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Cropping System Effects on Soil Monosaccharides in Western Burkina Faso

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Abstract

Labile pools of soil organic matter (SOM), including soil sugars, are important to the formation and stabilization of soil aggregates and to microbial activity and nutrient cycling. The effects of cropping systems at farm level in tropical areas on SOM labile pool dynamics have not been adequately studied and the results are sparse and inconsistent. The objective of this study was to determine the effects of soil management intensity on soil sugar monomers derived from plant debris or microbial activity in cotton (*Gossypium herbaceum*)-based cropping systems of western Burkina Faso. Thirty-three (33) plots were sampled at 0-15 cm soil depth considering field-fallow successions and tillage intensity. Two pentose (arabinose, xylose) and four hexose (glucose, galactose, mannose, glucosamine) monomers accounted for 2 to 18% of soil organic carbon (SOC) content. Total sugar content was significantly less with tillage, especially for the hexose monomeric sugars glucose and mannose, the latter of microbial origin. Soil mannose was 63 and 80% less after 10 years of cultivation, without and with annual ploughing respectively, compared with fallow conditions. Soil monosaccharide content was rapidly restored with fallow and soon approached the equilibrium level observed under old fallow lands. Therefore, the soil monosaccharides, in particular galactose and mannose from microbial synthesis are early indicators of changes in SOC.

Keywords: Cultivation intensity, cotton, fallow, Ferric Lixisol, monosaccharides, soil organic carbon.

Soil organic matter (SOM) is critical to sustainable management of tropical savannah soil fertility (Sermé *et al*., 2016). It provides energy, substrates, plant nutrients, and the biological diversity required to sustain numerous soil ecosystems functions (Ouattara *et al*., 2006), but SOM contents vary among environments and management systems. Generally, SOM is more with higher annual precipitation, lower annual temperature, higher clay content, and native vegetation compared to cultivated management, and conservation compared with plough tillage system (Chan *et al*., 2002; Sharma *et al*., 2013). In the African savannahs, farmers practiced shifting cultivation with a few years of cultivation followed by a longer fallow period to sustain soil fertility (Ruthenberg, 1971; Dhadli *et al*., 2016). Fallow affected production and ecological functions leading to improved nutrient availability and biodiversity (De Wolf *et al*., 2000; Liu *et al*., 2013). Land use has intensified and fallow is less frequent and of shorter duration with reduced SOM and SOM-related soil processes. The SOM decline was exponential with a great loss following first cultivation of virgin soils, but the decline continues after many years (Arrouays *et al*., 1994; Srinivasarao *et al*., 2014). However, SOM has diverse components with some SOM pools protected by mineral clays (Larré-Larrouy *et al*., 2003). Coarse sand size SOM fractions, carbohydrates, and soil microbial biomass can be considered as indicators of early changes in SOM stocks related to cultivation intensity (Haynes, 1999; Schulz *et al*., 2014). Labile pools of SOM, including soil sugars, are important to the formation and stabilization of soil aggregates (Oades, 1984; Gentile *et al*., 2013; Pérès *et al*., 2013; Tian *et al*., 2015) and to microbial activity and nutrient cycling (Belay-Tedla *et al*., 2009).

In tropical areas, the induced-effects of cropping systems on SOM labile pool dynamics have not been adequately studied and the results are sparse and inconsistent. The objective of this research was to determine the contents, composition of hydrolysable carbohydrates and their variation across a large range of cotton-based cropping systems. The study was carried out in on-farm fields, in the cotton area of western Burkina Faso. The hypothesis of the study was that the dynamics of monomer sugars, through the various cropping systems, is a good indicator of early soil organic matter changes.

1. Materials and methods

1.1 Site Description

The study was carried out at Bondoukui (11°51' N lat., 3°46' W long., 360 m a.s.l), located in the western cotton zone in Burkina Faso. This region provided contrasted situations, in terms of diversity of major cropping systems (shifting, cyclic and continuous cultivation) and tillage intensity (occasional, biennial and annual ploughing). Mean rainfall is between 900 and 1,000 mm yr^{-1} with a unimodal distribution with a high rainfall distribution from May to October. The daily maximum temperatures vary between 31 and 39 ℃. The average evapotranspiration is 1,900 mm yr^{-1}. Vegetation type prior to cropping was an open woody savannah and the main species *Vittelaria paradoxa* and *Parkia biglobosa* constitute parklands in the cultivated areas. The soil type is Ferric Lixisol (Table 1).

Table 1: Physical and chemical characteristics of Bondoukui soils under fallow (depth 0-15 cm).).

Soil characteristics	Values (N = 14)
Clay + fine silt (%)	26.6 ± 11.5
Total sands (%)	54.4 ± 14.1
Bulk density (kg/dm^3)	1.48 ± 0.08
Total basic cations (cmol/kg soil	3.3 ± 1.7
CEC (cmol /l)	3.7 ± 2.2

Organic carbon (g-C/kg-Soil)	6.0 ± 1.6
Nitrogen (g-N/kg-Soil)	0.4 ± 0.1
pH water	6.2 ± 0.3

CEC: Cation Exchange Capacity N: Number of fallow plots

1.2 Cropping Systems

Study plots were identified, based on-farm field typology according to the intensity of cultivation (IC), as defined by Ruthenberg (1971). The IC is the ratio of years in annual crops to years in fallow. Thus, three major cropping systems were identified:

i. Shifting cultivation system (IC < 0.33), characterized by short cultivation periods (< 10 years) and long fallow periods (> 30 years). These old fallow lands are locally called "*diur ȇ*";
ii. Fallow cultivation system or cyclical cultivation system (0.33 < IC < 0.66) with 5 to 10 years of cropping, followed by 10 to 20 years of fallow;
iii. Continuous cultivation system (IC > 0.66), often interrupted by very short fallow periods (1 - 3 years).

These cropping systems were split into length of cultivation-fallow phases and soil tillage system (Table 2). Three groups of fallow periods were recorded: 1 - 10, 11 - 20 and up to 30 years. Soil tillage included:

i. occasional ploughing (at least every three years) and hand hoeing were performed during shifting and fallow cultivation systems;
ii. biennial and annual ploughing were observed in the continuous cultivation system, respectively under cereal – cereal - cotton rotation and maize – cotton rotation.

Ploughing was done up to 15 cm depth with tractor or oxen power for planting of maize or cotton. Hand hoe tillage was less than 5 cm soil depth.

Organic matter fertilization (animal faeces, domestic wastes, compost), was performed mainly on-farm under permanent cultivation system. The amounts ranged from 2 to 5 tha^{-1} and of 2-3 years frequency.

Table 2: Number of plots according to major cropping systems and the tillage typologies.

	Shifting system		Fallow system			Continuous cultivation	
	F30	C10	F10	F20	C10	Plough./2years	Plough./year
Sampled plots	5	4	4	5	5	5	5

F30: 30-40 years fallow; F20: 11-20 year fallow; F10: 1-10 years fallow; C10: 1-10 years cultivation; Plough./2years: biennial ploughing; Plough./year: annual ploughing

1.3 Soil Sampling.

Soil samples were collected from 33 fields including 14 natural fallow lands which were sampled during the dry season. Soil sampling depth was 15 cm and corresponded to the soil layer that was much influenced by tillage. Soil was randomly sampled in three replications. The replicates were bulked to constitute one composite sample per field for laboratory analysis. Soils were air dried, gently ground to pass a 2 mm mesh sieve, and later finely ground to pass a 200 µm sieve for C and monosaccharide determinations.

1.4 Laboratory Analyses

Among the different methods of soil sugars extraction, Oades's sequential hydrolysis was used (Oades et al., 1970). It presents the advantage to extract the majority of soil carbohydrates, while minimizing their degradation. Four grams (4 g) of ground soil at 200 µm was pre-treated for 16 hours at room temperature with 72 % (22N) H_2SO_4. The solution was refluxed for three hours, after diluting the acid to 0.2 N. Interfering ions in the hydrolysate were reduced by elution, through anion and cation exchange resins. The solution was thereafter neutralized with 2M NaOH, in order to obtain a pH compatible with chromatographic eluants. The concentrations of the released soil sugar monomers were determined by a Dionex DX-600 (Dionex Corp., Sunnyvale, CA) ion chromatograph. The total polysaccharides content in each hydrolysate was calculated as the sum of the individual sugar contents. All measurements were expressed as carbon concentration in $mgkg^{-1}$ of soil.

The ratios R1 [(galactose+mannose): (arabinose+xylose)] and R2 (mannose : xylose) were calculated and used to assess the relative contribution of plants and microorganisms to the accumulation of carbohydrates in soils.

The soil organic carbon content (g Ckg^{-1}-Soil) was assessed using the Wakley and Black method, improved by Gnankambary et al. (1999) for Burkina Faso soils.

1.5 Statistical Analysis

The descriptive variables of cropping systems were coded from 1 to 7. The sampled plots were laid out in an unbalanced randomized block design where each of them constituted a replication (Table 2). Analysis of Variance (ANOVA) and means comparisons were performed, using Genstat software (6th edition).

2. Results

The variations of soil contents in total organic carbon, monomeric sugars and total carbohydrate across the cropping systems are presented on Table 3. It shows that the various cropping systems induced significant (**P < 0.01) modifications in total SOC contents. The higher values were registered in plots under shifting cultivation system while the lower ones were found in annual ploughing plots.

Extraction of soil carbohydrates gave two pentoses (arabinose, xylose) and four hexoses (glucose, galactose, mannose, glucosamine). The sum of the monomeric sugar contents (total carbohydrate) represented 2 to 18 % of soil organic carbon. The amount of the monomeric sugars studied varied across the cropping systems in the following order: glucose > arabinose > galactose > glucosamine > mannose > xylose (Table 3). Glucose was the most dominant sugar. It represented an average of 40 % of the total soil carbohydrate. On the other hand, xylose had the lowest concentration. The total soil hydrolysable carbohydrate concentrations varied significantly (*P < 0.05) with cropping systems. The change was statistically significant (*P < 0.05) for glucose, mannose and galactose.

Ratios R1 [(galactose + mannose) / (arabinose + xylose)], which assessed the relative contribution of microorganisms and plants to the accumulation of carbohydrates in soils, varied significantly (***P < 0.001) across the various cropping systems. The higher the ratio (R1) ≥1 was registered under fallow lands while the lowest one was observed in the annual ploughed plots (0.44). Therefore, the ratio R1 decreased with tillage intensity, and increased with the fallow age or duration. Ratio R2 [mannose : xylose] also varied significantly across the various cropping systems (*P<0.05) and the values were higher (≥2) both under fallow and cultivated lands. (Table 3).

Table 3: Contents of total organic carbon (g C/kg-Soil), monomeric sugar and the total carbohydrate of the soils (mg C/kg-Soil) from cropping landscape

	Shifting system		Fallow system		Continuous cultivation			LSD	P < F
	F30	C10	F10	F20	C10	Plough./2years	Plough./year		
Total Carbon	8.82a	7.0a	4.15bc	5.88bc	5.68bc	6.77ab	3.86c	2.62	**P < 0.01
Arabinose	121.4	122.2	72.8	79.2	109.8	84.6	93.9	-	NS
Xylose	29.2	20.2	29.2	19.7	11.0	8.9	13.	-	NS
Glucose	313.0*a*	189.0*a*	160.0 *a*	225.0*a*	77.0*b*	64.0*b*	107.0*b*	151.2	*P < 0.05
Glucosamine	53.3	52.2	46.0	39.4	25.6	24.1	23.0	37.9.0	NS
Galactose	81.9*a*	47.1*b*	35.8*b*	46.7*b*	36.6*b*	28.1*b*	30.7*b*	37.2	*P < 0.05
Mannose	78.6*a*	28.8*bc*	48.0*ab*	56.0*ab*	16.5*bc*	19.2*c*	18.1c	32.3	*P < 0.05
Total sugars	677.0*a*	459.2*ab*	374.0*b*	466.0*ab*	285.0*b*	229.0*b*	286.0*b*	271.9	*P < 0.05
Ratio (R1)	1.11*a*	0.56*bc*	1.00*ab*	1.01*a*	0.47*c*	0.50*c*	0.44*c*	0.33	***P < 0.001
Ratio (R2)	2.84	1.84	3.90	3.40	3.83	2.66	1.48	1.52	*P < 0.05

F30: 30-40 years fallow; F20: 11-20 year fallow; F10: 1-10 years fallow; C10: 1-10 years cultivation; Plough./2years: biennial ploughing; Plough./year: annual ploughing;

P < F: Levels of statistical significance
LSD: Least Significant Difference; NS: Not Significant;
Ratio (R1) = [(Galactose + Mannose) : (Arabinose + Xylose)]
Ratio (R2) = Mannose : Xylose
The numbers followed by the same letter in a row are not statistically different

Furthermore, expressing total soil carbohydrate contents as function of total SOC revealed that total sugar contents increased exponentially with increasing SOC contents (Fprobability = 0.04). This occurred under fallow lands but not under cropped soils (Figure 1).

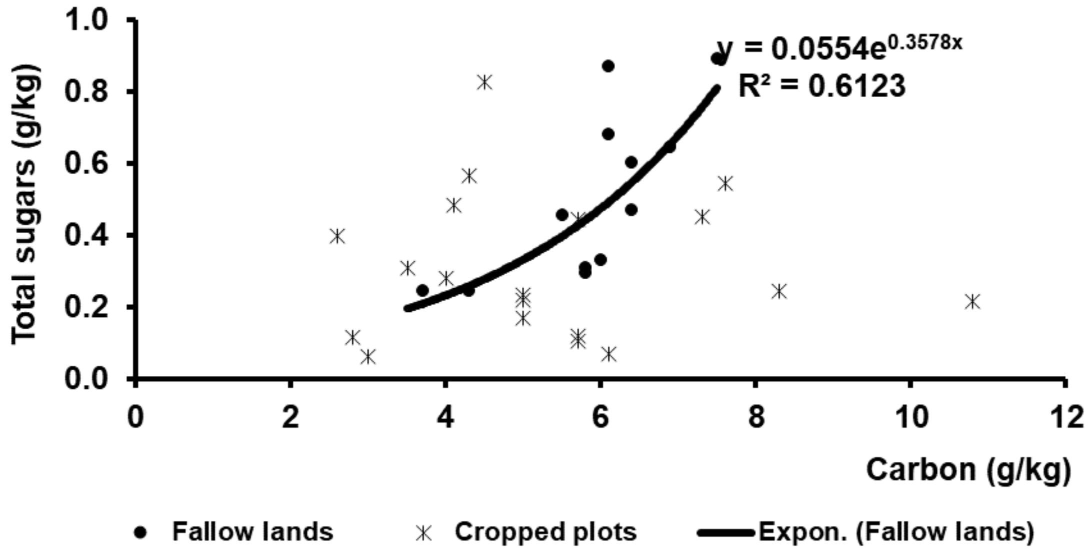

Figure 1. Relation between contents of total carbohydrates and total organic carbon of soils (g-C/kg-soil) from fallow and cropped lands

Conversion of aged-fallow lands to arable lands induced a deeper decline in total sugars concentrations compared to total SOC (Table 3). The rate of this decline was significantly higher in galactose and mannose concentrations compared to soil glucose contents although the latter significantly (*$P < 0.05$) varied across the cropping systems. Arabinose concentrations remained relatively constant; but they increased slightly during the first ten years of cultivation.

The change in land use (e.g. stopping cultivation) improves the accumulation of carbohydrates in the soil. The hydrolysable carbohydrate concentrations attained an equilibrium state faster under fallow practice. Indeed, the fallow lands did not induce significant differences in soil sugar contents regardless of their ages. Continuous cultivation led to the lowest soil sugar concentrations which remain relatively constant in spite of tillage intensity (Table 3).

3. Discussion

3.1Total Hydrolysable Carbohydrate Content

During our study, only six monomeric sugars were extracted. However, their sum across the cropping systems represented 3 to 11 % of SOC which was relatively low compared to the 5 to 25% of SOC reported by Cheshire (1979). Glucose was the most dominant monomeric sugar across the various cropping systems. This result is consistent with previous studies on both tropical and temperate soil (Baldock *et al*. 1987; Kouakoua *et al*. 1999; Larré-Larrouy *et* *al*. 2003; Nacro *et al*., 2005).

The contribution of total carbohydrate to total SOC under fallow practice (5-15%) was nevertheless higher than the range of 5 - 7% recorded under savannah soils from Côte d'Ivoire (Nacro *et al*., 2005) and 4 - 10% in shrub savannah soils from Congo (Kouakoua *et al*., 1999), and forested soils from Brazil (8 %) (Aminiyan *et al*., 2015). The results of this study are in agreement with Nacro et *al.* (2005) that high rainfall in wetter regions could induce deep leaching of carbohydrates. That explains the lower carbohydrates contents recorded in the top soils from Congo, Côte d'Ivoire and Brazil, which are located in wetter ecologies. Furthermore, the low clay and aggregate contents of these soils were not able to protect carbohydrates (Derrien *et al*., 2006). The contribution of carbohydrates to total SOC pool could differ significantly among the various ecosystems (soil and/or vegetation type, litter quality, soil microbial activity, etc.) as stated by Belay-Tedla *et al*. (2009). In addition, many methodological studies showed that the variation in carbohydrates concentrations of soils was largely dependent on the extraction method. It is known that the risk of sugar degradation is higher with pentose sugars (Fischer *et al*., 2007).

3.2 Origin Of Hydrolysable Carbohydrate

The variation in the content of a given sugar can be expressed relatively to the content of another one. This could provide an indication on the source of soil carbohydrate material. For that purpose, Oades (1984) proposed the ratio R1 [(galactose + mannose) / (arabinose + xylose)]. This was due to the fact that microbial populations mostly synthesize galactose and mannose (**P < 0.01). In contrast, materials derived from plants contain substantial amount of arabinose and xylose.

In this study, the highest ratio R1 was lower (< 2) than that of Oades (1984), due to the tropical climate that promotes a rapid turn-over of labile pools of soil organic matter (Nacro *et al*. 2005; Ouattara *et al*., 2006). But this ratio is higher than 1 under fallow lands and lower than 0.5 in cultivated soil. This suggests that most soil sugars could be derived from microbial biomass, under natural vegetation. Many authors reported similar results in in tropical and temperate soils conditions (Baldock *et al*. 1987; Kouakoua *et al*. 1999; Rumpel and Dignac, 2006).

However, other authors suggested that the ratio R2 [mannose / xylose] would be a more accurate indicator of the origin of soil carbohydrates (Murayama, 1977; Nacro *et al*., 2005). They argued that substantial amount of galactose and xylose can be derived from soil microorganisms and plant materials can synthetize arabinose. The high values of R2 clearly show that the soil carbohydrates were derived largely from microbial activities both under fallow lands and cultivated soil. This assertion is consistent with that of Nacro *et al*. (2005) who conducted a similar study under tropical forest and savannah conditions. Indeed, the rapid decomposition and turnover of organic matter which occur under tropical climate, resulted in the formation of microbial products (Larré-Larrouy *et al*., 2003; Nacro *et al*., 2005).

The ratios increased rapidly (mainly R1) as soon as cropped lands were laid fallow and decreased with tillage intensity. This clearly indicates that soil carbohydrates are strong and early indicators of soil organic matter dynamics.

3.3 Dynamics of Total SOC and Carbohydrates.

The study showed that land uses induced significant effects on soil organic carbon. Organic matter stocks were higher under natural fallows than cultivated soils. This is in accordance to the fallowing function of soil fertility restoration (Arrouays *et al*., 1994; Nacro *et al*., 2005; Ouattara *et al*., 2006, Kahlon *et al*., 2013). The lowest SOC stock was recorded with the continuous cultivation system under annual ploughing. Soil tillage contributes to the creation of favourable pedo-climatic conditions for the biodegradation of organic substrates (litter, crop restitution, compost, etc.) and/or SOC mineralization (Balesdent *et al*., 2000). Mechanical destruction of the soil structure under annual ploughing could therefore expose SOC to rapid mineralization (Ouattara *et al*, 2006; Ouattara *et al*., 2011).

Conversion of fallow lands to cropped soils resulted in significant decline in total carbon and carbohydrates contents. Similar findings were recorded in tropical soils (Rumpel and Dignac, 2006; Ratnayake *et al*., 2013). This decline occurred with hexose sugars and mainly with galactose and mannose. In contrast, soil pentose sugars (arabinose, xylose) contents remained relatively constant irrespective of cropping systems, while those of arabinose increased slightly during the ten first years of cultivation. This latter situation could result in rapid decomposition and turnover of incorporated litter in soils (Nacro *et al*., 2005; Bernardi *et al*., 2015), since soil microorganisms can synthesize arabinose. Furthermore, the significant contribution of arabinose to total hydrolyzable carbohydrates across cropping systems, with high values in cropped soil compared to fallow lands, corroborated this assertion.

Since cultivated soils were converted to fallow lands, it resulted in a renewed increase in soil hexose sugar content (mannose and galactose). They increase rapidly and reach a state closer to a highest level, recorded under over 30 years-fallow lands. The exponential growth of total carbohydrates as function of increase in total SOC contents under fallow lands was in agreement with that observation. These results showed that total soil carbohydrates, and mainly those of microbial origin, are sensitive indicators of early changes in organic matter status under cropping systems (Ball *et al.*, 1996). They revealed the key role of soil microbial activities in SOC accumulation and/or mineralization due to cropping systems (Ball *et al*., 1996; Ouattara *et al*., 2009).

However, this dynamic nature of carbohydrates was not always expressed in all soils as recorded by Baldock *et al*. (1987) who observed relatively constant total soil carbohydrates contents or each monomeric sugar irrespective of the cropping treatments in temperate soils. Loum *et al*. (2014) also showed that SOM dynamics was more expressive under tropical climate, where the pedoclimatic conditions were more favorable for rapid SOM' turn over.

4. Conclusion

This study revealed the dynamic character of total soil carbohydrates across cropping systems, including fallow and cultivated lands. The total soil carbohydrates accounted for only 3 - 11 % of the total soil organic carbon, and they appeared to be one of early indicators of management-induced changes in organic matter. These changes occurred more on monomeric sugars which were derived from microbial synthesis. The high soil carbohydrate contents under fallow lands and their relative stability irrespective of fallow ages, emphasized the key role of fallowing in soil organic matter storage and the likely impact on soil sugars. Furthermore, the strong decomposition and rapid turnover of primary organic products (litter, crop restitution, compost, etc.), under tropical conditions, resulted in the formation of secondary microbial products. This process was more accelerated when fallow lands were converted to cropped soils. This occurred under annual ploughing, usually practiced in the cotton-based cropping system in West Burkina Faso. Unfortunately, fallowing, known as traditional practice for soil fertility restoration; is disappearing from the agricultural landscape of tropical savannah, due to population growth and continuous cropping. Therefore, in terms of perspective, the sustainable management of soil organic carbon in savannah cropped soil requires the use of cover crop, including fodder crop through viable and coherent cropping system practices. This can serve as an alternative to fallow practice.

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Conflict of interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this paper.

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