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ORIGINAL ARTICLE

Soil organic carbon storage and contribution of management strategies to the "4 per 1000" target in a wet savanna, Côte d'Ivoire

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Abstract

Identifying and scaling up agricultural practices that promote atmospheric carbon transfer into the soil are keys to tackle climate change. A study was carried out in Central Côte d'Ivoire (West Africa) to assess soil organic carbon (SOC) storage and its edaphic constraints under diverse fallow management options. Trials were conducted at two locations—Ahérémou-II village and near the Lamto reserve. The impact of long-term *Chromolaena odorata* (Asteraceae) fallow was assessed relative to the native savanna. Those of short-term herbaceous (*Mucuna pruriens*, *Lablab purpureus*, *Pueraria phaseoloides* and a mixture of these three) and shrub (*Cajanus cajan*) legume (Fabaceae) fallows were assessed relative to the time of sowing (T_0) or relative to *C. odorata* fallow. In Lamto, the legumes were grown simultaneously at two sites side-by-side—a native shrub savanna ("savanna") and a 17-year *C. odorata* fallow ("fallow")—with contrasting soil fertility levels. At both locations, SOC stock was higher in *C. odorata* than in the natural savanna, the increase being restricted to the 0–0.1-m depth. SOC accumulation rates at 0–0.4 m depth were 0.46% year^{-1} and 1.87% year^{-1} in the Lamto 17-year and Ahérémou-II 10-year *C. odorata* fallows, respectively. In Ahérémou-II, *L. purpureus* rather than *C. cajan* significantly increased SOC stock (0–0.1-m depth) relative to *C. odorata* (2-year fallows). In Lamto, SOC stock significantly increased in all legume plots (0–0.1-m depth) relative to T_0, particularly the mixture (14.1% year^{-1}) and *L. purpureus* (13.7% year^{-1}). SOC storage was not found to be influenced by legume biomass yield nor by legume species x site interaction, although it was greater at the more fertile "fallow" than at the "savanna" sites. That increase was positively linked to the initial SOC, total N, clay + fine silt, Mg^{2+} and Ca^{2+} concentrations, with the latter exhibiting the strongest influence. This study highlights the agronomic and climatic benefits *C. odorata* may provide in savanna environment despite the inimical attributes linked to its invader status. Mixed legume fallowing should be further encouraged in Côte d'Ivoire and other West African coastal countries in the framework of the 4p1000 Initiative.

Keywords 4 per 1000 Initiative · Carbon storage cap · *Chromolaena odorata* · Mixed legume cropping · Savanna soils

Introduction

The agricultural sector is a key contributor to anthropogenic greenhouse gas (GHG) emissions into the atmosphere, with this sector contributing about 21% of the global GHG emissions in 2010 (Tubiello et al. 2015). At the same time, agricultural soils can play a key role in climate change mitigation due to their recognized potential for soil organic carbon (SOC) storage (Akpa et al. 2016; Sousa Junior et al. 2018; Rumpel et al. 2020). This process depends not only on climate, soil-inherent pedologic characteristics (Akpa et al. 2016; Barré et al. 2017; Torres-Sallan et al. 2018), organic inputs and quality (Cotrufo et al. 2015; Fujisaki et al. 2018) and the stage of soil development (Schiefer et al. 2018) but also on soil management strategies (Lal 2020; Veldkamp

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et al. 2020; Wiesmeier et al. 2020). This calls for further research into strategies to increase carbon storage in soils, especially to increase the stable SOC pool, which is the pillar of the international initiative "4 per 1000, Soils for food security and climate"—hereafter the "4p1000 Initiative" (Soussana et al. 2019). It is expected that a global SOC stocks increase by 0.4% (or 4‰) year^{-1} in the top 0.3–0.4-m soil layer would counterbalance parts of increasing GHG emissions from anthropogenic sources (Paustian et al. 2016). To reach this goal, the 4p1000 Initiative focuses on agricultural soils with low SOC levels due to continuous cultivation and often unsustainable crop intensification practices (Pingali 2012). In this respect, Vågen et al. (2005) reported that the largest potential for increasing SOC stock in sub-Saharan Africa is through the establishment of natural or improved fallow systems. However, implementations of these SOC storage strategies should be differentiated, each adapted to local or regional soil conditions and management realities (Wiesmeier et al. 2020).

Soils in West African savannas are characterized by low organic matter levels, due to the predominance of low-activity clays and a sandy texture (Oorts et al. 2003; Koné et al. 2020). In addition, the majority of this region's agricultural soils are not managed sustainably (Tully et al. 2015; N'Dri et al. 2019), making them good candidates for SOC storage strategies (Sousa Junior et al. 2018; Fan et al. 2020). To improve soil fertility in the savannas of Côte d'Ivoire (West Africa), herbaceous legume-based fallows have been implemented for two decades (Kouassi 2000; Carsky et al. 2001; Koné et al. 2008, 2020). These man-made fallows have the potential to produce high and quality biomass in a short period of time, fostering soil biological processes and resulting in improvements in SOC content, soil structural stability, nutrient levels and use efficiency and agronomic yields (Azontonde et al. 1998; Fofana et al. 2005). In addition, high-organic soils are associated with high water storage capacity that makes them more resilient to drought (Fan et al. 2020; Lal 2020; Garcia-Franco et al. 2021). Legume species such as *Pueraria phaseoloides* (Roxb.) Benth. and *Mucuna pruriens* (L.) DC. var. *utilis* are commonly used in Côte d'Ivoire in cash crops to fight against weeds or as short-term fallow crop in subsistence agriculture (Kouassi 2000; Keli et al. 2005). These species are also used among farmers in Ghana and Benin (Azontonde et al. 1998; Carsky et al. 2001). *Cajanus cajan* (L.) Millsp. is grown as a food crop or for cattle fodder in Côte d'Ivoire (Koutouan et al. 2017). However, these legumes are rarely grown in a mixture. To optimize the impact of legume cropping on the SOC stock, it is necessary to understand the influence of initial soil fertility variables as these influence plant biomass production and subsequent microbial-mediated soil processes (Koné et al. 2008). Unfortunately, this consideration is overlooked by soil managers and farmers, often leading to the unsuccessful use of legumes.

In West and Central Africa, ecosystem disturbance associated with land clearance favours invasion by the shrub *Chromolaena odorata* (L) King & Robinson (Asteraceae). Currently, agricultural lands in 12 of the 16 countries in West Africa have been invaded by *C. odorata* (Aigbedion-Atalor et al. 2019). This phenomenon began in the 1930s, and by the 2000s *C. odorata* was deemed a plague because of the negative effects it has on indigenous flora (declined biodiversity) and fauna (constrained movement of wildlife and livestock), and on crop yields through competition for light and water (Timbilla et al. 2003; Maroun 2017; Shackleton et al. 2017). Thus, the shrub has been combatted by physical, chemical and biological means in the invaded countries (Aigbedion-Atalor et al. 2019) including Côte d'Ivoire (Philippe 1986). Today, however, many farmers in Côte d'Ivoire, Ghana, Nigeria and Cameroon consider *C. odorata* a suitable fallow plant for soil fertility replenishment (Koutika and Rainey 2010; Maroun 2017; Aigbedion-Atalor et al. 2019; Aigbedion-Atalor 2020). In fact, *C. odorata* is increasingly associated with improved soil organic and nutritional status, and food crop yields (Obatolu and Agboola 1993; Slaats 1995; Koné et al. 2012a; Kassi et al. 2017; N'Dri et al. 2019). These agronomic benefits frequently outweigh biodiversity considerations in the minds of farmers, resulting in wide adoption of the *C. odorata* fallow system (Maroun 2017; Aigbedion-Atalor 2020).

The purpose of this study was to assess SOC storage in the Guinean savanna of Côte d'Ivoire and to identify promising legume species and options of use for efficient SOC accumulation into the soil. It also assesses whether the 4p1000 Initiative's target of 0.4% increase in SOC stock year^{-1} can be achieved using legume and *C. odorata* fallows, and ultimately focus on edaphic constraints to SOC accumulation. The study was underpinned by four hypotheses including (1) *C. odorata* would improve SOC stock relative to the native savanna but the corresponding rate would rapidly decline over time due to the sandy soil texture, which translates into low C storage capacity, (2) mixed herbaceous legume cropping would lead to faster SOC accumulation relative to monospecies legume cropping, (3) SOC accumulation rate would be greater under the legumes than under the invasive *C. odorata* and (4) SOC storage would be determined by soil characteristics rather than plant biomass yield as Guinean savannas hold a high biomass production potential (Gignoux et al. 2006).

Materials and methods

Study area

This study was carried out in the forest-savanna transition area of Central Côte d'Ivoire (SI 1) where the natural vegetation is consisted of a mosaic of woody and grass savannas dotted with forest islands. In the savanna, which constitutes 80% of vegetation, the woody stratum is dominated by shrub species such as *Crossopteryx febrifuga* (Rubiaceae), *Annona senegalensis* (Annonaceae), *Piliostigma thonningii* (Ceasalpiniaceae) and *Bridelia ferruginea* (Euphorbiacea), and grass species such as *Hyparrhenia diplandra* (Poaceae), *Imperata cylindrica* (Poaceae) and *Andropogon schirensis* (Poaceae) (Soro et al. 2018). As a result of perturbation or conversion of the natural ecosystems to agriculture, *C. odorata* invades lands and forms dense and tangled bushes 1.5–2.0 m in height, which now constitutes one of the main vegetation features in the region. The climate falls under the tropical savanna's type as per the Köppen-Geiger classification (Peel et al. 2007). Average annual rainfall and daily temperature are 1200 mm and 28 °C, respectively. Soils are predominantly Oxisols with granite as the main bedrock. Topsoil is generally sandy textured (60–80% sand), clays consist of illites and slightly crystallized kaolinites with a low cation adsorption capacity. SOC concentration (0-0.1 m depth) is ~ 10 g C kg^{-1} in savanna and ~ 20 g C kg^{-1} in forest (Koné et al. 2020).

Description of the experiments

Trials took place at two distinct locations (approx. 10 km apart): one was referred to as "Lamto", on the outskirt of the Lamto natural reserve (6°9′–6°13′ N, 5°15′–4°57′ W and 120 m a.s.l.), and the other was referred to as "Ahérémou-II", in the agricultural landscape around Ahérémou-II village (6°10′–6°15′ N, 4°55′–5°00′ W and 120 m a.s.l.). At both locations, the capacity of *C. odorata* and legumes to store SOC was tested in native shrub savanna and new fallow environments, as described in Table 1. Specific links with the hypotheses of the study are explained below.

- In Lamto, experiments conducted from 2003 to 2005 were used to test hypotheses 1, 2 and 4. Two experiment sites were delineated in adjacent (about 30 m apart) native shrub savanna ("savanna" site) and 17-year-old *C. odorata* fallow ("fallow" site). Initially, prior to land clearance, both sites consisted of a completely randomized design with 15 replicate plots where measurements were conducted to evaluate the long-term impact of *C. odorata* on SOC stocks relative to the native savanna (hypothesis 1), using the synchronic sampling approach. Subsequently, the experimental design turned to a randomized complete block design with five treatments replicated thrice each, at both sites. At the savanna site, there were four legume covers with *Mucuna pruriens*, *Pueraria phaseoloides*, *Lablab purpureus* (L.) Sweet and the mixture of the three species, in addition to control treatment with grass cover. The same legume treatments were used at the fallow site with the exception that *L. purpureus* was replaced by *Cajanus cajan,* the control being a *C. odorata* regrowth. Thus, two legume treatments were common to both sites, being *M. pruriens* and *P. phaseoloides*, and were used to explore the effect of the site on SOC storage under the legumes. The legume treatments at the savanna site were compared to each other in terms of SOC gain to test hypothesis 2 using the diachronic sampling approach while the legumes treatments that were common to both sites were used to test hypothesis 4. Prior to legume cropping, both sites were cleared through traditional methods (i.e. slashed with a machete and subsequent burning).
- In Ahérémou-II, a set of two experiments were conducted. The first, in 2012, explored the effect of 10-year *C. odorata* fallows on SOC stock in native savanna environment using the synchronic sampling approach, which contributed to testing hypothesis 1. The second experiment, in 2012–2014, included three *C. cajan vs. C. odorata* and three *L. purpureus* vs. *C. odorata* paired plots of 2 years old established on formerly cultivated sites (new fallows). SOC storage under each legume vs. control *C. odorata* fallow was explored using the synchronic sampling approach and served to test hypothesis 3.

Plant biomass and soil sampling methods

Plant biomass

Plant biomass sampling in natural vegetation was conducted at the start of the trials in April 2003 during the rainy season. This initial sampling was conducted only at the Lamto savanna and fallow experiment sites. Subsequently, after the legume covers were established, biomass sampling in the legume plots was carried out successively when the legume carried dry pods (9 to 12 months after sowing). In Ahérémou-II, biomass sampling in the legumes and their adjacent control *C. odorata* plots took place 2 years after establishment. Total plant and leaf litter biomass productions were determined in each replicate plot in Lamto while only leaf litter mass was determined in Ahérémou-II. This was done using a 1 m^2 frame placed in three distinct positions, which contributed to the average mean biomass value for each plot. Sampled plant materials were oven-dried at 60 °C for 72 h, then weighed. A 20-g subsample of leaf litter material was finely ground and stored in a plastic bag for further chemical analyses.

Table 1 Location, experiment designs and sampling schemes

Location	Experiment	Natural environment	Treatment & duration	Plot size and *n**	Sampling scheme & depths	Soil texture
Lamto	Effect of *C. orata* on SOC stock in savanna	Shrub savanna and *C. odorata* fallow	Savanna site (NA)	24 m × 8 m (15)	Synchronic sampling 0–0.1-, 0.1–0.2-, 0.2–0.3- and 0.3–0.4-m depths	Yellow-coloured, with a sandy low clay (0–0.3 m) overlying sandy clay (0.3–0.7 m) and stony (> 0.7 m) horizons
			C. odorata fallow (17 years)	24 m × 8 m (15)		
	Effect of legumes on SOC gain in savanna	Shrub savanna	*Mucuna pruriens* (1 year)	24 m × 8 m (3)	Diachronic sampling; 0–0.1-, 0.1–0.2-m depths	
			Pueraria phaseoloides (1 year)	24 m × 8 m (3)		
			Lablab purpureus (1 year)	24 m × 8 m (3)		
			Legume mixture (1 year)	24 m × 8 m (3)		
			Control (1 year)	24 m × 8 m (3)		
	Site effect on SOC storage under legume	Shrub savanna and *C. odorata* fallow	*M. pruriens* on savanna soil (1 year)	24 m × 8 m (3)	Both Diachronic (0–12 month variation under each species) and Synchronic (between sites variation of SOC gain); 0–0.1-, 0.1–0.2-m depths	
			P. phaseoloides on savanna soil (1 year)	24 m × 8 m (3)		
			M. pruriens on fallow soil (1 year)	24 m × 8 m (3)		
			P. phaseoloides on fallow soil (1 year)	24 m × 8 m (3)		
Ahérémou-II	Effect of *C. odorata* on SOC stock in savanna	Shrub savanna and *C. odorata* fallow	Savanna (NA)	50 m × 50 m (3)	Synchronic sampling; 0–0.1-, 0.1–0.2-, 0.2–0.3- and 0.3–0.4-m depths	Yellow coloured (i) sandy with low clay to sandy clay and (ii) sandy clay to clayey sand (0–0.25 m and 0.25–0.9 m, respectively)
			C. odorata fallow (10 years)	50 m × 50 m (3)		
	Effect of legumes vs. *C. odorata* on SOC storage	Shrub savanna	*L. purpureus* (2 years)	20 m × 15 m (3)	Synchronic sampling (individual legume species vs. *C. odorata*, paired-plots); 0–0.1-m depth	
			Cajanus cajan (2 years)	20 m × 15 m (3)		
			C. odorata (2 years)	20 m × 15 m (3)		

NA, not applicable

*Number of replications in brackets

Soil sampling

In Lamto, soil samples were collected under the native savanna (savanna site) and the *C. odorata* fallow (fallow site) from the depths of 0–0.1 m, 0.1–0.2 m, 0.2–0.3 m and 0.3–0.4 m, and under legume plots 12 months later, from the 0–0.1-m and 0.1–0.2-m depths. In Ahérémou-II, soil samples were collected once from the 0–0.1-, 0.1–0.2- and 0.2–0.4-m depths under *C. odorata* fallows and native savanna, and only from 0–0.1-m depth under the 2-year old paired legume-*C. odorata* plots. At both locations, soil samplings were carried out at the onset of the rainy season. Soil sampling in the legume plots was restricted to the 0–0.2-m depth because this corresponds to (i) the depth where changes in soil properties may be perceptible in the short term and (ii) the plowing depth in the region (Diby et al. 2009; Kassi et al. 2017).

In each experimental plot, soil samples were collected at five distinct points using an auger, after non-decomposed plant residues were carefully removed from the soil surface. They were then thoroughly mixed into a composite sample, which was air-dried at room temperature, weighed and passed through a 2-mm sieve to obtain two fractions: Ø < 2 mm (fine soil) and Ø > 2 mm (coarse particles). The proportion of the coarse particles was then determined and used for further SOC stock calculations. The fine soil fraction was kept in plastic bags for further chemical analyses (C, N, P, K^+ Ca^{2+}, Mg^{2+} and pH). Soil bulk density was determined at the respective depths from core samples obtained using the cylinder method. Soil cores were weighed before and after oven-drying at 105 °C for 48 h to calculate bulk density (Anderson and Ingram 1993).

Laboratory analyses of soil and leaf litter samples

Carbon and nitrogen were determined on both plant materials (4 mg dried, ground and $<$ 0.1 mm sieved) and soil samples (25 mg dried, ground and 0.2 mm sieved) by dry combustion procedures using a CHN autoanalyzer (EA1112 Thermo Finnigan Series, France). Available P was extracted according to the Olsen-Dabin method (in a mixture of $NaHCO_3$ and NH_4F, at pH 8.5) and total P in a mixture of HNO_3 and $HClO_4$ (Olsen and Sommers 1982). The two extracts were then analysed for P by colorimetry at 660 nm (Murphy and Riley 1962). Major cations (Ca^{2+}; Mg^{2+} and K^+) were extracted using ammonium acetate buffer (pH 7) and determined by means of atomic absorption spectrophotometry techniques (VARIAN SPECTRAA 220 SF model). Soil pH was determined using a glass electrode in a 1/2.5 soil/water ratio. Soil texture was determined using the Robinson pipette method (Anderson and Ingram 1993).

Data processing and statistical analyses

SOC stock was calculated using the following formula (Grinand et al. 2009):

$$\mathrm{SOCS} = \mathrm{SOC} \times \mathrm{BD} \times (100 - \mathrm{CP}) \times \mathrm{D}$$

where SOCS is the SOC stock (Mg ha^{-1}), SOC is the SOC concentration (g kg^{-1}), BD is the soil bulk density (g cm^{-3}), CP is the coarse particle fraction size (%) and D is depth interval thickness (dm). The SOC storage or SOC gain is the net variation in SOC stock (ΔSOC)—between a given treatment and the adjacent control treatment (Synchronic approach) or between two sampling times in the same treatment (Diachronic approach). The rate of SOC accumulation (expressed in % SOC stock $year^{-1}$) is obtained by dividing the percent SOC gain by the duration of the fallow ($year^{-1}$), where

$$\text{Percent SOC gain} = 100 \times \text{SOCgain}/\text{SOC}i$$

with SOC_i corresponding to the SOC stock in the reference treatment.

Mean value comparisons between a given treatment and its adjacent control (in Lamto and Ahérémou-II) or between two sampling times (at the Lamto savanna site) were done using a student *t*-test. At the Lamto savanna site, a one-way analysis of variance (ANOVA) was used to compare the legume treatments in terms of biomass yield and soil variables, including SOC stock, after data were checked for homogeneity of variances using Levene's test and root square-transformed where appropriate. The effects of legume (*M. pruriens* and *P. phaseoloides*) and site (savanna and fallow) as well as that of their interaction on legume biomass yield and SOC storage were tested using a two-way ANOVA. Linear regression was used to test whether SOC gain was influenced by legume biomass yield from the Lamto "savanna" site where the initial soil conditions were homogenous among plots (Eq. (1)). The same test was used to explore relationships between the initial soil fertility parameters and SOC storage in the legume covers established on both the Lamto savanna and fallow sites (Eq. (2)). This was done using distinctly the legume covers, thereby avoiding any species effect, which may be linked to biomass yield. The regression model was as follows:

$$\text{SOC gain} = \beta \text{ legume biomass yield} + \alpha \quad (1)$$

$$\text{SOC gain} = \beta \text{ soil parameter content} + \alpha \quad (2)$$

where β is the regression coefficient (or β-weight) and α, the constant. All statistical analyses were performed using the R ver. 4.0.3 software (http://www.r-project.org/). Results were considered significant when $p < 0.05$.

Results

Plant biomass yields and soil characteristics in Chromolaena odorata fallow vs. savanna

Natural vegetation biomass yields

Natural vegetation biomass was found to be greater ($p <$ 0.05 for all plant parts) at the fallow site than at the savanna site. Aboveground, root and total biomasses recorded for *C. odorata* were 11.9 ± 2.6, 1.9 ± 0.4 and 13.8 ± 2.9 Mg ha^{-1}, respectively, versus 4.2 ± 0.5, 0.9 ± 0.1 and 5.1 ± 0.6 Mg ha^{-1} for the savanna.

Soil characteristics

In Lamto, no significant difference was observed between the savanna and fallow sites at 0–0.1-m depth for the clay + fine silt fraction size (17.6 ± 0.5 vs. 17.1 ± 0.5%, respectively), available P (16.1 ± 1.2 vs. 16.8 ± 2.5 mg kg^{-1}) and K (0.26 ± 0.02 vs. 0.29 ± 0.04 $cmol_c$ kg^{-1}) concentrations. The other soil (0–0.1 m) characteristics showed higher values at the fallow than at the savanna sites: pH (6.7 vs. 6.5, $p = 0.02$, respectively), total P (175.0 ± 16.3 vs. 258.7 ± 15.5 mg kg^{-1}, $p <$ 0.001), Ca^{2+} (1.9 ± 0.1 vs. 3.2 ± 0.4 $cmol_c$ kg^{-1}, $p <$ 0.001), Mg^{2+} (0.65 ± 0.05 vs. 1.49 ± 0.15 $cmol_c$ kg^{-1}, $p <$ 0.001) and total N (0.07 ± 0.01 vs. 0.15 ± 0.02 g kg^{-1}, $p <$ 0.001). SOC concentration was also significantly higher ($p <$ 0.001) in fallow (10.0 ± 0.2 g kg^{-1}) than in savanna (7.5 ± 0.1 g kg^{-1}) in the 0–0.1-m depth. No significant difference in SOC concentration was observed between the fallow and savanna sites in the deeper 0.1–0.2 m (6.9 ± 0.2 vs. 6.7 ± 0.1 g kg^{-1}, respectively), 0.2–0.3 m (4.9 ± 0.2 vs. 4.8 ± 0.3 g kg^{-1}) and 0.3–0.4 m (4.3 ± 0.2 vs. 4.2 ± 0.3 g kg^{-1}) depths. However, SOC concentrations at 0–0.2, 0–30 and 0–0.4 m in fallow were greater than those in savanna ($p < 0.001$ for the first two depths and $p < 0.01$ for the latter). SOC stock was also higher at the fallow compared to the savanna site in the 0–0.1-m depth ($p < 0.001$) but values were similar at the distinct 0.1–0.2 m, 0.2–0.3 m and 0.3–0.4-m depths (Table 2). However, the cumulative SOC stocks in the 0–0.2-, 0–30- and 0–0.4-m depths were greater in fallow than in savanna. The rate of SOC accumulation at 0–0.4-m depth over 17 years under *C. odorata* fallow was found to be 0.46% $year^{-1}$ or 4.6 ‰ $year^{-1}$.

In Ahérémou-II, the *C. odorata* fallow and the natural savanna were similar in terms of soil bulk density (1.3 ± 0.01 vs. 1.4 ± 0.04 g cm^{-3}, respectively), pH (7.0 ± 0.3 vs. 6.6 ± 0.2), clay + fine silt fraction size (12.0 ± 1.7 vs. 10.2 ± 1.3%) and K^+ (0.10 ± 0.02 vs. 0.07 ± 0.01 cmol kg^{-1}) at 0–0.1-m depth. *Chromolaena odorata* was significantly higher than the savanna in available P (64.3 ± 11.6 vs. 21.0 ± 5.7 mg kg^{-1}, respectively, $p = 0.03$), Ca^{2+} (3.2 ± 0.4 vs. 0.8 ± 0.2 cmol kg^{-1}, $p < 0.01$) and Mg^{2+} (2.41 ± 0.54 vs. 0.64 ± 0.05 cmol kg^{-1}, $p = 0.03$) at 0–0.1-m depth. *Chromolaena odorata* fallow was higher than the savanna in SOC (14.2 ± 1.0 vs. 10.2 ± 2.5 g kg^{-1}, respectively) and total N (1.1 ± 0.1 vs. 0.8 ± 0.1 g kg^{-1}) at 0–0.1-m depth but not at 0.1–0.2-m and 0.2–0.4-m depths. As for SOC stock, it was found to be greater in *C. odorata* than in the savanna at 0–0.1-m and 0–0.2-m depths but not at 0.1–0.2-m or 0.2–0.4-m depths or the whole 0–0.4-m depth. The rate of SOC accumulation at 0–0.4-m depth over 10 years under *C. odorata* fallow was estimated to be 1.9% $year^{-1}$ or 18.7‰ $year^{-1}$.

Legume biomass yield, leaf litter quality and effect on soil organic carbon

Legume biomass yields and leaf litter quality

At the Lamto savanna site, total plant biomass yield did not vary among legume species, and values were close to that of the grasses dominated by *H. diplandra* in the control plot (SI 2). Litter C concentration was the greatest in *M. pruriens* and the lowest in *H. diplandra*. Litter N was the greatest in *M. pruriens* followed by *L. purpureus* and was least in *H. diplandra*. *Mucuna pruriens*, *L. purpureus* and the legume mixture showed similar leaf litter P concentration, which was higher than that of *P. phaseoloides*. The litter C:N ratio was the least in *M. pruriens* and *L. purpureus* and the highest in *H. diplandra*. The reverse trend was observed for the N:P ratio, with *P. phaseoloides* and the legume mixture showing intermediate values.

In Ahérémou-II, the standing leaf litter mass was higher in *C. cajan* than in *C. odorata* (SI 3). The legume also exhibited a greater litter N:P ratio but lower P. No significant difference was observed for C, N and C:N ratios. On the other side, *L. purpureus* was higher than *C. odorata* in terms of leaf litter mass and N:P ratio but it exhibited a lower C:N ratio. No significant difference was observed for the C, N and P concentrations.

Effect of the legumes on soil organic carbon

At the Lamto savanna site, 1 year after sowing, SOC concentration significantly increased at 0–0.1-m depth under all legume covers relative to the initial time (Table 3). In terms of a percent increase, the legume covers ranked as follows: legume mixture (17.7%) > *L. purpureus* (13.7%) > *P. phaseoloides* (9.6%) > *M. pruriens* (6.5%). No significant change occurred in the control plot (+ 5.1%). Only *P. phaseoloides* showed a significant increase in SOC concentration at 0.1–0.2-m depth. At 0–0.2-m depth, SOC concentration significantly increased under *L. purpureus*, *P. phaseoloides* and the legume mixture.

SOC stock also significantly increased at 0–0.1-m depth under the four legume covers. However, at 0.1–0.2 m, it only increased significantly under *P. phaseoloides*. The cumulated SOC stock for the 0–0.2-m depth significantly increased under all legume covers except for *M. pruriens*. The extents of increase were 14.7%, 18.0% and 10.2% $year^{-1}$ under *P. phaseoloides*, *L. purpureus* and the legume mixture, respectively. No significant change was observed in the control plot. In addition, SOC gain showed significant variation among legume plots only at 0–0.1-m depth ($F = 3.0$; $p = 0.05$) (Fig. 1) with the legume mixture and *L.*

Table 2 Soil organic carbon (SOC) stocks (mean ± standard error) across soil depths under adjacent natural shrub savanna and *C. odorata* fallows in Lamto and Ahérémou-II

Soil depths	SOC stock (Mg ha^{-1})—Lamto			SOC stock (Mg ha^{-1})—Ahérémou-II		
	Savanna ($n = 15$)	*C. odorata* ($n = 15$)	*p*-value	Savanna ($n = 3$)	*C. odorata* ($n = 3$)	*p*-value
0–0.1 m	10.5 ± 0.1	13.1 ± 0.3	***	14.2 ± 1.2	18.6 ± 1.5	*
0.1–0.2 m	9.9 ± 0.2	10.2 ± 0.2	ns	10.0 ± 1.0	12.8 ± 1.4	ns
0–0.2 m	20.4 ± 0.3	23.3 ± 0.3	***	24.2 ± 2.1	31.4 ± 2.7	*
0–0.4 m	34.4 ± 0.8	37.1 ± 0.9	*	40.0 ± 3.9	47.5 ± 3.8	ns

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; *ns*, no significant difference

purpureus exhibiting significantly higher gains compared to that of the control plot.

In Ahérémou-II, 2 years after planting, no significant difference was found between *C. cajan* and the control *C. odorata* in terms of total N and SOC concentrations and SOC stocks at 0–0.1-m depth (Table 4). In contrast, SOC concentration and stock were found to be greater in *L. purpureus* compared to *C. odorata*.

Influence of plant biomass yield and initial soil characteristics on subsequent soil organic carbon storage

In Lamto, although the gain of SOC varied significantly among the legume covers at the savanna site, the value at 0–0.1-m depth did not show any significant link with total legume biomass ($F=1.7$; $R^2=0.14$; $p=0.2$). SOC gain at 0–0.2-m depth only showed a weak link with total legume biomass ($F=3.0$; $R^2=0.24$; $p=0.1$).

Combining the two sites, *M. pruriens* and *P. phaseoloides* biomass yields averaged 5.5 ± 1.0 and 6.8 ± 0.8 Mg dry matter (DM) ha^{-1}, respectively. Combining the two species, biomass yields were 5.7 ± 0.6 and 7.0 ± 1.3 Mg DM ha^{-1} at the savanna and fallow sites, respectively. None of the effects of the species, site and species × site interaction on the legume biomass yield measured on *M. pruriens* and *P. phaseoloides* was significant (SI 4). In contrast, a significant site effect was observed on SOC gain at both 0–0.1-m and 0–0.2-m depths. The average gain at fallow (the two species pooled) was twice as high as that at savanna: 2.6 ± 0.3 vs. 0.8 ± 0.1 Mg SOC ha^{-1} at 0–0.1-m ($p=0.005$) and 3.4. ± 0.4 vs. 2.0 ± 0.2 Mg SOC ha^{-1} at 0–0.2-m depth ($p=0.009$).

Specifically, SOC gain under *M. pruriens* was significantly higher at fallow than at savanna in the 0–0.1-m and 0–0.2-m depths ($p=0.04$ and $p=0.05$, respectively). Under *P. phaseoloides*, it was significantly higher in fallow than in savanna only at 0–0.1-m depth (Fig. 2). In addition, SOC stock gain was found to be associated with high initial soil Ca^{2+} and Mg^{2+} at 0–0.1-m depth, and SOC concentration at 0–0.2-m depth under *M. pruriens* (SI 5). It was positively influenced by initial concentrations of SOC, total N, Ca^{2+} and clay + fine silt at both 0–0.1-m and 0–0.2-m depths under *P. phaseoloides*. Under the two legume covers considered together, SOC gain was found to be associated with high initial SOC, total N, Ca^{2+} and Mg^{2+} at both 0–0.1-m and 0–0.2-m depths, and clay + fine silt at 0–0.1-m depth. The influence of Ca^{2+} appeared to be the strongest.

Discussion

Sandy soils such as those of this study are prone to a faster loss of organic matter because of their low structural stability (Six et al. 2002). In addition, the physical disturbance (plowing) and solar exposure of soils during the cropping phase, coupled with the consistently high temperature (25–30 °C) that prevails throughout the year, will increase the soil respiration (van Noordwijk et al. 2014; Chen et al. 2020). As a result, the SOC stock will inevitably drop to a level that is lower than that under the initial plot before it was turned to crop, i.e. old fallow, savanna or forest systems (Van Noordwijk et al. 2014; Sanchez 2019). Moreover, savannas in the region are prone to fire (N'Dri et al. 2018), further depleting SOC (N'Dri et al. 2019). Thus, the previously cropped and

Table 3 Change in soil organic carbon (SOC) concentration and stock (mean ± standard error, $n=3$) over 1 year under legume cover crops at the Lamto savanna site

Legume cover	0–0.1 m			0.1–0.2 m			0–0.2 m		
	0 month	12 months	*p*-value	0 month	12 months	*p*	0 month	12 months	*p*-value
SOC concentration (g kg^{-1})									
M. pruriens	7.7 ± 0.1	8.2 ± 0.2	*	7.2 ± 0.4	7.8 ± 0.4	ns	7.4 ± 0.2	8.0 ± 0.3	ns
P. phaseoloides	7.3 ± 0.2	8.0 ± 0.2	*	6.1 ± 0.2	7.1 ± 0.3	*	6.7 ± 0.2	7.5 ± 0.2	*
L. purpureus	7.3 ± 0.2	8.3 ± 0.2	*	6.6 ± 0.3	7.4 ± 0.3	*ns*	6.9 ± 0.2	7.8 ± 0.3	*
Mixed legumes	7.5 ± 0.2	8.6 ± 0.3	*	6.6 ± 0.1	7.2 ± 0.3	*ns*	7.0 ± 0.1	7.9 ± 0.3	*
Control	7.8 ± 0.2	8.2 ± 0.4	ns	6.9 ± 0.4	7.6 ± 0.4	ns	7.3 ± 0.3	7.9 ± 0.4	ns
SOC stock (Mg ha^{-1})									
M. pruriens	10.8 ± 0.1	11.5 ± 0.3	*	10.6 ± 0.6	11.5 ± 0.5	ns	21.4 ± 0.5	23.0 ± 0.9	ns
P. phaseoloides	10.2 ± 0.3	11.2 ± 0.2	*	9.1 ± 0.3	10.5 ± 0.3	*	19.3 ± 0.5	21.7 ± 0.5	*
L. purpureus	10.2 ± 0.3	11.6 ± 0.3	*	9.8 ± 0.4	10.9 ± 0.5	ns	20.0 ± 0.7	22.5 ± 0.7	*
Mixed legumes	10.6 ± 0.3	12.1 ± 0.4	*	9.7 ± 0.1	10.6 ± 0.5	ns	20.3 ± 0.3	22.7 ± 0.8	*
Control	10.9 ± 0.3	11.4 ± 0.5	ns	10.2 ± 0.5	11.2 ± 0.6	ns	21.1 ± 0.9	22.6 ± 1.1	ns

*$p < 0.05$ (significant change); *ns*, no significant difference at $\alpha=0.05$

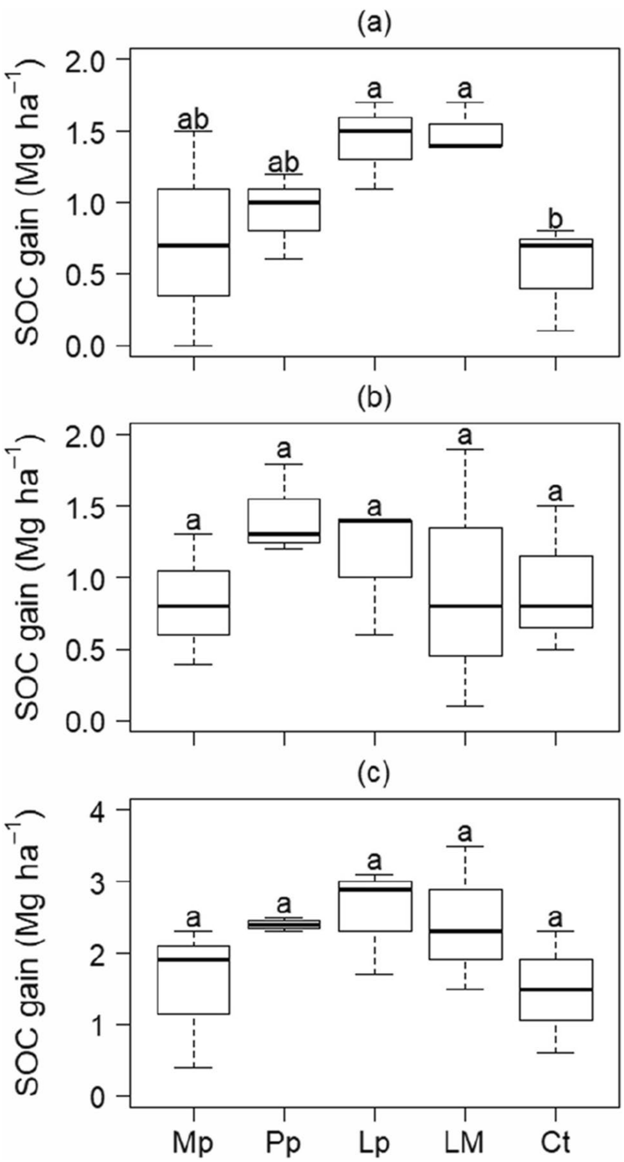

Fig. 1 One-year soil organic carbon (SOC) gain under the legume covers at the Lamto savanna site at the depths of 0-0.1 m (a), 0.1-0.2 m (b) and 0-0.2 m (c). Horizontal bold lines of the boxes indicate the median, the lower and upper bounds of the boxes represent the 25th and 75th percentiles, respectively. Vertical dotted bars include all values. Different letters indicate significant differences among legume plots (least significant difference, LSD test) at the 005 level. Mp, *Mucuna pruriens*; Pp, *Pueraria phaseoloides*; Lp, *Lablab purpureus*; LM, Legume mixture; Ct, control

native savanna sites used to test the capacity of *C. odorata* and the legumes to store SOC are suitably relevant.

Chromolaena odorata is known to continuously shed abundant and high-quality litter (Slaats 1995; Koné et al. 2012a), which may explain the greater SOC and nutrient concentrations compared to those found in the savannas. In the study region, *C. odorata* leaf litter N concentration was found to vary between 1.8 and 2.5% (Koné et al. 2012b), which is comparable even sometimes higher than those of the legumes species of this study. In the sandy and low organic soils of the region, any increase in the supply of quality plant residues will promote the soil biological activity, hence the accumulation of carbon into the soil (Koné et al. 2008; Sousa Junior et al. 2018; Fan et al. 2020). However, the improvement was found to be restricted to the top 0–0.1 m, as observed in the long-term *C. odorata* fallows both in Lamto and Ahérémou-II. One factor possibly responsible for this restriction could be the absence of anecic earthworm species in the region, as is found in tropical soils in general (Lavelle 1978). In fact, these organisms play a great role in processing plant residues and incorporating them into the soil in the form of organic matter (Lavelle 1978). In addition, they indirectly mediate changes in SOC stocks by controlling the physical protection of low-humified aggregate occluded SOC (Franco et al. 2020; Garcia-Franco et al. 2021). Despite these limitations, *C. odorata* stored 2.7 Mg SOC ha^{-1} in Lamto and 7.5 Mg SOC ha^{-1} in Ahérémou-II at 0–0.4-m depth, which may reflect considerable atmospheric CO_2 mitigation (Rumpel et al. 2020).

Similarly, legumes continuously provide significant amounts of quality litter residues to the soil; the recorded total biomass varying between 5 and 6 Mg dry matter ha^{-1} in this study, not taking into account the litter input throughout the year. This could explain the significant increase of the SOC stocks after only 1 year relative to the initial time or the control grass plot. However, the SOC gains were not found to be proportional to legume biomass inputs, probably due to the limitations explained above (i.e. high temperature, faster mineralization, low SOC protection). This may suggest that biomass production is not a limiting factor for SOC storage in the region. However, SOC gain was found to be determined by some soil variables including Ca^{2+}, which exhibited the strongest influence. As a binding agent, this exchangeable cation indeed greatly contributes to stable soil aggregate formation, hence SOC protection (Garcia-Franco et al. 2021). Contrary to the reported slow SOC recovery (Knops and Tilman 2000), a large increase was in general observed in the short-term legume fallows, which might partly be ascribed to the coarse texture of the soils (Six et al. 2002; Fan et al. 2020). The largest SOC gain recorded under the legume mixture and *L. purpureus* of the Lamto savanna site could be considered due to litter quality or the heterogeneity of residue quality that are conducive to decomposer's diversity and activity (Damour et al. 2018; Sauvadet et al. 2020; Koné and Yao 2021). In fact, the mixed legume plot was comprised of *M. pruriens* that sheds harder leaf litter, better-promoting SOM build-up (Cotrufo et al. 2015), and *P. phaseoloides* and *L. purpureus* that provide more readily decomposable leaf litters. *Lablab purpureus* leaf litter exhibited the second highest N:P and the lowest C:N ratios following *M. pruriens*, two main drivers of

Table 4 Soil (0–0.1-m depth) physical and chemical characteristics (mean ± standard error, $n = 3$) under legume and adjacent *C. odorata* fallows in Ahérémou-II

Soil variables	Paired plots					
	C. odorata	*C. cajan*	*p*-value	*C. odorata*	*L. purpureus*	*p*-value
pH_{-water}	7.3 ± 0.5	7.2 ± 0.5	ns	7.1 ± 0.2	7.6 ± 0.2	ns
Bulk density (g cm^{-3})	1.4 ± 0.1	1.4 ± 0.9	ns	1.2 ± 0.8	1.4 ± 0.9	ns
SOC (g kg^{-1})	18.6 ± 3.1	21.3 ± 1.2	ns	22.7 ± 1.7	26.9 ± 2.5	*
SOC stock (Mg ha^{-1})	25.5 ± 4.7	24.0 ± 1.8	ns	28.4 ± 2.4	35.3 ± 5.3	*
Total N (g kg^{-1})	1.8 ± 0.2	2.1 ± 0.2	ns	2.3 ± 0.2	2.7 ± 0.4	ns
C:N	10.4 ± 0.4	10.4 ± 0.1	ns	10.1 ± 0.1	10.2 ± 0.3	ns

$^{*}p < 0.05$ (significant change); *ns*, no significant difference at $\alpha = 0.05$

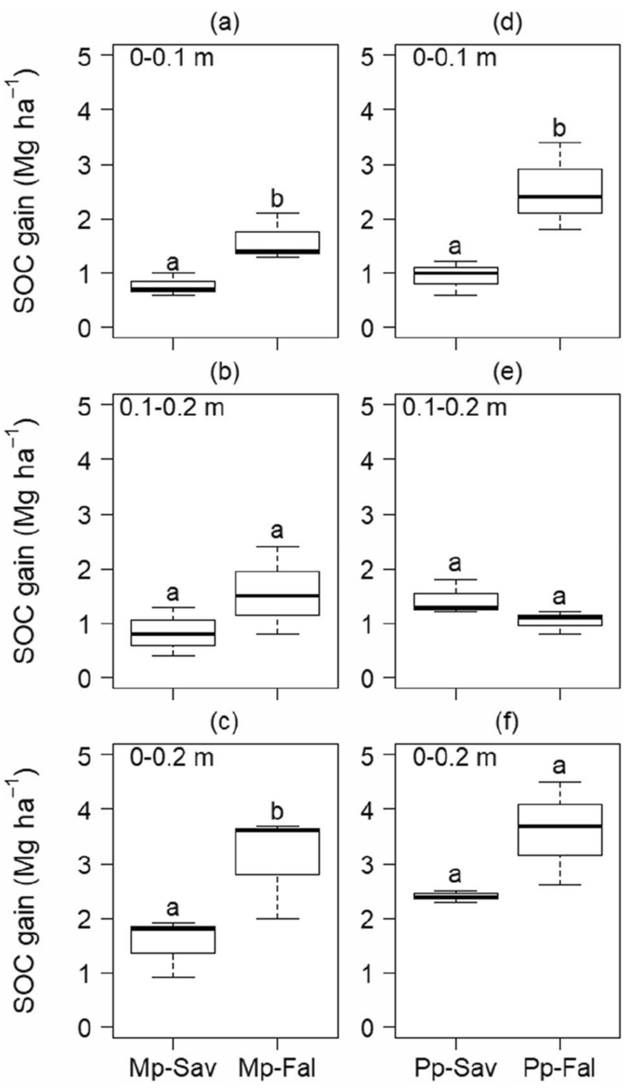

Fig. 2 Between-site comparison of 1-year soil organic carbon (SOC) gain under *Mucuna pruriens* and *Pueraria phaseoloides* in Lamto. Horizontal bold lines of the boxes indicate the median, the lower and upper bounds of the boxes represent the 25th and 75th percentiles, respectively. Vertical dotted bars include all values Different letters indicate a significant difference between sites (least significant difference, LSD test) at the 005 level. Mp-Sav and Mp-Fal are *Mucuna pruriens* grown at the Lamto savanna and fallow sites, respectively. Pp-Sav and Pp-Fal are *Pueraria phaseoloides* grown at the Lamto savanna and fallow sites, respectively

leaf litter decomposition (Yao et al. 2021). In addition, the species produced the second-highest standing total biomass following *P. phaseoloides*, and the highest root biomass at 300 kg ha^{-1} compared to those of *P. phaseoloides* and *M. pruriens* at 200 kg ha^{-1} and 150 kg ha^{-1} respectively. Roots of *L. purpureus* are less suberized, potentially reflecting a faster rate of decomposition and a more efficient contribution to SOC accumulation compared to those of *C. odorata* (Torres-Sallan et al. 2018; Saputra et al. 2020). Overall, *L. purpureus* and the legume mixture appeared as the most promising options that deserves promotion among farmers and soil fertility managers in the savanna zones of Côte d'Ivoire.

Poeplau and Don (2015) estimated the global C sequestration rate by cover cropping to be 0.32 Mg ha^{-1} $year^{-1}$. This value is lower than those recorded in Lamto, where the values ranged from 0.7 (*M. pruriens*) to 1.5 Mg ha^{-1} $year^{-1}$ (legume mixture) at 0–0.1-m depth and from 1.6 (*M. pruriens*) to 2.6 Mg ha^{-1} $year^{-1}$ (*L. purpureus*) at 0–0.2-m depth. This study strengthens the perception that herbaceous legume cropping can be a key soil management practice for C storage in agricultural soils, particularly in savanna areas. Under all plant covers of this study, the rate of SOC accumulation was higher than the expected 4‰ $year^{-1}$, particularly the legumes. However, these rates (in terms of quantity) remained below the higher rate reported by Vågen et al. (2005) for natural or improved fallows in sub-Saharan Africa (5.3 Mg ha^{-1} $year^{-1}$). In any case, the rates under the legumes will decrease rapidly over time because of the low finer soil particle size in the study region that translates into low SOC storage capacity, hence faster SOC saturation (Stewart et al. 2008; Wiesmeier et al. 2020; Garcia-Franco et al. 2021). This is shown by the rates of SOC accumulation in the *C. odorata* fallows (0–0.4-m depth) in Ahérémou-II (0.75 Mg C ha^{-1} $year^{-1}$ over 10 years) vs. Lamto (0.16 Mg C ha^{-1} $year^{-1}$ over 17 years). One could suggest that the SOC incorporation rate was declining over time as the SOC stock was approaching an upper limit that corresponds to an equilibrium value (Stewart et al. 2008; Wiesmeier et al. 2020). Raji and Ogunwole

(2006) reported a rate of 0.57 Mg C ha^{-1} $year^{-1}$ under afforestation in Nigerian savanna agroecologies for a period of 35 years. This rate is higher than that recorded in the Lamto *C. odorata* fallow (0.46 Mg C ha^{-1} $year^{-1}$) but lower than those in the Ahérémou-II *C. odorata* and Lamto legumes fallows (0.75–1.7 Mg C ha^{-1} $year^{-1}$). The rate of SOC accumulation recorded under the Lamto *C. odorata* fallow could be considered realistic since this was found on a long-term period of 17 years, which is close to the 20-year threshold defined by the IPCC (2006). More interestingly, it is close to the 0.41 Mg C ha^{-1} $year^{-1}$ found by Fujisaki et al. (2018) from a meta-analysis on tropical croplands of 13 years on average. However, it is likely that the SOC storage found in the *C. odorata* fallows of Lamto and Ahérémou-II was underestimated. The reason is that the control treatment considered was the uncropped savanna where the SOC stock was probably higher than any cropped savanna site in the study area, which should have been taken as the "right" control. Indeed, natural ecosystem conversion to agriculture is known to result in a 20 to 50% loss of the SOC stock (Veldkamp et al. 2020).

Unfortunately or not, *C. odorata* is still spreading throughout West Africa, and farmers in this region have adopted *C. odorata* fallows (Maroun 2017; Aigbedion-Atalor 2020). In Côte d'Ivoire, *M. pruriens* is used on sugarcane production sites—over 20 000 ha (FIRCA 2015) as short-term fallow plant (Kouassi 2000). *Pueraria phaseoloides* and *M. pruriens* are used as short-term fallows in rice (*Oryza sativa*), maize (*Zea mays*) and yam (*Dioscorea* sp.) systems in the South, the Centre and the North of Côte d'Ivoire (Gbakatchetche et al. 2010; N'Goran et al. 2012). Both legumes are also increasingly used as short-term fallow plants and to control weeds and pests on dessert banana fields that cover 7500 ha (FIRCA 2015). *Pueraria phaseoloides* has long been used as a cover crop in rubber and oil palm tree plantations that extend over 450,000 ha and 250,000 ha, respectively (EFI 2013) to control weeds. This equates to considerable areas for SOC storage in the 4p1000 Initiative programme in Côte d'Ivoire. In forest zones, any SOC gains may be greater and more stable than in the savanna zones because of the forest's richer clay soils, e.g. 20–35% in Oumé in Central-West Côte d'Ivoire (Koné and Yao 2021). Importantly, the vegetative covers examined in this study are of widespread use in the other West African countries under similarly humid conditions (Azontonde et al. 1998; Aigbedion-Atalor et al. 2019). Nonetheless, further studies are needed to make an estimate of the increase in SOC stocks under the studied management practices at the national scale, which would constitute a valuable contribution to the 4p1000 Initiative's goal.

Conclusions

This study was conducted to provide data relevant to the framework of the 4p1000 Initiative in savanna areas of Côte d'Ivoire. Despite the known negative impact of invasive plants on biodiversity, a significant improvement in SOC stock was found under *C. odorata* fallow. This improvement was unfortunately restricted to the top 0–0.1-m soil depth, despite the long fallow duration. The rate of SOC accumulation under *C. odorata* and legume fallows was greater than 0.4% $year^{-1}$, suggesting these vegetative covers may be congruent with the 4p1000 Initiative's aim in Côte d'Ivoire, particularly *L. purpureus* and the legume mixture. The SOC storage appeared to be limited by concentrations of SOC and total N, and soil clay and exchangeable cations, with Ca^{2+} being the most influencing factor. No linearity was observed between biomass inputs and SOC gains, probably, suggesting that biomass production is not a limiting factor to SOC storage in Central Côte d'Ivoire. However, the results obtained under the legumes need to be confirmed in the long term. In addition, in such a low clay-soil context, ligneous plant species should be associated with *C. odorata* and legume species to improve stable SOC, which is of direct interest to the 4p1000 Initiative.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-021-01861-4.

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