.8	0.5	0.5	0.5	0.6	0.8	0.4	0.6	0.8
Dry biomass (g)	mean	4.9	13.7	12.1	17.6	12.3	19.5	22.0	24.2	37.7**	44.6**	37.0**	41.3***	25.6	32.4	37.4*	45.7*	42.2**	52.9***
	std	2.6	5.3	5.9	9.2	6.0	7.2	7.2	7.2	6.7	13.1	5.2	7.9	12.5	11.9	14.5	7.6	8.9	14.7

Our results indicate that the impact of biochar on height, base diameter and biomass production is always positive for all three soil types. Biochar amendments' impact on height and dry biomass for FLC soils were always at least highly significant. In most cases, crop height, diameter and biomass production were also enhanced for HPGS soils ($p<0.05$). However, few results were significant for FLIPP soils, although biochar addition to these soils induced the greatest relative increases in all four parameters recorded (+ 151 % dry biomass for FLIPP-R-100 compared to FLIPP-T-100, for example). For all soil types, relative increases in biomass, height and diameter after biochar addition compared to the controls were reduced when the application rate of NPK was 150 kg ha^{-1} compared to 100 kg ha^{-1}. This trend was particularly pronounced for FLIPP soils. Biochar had little impact on development stage, though some significant increases could be demonstrated. No significant differences could be highlighted between rice husks and cotton stalks biochars.

Higher fertilization rate (150 kg ha^{-1}) always induced greater heights, base diameters and biomass productions, though these results were rarely significant. This was particularly pronounced in controls, when no biochar was added. FLIPP soils also showed stronger responses to higher NPK rates. Crops grown on FLIPP soils always shown lower base diameters, heights, and biomass productions than their corresponding modalities in HPGS and FLC soils ($p<0.05$). Crops from FLIPP soils usually reached lower development stages than those from FLC and HPGS soils, which reflects stunted growth.

The results of crop measurements made on days 30 and 55 after sowing are shown in Table 6*:*

Table 6: Crop development measurements at days 30 and 55 after sowing. *[Yellow = control, Red / Green = significant decrease / increase compared to the corresponding control (according to Fisher's LSD test at *: $p<0.05$, **: $p<0.01$)]. n = 6.*
[1]: Qualitative scale: 0 = not deficient, 1 = slightly deficient, some reddening especially in leaf margins, 2 = deficient, depigmentation of about half of leaves, 3 = very deficient, almost complete depigmentation of leaves.
[2]: Qualitative scale: 0 = no tasselling, 1 = emerging tassel, 2 = visible tassel, 3 = fully developed tassel.

Soil type			FLIPP						FLC						HPGS					
Biochar type			Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks	
NPK (kg ha^{-1})			100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150
D + 30	Height (cm)	mean	18.8	23.1	23.9	23.3	22.4	23.7	25.1	26.8	29.8	34.1*	30.3	32.3	28.0	30.2	29.6	38.3**	32.9	36.8*
		std	0.7	4.3	3.4	6.5	5.6	3.8	3.8	5.2	2.3	4.9	6.4	2.6	6.9	4.2	7.9	7.6	4.4	7.9
	Number of ligulated leaves	mean	4.6	5.0	5.2*	5.1	5.3**	5.2	5.4	5.4	5.4	5.5	5.7	5.6	5.3	5.4	5.3	5.5	5.5	5.7
		std	0.4	0.6	0.4	0.4	0.3	0.3	0.4	0.4	0.2	0.5	0.3	0.5	0.4	0.4	0.4	0.6	0.5	0.4
	Level of deficiency[1]	mean	2.5	1.7	1.7*	1.7	1.3**	1.5	0.5	1.2	0.3	0.2**	0.3	0.6	1.0	0.8	1.1	0.4	0.7	0.7
		std	0.3	0.8	1.0	0.6	0.9	0.8	0.6	0.8	0.3	0.3	0.4	0.5	0.3	0.3	0.8	0.4	0.5	0.9
D + 55	Height (cm)	mean	30.8	50.0	48.8**	52.5	50.0**	57.1	64.6	67.5	73.8	80.0*	77.1*	77.9	60.4	68.3	72.5*	80.4*	75.0*	82.1*
		std	3.0	9.4	10.0	14.1	10.6	8.6	8.7	4.2	9.3	12.6	4.0	6.2	12.8	12.5	12.5	12.6	6.7	13.7
	Level of tasseling[2]	mean	0.0	0.2	0.3	0.1	0.2	0.3	0.4	0.0	0.6	0.5*	0.4	0.6*	0.2	0.4	0.5	0.6	0.7*	1.0*
		std	0.0	0.3	0.4	0.2	0.3	0.4	0.8	0.0	0.4	0.6	0.4	0.2	0.3	0.4	0.6	0.4	0.5	0.7

Biochar amendments always induced a positive effect on crop height, both at days 30 and 55 after sowing. These increases were less pronounced at D+30, ranging from 1 to 27 % compared to the corresponding controls. Few of these results were significant. However, at D+55, these increases ranged between 4 and 62 %, for an average of 24 %. This trend was also more significant on D+55 than on D+30 and was even highly significant for FLIPP-C-100 and FLIPP-R-100. Biochar also enhanced leaves production, though this was only significant in some FLIPP modalities.

No significant difference could be found when comparing rice husks and cotton stalks biochar using Fisher LSD test ($p>0.05$). However, the impact of biochar on height at D+55 was reduced when coupled with a high NPK application rate (150 kg ha^{-1}), especially for FLIPP soils. Indeed, the addition of biochar in these soils led to an average increase of 10% in height at D+55 with 150 kg ha^{-1} of NPK, while it was 60% for the modalities with 100 kg ha^{-1} of NPK. No significant differences could be identified between the different fertilization rates when biochar was added to the soils.

Crops grown on FLIPP soils were more deficient than those grown on HPGS or FLC. The addition of biochar can help to reduce this level of deficiency, sometimes significantly as shown by FLIPP and FLC at D+30. Biochar had a little impact on tasseling, though it enhanced it in some cases for FLC and HPGS soils ($p>0.05$). The effect of the fertilization rate was more pronounced on FLIPP grown crops. In fact, FLIPP-T-150 were on average 38 % higher than FLIPP-T-100 at D+55 ($p<0.05$), while the differences between controls in FLC and HPGS soils were only about 4 and 13 % respectively though not significant.

IV. Discussion

In this section, nutrients inputs will first be described by comparing rice husks and cotton stalks biochar, as well as the total nutrients outputs of all treatments. Afterwards, nutrient outputs of the different modalities will be assessed by determining relative shares of plant uptake and loss by leaching. Overall nutrient budgets will then be compared for each modality, in order to evaluate their nutrient use efficiencies. Finally, the impacts of the different treatments on above-ground biomass production will be assessed for each soil type.

1. Nutrient inputs

1.1. Biochars comparison

The nutrient contents of the two pristine biochars studied here were in line with those produced with the same feedstock and described in the literature (Masulili, Utomo and MS, 2014; Windeatt *et al.*, 2014; Ippolito *et al.*, 2015).

Both biochars saw their nutrient content increase as a result of urine enhancement. The Ca content of rice husks and cotton stalks biochars respectively rose by 245 and 11%, while their K content respectively increased by 128 and 173%. Mg and Mn contents remained stable in both biochars. However, in RHB only, N content rose by 32 % while it slightly decreased in CSB. This could be explained by the fact that RHB showed a greater specific surface than CSB, allowing it to retain more efficiently NH_4^+ present in urine to its negatively charged surface (Liang *et al.*, 2006; Clough and Condron, 2010; Chia, Downie and Munroe, 2015). On the other hand, the increase in P content of CSB might be due to its high water-holding capacity, about six times that of RHB. In fact, negatively charges phosphate ions contained in urine could have been trapped in CSB thanks to its high porosity, without being bound to its surface (Lehmann *et al.*, 2003). Thus, urine loading mostly influenced Ca and K contents of biochar making them more concentrated in these two elements than the vast majority of non-activated crop residues biochars found in the literature (Ippolito *et al.*, 2015). Moreover, urine-enhanced biochar can rapidly release the nutrient it contains, making them available for plant uptake (Rauw, 2018).

RHB is probably more inclined to release these nutrients quickly into the soil solution as a result of its small size compared to CSB, since its pores were more accessible, making it easier for water to be loaded with nutrients (Angst and Sohi, 2013). Nevertheless, since CSB is more alkaline, it has the potential to induce a greater liming effect, improving nutrient availability, particularly in acidic soils (Verheijen *et al.*, 2009; Atkinson, Fitzgerald and Hipps, 2010).

1.2. Impact of biochar amendment on nutrient input and availability

The origins of N, P and K inputs to the soil columns for each combination are shown in Figure 5:

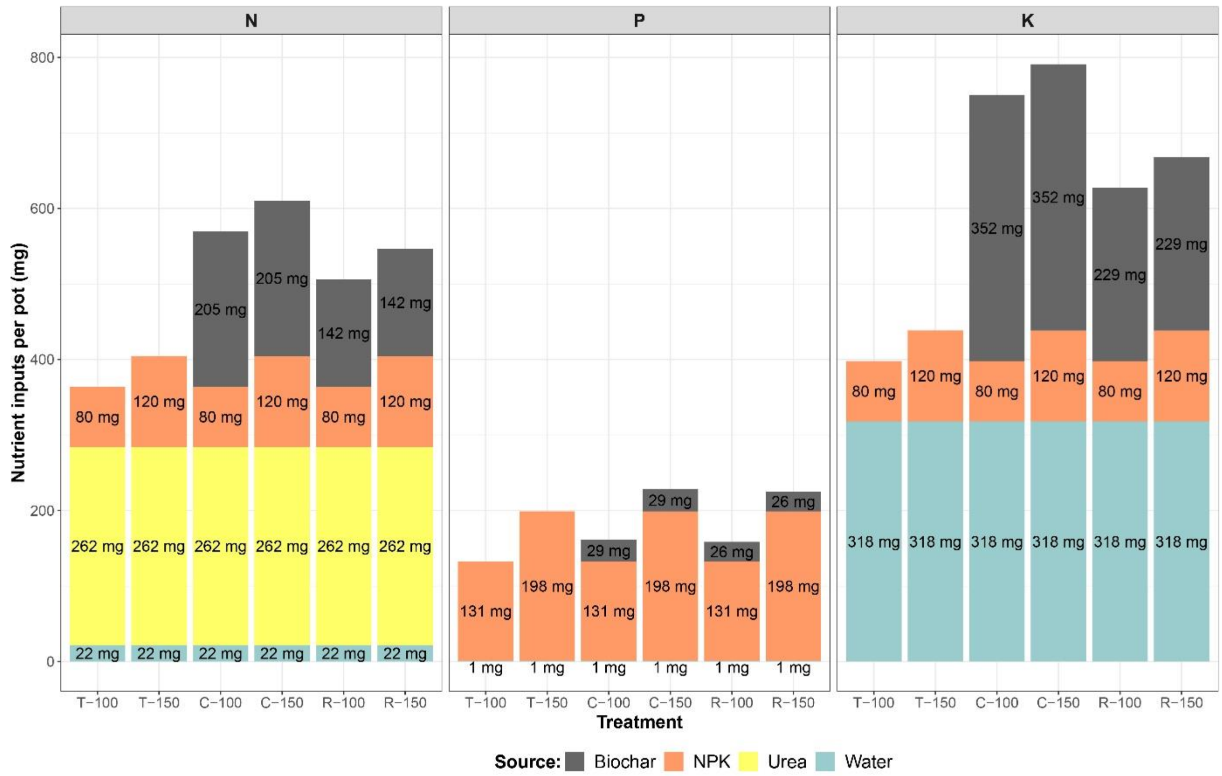

Figure 5: Contributions of the different nutrient sources to the total inputs of N, P and K per pot for each combination.

Regarding nitrogen, only a small amount (22 mg on average per pot) was provided by irrigation water, almost entirely in ammoniacal form. Most of the N input was supplied by urea (262 mg) equally for all soils. Different NPK fertilization rate had thus a minor impact on N inputs. However, biochar amendments added remarkable amounts of N, greater than that of NPK, regardless of the feedstock. In fact, C-100 and R-100 provided respectively 41 and 25% more N to the soil than T-150. In terms of N, biochar can thus be a great economical alternative to increase inputs by decreasing mineral fertilization rates.

Irrigation water inputs of P were extremely limited (1 mg per pot). In fact, most of the P was provided by mineral fertilization for all modalities, ranging from 81 to 100%. Biochar addition only contributed poorly to P inputs, by adding 29 and 26 mg for CSB and RHB respectively. Biochar does therefore not suffice as a P alternative to reduce the fertilizer application.

Concerning K, great quantities were brought by irrigation water (318 mg per pot), which correspond approximately to three times that K provided by NPK. The addition of enhanced biochar also constituted a significant supply of K, which even exceeded that of irrigation water in the case of CBS, particularly rich in potassium. Enhanced biochar amendment can therefore be an efficient way to provide K to the soil, even at low application rates in the order of 2.5 t ha^{-1}.

2. Nutrient outputs

The shares of losses by leaching and crop mineral uptake for each combination and nutrient are shown in Figure 6. They are presented as relative quantities of T-150 treatment outputs to allow for comparison with commonly applied practices used by local farmers.

Figure 6: Contributions of losses by leaching and plant uptake to the relative changes in nutrient outputs (N, P and K) from different treatments compared to T-150. *0% corresponds to the nutrient output of T-150.*

2.1. Nitrogen outputs

N concentration in plant tissues did not increase in treatments with biochar, and even tended to decline in FLIPP and HPGS soils, which is conform with literature (Biederman and Stanley Harpole, 2013). Thus, the higher N uptake is mainly due to a greater biomass production. In FLIPP, the effect of the decline of N concentration in tissue on N uptake following biochar amendment was offset by enhanced biomass production. Therefore, the effect of both biochars on N uptake was subtle in FLIPP. Biomass production in FLC increased more than in HPGS soils as a result of biochar addition, probably because FLC contents were initially lower. Thus, N uptake from FLC increased faster when amended with biochar than that of HPGS corresponding treatments.

Biochar limited NH_4^+ losses by leaching, especially in FLIPP, and also NO_3^- leakages to a lower extent (Figure 4). This trend is also confirmed in the literature, and might be a result of the interactions between negatively charged biochar surface and NH_4^+ (Lehmann *et al.*, 2003; Clough and Condron, 2010; Dempster, Jones and Murphy, 2012).

The increase of N losses by leaching in T-100 compared to T-150 might be due to the lower biomass production. Though less N was brought in T-100, a smaller share of it could be absorbed by plants, since their growth was limited. In fact, N uptake by crops dropped by 48% for FLIPP-T-100, while its N input was only reduced by 10% compared to FLIPP-T-150. Thus, more N could be subject to leaching.

Except for FLC-C-150 and FLC-R-150, no significant differences between RHB and CSB could be identified in terms of plant N uptake. Though CSB showed a greater N content, RHB might have been able to release N faster than CSB, thanks to its smaller size (Angst and Sohi, 2013).

2.2. Phosphorus outputs

Biochar amendment and higher NPK rate tend to increase P outputs, mostly by enhancing its uptake by crops. However, the three soils used in this study reacted differently in terms of P dynamics to the different treatments.

P uptake increases outputs by 129 to 210% as a result of biochar addition compared to FLC-T-150. In fact, P concentration is plant tissue was very higher ($p<0.01$) when biochar was added to the soils. Above-ground biomass production was also enhanced in presence of biochar. The combination of these two changes led to a far greater P uptake by crops following biochar amendment, though biochar itself constituted a minor P input into the soil (Figure 5). In fact, biochar might have decrease P sorption by increasing soil pH. In the soil solution, the prevalence of $H_2PO_4^-$ supposedly decreased, conversely to that of HPO_4^{2-}. Though this latter is less easily absorbed by plants, the positive impact of the liming effect on the dissolution of P is thought to be much greater than the form of P anions (Weil and Brady, 2017). FLC is indeed an acidic soil enriched in iron and manganese concretions, especially in its Bt horizon (Pallo and Thiombiano, 1989). These concretions, whose surface is positively charged, can react with phosphate anions, making them unavailable for plant growth. However, as pH increases, these precipitates tend to become more soluble, releasing the P that had previously been entrapped into a form more readily available for plant sorption (DeLuca *et al.*, 2015; Weil and Brady, 2017). This could be the reason why CSB had been more effective in increasing the crop P uptake than RHB. In fact, CSB was more alkaline than RHB (Table 2), and could thus release more through the solubilization of Fe and Mn phosphates. Bornø et al. (2018) also studied biochar amendments in a ferric Oxisol and suggested that interactions with metal precipitates were the main P sorption mechanism. Influencing pH in this type of soil is therefore an efficient way to enhance P availability. P losses by leaching were limited by biochar addition, probably thanks to an enhanced plant P uptake which reduced the amount of P in the soil solution and to an improved water retention (Abel *et al.*, 2013).

In HPGS soils, a similar trend was observed. P uptake increased as a result of biochar addition, though less pronounced, ranging from 44 to 120% more than total outputs of HPGS-T-150, and increases in P concentration in plant tissues were less significant than in FLC. In fact, this soil contains less metal oxides and hydroxides, and thus less P can be released by the liming effect. Due to its downhill location, this soil is often saturated in water. Fe^{3+} can then be reduced to Fe^{2+} in anaerobic conditions, weakening the Fe-P bounds (Weil and Brady, 2017). Therefore, an important fraction of the trapped P could already have been released. The fact that RHB, which has a lower pH, had a greater impact on P uptake than CSB seems to confirm this hypothesis. In that case, RHB might have enhanced P uptake by directly releasing the P it contained more quickly than CSB, thanks to its smaller size (Angst and Sohi, 2013).

In FLIPP, the uptake also increased when biochar was brought to the soil columns. This soil type also contains great quantities of metal oxides, that can retain P. The liming effect of biochar could thus enhance their solubilization which released P in the soil solution. However, since FLIPP is more weathered and less acidic than FLC, this liming effect probably had a smaller impact on P availability. In fact, this soil type is extremely poor, and lacks nutrient pools. Its low C content and its sandy texture prevent it from retaining nutrients. Thus, a net input of P is necessary in order to ensure its fertility. Biochar amendment and high NPK rates (150 kg ha^{-1}) seemed to produce a synergetic effect, since NPK brings P to the soil, and biochar can limit its fixation to metal oxides hydroxides by increasing soil pH, leaving it available for plant absorption. In fact, this synergetic effect was observed in all soil types, though it was more pronounced in FLIPP.

Nutrient loss by leaching were reduced in biochar amended soils for FLC and HPGS soils. This might be a result of the enhanced P uptake by crops, which captured the P from the soil solution, preventing it from being leached. These two soils types are also a richer in organic matter and in clay fraction than FLIPP, improving conditions for P retention. Conversely, P losses in FLIPP soils increased since more P was released to the soil solution, and it could not be retained by interactions with organic matter or clay minerals. In addition, its sandy texture led to a poor water holding capacity, and most of the irrigation water was lost from soils very quickly, shortening the period during which plants could absorb P. Contrarily to expectations, P losses through leaching increased in controls when the NPK rate was reduced to 100 kg ha^{-1}, especially in FLIPP soils. This could be explained by the fact that without a sufficient amount of available nutrients, crops were not able to grow properly, leading to a lowered nutrient uptake and thus to a relative increased leaching.

2.3. Potassium outputs

K concentration in plant tissues always increased as a result of biochar addition compared to the corresponding controls, regardless of the feedstock, though it was not significant most of the time. This was also reported in the literature (Biederman and Stanley Harpole, 2013). Combined with the higher biomass production in biochar treatments, especially in HPGS and FLC soils, K uptake by crops usually increased. The greater increase in K uptake in biochar treated FLC soils than in the corresponding HPGS soils might be due to the fact that FLC was initially poorer in K than HPGS. Thus, the input of K by biochar probably had a greater impact on K availability.

K losses by leaching were enhanced when biochar was added to the FLIPP soil. In fact, biochar contributed between 33% and 47% to the total K input. In FLIPP soils, which are particularly sandy, weathered and poor in C, K cations were unlikely to be retained in soil, since its CEC is extremely low (Havlin *et al.*, 2014). K^+ leaching was thus fostered by a greater K input in FLIPP soils, which is commonly observed in the literature (Laird and Rogovska, 2015). Conversely, in FLC and HPGS, the higher CEC and the finer texture probably enhanced K cations retention, and crops were then able to absorb them. This could be the reason why K^+ leaching decreased in FLC and HPGS soils amended with biochar although they received more K than T-150. Nevertheless, as biochar's surface will oxidize, its CEC will supposedly increase with time, probably reducing the leaching of K^+ in the long term (Cheng et al., 2008a; Cheng et al., 2008b). Though FLC soils usually contain high proportions of kaolinite which cannot fix K cations, illite clays are also present to a lower extent, enhancing K cations' retention (Fauck, 1962; Havlin *et al.*, 2014).

Although CSB was more concentrated in K, it did not increase K outputs significantly more than RHB did. In fact, since RHB was smaller, it might have released K faster than CSB, leading to uptakes in the same range (Angst and Sohi, 2013).

3. Elemental budgets

In this part, fertilizer use efficiencies and nutrient budgets for N, P and K will be assessed. To do so, Figure 7 summarizes changes in inputs, outputs and soils bioavailable nutrient contents for all three types of soils and different treatments. All these values are calculated in comparison to T-150 which corresponds to the current practices used in the study site. Table 7 compiles use efficiencies of the different elements for all modalities.

Table 7: Nitrogen, Phosphorus and Potassium use efficiencies. *Use efficiency is calculated as the ratio of total nutrient uptake in above-ground biomass over total nutrient input. Color scales are independent between different soils and nutrient and range from red (lowest efficiency) to green (highest efficiency). NUE: Nitrogen Use Efficiency, PUE: Phosphorus Use Efficiency, KUE: Potassium Use efficiency.*

Soil type	FLIPP						FLC						HPGS					
Biochar type	Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks		Control		Cotton stalks		Rice husks	
NPK (kg ha^{-1})	100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150	100	150
NUE (%)	9	15	10	12	9	14	27	24	27	35	31	28	38	40	32	42	35	47
PUE (%)	4	4	6	7	5	6	11	8	25	22	24	22	16	12	22	21	25	24
KUE (%)	15	47	28	44	32	46	72	75	74	86	90	96	88	103	72	101	97	133

In FLIPP soils, N uptake compared to T-150 rose as a result of biochar addition, except for R-100. However, T-150 showed the greatest nitrogen use efficiency (NUE). In fact, the addition of biochar increased the amount of N supplied to the soil, but the N contained in biochar is not readily available. NH_4^+ is strongly adsorbed on biochar negatively charged surface, due to oxidized functional groups, though freshly produced biochars show low CEC. Thus, the release of NH_4^+ is delayed, which could explain why NUE was lower in presence of biochar (Cai *et al.*, 2016). This hypothesis is reinforced by the fact that N losses by leaching were reduced in biochar amended soils as seen on Figure 6, while N inputs increased. Biochar might have prevented N brought by NPK and urea from being leached, while building up a N pool that could be used in the long term (Utomo, Soehono and Guritno, 2011).

Biochar also strongly influenced P dynamics. PUE increased when treated with biochar, even though biochar itself represented a poor source of P. The liming effect induced by the addition of biochar has probably led to the solubilization of P fixed on metal oxides, thus increasing the amount of plant available P in the soil (DeLuca *et al.*, 2015).

Regarding K, KUE did not increase as a result of biochar, with respects to that of T-150. In fact, biochar constituted a major input of rapidly available K, which could not be entirely absorbed by crops. K leaching also increased but represented a smaller share of inputs than for T-150, suggesting that K was in fact less lost, surely thanks to biochar's high CEC (Major *et al.*, 2011). Indeed, soil's available K pool rose in all biochar treated modalities. Therefore, biochar had a positive impact on N, P and K cycling in FLIPP soils, especially R-150 treatment which showed improved nutrient use efficiencies and greater nutrient pools, while increasing soil's carbon content.

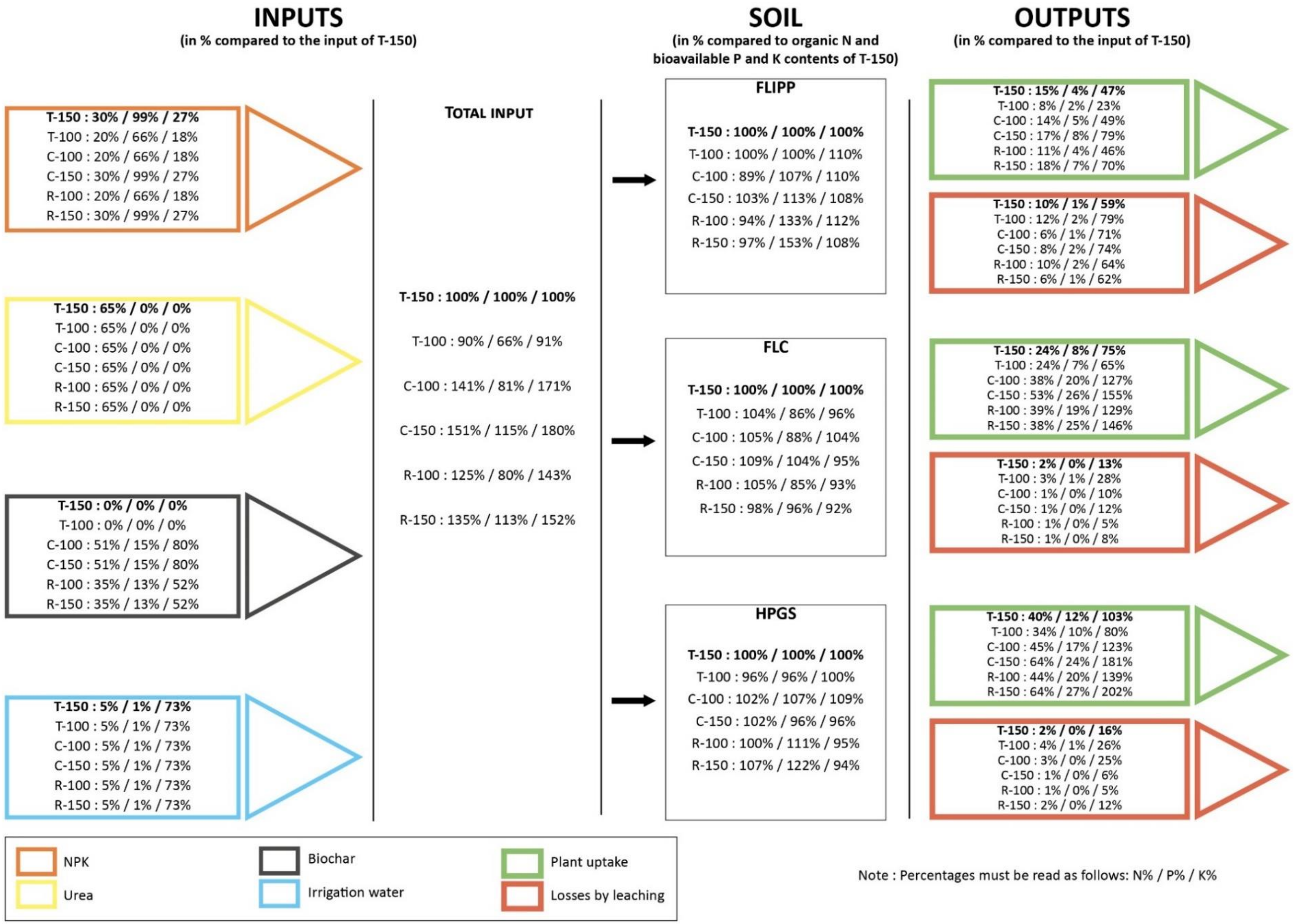

Figure 7: Nutrient budgets for N, P and K. *This diagram shows the nutrient dynamics as a function of treatment and soil type. Inputs are compared relatively to that of T-150 corresponding to the conventional farming practices. The evolution of the soils' nutrient content is also reported, as well as the changes in nutrient outputs relatively to the inputs of T-150. Percentages must be read as follows: N% / P% / K%.*

In FLC soils, the increase in N uptake as a result of biochar amendment was more pronounced, ranging from 53 to 116% more than T-150. N plant uptake increased more than N inputs in for all biochar treatments, leading to a greater NUE. However, soil's organic N content still increased in most biochar treated soils, potentially due to enhanced N immobilization since biochar can accelerate microbial activity (Lehmann *et al.*, 2011; DeLuca *et al.*, 2015). Regarding P, plant uptake has more than doubled in biochar treated modalities, in comparison with T-150. Thus, the PUE which was extremely low for T-150 rose sharply in FLC with biochar. As a result of this massive uptake, soil's bioavailable P decreased slightly in most biochar treated soils. Cotton biochar was more efficient in terms of PUE, supposedly due to its higher liming capacity which may have resulted in more solubilization of P through the dissolution of metal concretions (Weil and Brady, 2017). Despite the significant increase in K inputs by biochar, KUE was higher for biochar treatments compared to T-150. In fact, plant uptake increased more than K input. Unlike in FLIPP soils, K losses by leaching decreased in presence of biochar, surely thanks to the higher C and clay contents of FLC soil, and thus the greater CEC, which could retain K^+ more efficiently. Nevertheless, available K content was lower in presence of biochar, surely because of the enhanced uptake which has impoverished the soil in K. RHB showed greater KUE than CSB, probably thanks to a faster K release (Angst and Sohi, 2013). In fact, pH-KCl increased when biochar was added, suggesting a replacement of H^+ on the exchange sites, potentially by K cations. Positive effects on the availability of Ca, Mg and Na were also observed in presence of biochar.

In HPGS soils, lower NUE than T-150 were reported when biochar was applied alongside a low NPK rate of 100 kg ha^{-1} NPK. However, this NUE increased when 150 kg ha^{-1} NPK where amended to the soil. This can be explained by the fact that biomass production was strongly influenced by the addition of NPK, a higher NPK rate inducing a greater increase in plant uptake. On the opposite, PUE was higher with biochar when low NPK rates where applied. In fact, the main effect of biochar on P is to make available the P that is already present in the soil, but in an insoluble form. Thus, the lower the NPK rate, the lower the P input, and thus the higher the PUE. Biochar also induced positive changes in soil bioavailable P, probably because the uptake did not reach the amount of P that was made available through biochar's liming effect. Regarding K, KUE was already high for T-150, peaking at 103%. It only increased in R-150, potentially thanks to the rapid release of K cations, in the same way as for FLIPP and FLC soils (Angst and Sohi, 2013). Leaching losses were also reduced in HPGS as a result of biochar addition, but less than in FLC, surely because of a lower CEC. However, these results should be considered cautiously, since the pot conditions may differ from those in situ. Indeed, drainage could be carried out easily, whereas it is made difficult in field conditions because of the downhill position of the HPGS soil, which can be water saturated and therefore present reducing conditions.

Considering these results, it appears that lowering fertilization rates alone is not a solution to improve soil nutrient balances. In fact, negative budgets were assessed for T-100. However, in FLC, nutrient balances and nutrient use efficiencies were optimized as a result of biochar amendment together with 100 kg ha^{-1} NPK. In HPGS and FLIPP, a higher NPK rate of 150 kg ha^{-1} combined with biochar amendment were found to be more suitable. Similar results were found in the literature (Alburquerque *et al.*, 2013; Jeffery *et al.*, 2015). In FLIPP soils, these treatments even induced positive nutrient balances, which can thus be a way to improve fertility in the long term. In fact the low response to biochar of FLIPP soils was unexpected because of the abundance of literature suggesting great improvements as a result of biochar amendment in sandy loams (Nelissen *et al.*, 2012; Crane-Droesch *et al.*, 2013). However, the 2.5 t ha^{-1} amendment rate of biochar used in this study might be too little to have a short-term impact on this type of soil. In the long term, this amendment rate could still be adapted, since soil's nutrient content increased, and biochar did not release all the nutrient it contained, leaving an important pool that could be used in the next growing season. Nevertheless, some processes that can lead to nutrient depletion, such as erosion and volatilization, were not assessed in this study when they could have a major role (Wortmann and Kaizzi, 1998; Zougmoré *et al.*, 2004).

4. Impacts of biochar on yield

Figure 8 shows the relative changes in above-ground biomass for all treatments compared to T-150 for each type of soil.

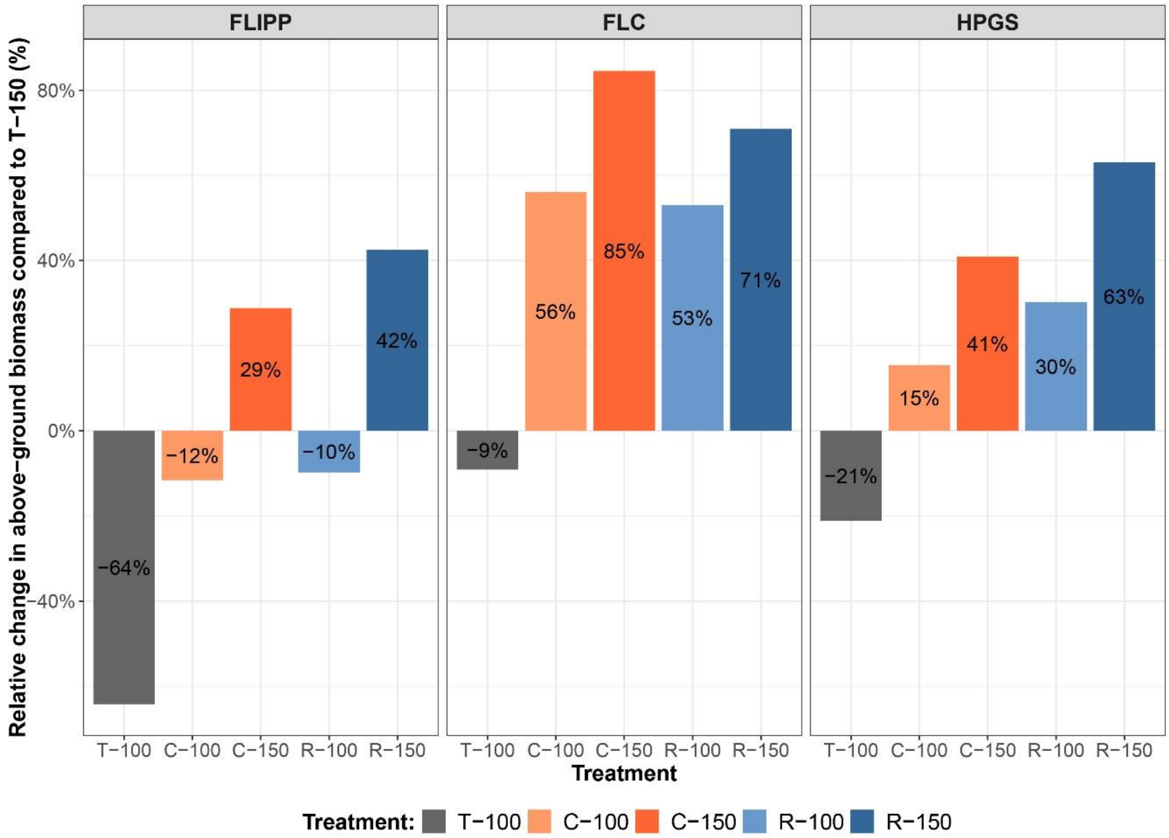

Figure 8: Relative changes in above-ground biomass compared to T-150 for the different modalities.
0% corresponds to an equivalent above-ground biomass production to that of T-150.

The impact of biochar amendment was contrasted between the different soil types. Indeed, FLC soils benefited more from biochar than HPGS soils. FLIPP soils, however, showed a more limited response to biochar addition. In fact, crops grown on FLIPP showed early signs of severe deficiencies, probably due to N and P limitations (Table 6). This was particularly exacerbated for T-100, which experienced a sharp drop in biomass production by 64% compared to T-150, surely due to the 34% lower P input. RHB and CSB greatly reduced the negative impact of the lower NPK rate of 100 kg ha^{-1}, mainly via solubilization of non-available P and N supply, though this latter seemed to be slowly released by biochar. In fact, the level of deficiency was significantly reduced when biochar was added in comparison to T-100. Regardless, the biomass productions observed on C-100 and R-100 was still lower than that of T-150. When applied alongside 150 kg ha^{-1} NPK, biochar significantly increased biomass production compared to NPK alone. In fact, thanks the liming effect of biochar and its impact on metal oxides solubilization, P was not limited, since P uptake and soil available P rose sharply. Nevertheless, N appeared to be limiting as crop development was enhanced, since N uptake did not increase as fast as P and K uptakes did, and soil organic N contents decreased. The slow release of NH_4^+

by biochar might explain this limitation although biochar supplied great amounts of N to the soil (Cai *et al.*, 2016). This assumption is supported by the fact that yields were higher in the presence of RHB than CSB, surely thanks to a faster release of NH_4^+ contained in RHB, which reduced N limitations. However, the greater Si content of RHB (19.8%) might also explain the fact that it enhanced biomass production to a greater extent than CSB did (Li *et al.*, 2018). In fact, Si is a non-essential element which can notably help crops to overcome biotic and abiotic stresses, and enhance their growth (Meunier, 2003).

In FLC soils, biochar addition induced greater biomass increases, ranging from 53 to 85% more than that of T-150. In fact, FLC soils final N content was higher than that of FLIPP soils. Thus, the impact of enhanced P availability produced by the liming effect of biochar was not limited by N shortage. In addition, the liming effects had a greater impact on FLC because of its low initial pH. Crops could continue to develop at a higher pace, and significant differences in heights were already observed at D+30 and D+55. FLC soils could therefore fully benefit from biochar addition. In these soils the CSB resulted in the higher increase in biomass production, surely because of its higher pH that led to the dissolution of more fixed P, enhancing crop growth. Relative increases were highest when biochar was applied together with 150 kg ha^{-1} NPK, thanks to the greater direct N and P inputs that could be used efficiently (Table 7).

In HPGS soils, the impact of biochar on biomass production, though still positive was less pronounced than in FLC. In fact, biomass production and nutrient use efficiency were already high for soils treated solely with T-150, and therefore having a lower potential for a large relative increase. Only the PUE was low (12%) and showed a significant increase as a result of biochar addition, reaching 25% for R-100. However, in presence of biochar, nutrient use efficiencies and biomass production were still optimized, this latter increase ranging from 15 to 63%. RHB enhanced biomass production more effectively than CSB, probably thanks to the faster release of K thanks to its smaller size (Angst and Sohi, 2013). In fact, for both C-150 and R-150 treatments, the amount of K absorbed by crops exceeded that of inputs. Thus, the rapid release of K by RHB could buffer this depletion in K, enhancing crop growth.

For all types of soil, biochar showed a great potential in improving crop yields and nutrient use efficiencies. In FLIPP soils, low fertility could potentially be overcome by biochar amendment together with a complementary N supply, since N shortage seemed to occur and to limit plant growth. This could explain the lower response to the treatment of FLIPP soils as opposed to the two other soil types, though weathered sandy loams were often reported to benefit the most from biochar addition (Glaser, Lehmann and Zech, 2002; Crane-Droesch *et al.*, 2013; Jeffery *et al.*, 2015). In FLC and HPGS soils, significant improvements in biomass production were reported when biochar was applied together with low NPK rate, suggesting that fertilizer use could be lowered in these soils thanks to biochar application. However, the greatest biomass productions in FLC and HPGS were reported with treatments C-150 and R-150 respectively. Our work suggests that reducing NPK application rate without biochar application is not a viable alternative as shown through diminished biomass production and poor NUE. The biomass production increases reported in this study were well above those reported in the literature for low biochar application rates, suggesting that biochar activation was of paramount importance to improve crop growth (Jeffery *et al.*, 2015; Schmidt *et al.*, 2015).

V. Conclusion

Biochar amendments strongly influenced soil fertility depending on feedstock type and on the nature of the soil being amended. FLIPP soils benefited from biochar's liming effect, which solubilized P from metal oxides rendering it plant available. However, biochar's N content could not be released quickly enough, leading to N deficiencies which inhibited crop growth. R-150 was the most efficient at increasing above-ground biomass, through a co-effect of liming and faster release rates of N. FLC soils strongly benefited fully from biochar's liming effect and where not limited in N. Cotton stalks biochar was more adapted to this soil, since it enhanced above-ground biomass production by 83% with respect to T-150, thanks to a greater liming effect. Regarding HPGS soil, biochar amendment solubilized P from metal oxides and constituted a massive K supply that could cover the additional needs of maize due to enhanced growth. Therefore, RHB was particularly adapted to HPGS soil, since it was able to release K^+ faster than CSB, improving overall above-ground biomass by 63% compared to T-150. Contrary to our initial expectations, FLIPP soil was is fact the soil type that least benefited from urine-enhanced biochar amendments.

PUE was also greatly improved in all soil types as a result of the addition of biochar, supposedly by solubilizing the P that was already present in soil but in an unavailable form due to strong interactions with metal oxides. KUE and NUE were enhanced by (i) increased plant uptake, (ii) reduced K and N losses though leaching. In FLIPP soils, however, KUE and NUE decreased, supposedly because of the greater supply of K that could not be taken up by plants due to important loss through leaching and because of the slow release of N by biochar. Looking back to our initial assumption, nutrient use efficiency was indeed optimized in FLC and HPGS soils as a result of biochar amendments, notably thanks to reduced losses through leaching. In FLIPP soils, although PUE was improved, NUE and KUE decreased, relatively because of a non-readily available supply of N and enhanced losses through leaching of K.

CSB and RHB induced different effects on soil fertility and on crop growth that were directly driven by their physico-chemical properties. In fact, CSB showed and greater overall nutrient content, and was more alkaline, leading to a more pronounced liming effect. On the other hand, RHB was more inclined to supply rapidly available nutrient that could overcome limitations in the short term.

It was found in this study that the application of urine-enhanced biochar at low rates (2.5 t ha^{-1}) could have a major impact on maize growth in all three types of contrasted soils, by influencing nutrient dynamics. Thus, the use of urine-enhanced biochar is extremely promising in Burkina Faso as the soils studied here occupy about 52% of the country's total area (Kissou *et al.*, 2000), especially to inhibit soil degradation. Indeed, 22 kg of N, 2.5 kg of P and 15 kg of K are depleted annually from soils in Sub-Saharan Africa (Sanchez, 2002). Urine-enhance biochar amendment could be of great help to restore soil fertility of extremely weathered soils, such as FLIPP, by improving their nutrient content in the long term. The use of mineral fertilizers could also be reduced in richer soils, like FLC and HPGS, while enhancing crop yields, offering greater economic opportunities to local farmers. Overall, amending soils with urine-enhanced biochar can significantly improve yields and nutrient use efficiency of soils in Burkina Faso and is a promising alternative to smarter agroecosystems, that shows a great potential to tackle food insecurity in Western Africa.

VI. Perspectives

Further investigations are needed in order to better understand why urine-enhanced biochar showed to be less promising on FLIPP soils, though it was by far the poorest soil used in this study. N limitation was suspected, due to the slow release of NH_4^+ by biochar, but it could not be demonstrated. Thus, trials combining urine-enhanced biochar amendments at higher application rates and complementary N inputs could be set to shed light on this hypothesis. Manure-based biochars might also be more adapted to FLIPP soil, since they usually show an overall higher nutrient content and pH than residue-derived biochars (Ippolito *et al.*, 2015).

Field-scale trials should also be installed, in order to determine (i) the effects of urine-enhanced biochar application in in situ conditions, (ii) the practical and economic feasibility of urine-enhanced biochar amendments for local farmers.

Assessing the impacts of urine-enhanced biochar, and even biochar in general, on other nutrient dynamics such as Ca, Mg, Mn and S would equally be of great use, since very few biochar-related studies focused on these element

Section II: State of the Art

I. Background

1. Global issues

1.1. Climate change: a challenging issue

Under the Paris Agreement on Climate Change (COP 21), 195 countries committed to contain the global warming well below 2°C above pre-industrial levels. Efforts should also be made to limit this temperature increase to 1.5°C, in order to mitigate its impacts. However, it seems that these goals are unlikely to be fulfilled. Indeed, Raftery et al. (2017) estimated that the probability to restrain the rise of global temperature to 2°C is only of 5%. Therefore, strong actions and policies must be carried out in order to mitigate climate change.

In its latest report, the Intergovernmental Panel on Climate Change (IPCC) stated that global warming had reached 1°C above pre-industrial levels in 2017 (Allen *et al.*, 2018). The consequences of this warming are already tangible: rising sea levels, oceans warming and acidification, decreasing Arctic sea-ice extent, biodiversity loss, extreme weather events… (IPCC, 2014). However, an overall increase of 2°C means temperature would exacerbate these impacts, leading notably to an undermined food security (IPCC, 2014).

Regarding the causes of climate change, it is now clear that it is human-induced and arises from rising concentrations of greenhouse-gases in the atmosphere (Gillett *et al.*, 2012; IPCC, 2014). USA, China and Russia alone account for 39% of the observed increase in global temperature (Matthews *et al.*, 2014). Heat and electricity production generates about 25% of the global GHG emissions, followed closely by Agriculture, Forestry and Other Land Use (AFOLU), taking a 24% share (IPCC, 2014). Agriculture alone accounted for 5.3 Gt $CO_{2\text{-eq}}$ in 2011, in other words 15% of the annual global GHG emissions (FAO, 2014b).

However, agriculture could play a key role in climate change mitigation. Indeed, soil organic carbon (SOC) is the largest terrestrial carbon pool, containing around 1500 Gt of C (Scharlemann *et al.*, 2014). Recognising this, soil scientists launched the 4 per 1000 Initiative, which aims at increasing soils carbon content by 0.4% in the first 30 to 40 cm. This initiative could significantly lower the impacts of human-induced GHG emissions, by sequestrating carbon in soils, while helping to fight against food insecurity (Soussana *et al.*, 2019).

1.2. World hunger status: a step backward

Until 2014, world hunger seemed to be losing ground steadily and continuously, providing hope that it could be defeated. Indeed, during the 1990-2014 period, the prevalence of undernourishment fell from 23.4% to 10.7%. Similarly, the number of undernourished people decreased by 210 million on the same interval, reaching 784 million in 2014 (FAO, FIDA and PAM, 2014; FAO *et al.*, 2018). This decline can partly be explained by the increasing yields due to successive agricultural revolutions worldwide which managed to overcome the increasing food demand, due to a steady demographic growth (Nah and Chau, 2010; Pretty and Bharucha, 2014).

However, this trend has reversed since then. The number of undernourished climbed back to 821 million in 2017, affecting roughly one person over nine (FAO *et al.*, 2018). This reversal might be due to unfavourable climatic conditions and to instability caused by conflicts in some regions, notably in Africa (United Nations, 2018). In fact, 21% of the African population struggles with undernourishment, while it concerns 11.4% of the people living in Asia (FAO *et al.*, 2018).

Regarding children under the age of 5, 50 million of them are facing emaciation. In addition, 151 million are dealing with growth delay, in other words 22% of them, whereas 5.6% suffer from excess weight. At the same time, the prevalence of obesity keeps rising, reaching 13.2% of the adults worldwide in 2017 (FAO *et al.*, 2018).

These numbers and trends tend to suggest that the Sustainable Development Goals (SDG's) linked to food security compiled in the 2030 Agenda for Sustainable Development (United Nations, 2015) are unlikely to be fulfilled. The UN's SDG's are, amongst other things, to bring down to 0% the prevalence of undernourishment and to drop the prevalence of emaciation to 3%. According to the FAO, further efforts are required to meet these SDG's (FAO *et al.*, 2018).

2. The case of Burkina Faso

2.1. Food insecurity

Although figures about food insecurity worldwide are alarming, they are even more so at the local scale. Indeed, Burkina Faso is a landlocked West African country which is facing severe food insecurity. Between 2015 and 2017, 21.3% of Burkinabe people suffered from undernourishment (FAO *et al.*, 2018). Even though this prevalence is alarming, it tends to decrease, since it concerned 4.4 million people between 2011 and 2013, that is about a quarter of the total population at that time (FAO, 2014a). Children are not spared by this scourge. In 2017, 27.3% of children under 5 years faced growth delay, which is 5.3% less than in 2012 (FAO *et al.*, 2018). However, this national prevalence hides regional disparities. Indeed, it climbed up to 46.6% in the Sahel region in 2015 (Ministère de la Santé du Burkina Faso, 2016). It is still far from the goal set by the Burkinabe government, to bring down this prevalence under 20% by 2025.

In addition to undernourishment, malnutrition is also extremely frequent in Burkina Faso. Daboné et al. (2011) demonstrated that 57% of the children between 7 and 14 years old in the vicinity of Ouagadougou showed at least one sign of malnutrition. Also, 49.6% of women of childbearing age suffered from anaemia in 2017 (FAO *et al.*, 2018), which can lead to serious complications during pregnancy. Malnutrition in Burkina Faso seems to be caused, at least partly, by inadequate eating habits. Only 55% of infants under 5 months are exclusively breastfeeded, and most of them are exposed to non-potable water. The lack of dietary diversity can also lead to malnutrition, through micronutrients deficiency notably (European Commission, 2017).

This situation is worsened by extreme poverty. According to the Human Development Index, Burkina Faso was ranked 183rd country out of 186 in 2012 (FAO, 2014a). 43.9% of the population is living below the poverty line (Ministère de la Santé du Burkina Faso, 2016). Yet, growth delay is 2.2 times more common in the poorest households than in the wealthiest ones. In addition, losses caused by undernourishment in Burkina Faso amount to 409 billion Fcfa, that is 7.7% of the country's GDP (European Commission, 2017). Therefore, undernourishment and poverty must be fought simultaneously.

Moreover, Burkina Faso is highly sensitive to food crisis, since it strongly relies on staple food imports. However, food prices can be extremely volatile and lead to shortages and dramatic famines (López and Ángel, 2012). Self-dependency in terms of food production must be achieved to ensure food security.

2.2. A transitional country

In addition to the food insecurity issue, Burkina Faso is facing several types of transitions. First of all, the country is in the middle of a demographic transition, driven by a rate of population growth of 3.1% annually, and a fertility rate of approximately 6 children per woman (Ministère de la Santé du Burkina Faso, 2016). The total population has risen by approximately 30% between 2007 and 2015, and reached 18.5 million people (FAO, 2014a). Therefore, more and more people must be fed, worsening the food situation in the country.

Intra and extra-territorial migrations are also threatening the food production. Indeed, the ongoing rural exodus coupled with urbanization is leading to rural depopulation. In West Africa, the share of the population living in cities rose from 4% in 1930 to 40% in 1990, and it should reach 63% by 2020 according to projections (Drechsel, Quansah and Penning de Vries, 1999). In Burkina Faso, migration towards cities such as Ouagadougou or Bobo-Dioulasso are frequent. Ouagadougou, the capital city, accounted for 3% of the Burkinabe population in 1975, compared to 7% in 1996. These migrations are fostered by climate variability which threatens agriculture in rural areas (Henry, Schoumaker and Beauchemin, 2004), but also by the poor living conditions in the sending areas and the economic opportunities in cities (Beauchemin and Schoumaker, 2005). Migrations towards neighbouring countries, such as Ghana or Ivory Coast, are also common since people tend to seek better living conditions (Englebert, 2018). As an example, 4.5 million Burkinabe are living in these two countries (Thorsen, 2009). Thus, rural population is slowly declining in Burkina Faso, causing a drop in the agricultural labour force.

The country is also dealing with political instability, due to the fall of the Blaise Compaore regime in 2014 (Chouli, 2015). Moreover, security issues are emerging, as a consequence of the recent terrorist attacks all across the country, especially in the northern and eastern regions (Benedikter and Ouedraogo, 2019). The deterioration of the security situation also leads to migration from these regions towards safer areas in the country (FAO, 2019). This political instability makes it difficult to put in place sustainable policies in Burkina Faso.

In spite of all this, economic growth remained relatively steady for the last two decades, with a GDP growth rate fluctuating around 6%. The agricultural sector still plays a prominent role in the country's economy, employing 92% of the total labour force, and accounting for about 30% of the GDP in 2014 (FAO, 2014a). However, this sector is declining due to the gold mining boom and the developing tertiary sector. As an example, cotton has long been considered as the "white gold" of the country, contributing to 60% of exports revenues before the gold boom, but only accounted for 15% of these in 2012 (FAO, 2014a). Thus, food production must rise, but the agricultural sector and the rural population are declining, making it even more challenging.

2.3. Harsh pedo-climatic conditions

Burkina Faso is a Sahelian country which can be divided into three climatic zones, thanks to a decreasing gradient of annual rainfall heading from the south to the north (Henry, Schoumaker and Beauchemin, 2004). These three zones are defined as follows (Ouédraogo, 2012):

- The Sahelian zone in the North of the country (above 14°00' N), characterized by average rainfall between 300 and 600 mm per year, distributed over three months.
- The Sudano-Sahelian zone, located between latitudes 14°00' N and 11°30' N, with an average rainfall ranging between 600 and 900 mm per year. The rainy season lasts for four to five months.
- The Sudanian zone, below 11°30' N latitude, with an average rainfall lying between 900 and 1200 mm per year, spread over six months.

All these zones are characterized by a dry season, with no rainfall, and by a rainy season which contains all precipitations. Therefore, only one crop season per year is possible, and it can be very short, especially in the northern region. The wet season usually takes place between May and September, depending on the region (Henry, Schoumaker and Beauchemin, 2004). During this season, rain intensity often exceeds 80 mm h^{-1} (Dugué, Roose and Rodriguez, 1993). This leads to the use of fast-growing crops, and to a hunger season which is often occurring between the beginning of the rainy season and the first harvests, when food stocks are running low. The Sahelian zone is more impacted by this seasonal variability than the Sudanian zone, which is more suitable for agriculture. The different climatic zones are illustrated in Figure 9 :

Figure 9: Climatic zones of Burkina Faso (Ouédraogo, 2012).

Temperatures in Burkina Faso also show strong spatio-temporal variations. Spatially, temperatures tend to have wider variations in the North, where the coldest and hottest temperatures are recorded, than in the South. Temporally, monthly means temperatures vary between approximately 25°C and 35°C. They are the lowest between November and February, then increase gradually until June. During the wet season, temperature drops until September, thanks to the frequent rainfalls (Vlaar, 1992).

These climatic conditions, as a soil formation factor, shaped soils in Burkina Faso. Since the Cretaceous, rainfall was way more abundant: humidity and warm temperature led to an intense pedogenesis (Dabin and Maignien, 1979; Bainville and Dufumier, 2009). Deep and depleted soils were formed, such as iron-rich tropical soils. These soils are the most common in Burkina Faso, covering approximately 39% of land areas (Kissou *et al.*, 2000). They are characterized by individualized iron and manganese oxides and are generally poor. Moreover, parent materials in Burkina Faso are mostly granites, gneisses and sandstones, forming soils with low clay contents, and enriched in quartz mineral

(Hotti and Ouedraogo, 1976; Gray and Murphy, 1999). Therefore, the Cationic Exchange Capacity (CEC) of these soils is usually low, leading to a poor chemical fertility, and to a lack of structure due to a high sand content (Roose, 1985; Abba, Hofs and Mergeai, 2006).

The soils used in this study were sampled in the region of Koumbia, approximately 60 km east of Bobo-Dioulasso. Three soil types were collected:

- FLIPP, for *"sol ferrigineux lessivé peu profond"* as mentioned in the local soil classification BUNASOL which is based on that of CPCS (1967). In the WRB classification, it corresponds to an epipetric Plinthosol (WRB, 2015). This type of soil possesses a plinthic (cemented) horizon between 20 and 40 cm deep. It is extremely weathered and contains precipitated iron oxides. Superficial, sandy and poor, this soil is difficult to manage.
- FLC, for *"sol ferrigineux lessivé à concrétions"* according the BUNASOL classification, or ferric Lixisol in the WRB classification system. This type of soil, such as FLIPP, are formed with an acidic parent material enriched in quartz (Dabin and Maignien, 1979). Enriched in clay in its subsoil, it also contains iron concretions in a ferralic horizon governed by low activity clays and sand/silt fractions. It is usually acidic (pH between 5.5 and 6.5) with low CEC (Pallo and Thiombiano, 1989). It is also a poor soil which needs to be managed in order to grow crops.
- HPGS, for *"sol hydromorphe peu humifère à pseudogley de surface"*, or eutric Gleysol. This soil is influenced by the presence of excess water, leading to anaerobic or anoxic conditions, usually due to its topographic position downhill (Dabin and Maignien, 1979). This lack of oxygen results in reducing conditions, where soil can develop gleyic properties. This type of soil is usually richer than the ones mentioned above.

These soils are described more in detail in a later section of this paper. FLIPP and FLC are part of the iron-rich tropical soils subclass which covers 39% of Burkina Faso's total area. HPGS soil is representative of the hydromorphic soils class which occupies 13% (Kissou *et al.*, 2000). Thus, this study can be considered as representative for 52% of Burkina Faso's area. Most soils in Burkina Faso are poor and difficult to manage, often resulting in low crop yields. These soils require an efficient and adapted management in order to be able to grow crops sufficiently and sustainably (Glatzel *et al.*, 2014).

2.4. An inadequate form of agriculture

Agriculture in Burkina Faso is mainly extensive and small-scaled. Most farms cover less than 5 ha, and the most common crops are sorghum, millet, maize and cotton (FAO, 2014a). Cereals covered approximately 77% of cultivated lands between 2001 and 2010 (Ouédraogo, 2012). This agriculture is mainly rainfed, and therefore subject to the vagaries of climate. As mentioned before, soils of Burkina Faso are extremely poor and weathered, so yields are usually low. Thus, it is rather a subsistence, unproductive agriculture that fails to ensure enough production to guarantee food security in the country.

Contrary to Asia and south America, Africa didn't benefit from the Green Revolution, maintaining yields at their low level (Bationo *et al.*, 2013). In fact, in sub-Saharan Africa, per capita food production stagnated for the last 50 years, which shows the incapacity of this form of agriculture to meet the rising demand (Sanchez, 2002; Lal, 2009). During the 60's and the 70's, policies tended to push forward the exclusive use of mineral fertilisers, for their quick effects on yields and their technical simplicity (Dugué, 1998). Later one, the combined use of mineral and organic fertilisers has been promoted (Bationo *et al.*, 2013).

Despite the use of fertilisers, soil degradation became a major concern in West Africa since the 90's. The rising food demand led to an anthropogenic pressure on soils which were cultivated continuously, and fallows were discarded. However, fallows are necessary to maintain sufficient fertility in tropical soils with few inputs (Louppe, Ouattara and Oliver, 1998). Therefore, important nutrients depletion rates were observed (Cono, Dercon and Cadisch, 2010). Over the last 30 years, 22 kg of N, 2.5 kg of P, and 15 kg of K were removed annually per hectare from cultivated soils (Sanchez, 2002). Carbon content of soils also decreased annually, inducing falling crop yields, and poor soil structure (Glatzel *et al.*, 2014). CEC of these soils also dropped, so their nutrients retention potential became even lower (Abba, Hofs and Mergeai, 2006). Due to their lack of structure, these soils also became highly vulnerable to erosion, which is degrading soils extremely fast in West Africa. In fact, land degradation is now a major issue which costs $168 billion annually in sub-Saharan Africa (Nkonya *et al.*, 2016).

Nowadays, soils in Burkina Faso are lacking nutrients and carbon. 0.6% C being the minimum threshold to observe the response to fertilisers in these soils, the use of fertilisers in becoming more and more inefficient (Traoré, Koulibaly and Dakuo, 2007). The slash-and-burn, commonly used in Burkina Faso, is also ineffective because of the heavy rainfalls during the wet season, during which most nutrients are leached (Glaser, Lehmann and Zech, 2002). Therefore, sustainable and efficient ways to improve soils properties, such as nutrients content, carbon content, structure and CEC have to be found. A smarter use of fertilisers, water and crops should be developed. The fertility of these soils could be restored using new technologies, that tend to understand soil functioning in order to design appropriate solutions (Glatzel *et al.*, 2014).

2.5. The threat of climate change

West Africa's contribution to climate change is minor, with 2.03% of global emissions. Burkina Faso only accounts for 0.07% of world's GHG emissions annually (USAID, 2019). However, West Africa is going to face with full force the impacts of climate change. It is considered as a climate change hotspot, which is going to suffer from its effects in numerous ways. Temperatures in Africa have already risen by 0.7°C during the 20th century (Liniger *et al.*, 2011).

In sub-Saharan Africa, temperature will increase at a higher rate than globally (Bindi *et al.*, 2018). Mean temperature is expected to rise by 1.7 to 4.7°C in West Africa by 2090 (Roudier *et al.*, 2011). Regarding precipitation trends, no consensus was reached, as they seem to vary largely at local scales. In the Sahelian zones, precipitations have been declining since the 1970's, with some extremely severe droughts occurring since then (Henry, Schoumaker and Beauchemin, 2004; Mahé *et al.*, 2010; Ouédraogo, Dembélé and Somé, 2010). However, precipitations should increase slightly in the Sudanian zone, but estimations are differing depending on the model and the scenario chosen (Compaore, 2013).

Weber et al. (2018) showed that the frequency of heat waves and the number of hot nights should climb, while the mean length of rainy season is expected to become shorter, for all 1.5, 2 and 3°C increase scenarios. Extreme rain events should also be more frequent in the future (Debray, Derkimba and Roesch, 2015; Taylor *et al.*, 2017). In addition, marginal areas should be gaining ground in the future, reducing the areas of arable lands (Liniger *et al.*, 2011). Desertification should also be enhanced by human activities (FAO *et al.*, 2018).

Regarding agriculture, the effects of climate change will be dramatic. In addition to the loss of arable lands, yields are expected to decrease by 18% in the Sudano-Sahelian zone, and by 13% in the Guinean zone (Roudier *et al.*, 2011), and to reduce farm incomes (Ouédraogo, 2012). In Burkina Faso, yields of sorghum (the most cultivated crop) should drop by 5 to 25%. The same trend is expected with regards to maize, in the areas where it is now cultivated (Compaore, 2013). In fact, the rain fed agriculture is going to suffer from a changing climate, and crops varieties such as sorghum will be exposed to temperatures exceeding their tolerance threshold (Jalloh *et al.*, 2013). However, due to their lack of financial resources, farmers won't be able to adapt to these changes, leading to dramatic consequences that will consolidate food insecurity in West Africa.

Therefore, there is an urgent need to reconsider agriculture and the ways soils are managed in order to establish sustainable and efficient production systems, since it is the only way to face all the different and cumulative challenges exposed above.

II. Biochar: a part of the solution

1. Background information

1.1. An introduction to biochar

Biochar could be part of the answer to the problems outlined above. Biochar is the carbon enriched by-product of the pyrolysis of biomass, which is the process of heating biomass at temperatures above 250°C with limited oxygen supply (Lehmann & Joseph, 2015). Recent interests in biochar results from studies about Amazonian Dark Earth, also called t*erra preta de Indio*, which are anthropogenic soils that were created hundreds or even thousands of years ago, in Brazil. These soils are enriched in black pyrogenic carbon, as a result of past human activities, and are way more fertile than surrounding soils, mainly Acrisols and Ferralsols, which are extremely weathered (Woods and Denevan, 2009; Glaser and Birk, 2012). Therefore, researchers focused on biochar amendments to understand notably it's impacts on soils and crops.

Biochar can be produced from all types of biomass, from wood to poultry manure to sewage sludge. However, its production from agricultural residues seems to be the most promising, since it would be an efficient way of valuing these wastes. During pyrolysis, 20 to 50% of the original biomass can be turned into biomass, while 40 to 75% are transformed into gases, mostly CO_2 and CH_4. Bio-oil can also be created during this process at a rate between 0 to 15% of the original biomass (Boateng *et al.*, 2015). The lower the temperature and the heating rate, the higher the proportion of biochar produced (Duku, Gu and Hagan, 2011; Devi and Saroha, 2013; Zhang, Liu and Liu, 2015).

Even though biochar structure and properties widely variate depending on the type of biomass from which it was produced, biochar is always a black, light, carbon-enriched product. Biochar contains a high proportion of aromatic carbon that is amorphous when produced at low temperatures, and that tends to turn into a graphite-like layered structure when the pyrolysis peak temperature increases (Chia, Downie and Munroe, 2015), as shown in Figure 10:

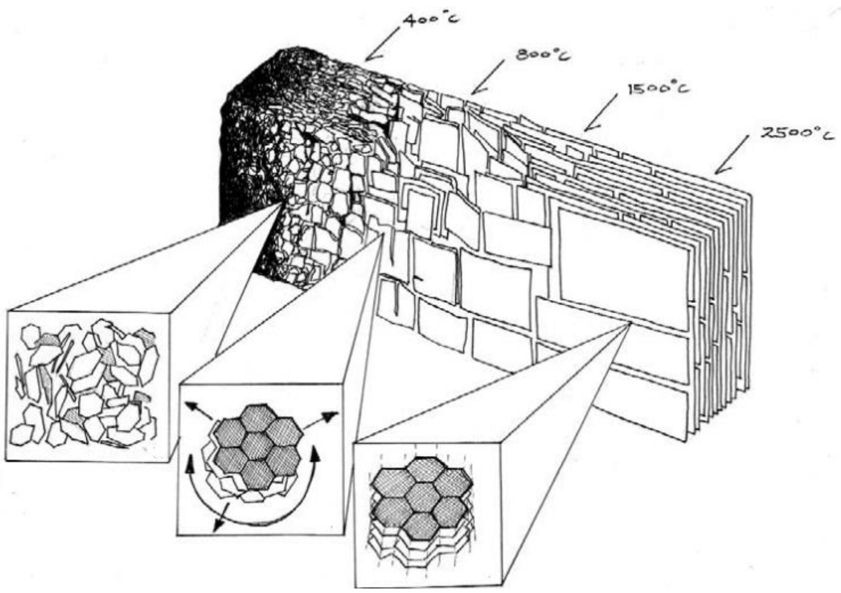

Figure 10: Ideal biochar structure development with highest treatment temperature (Chia, Downie and Munroe, 2015)

This condensed aromatic structure makes biochar stable and resistant to biotic and abiotic degradation, allowing it to remain for long periods in soils (Keiluweit, Nico and Johnson, 2010; Xu *et al.*, 2012; Wiedemeier *et al.*, 2015). Biochars, especially the ones made from vegetal biomass, are highly porous and thus have an important surface area. Inside these micro, meso and macro-pores, oxygenated functional groups can be developed when exposed to oxygen or water, increasing biochar CEC and thus its nutrient and water retention capacity (Ippolito *et al.*, 2015). Biochar has indeed a strong sorption capacity for inorganic ions, such as K^+, Ca^{2+} or NO^{3-}, which is a property of great use for agricultural purposes (Xu *et al.*, 2012).

However, biochar properties are considerably dependent on feedstock and pyrolysis conditions. Besides determining the molecular structure of biochar, pyrolysis also influences its ashes content, and thus its nutrient content. In fact, as the peak temperature of pyrolysis rises, the ashes content of biochar and its pH also increase, except for nitrogen (Hossain *et al.*, 2011; Al-Wabel *et al.*, 2013; Zheng *et al.*, 2013). Feedstock type is also decisive and leads to a large range of biochar types. Ashes content, carbon content, pH, and porosity are highly dependent on the original biomass. Animal-derived biochars tend to be richer in P and N, but have lower C and K content, and their CEC is lower than vegetal-derived biochars (Atkinson, Fitzgerald and Hipps, 2010; Spokas *et al.*, 2012; Xu *et al.*, 2012).

Thanks to its previously exposed properties, interest in biochar is rising, especially regarding the management of weathered soils of the tropics. In these soils, yields can be increased substantially, notably by increasing nutrients retention, by bringing ashes, increasing pH, in soils which are acidic and whose nutrient retention capacity is extremely low due to their lack of structure, their high sand content and their carbon content often less than 1% (Glaser, Lehmann and Zech, 2002; Duku, Gu and Hagan, 2011; Spokas *et al.*, 2012). In addition, slash-and-char could be a promising alternative to slash-and-burn, which leads to soils degradation and whose advantages only last in the short term. Ashes could be retained for longer periods, since biochar could help nutrients to resist leaching, and the carbon content of soils could rise again, unlike slash-and-burn which turns C from plants into GHG almost exclusively (Glaser, Lehmann and Zech, 2002; Lehmann *et al.*, 2002; Jha *et al.*, 2010)

1.2. The potential role of biochar in climate change mitigation

The rise for interest in biochar is also due to its potential to sequester carbon in order to mitigate climate change. In fact, during pyrolysis, approximately a third of the biomass is turned into an aromatic and highly stable carbon form, which can resist to mineralization and persist in soils for thousands of years, which means 10 to 1000 times longer than most of organic carbon in soils (Verheijen *et al.*, 2009). Biochar application in soils can thus be an efficient way of sequestering carbon. Only a small fraction of the applied biochar is turned into CO_2 in the short term, since it contains few labile carbon (Major, Lehmann, *et al.*, 2010). In fact, biochar application in soils leads sometimes to a priming effect, which means that the mineralization rate can be accelerated for a short period of time following the biochar amendment, enhancing GHG emissions (Zimmerman, Gao and Ahn, 2011).

Biochar increases the carbon pool in soils, contrarily to slash-and-burn which turns most of the carbon into CO_2. Actually, the total human-induced GHG emissions due to land-use change could be reduced by 12% if the slash-and-burn system was replaced by slash-and-char (Jha *et al.*, 2010). In addition, biochar can significantly offset GHG emissions from soils, notably by absorbing ammonium, preventing its loss through volatilization and thus the release of nitrous oxide (N_2O), which has an enormous global warming potential (Lehmann, 2007; Cayuela *et al.*, 2013; Stavi and Lal, 2013). Biochar amendment could also be a way to reduce the use of fertilizers, and thus the emissions of GHG through their mineralization (Barrow, 2012).

In addition, small-scale pyrolytic stoves can be used to produce energy, and could serve as cooking fire to replace traditional stoves. In the world, over three billion people use traditional stoves to cook, which work with wood as a fuel (Birzer *et al.*, 2014). In sub-Saharan Africa, wood fuel accounts for 70% of the total energy consumption: harvesting wood can thus lead to deforestation and exacerbate climate change (Kebede, Kagochi and Jolly, 2010). In fact, Whitman et al. (2011) showed that, pyrolytic stoves could offset GHG emissions by 26 to 42% compared to the traditional stoves. Therefore, using pyrolytic stoves with agricultural wastes as fuel instead of the traditional ones could be an efficient way to moderate deforestation, and to produce biochar which can sequester carbon in soil in the long term.

Woolf et al. (2010) estimated that biochar has the potential to abate carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions up to 1.8 Gt CO_2-C equivalent annually, in other words 12% of current anthropogenic GHG emissions. Therefore, biochar could play a significant role in climate change mitigation. In fact, in its Fifth Assessment Report (AR5), the IPCC (2014) is presented as an efficient way to increase soils C pool and to boost biomass productivity.

1.3. Risks and limits of biochar

Although biochar seems to contribute to solve the issues exposed above, it may also pose risks that need to be assessed clearly. First of all, some studies reported high concentrations sometimes coupled with high bioavailabily of potentially toxic elements, such as As, Pb, or Zn that can have harmful impacts on crops and biodiversity (Buss *et al.*, 2016). Moreover, high levels of polyaromatic hydrocarbures (PAHs) in biochar have been reported (Hilber *et al.*, 2012). Those are highly toxic and carcinogenic organic compounds, that can induce damages to the environment. However, there is no consensus about the risk associated with PAHs contamination by the mean of biochar, since other studies suggest that this risk is minimal (Freddo, Cai and Reid, 2012).

Biomass gasification that occurs during the pyrolysis process may also be hazardous. In fact, potentially harmful gases can be produced through this process, causes atmospheric pollution which can have a negative impact on health and environment (Mishra, Singh and Mishra, 2015).

In addition, biochar production mustn't become a source of competition for food crops (Scholz *et al.*, 2014), since it could threaten food production and therefore food security. Moreover, only "true wastes" biomass should be used as feedstock to produce biochar. Indeed, some agricultural residues may have others uses, such as animal fodder. Therefore, biochar production with agricultural residues could also, to some extent, lead to competition with other sectors (Scholz *et al.*, 2014).

Finally, biochar amendments at a global scale could also drive climate change. Indeed, biochar is a dark material, that could darken soils surfaces if applied at high rates. Albedo of soils could be decreased, which would have an impact on the energetic budget of Earth, since it would absorb more energy and thus accelerate its warming (Smith, 2016).

2. Impacts of biochar amendments

2.1. Effects on soils

Biochar amendments produce significant changes in soils physical and chemical properties. First of all, biochar is known for enhancing water retention in soils thanks to its porous structure, which could be of great help in sandy and aridic soils (Allaire and Lange, 2013). Tryon (1948) reported that biochar addition to soils increases water availability in sandy soils, had no effects on loamy soils, and decreased water availability in clayey soils. Biochar amendment enhance water infiltration, and thus reduce runoff, which can be a way to mitigate soil erosion (Ayodele *et al.*, 2009). Bulk density of soils is also lowered when biochar is added, due to its porous structure and thus low density (Major, Lehmann, *et al.*, 2010). Biochar can also affect soil structure. In fact, it facilitates chemical interactions between soils' particles, enhancing the formation of aggregates and thus improving soil's structure (Glaser, Lehmann and Zech, 2002; Verheijen *et al.*, 2009; Jeffery *et al.*, 2011; Allaire and Lange, 2013).

Chemical properties of soils are also influenced by biochar amendments. Biochar usually leads to a liming effects thanks to its high pH, though some studies suggested a decrease in pH (Jeffery *et al.*, 2011). This increase in pH enhances nutrients' availability, especially for P and K in acidic soils (Verheijen *et al.*, 2009; Atkinson, Fitzgerald and Hipps, 2010). Nutrients' availability is indeed highly dependent on soil's pH, as show in Figure 11:

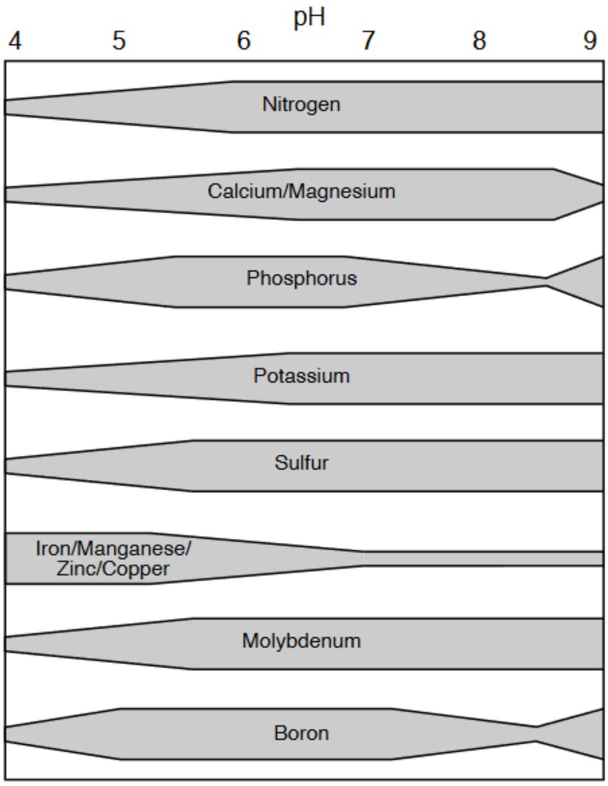

Figure 11: Nutrient availability in soils as affected by soil pH (Rosen, Bierman and Eliason, 2008)

Biochar is also a direct input of nutrients in soils thanks to its ashes content. In their review, Biederman et al. (2013) reported very highly significant increases in P, K and total N concentrations in soils following biochar application. Others nutrients, such as Ca and Mg, are also found at higher levels in soils when biochar is added (Lehmann *et al.*, 2003). Total organic carbon in soils is augmented by biochar application (Schulz, Dunst and Glaser, 2013). Biochar addition can also increase CEC, especially in the long term when the biochar surface gets oxidized (Verheijen *et al.*, 2009; Mukherjee and Lal, 2013), especially in sandy and weather soils which usually have low initial CEC (Glaser, Lehmann and Zech, 2002). Nutrients such as NO^{3-}, NH^{4+}, Ca or Mg losses by leaching were also reduced after biochar addition, probably due to their interaction with biochar surface (Glaser, Lehmann and Zech, 2002; Knowles *et al.*, 2011; Major *et al.*, 2011).

Biochar also affects soils biota. Microbial reproduction rate, and the abundance of mycorrhizal fungi are often positively impacted by biochar amendment, notably thanks to improved water and nutrient availability, an increase in soil pH (Warnock *et al.*, 2007; Lehmann *et al.*, 2011). Biological fixation of nitrogen by *Rhizobia* was also enhanced by biochar addition, surely because of a greater boron and molybdenum availability (Rondon *et al.*, 2007).

2.2. Impacts on yields and agronomic interests

The effects of biochar amendment in soils induce responses in crop yield. However, the responses of crops to biochar are extremely heterogeneous. In their review, Jha et al. (2010) listed yield variations ranging from -21 to +800% for crops amended with biochar and fertilizers, compared to the controls which were only given fertilizers. Thanks to a meta-analysis, Biederman et al. (2013) showed that biochar treatments increase highly significantly above-ground biomass and crop yield. On average, Jeffery et al. (2015) estimated that biochar addition increased crop yield by 18%, and only few cases of yield drop were documented. Though the response to biochar is heterogeneous, its seems that weathered soils are the ones that could benefit most from biochar amendments (Crane-Droesch *et al.*, 2013). Indeed, in Ghana, Oguntunde et al. (2004) reported a 91 and 44% increase of maize grain and biomass yield respectively on charcoal-making sites.

The change in crop productivity seems to depend on the application rate. Jeffery et al. (2015) found that the crop response to biochar is not linear with the application rate, since it peaks around 71 to 80 t ha^{-1}. On average, only positive variations of yield were reported for application rates higher than 5 t ha^{-1}. However, these effects also depend on the feedstock type used to produce biochar, and on the pyrolysis conditions, since they impact biochar's structure and nutrients content (Atkinson, Fitzgerald and Hipps, 2010; Spokas *et al.*, 2012; Jeffery *et al.*, 2015). Also, different crops show heterogeneous responses to biochar amendments. Though most of them responds positively to biochar addition, some, such as ryegrass, showed significant decrease in yield. Maize yield increases on average by 19% as a results of biochar addition (Jeffery *et al.*, 2015).

In addition, biochar impact on crop yield seems to strengthen with time. In a Colombian Oxisol, no response to biochar amendment was observed the first year, but yield increased significantly in the following three years (Major, Rondon, *et al.*, 2010). Such delayed responses were also reviewed by Spokas et al. (2012) and Glaser et al. (2002). In order to ensure a positive response in the first year after application, biochar can be activated. Activation is the process of adding biochar to a substrate (compost, urine, mineral fertilizers) for a short period of time. Biochar, which acts like a sponge, will absorb important quantities of nutrients, thanks to its porous structure and its CEC. This process can also increase biochar surface area. Nutrients can then be released in the soil, leading to improved crop yields (Schmidt, 2012; Pandit *et al.*, 2019).

III. Biochar, a nutrient cycles modifier

1. Biochar, a slow release fertilizer

As explained above, biochar is loaded with nutrients such as N, P or K, especially when activated (Ippolito *et al.*, 2015; Pandit *et al.*, 2017). However, these nutrients are not immediately available in soils, as opposed to mineral fertilizers. In fact, a part of these nutrients are bound to biochar surface, and require several extractions in order to be released (Angst and Sohi, 2013). Thus, nutrients inputs in soils are delayed, hence biochar's designation as a slow release fertilizer.

This property could be of great help in weathered sandy soils of the tropics, which are exposed to intense rainfalls, and whose CEC is extremely low, due to a dominant sand fraction and a poor carbon content. Thus, biochar could prevent nutrients from being lost by leaching during intense rainy event (Major *et al.*, 2011; Yao *et al.*, 2012). Therefore, biochar can play a significant role in nutrients cycling and fertilizers efficiency, especially in these weathered soils (Arif *et al.*, 2017; Backer *et al.*, 2017). As a result of biochar's ability to reduce nutrients leaching, it can also mitigate eutrophication of surrounding water bodies (Ngatia *et al.*, 2017).

The ability of biochar to retain nutrients can be explained by different means. First, biochar's porous structure allows it to stock water the nutrients it contains, just as a sponge (Ippolito *et al.*, 2015). The considerable surface area of biochar also enhances its interactions with soils nutrients thanks to electrostatic adsorption and carboxylate or phenolate groups (Cheng *et al.*, 2006; Ippolito *et al.*, 2015; Qadeer *et al.*, 2017). These groups can develop when biochar is exposed to oxidizing conditions, in presence of water and oxygen. Thus, biochar's CEC increases with time, allowing it to retain soil's cations more efficiently (Ippolito *et al.*, 2015).

2. Nitrogen cycle and biochar

2.1. Nitrogen cycle

Nitrogen (N) is an essential nutrient for plant growth and health, often causing deficiencies due to a lack of available N in the soil. The largest N reservoir is the atmosphere, composed of 78% N_2, a N form rendered inert by a triple bond between the two N atoms. Thus, plants can't directly benefit from this huge nitrogen reservoir to ensure their growth. In fact, the only available forms of N for plants are ammonium (NH_4^+) and nitrates (NO_3^-). However, this unavailable N can undergo a succession of transformations, making it available to plants. These transformations (N_2 fixation, mineralization, nitrification, plant uptake, immobilization, NO_3^- leaching, NH_4^+ fixation, volatilization and denitrification) are part of the nitrogen cycle, which is illustrated in Figure 12:

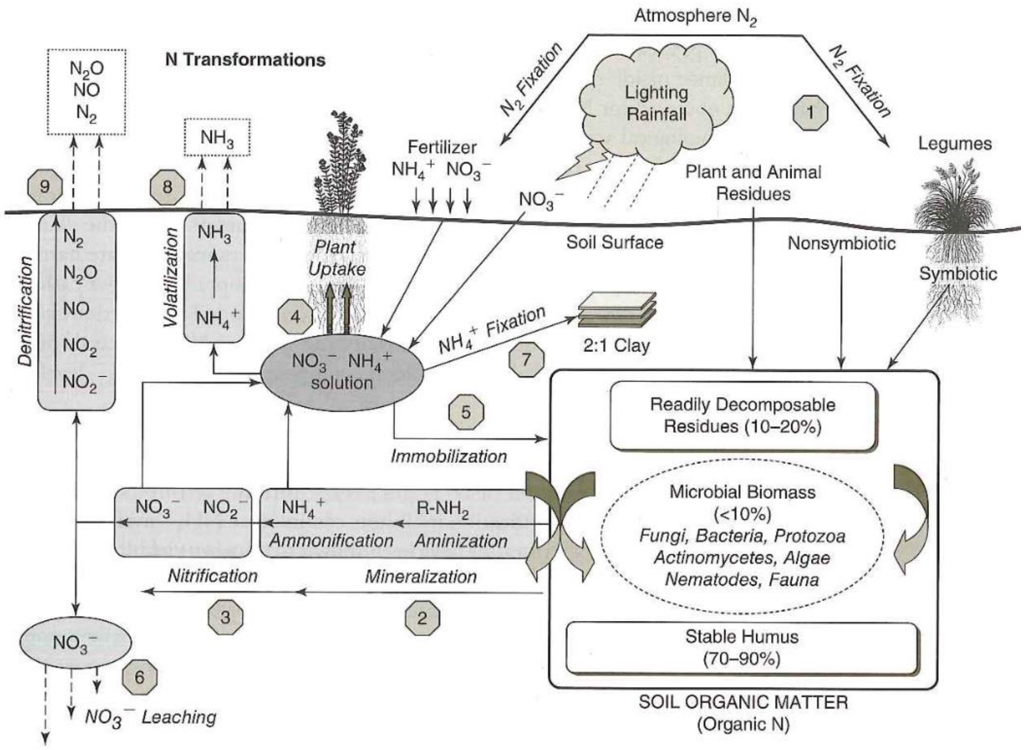

Figure 12: The Nitrogen cycle in soils (Havlin et al., 2014)

Atmospheric N2 can be fixed by microorganisms. Bacteria of the genus *Rhizobium* living in symbiosis in legumes nodules, are responsible for approximately 50% of the N fixation in soils in NH_4^+ form (Havlin *et al.*, 2014). Others non-symbiotic bacteria genus, such as *Azobacter*, can also fix N_2. Fertilizers and biomass residues are another source of N in soils. Apart from fertilizers inputs, which release N directly under NH_4^+ and NO_3^- forms that are available to plants, N is supplied in its organic form which accounts for 95 to 99% of soils' N (Weil and Brady, 2017).

Organic N can then be converted into ammonium (NH_4^+) by microbial decomposition, in a process called mineralization. NH_4^+ can then be removed from the soil solution by plant uptake or oxidized into NO_3^- by nitrification by some specific soil microorganisms, such as *Nitrosomas* and *Nitrobacter*.

The ammonium and nitrates present in the soil solution can then follow different paths. These inorganic ions can be converted back into organic N by biotic or abiotic processes, known as immobilization. They can also be extracted from the soil solutions by plant roots. NO_3^- is highly mobile in soils, since it is very soluble in water and it isn't retained much by soils anion exchange capacity (AEC). Thus, N in soils is mainly leached in the form of nitrates, especially in temperate regions, in which clays with negative charges predominate (Mancino and Troll, 1990; Weil and Brady, 2017). Positively charged ammonium can be absorbed on the negatively charged surfaced of clays and organic matter (OM). Because of its small size, it can even be stuck inside the structure of some clay minerals. However, in highly weathered soils of the humid tropics, AEC dominates because of the abundance of Fe and Al oxides and 1:1 clays, which are positively charged. Ammonium is thus more subject to leaching in these soils (Xiong *et al.*, 2010).

Both NO_3^- and NH_4^+ can be returned to the atmosphere in a gaseous state. When soil is saturated in water, anaerobic conditions occur. Then, some anaerobic organisms such as Pseudomonas and Bacillus use NO_3^- as an oxygen provider and turn it into gaseous N_2O or N_2: this is denitrification (Havlin *et al.*, 2014). NH_4^+ can react with OH^- in soil to produce ammonia gas (NH_3), which then leaves the soil system, in a process called volatilization. NH3 can also be produced by biomass decay (Weil and Brady, 2017).

The soils used in this study could show specificity with respect to the N cycle. Indeed, FLIPP soil is extremely weathered, poor in OM, coarse-textured, and enriched in positively charged iron oxides. It is therefore the AEC that should control the fixation of nutrients in the soil. Anions should therefore be less sensitive to leaching. Thus, it is likely that ammonium may leach more than nitrates. On the other hand, HPGS and FLC soils have a larger clay fraction and are less poor in C. Their CEC is therefore higher: ammonium should be retained more efficiently than in FLIPP soils. In addition, their chemical properties show that they appear to be more fertile than FLIPP soil. Thus, plant uptake may be greater in these soils.

2.2. Impacts of biochar on the Nitrogen cycle

Biochar amendments impact soil's N dynamics in different ways. First, biochar is a direct input of N into the soil, since it can contain up to nearly 3% N (Ippolito *et al.*, 2015). Biochar surface is in fact covered with nutrients salts, particularly NH_4^+-based for low- temperature biochars, while NO_3^- predominates for high-temperature biochars (DeLuca *et al.*, 2015). Although biochar does not increase N concentration in plant tissues, it is known for improving biomass yield, and thus total N uptake by plants (Biederman and Stanley Harpole, 2013). This also induces a feedback effect, as more and better-quality N-containing plant organic matter is reintroduced into the soil by litter, residues, or novel biochar (DeLuca *et al.*, 2015).

Biochar also significantly reduces NH_4^+ losses by leaching in soils, certainly thanks to its porous structure, its negatively charged surface, and water retention improvement (Clough and Condron, 2010; Dempster, Jones and Murphy, 2012; DeLuca *et al.*, 2015). Biochar also seems to decrease NO_3^- losses by leaching, (Clough and Condron, 2010; Knowles *et al.*, 2011; Dempster, Jones and Murphy, 2012; Yao *et al.*, 2012). In addition, biochar provides available C, enhancing immobilization and thus protecting N from being leached (DeLuca *et al.*, 2015).

Biochar is also known for reducing N_2O emissions from soils, possibly by enhancing denitrifying microbial communities (Harter *et al.*, 2013; DeLuca *et al.*, 2015). In fact, Cayuela et al. (2013) reported a decrease of N_2O emissions by 10 to 90% on 14 different agricultural soils. Although biochar increases nitrification rates in forest soils, no evidence suggests that it can also affect agricultural soils (DeLuca *et al.*, 2015). Biochar can however enhance N_2 fixation by increasing the abundance of soil microorganisms capable of doing so (Harter *et al.*, 2013). Thanks to its ability to absorb ammonia, biochar can also slows down volatilization rates (Clough and Condron, 2010).

3. Phosphorus cycle and biochar

3.1. Phosphorus cycle

Phosphorus (P) is the second most important element for plant growth and health, after Nitrogen. In plant tissues, P is used to synthesize the adenosine diphosphate (ADP) and triphosphate (ATP), which are responsible for energy storage and transfer. Unlike N, the main source of soil P is the alteration of parent material and soil minerals. The Phosphorus cycle is illustrated in Figure 13:

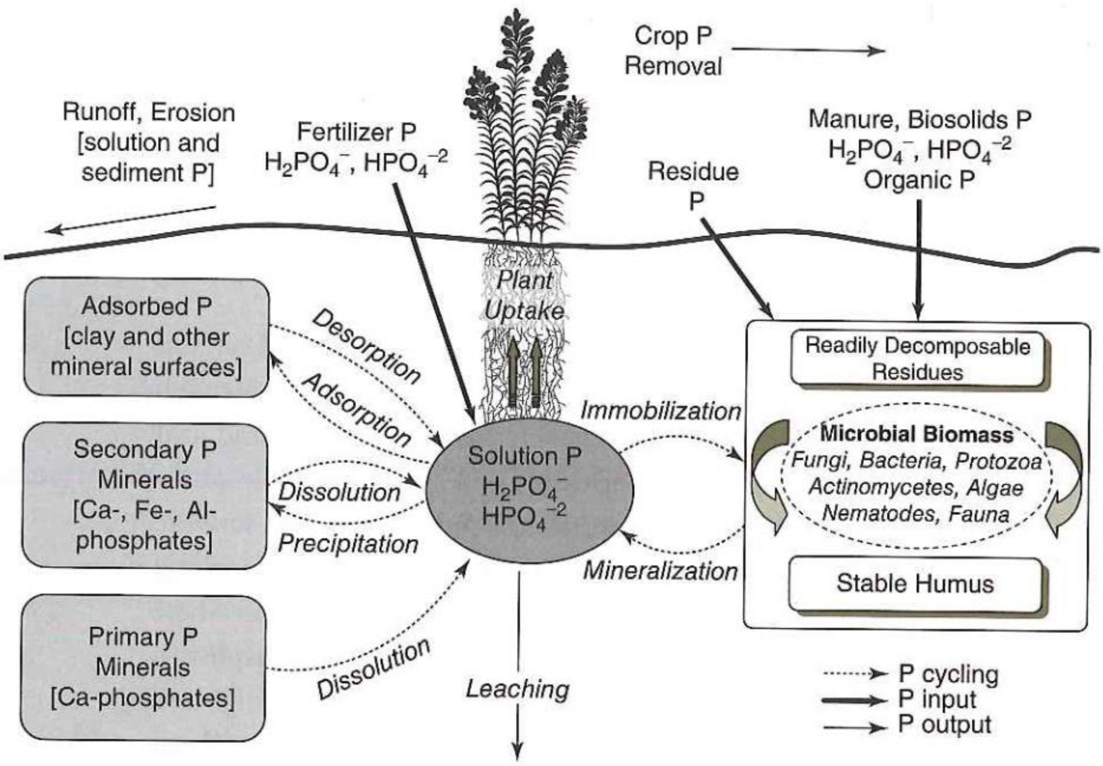

Figure 13: The Phosphorus cycle in soils (Havlin et al., 2014)

P can enter the soil system in different ways. Organic wastes, such as manure or agricultural residues can be supplied to the soil and undergo mineralization by soil microorganisms. The P they contained is then released in the soil solution in $H_2PO_4^-$ and HPO_4^{-2} forms and are made available for plant uptake. This operation can be reversed, and organic P can be formed from these orthophosphate anions, known as immobilization (Weil and Brady, 2017). These processes are similar to N mineralization and immobilization. Organic phosphorus can also be part of the labile organic matter pool or be stabilized in the humus fraction. Dissolution of primary P mineral, such as Calcium Phosphates, is also a way for P to enter the soil solution. Mineral fertilizers can supply P under their readily available forms for plant absorption. To a lower extent, dust and rain can also provide P inputs into the soil.

In the soil solution, phosphorus is in equilibrium with mineral phases such as primary minerals, clays and iron and aluminum oxides. In alkaline soils, calcium phosphate compounds are highly insoluble. Conversely, these compounds tend to dissolve rapidly in acidic soils, were Fe, Al an Mn oxides precipitate. P is rapidly fixed to these compounds (calcium carbonate or metal oxides) when present in the soil solution, since their surface is positively charged, and its solubility gradually decreases until they bind permanently. Organic molecules can also be adsorbed on these surfaces, reducing their ability to fix P. Phosphate ions can also directly precipitate with Ca^{2+} or metal cations. In the latter case, precipitates are highly insoluble, and thus P is made unavailable for plant uptake.

P is present in very low concentrations in soil solution, ranging from 0.001 mg L^{-1} in infertile soils to 1 mg L^{-1} in rich and fertilized soils (Weil and Brady, 2017). P can be absorbed by plants through root hairs and Mycorrhizae with which they have a symbiotic relationship. Plants are responsible for most of the P lost, from 5 to 50 kg ha^{-1} yr^{-1}. Other P outputs are, in decreasing order of importance, soil particles erosion, surface water runoff and leaching. Phosphate ions generally move very slowly in the soil profile due to their strong interactions with the surface of soil particles.

The soils used in this study are rather acidic and weathered. Therefore, P should mainly interact with metallic cations and Fe or Al oxides. FLIPP soil is coarse-textured, thus interaction between P and clay minerals are unlikely to control P dynamics. However, its low C content and the presence of Fe concretions suggest that interaction with metallic oxides should be enhanced. On the opposite, FLC and HPGS soil contain approximately 20 and 35% of clay respectively, which means that clay-P interactions might be prevailing. Metallic oxides are also present in FLC soil, so they might be an additional way to fix P and prevent it from leaching.

3.2. Impact of biochar on the phosphorus cycle

In the same way as for nitrogen, a biochar amendment is also a direct input of P. Biochar P content ranges from less than 0.01% to more than 0.1%, depending on the feedstock type (Ippolito *et al.*, 2015). Pyrolysis at temperatures below 760°C does not cause a loss of P by volatilization: P in the biomass is then preserved (Knicker, 2007). However, P inputs from biochar are partly in organic form, making them unavailable to plants until they are broken down by soil microorganisms.

Biochar amendments also lead to a liming effect. In acidic soils, where highly insoluble Al and Fe oxides can precipitate and control P availability, this pH rise mitigates P precipitation with Al^{3+} and Fe^{3+}. In alkaline soils, this liming effect can conversely accelerate Ca-P precipitation, exacerbating P limitations (DeLuca *et al.*, 2015). Biochar can also sorb soil cations on its negatively charged surface, and organo-mineral can form, improving the retention of exchangeable and soluble P.

Crop yield and P concentration in plant tissue tend to increase as a result of biochar application, thus expanding the total P uptake by plants (Biederman and Stanley Harpole, 2013). Biochar is usually applied at high rates, around 50 t ha^{-1}. This can lead to P over-fertilization, which can enhance P leaching. However, these processes have not been demonstrated yet (DeLuca *et al.*, 2015).

4. Soil cations cycles (K, Ca, Mg, Mn)

4.1. Cations cycles

K, Ca, Mg and Mn also play key roles in plant metabolism. K, which is abundant in plant tissues is notably used charge balance between cell walls and enzymes activation. Ca is an essential cell wall component, while both Mg and Mn are necessary for photosynthesis to take place, respectively as a primary constituent of chlorophyll, and as an electron donator (Havlin *et al.*, 2014). Their cycles show many similarities, as they all originate from the weathering of soil primary minerals and are present in cationic forms in the soil solution. K cycle in soils is illustrated in Figure 14:

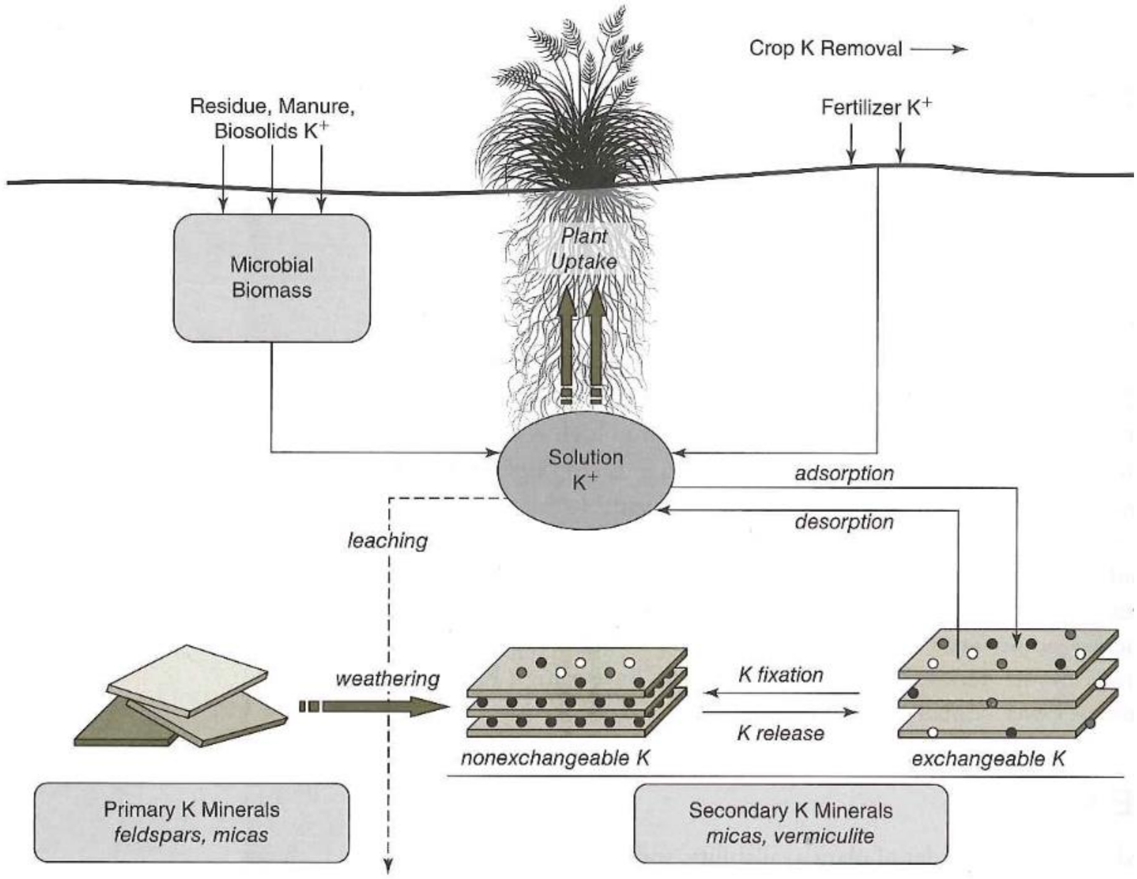

Figure 14: The Potassium cycle in soils (Havlin et al., 2014)

These cations can be directly brought to the soil by fertilizers, microbial biomass through mineralization of crop residues or manure. Parent material and soil minerals weathering is also a great source of K, Ca, Mg and Mn. However, this nutrient supply cannot meet crops needs during the growing season, since this process takes place over the long term.

Layers of 2:1 minerals, such as micas, are held together thanks to dehydrated K ion. K^+ is thus strongly fixed and unavailable. Other cations of larger radii cannot penetrate interlayer spaces and are therefore not retained. However, as weathering intensifies, interlayer spaces expand and larger cations such as Ca^{2+} or Mg^{2+} can then be fixed between these layers, or on their outer surfaces (Weil and Brady, 2017). This process is shown in Figure 15:

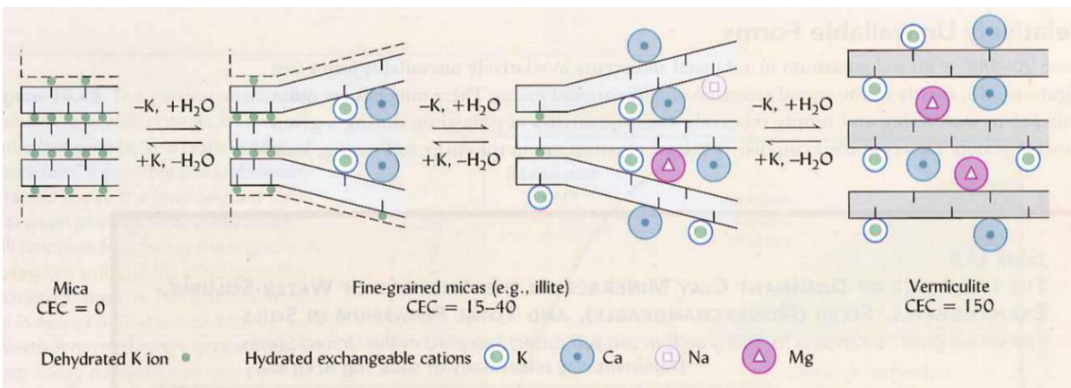

Figure 15: Diagrammatic illustration of the release and fixation of potassium between primary micas, fine-grained micas (illite clay) and vermiculite (Weil and Brady, 2017)

As primary minerals are weathered, secondary clay minerals are formed, CEC increases, and more cations can be retained in the soil. However, K^+ can be chased from the exchange sites by Ca^{2+}, Mg^{2+}, Mn^{2+} and other cations, since their positive charge is greater. Thus, the presence of these cations can reduce the availability of K. Ca^{2+}, Mg^{2+} and Mn^{2+} can also precipitate into oxides depending on pH conditions. 1:1 minerals, such as kaolinite, are not able to fix K^+ (Weil and Brady, 2017).

These cations can be removed from the soil system by plant uptake or by leaching. However, K losses by leaching are small in most soils, except in sandy and weathered soils of the humid tropics, where the CEC is too low to retain K^+ efficiently.

FLIPP soils might be subject to cations leaching. In fact, their coarse-texture and their poor C content lead to a low CEC. Thus, they cannot retain cations efficiently. However, FLC and HPGS soils are enriched in clay and have a higher C content. Their CEC, although it is still low, far exceeds that of FLIPP soils. They should be able to fix cations more successfully. FLC soils show a greater CEC than HPGS soils, and thus a better potential for cation stabilization. In addition, HPGS soils contain more Ca, Mg and Mn than FLC soils. These cations may occupy the exchange sites, enhancing K^+ losses by leaching.

4.2. Impact of biochar on these cycles

Once again, biochar is a direct input of K, Ca, Mg and Mn to the soil. It can contain up to 1.5% K from which 3 to 100% is directly available (DeLuca *et al.*, 2015; Ippolito *et al.*, 2015). Ca and Mg concentrations of biochar are of the same order of magnitude, and can reach more than 0.01%. (Ippolito *et al.*, 2015). However, the release of Mg by biochar seems to be slower than the release of K (Angst and Sohi, 2013).

Very few studies focus on the impact of biochar on Ca, Mg and Mn dynamics in soils. Nevertheless, biochar is known for increasing CEC, especially in the long term. Thus, it might be able to fix these cations into the soil, reducing their losses by leaching. In addition, biochar amendments enhance plant growth, and thus plant uptake. This effect might be more pronounced for K, since biochar significantly increases K concentration in plant tissue (Biederman and Stanley Harpole, 2013). Due to its liming effect, biochar might also foster the formation of calcareous concretions in alkaline soils.

IV. Maize

1. A quick overview

Maize (*Zea mays* L.), also known as corn, belongs to the *Poacea* family, which also includes grass, wheat and rice. It originates from Mexico and Central America, where it was domesticated by indigenous people in the early days of agriculture, approximately 10 000 years ago. Maize stems from the domestication of *teosinte* which was a wild grass (Beadle, 1939).

Maize is a monoecious crop and a C_4 plant, which means that it fixes CO_2 into a compound based on four carbon atoms. Thus, it suits well to hot and dry climate, since its use of water is optimized. However, extensive breeding interventions enabled it to adapt to more varied climatic conditions. Its growth cycle is short, and lasts from 3 to 7 months, depending on the variety. Maize is now grown in more than 160 countries, from 58°N to 40°S, at high altitude and at sea level, under arid and humid climates.

In 2017, maize was grown on 200 million hectares, for a total production of about 1130 million tons. It is now one of the top 3 most popular crops, just behind rice, and ahead of wheat (FAOSTAT, 2019). 30% of the annual production is dedicated to human nutrition and industrial purposes, the remaining 70% being used as fodder.

2. Maize in Burkina Faso: a growing importance

Maize cultivation is expanding rapidly in Western Africa, including in Burkina Faso. Although it was introduced in Africa, it has quickly gained popularity and is now considered a staple food. Maize is now grown in the 13 regions of Burkina Faso, mainly in rainfed agriculture. It is mainly used as a subsistence crop, and its residues usually serve as fodder (Sarr and Kafando, 2011).

In terms of cultivated area, maize is the third most popular cereal in the country with 956 kha, behind sorghum (1667) and millet (1223). According to the data provided by FAOSTAT, (2019), between 2007 and 2017, the area under maize cultivation in Burkina Faso doubled (+ 103%), whereas the increases for sorghum and millet were more subtle (respectively + 4% and + 3%).

The changes in maize yields are also dramatic. In fact, for the period 1961-1990, the average yield was 0.76 t ha^{-1}, but it reached 1.60 t ha^{-1} between 1991-2017, an increase of 109%. In comparison, for the same periods, sorghum yields only increased by 64%, levelling at 0.95 t ha^{-1}, and millet yields grew by 66% to 0.76 t ha^{-1} (FAOSTAT, 2019). The development of enhanced seeds and the support of the State and its partners might be the driving factors behind this remarkable jump in yields (Sarr and Kafando, 2011). Nevertheless, yields are still low compared to other regions of the world.

Annual production of food crops (sorghum, maize and millet) remained stable between 1961 and 1985. Sorghum and millet were clearly dominating the market, while annual production of maize was far behind those of these crops. Until the mid-2000's, all three crops have seen their production rise in a linear and continuous way. However, since then, the growth rate of maize production has increased, while millet and sorghum production has remained stable and even tending to decline. One of the reason for this shift in crop production might be the fact that improved varieties of maize show a better response to fertilization than sorghum and millet (Fakorede *et al.*, 2003). For the first time in 2017, maize annual production surpassed that of sorghum, reaching more than 1500 kt. Thus, maize tends to become the most important food crop in Burkina Faso. The evolution of food crops production is illustrated in Figure 16:

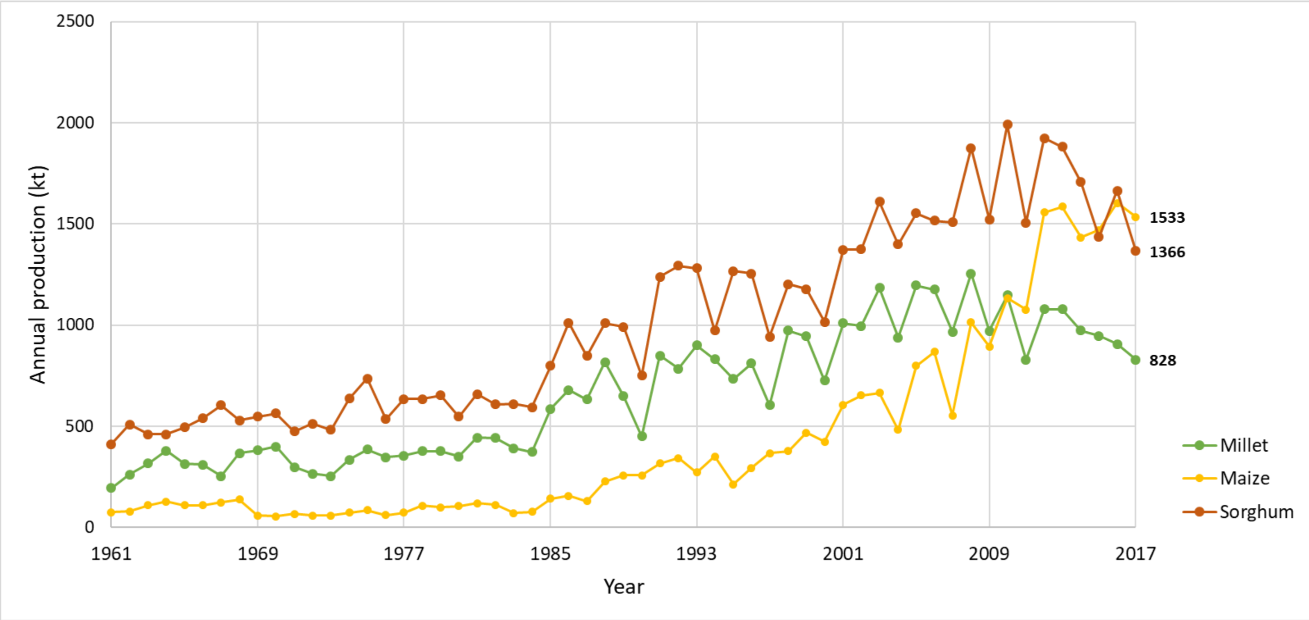

Figure 16: Evolution of the annual production of the main food crops (millet, maize and sorghum) in Burkina Faso between 1961 and 2017 (based on the data provided by FAOSTAT, 2019).

3. Crop physiology

3.1. Development stages

It is fundamental to know the development stages of maize, in order to ensure adequate conditions during critical periods of growth, and to optimize the use and the response to fertilizers. In fact, water stress during the critical period from 20 to 30 days before silking to 10 to 15 days after can result in a 60% yield loss (Robelin, 1963, cited by Sarr et al., 2011). Development stages are classified in two different categories: vegetative (V) and reproductive stages (R). The different stages are listed in Table 8:

Table 8: Development stages of maize

Vegetative		Reproductive	
Stage name	**Description**	**Stage name**	**Description**
VE	Emergence	R1	Silking
V1	1^{st} ligulated leaf	R2	Blister
V2	2^{nd} ligulated leaf	R3	Milk
V3	3^{rd} ligulated leaf	R4	Dough
Vn	n^{th} ligulated leaf	R5	Dent
VT	Tasseling	R6	Maturity

VE corresponds to the germination and the emergence of seedlings. High level of soil moisture is required for the corn seed to germinate. Radicle emerges first, followed by the coleoptile. A week after emergence, the seedling enters V1 to V2 stages. The root system is developing, and the nutrient requirements are still low. Two weeks after emergence, V3 stage is initiated. The root system development of the seedling ends. This stage is critical, since leaf and ear shoots are being established. The number of potential ears is thus determined at that point. This will continue until V5, when a microscopic tassel is being initiated at the growing point, which is now at the surface level.

Another week after, V6 stage begins. Plant root system continues spreading, and the stem starts elongating rapidly. Fertilizers should be applied, since the plant requires great amounts of nutrients. In the fourth week after emergence, plant enters V8 stage. Nutrient deficiencies can have dramatic impacts on leaf growth at this point.

From the fifth to the seventh week (V10 to V15), the plant grows rapidly, and new leaves appear every two or three days. As a result, the demand for nutrient is high. The number of kernels and ears size are being determined during this period. The first brace roots are developing. At V15, the tassel almost reaches its full size but is not yet visible.

Then, the late vegetative phase begins, about eight weeks after emergence (V16 to Vn). Upper-ear shoots and the tassel might already be visible. As silking approaches, the plant is now highly vulnerable to water stresses, which can cause dramatic yield reductions. The plant reaches its full size, and ears continue developing. Finally, a couple of days before silking, tasseling (VT) begins. Vegetative growth stops, and the pollen is now released.

Reproduction stages are now beginning with R1 (silking), 55 to 66 days after emergence. Silks are visible and are being pollinized. The plant uptake of Nitrogen and Phosphorus is high. Deficiencies and water stress can cause severe yield drops during this stage. About 12 days later, the plant enters the R2 stage. Ears almost reached their full size, and kernels are white and start to fill up with starch. 20 days after silking, R3 (milk) stage begins and kernels are filled with a white fluid. Their moisture content is about 80%. About 6 days after, kernels are thickening and are turning yellow. Their moisture content is also decreasing (R4 to R5). Finally, 55 days after silking, kernels are now mature and contain approximately 30% water. Leaves and kernels are drying until harvest (Nielsen, 2000; Berglund, 2013).

3.2. Nutrient requirements

In order to fulfil correctly its growth cycle, maize requires enough fertilizers supply. In fact, it accumulates large quantities of nutrients as it grows. Table 9 compiles the results of various studies in terms of grain and leaf concentrations in nutrient, and total uptake of nutrient (Singh, 1971; Hussaini *et al.*, 2008; Ullah, Ali and Farooqi, 2010):

Table 9: Ranges of concentrations in maize leaves and grains, and total uptakes in different elements (data from Singh, 1971; Hussaini et al., 2008; Ullah et al., 2010)

Element	Range of concentrations in grains (mg $100g^{-1}$)	Range of concentrations in leaves (mg $100g^{-1}$)	Range of total uptake (kg ha^{-1})
N	1420 - 1850	1450 - 2800	10.0 - 74.2
P	240 - 330	230 - 250	5.4 - 44.5
K	291 - 430	1200 - 1250	7.0 - 56.3
Ca	5 - 59	45 - 48	2.4 - 10.7
Mg	72 - 163	70 - 78	0.4 - 8.7

Concentrations in N and K are high in maize tissues. As grains are filled with about 70% carbohydrates (mostly starch), their nutrient concentrations tend to be lower than in plant tissues (Ullah, Ali and Farooqi, 2010).

Ranges of nutrient uptake vary considerably on the fertilizing rates. However, P and N uptakes of continuously cultivated always exceeded mineral fertilizers inputs during a 2 year-long trial in Benin (Sogbedji, Van Es and Agbeko, 2006). According to this study, increasing the fertilization rate does not necessarily induce positive changes in maize yields, though its uptake rises. In fact, luxury uptake of nutrient might occur. Thanks to a field trial in Southern Nigeria, Onasanya et al. (2009) estimated that the optimized fertilizers input to maximize maize yield was 120 kgN ha^{-1} and 40 kgP ha^{-1}. Nevertheless, it might not be suitable for local farmers, as fertilizers are expensive. In addition, although exchangeable K in soil is usually high in Western Africa, K input might be necessary since K uptake increases with N and P fertilization (Ayodele and Omotoso, 2008).

The use of models such as QUEFTS might be of great help to estimate the optimal input of fertilizers depending on the soil fertility (Setiyono *et al.*, 2010). However, the environmental impacts of the use of mineral fertilizers should also be assessed, in order to avoid environmental impacts such as eutrophication or groundwater pollution.

3.3. Variety chosen for the study

The maize variety used in this study is Barka. Produced by the *Institut de l'Environnement et Recherches Agricoles* (INERA) in Farako-Bâ, Burkina Faso, it is the result of the crossbreeding of 6 drought-resistant lines. It has thus been designed to be grown in areas where annual precipitations do not exceed 750 mm.

Barka is an extremely early variety of maize with a seedling-maturity cycle of only 80 days, including 42 days to reach tasseling. This is the main reason why it was chosen for this study. Its potential yield is 5.5 t ha^{-1}, and its height is about 175 cm. Fitted with white grains, it can be used for human consumption, as fodder, as well as in the brewing industry or in the starch manufacture. It is also resistant to several diseases, such as rust and helminthosporiosis, and tolerates high crop densities (Sanou, 2007).

4. The impact of biochar on maize production

Many studies reported positive effects of biochar amendments on maize yields. In Ghana, Oguntunde et al. (2004) showed that maize grown on charcoal sites increased its grain and biomass yield respectively by 91% and 44% compared to adjacent field soils. Major, et al. (2010) set a 4 year-long field trial with biochar applied at a rate of 20 t ha^{-1} on a Colombian Oxisol. Yield did not increase significantly the first year, but it did for the next three years. The harvest index (grain biomass divided by the total biomass) also rose, as well as the total nutrient uptake. In fact, Ca and Mg concentration in leaves increased significantly. Arif et al. (2017) also have seen an improvement in yields following biochar application, as well as a better Phosphorous use efficiency. On average, biochar addition increased maize productivity by 19% (Jeffery *et al.*, 2015). The sharpest rise in yield is observed with the addition of biochar enhanced with NPK and compost, with +248% and +243% respectively (Pandit *et al.*, 2017, 2019). However, biochar did not impact the germination and early growth of maize seeds (Free *et al.*, 2010).

Maize is also a promising source of biochar production. In fact, neighbouring Ghana produced more than 1400 kt of residues in 2008, which is more than sorghum and millet residues combined (Duku, Gu and Hagan, 2011). In addition, application biochar made from maize stover induced on average an increase in crop productivity by 35% (Jeffery *et al.*, 2015). Thus, maize shows a great potential to produce biochar.

V. Soil description

In this section, the three different soil types that were used in this study will be described. The physico-chemical properties of these soils were determined by Drissa CISSE in 2018 and are shown in Annex 1 and Annex 2.

1. FLIPP

FLIPP stands for "*sol ferrugineux lessivé induré peu profond*". In the French soil classification system (CPCS, 1967), it is classified as such: "*sous-groupe induré*", "*groupe lessivé*", "*sous-classe des sols ferrugineux*", "*classe des sols à sesquioxydes de fer et de manganèse*". In the WRB classification (WRB, 2015), it is considered as a epipetric Plinthosol.

FLIPP soils contain an eluviated horizon lying on a cemented plinthic horizon arising at low depth (< 30 cm). The transition between the two horizons is usually sudden. The cemented horizon is enriched in iron oxides and kaolinite clay. The sand content of the E horizon is high and regularly exceeds 60%. It also contains low activity clays to a lower extent (< 15 %). Usually located uphill, FLIPP soils show few to no structure and are washed away by water, resulting in strong clays and nutrient leaching. They are also enriched in metal oxides whose dimensions frequently exceed 2 mm. Their carbon content is extremely low due to enhance decay of biomass, and are poor in nutrient (Kissou *et al.*, 2000).

2. FLC

FLC stands for "*sol ferrugineux lessivé à concrétions*". As FLIPP soils, it is part the "*lessivé*" group, but it belongs to the "*à concretions*" subgroup (CPCS, 1967). It is considered as a ferric Lixisol according to the WRB (2015). The word ferric refers to the presence of a horizon enriched in iron (or iron and manganese) concretions arising at a maximum depth of 100 cm. FLC soils are usually located uphill, and are lying on a granitic bedrock (Pallo and Thiombiano, 1989). They show high sand content in the surface, and are enriched in clay (mostly kaolinite and illite) in their subsoil (Kissou *et al.*, 2000). FLC soils are most generally 2 to 2.5 m deep. The horizons of FLC soils are usually arranged as such (Fauck, 1962):

- <u>A humic horizon (A):</u> about 20 to 25 cm thick, grey to light grey. The structure, which is poorly to moderately developed, is rough and soil aggregates are of a moderate cohesion. The texture is sandy, and the clay content is low. Organic matter often shows waterlogging signs due to the underlying clay-enriched horizon.
- <u>An eluviated horizon (E):</u> about 15 to 25 cm thick, beige. Clays, iron and nutrient are washed away. Its structure is poorly developed.
- <u>A clay-enriched horizon (Bt):</u> reddish to beige with a subangular blocky or polyhedral structure.
- <u>One or seral ferric horizons:</u> characterized by the presence of iron concretions, whose size ranges between 0.5 to 4 cm. Manganese oxides can also be found.

3. HPGS

HPGS stands for "*sol hydromorphe peu humifère à pseudogley de* surface" (CPCS (1967). It is considered as an eutric Gleysol in FAO soil classification (WRB, 2015). This type of soil is affected by the presence of excess water, notably due to its downhill location, which induces anaerobic conditions, In the absence of oxygen, the reduction of Fe^{2+} to Fe^{3+} is occurring. However, these reducing conditions are periodic, hence the term “*pseudogley*”. In fact, during dry seasons, the soil is no more saturated in water and iron can thus be oxidized, which is shown by reddish nodes in the soil profile (Vizier, 1984).

HPGS soils are usually deep and are defined by the presence of a gleyic horizon (G) at a maximum depth of 1.30 m. Their colour is greyish brown or light greyish brown. They show grey and reddish spots due to the reduction and oxidation of iron. Their texture is loamy to clayey, which enhances their water retention capacity. Organic matter and nitrogen contents are generally fair, but phosphorus contents are extremely low. pH is moderately to weakly acidic (Kissou *et al.*, 2000).

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