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Push-pull technology improves carbon stocks in rainfed smallholder agriculture in Western Kenya

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ABSTRACT
Push-pull technology improves agricultural productivity. However, its long-term effect on biomass carbon and soil organic carbon (SOC) is not yet known. The aims of this study were: to assess the effect of push-pull technology on (1) biomass carbon and (2) SOC, considering climatic conditions and the length of time that push-pull had been practiced on a farm; and (3) to establish the relationship between biomass carbon and SOC on farms. Aboveground biomass carbon and SOC were measured on 36 farms in western Kenya, encompassing three contrasting sites (Bondo, Siaya and Vihiga) and six cropping systems (push-pull and five non-push-pull systems). Farms in western Kenya stock between 3.0 ± 0.3 and 4.0 ± 0.4 t C ha^{-1} in crop biomass and between 24.4 ± 2.1 and 37.0 ± 2.6 t C ha^{-1} in the soil for those practicing push-pull, and between 1.1 ± 0.3 and 2.1 ± 0.2 t C ha^{-1} biomass carbon and between 19.2 ± 2.1 and 31.1 ± 1.7 t C ha^{-1} soil carbon for those without push-pull. There was no correlation between biomass carbon and SOC. Adoption of push-pull offers opportunities to mitigate climate change through carbon sequestration in plants and soils in low-, medium- and high-rainfall environments in both long and short rain seasons.

KEYWORDS
Biomass carbon; carbon sequestration; mixed cropping; desmodium; soil organic carbon; western Kenya

Introduction

Soils stock the largest amount of carbon, about three and four times what is present in the atmosphere and vegetation, respectively [1, 2]. In sub-Saharan Africa (SSA), this role has been compromised by depletion of soil organic matter due to continuous cropping over the years [3, 4]. Soil organic matter (and by implication soil organic carbon, SOC) in the region is reported to be very low [3, 4]. Carbon levels are estimated to have dropped by between 50 and 75% compared to pre-agricultural periods [1, 5, 6]. Low SOC in the region is attributed to a loss of carbon resulting from farm operations (e.g. tillage or plowing), removal of crop residues (e.g. for feed or fuelwood), biomass burning, soil degradation (e.g. erosion) and low-input depletive subsistence agriculture [5, 7]. To reverse this trend, land management practices that increase productivity while adapting agriculture to climate change or, where possible, contributing to climate change mitigation by conserving carbon stocks in soils or allowing additional carbon stocks to be taken up from the atmosphere have been recommended [8, 9].

Crop production affects the amount of carbon in the soil. Through photosynthesis, carbon in the atmosphere is incorporated into plant organic compounds. Part of this carbon is transferred into the soil when roots release sap exudates or during root sloughing or when litter, mulch or roots decompose [10, 11]. The amount of carbon stored in the soil depends on the balance between carbon inputs and outputs from respiration of roots, root symbionts, free-living decomposers, and from soil erosion and leaching of dissolved organic carbon [12]. In agricultural systems, crops transfer between 10 and 50% of the carbon derived from photosynthesis to belowground, of which 45% is stabilized as soil organic matter [11, 13]. It follows that cropping systems that increase productivity (e.g. that produce more biomass) can increase the amount of carbon stored in soils as they add more organic residues into soils [14]. These include intensive systems such as multiple cropping which

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stock more carbon than monocrops (when plants involved have deeper and bushy root systems and the biomass is returned to the soil) or diversified cropping systems which increase soil carbon sequestration processes by maintaining continuous crop cover and reducing soil erosion [15]. With time, carbon stored in soil can be released back into the atmosphere depending on the way the land is managed and/or on the climatic conditions. Identification of cropping systems that capture and store more carbon in the system is therefore critical for sustainable intensification of smallholder agriculture in SSA [16].

Increasing SOC is an important strategy for mitigating climate change and improving soil health across the globe [17, 18]. Carbon sequestration in the soil and the conservation of existing soil carbon stocks is one of the strategies identified by the Paris Agreement as critical to limiting global temperature rise to well below 2 °C above preindustrial levels [19]. Soil carbon sequestration delivers large-scale carbon storage at low cost. A recent review shows that well-managed farmlands have the potential to sequester up to 7 billion tons of carbon dioxide [20]. The synthesis found that increasing SOC content in the top 0–30 cm layer of all available cropland could sequester between 0.56 and 1.15 t C $ha^{-1}year^{-1}$ [20]. This supports claims that about 98% of the global cropland is potentially available for enhanced carbon sequestration through improved soil management and farming practices [21], and that between 0.2 and 1.5 t C $ha^{-1}year^{-1}$ could be sequestered on permanent cropland in SSA in areas where improved cultivation systems such as no tillage are practiced [3]. However, this potential varies due to differences in rainfall, temperature, vegetation, soil type and the type of land management practice [22, 23]. At the global scale, lower SOC levels are found in the tropics where it is hot and/or dry; the opposite is true in the temperate areas [20]. When specific ecosystems are considered, carbon levels in agricultural soils are lower than in corresponding soils under natural vegetation [2, 24]. This suggests the potential for increasing soil carbon storage on farmlands [18].

The benefits of increasing SOC in croplands transcends climate change mitigation objectives. SOC is important for all aspects of soil fertility (nutrient availability, soil structure and soil physical properties, biological soil health) and as a buffer against toxic and harmful substances [17]. These conditions control agricultural productivity and may determine the resilience of farming systems [17, 25]. Agricultural practices that increase SOC also improve crop yields. For example, an increase by 1 ton of soil carbon per hectare in degraded cropland soils can increase crop yield by 20 to 40 kg/ha for wheat, 10 to 50 kg/ha for rice, 10 to 20 kg/ha for maize, 10 to 20 kg/ha for beans and 0.5 to 1 kg/ha for cowpeas [26, 27]. In the central highlands of Kenya, a treatment whose SOC was 23.6 t ha^{-1} produced 1.4 t ha^{-1} of maize grain while a treatment whose SOC was 28.7 t ha^{-1} produced 6.0 t ha^{-1} of maize grain [28]. Scientific evidence shows that increasing SOC can reverse soil fertility deterioration [29], the primary cause of declining crop productivity in SSA [30]. This is because SOC is strongly and positively related to soil physical and chemical properties [28]. Adoption of practices that can improve soil carbon is a low-cost sustainable land management practice with benefits in terms of improved soil fertility and high farm productivity [30].

Push-pull technology is a climate-smart agriculture technology with the potential to reduce greenhouse gas emissions, build resilience of farming systems and increase agricultural productivity [31]. It is an intensive agricultural system that allows farmers to grow cereals (e.g. maize or sorghum) with desmodium (*Desmodium intortum* Mill. Urb – greenleaf desmodium or *D. uncinatum* (Jacq.) DC. – silverleaf desmodium) and Napier grass (*Pennisetum purpureum* Schumach.) or *Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf. (brachiaria, Mulatto II cultivar) simultaneously on the same piece of land. Push-pull sustains a high level of productivity [32–34] and is climate resilient [31, 35, 36]. Improved yields of push-pull farms are attributed to improvement in the control of cereal pests such as stem-borer, fall armyworm and striga weed [36, 37]; soil fertility improvement through nitrogen fixation [38], increase in organic matter [37] and alleviation of phosphorus fixation problems [39]; and improvement of soil moisture content. However, the ability of push-pull technology to mitigate climate change through carbon sequestration and storage is unknown. In addition, the effectiveness of any practice in increasing soil carbon is context-specific and depends on local factors such as climatic conditions, soil type and the way the crops are managed on the farm. These aspects have not been evaluated for push-pull technology in relation to carbon sequestration and storage. Estimation of carbon storage on push-pull farms is a good starting point for tracking and evaluating desmodium-based interventions and will provide a basis for monitoring, reporting and verifying impacts of programs aimed at mitigating climate change with push-pull [18].

There is also a general lack of information on estimates for SOC in maize-based mixed cropping systems in western Kenya. Many estimates for SOC have focused on carbon sequestration in specific climate smart agriculture practices, such as conservation agriculture and integrated soil fertility management (ISFM) [40]. Like many cropping systems, conservation agriculture practices or ISFM technologies increase primary productivity and therefore are assumed to increase plant organic inputs to soils [41]. However, this assertion was recently challenged by results from long-term trials in humid tropics of western Kenya [40]. The study found that conservation agriculture and ISFM practices helped to preserve carbon in the soil but did not sequester carbon [40]. This suggests that soils in certain areas do not always offset anthropogenic greenhouse gas emissions but contribute to climate change mitigation by avoiding loss of carbon from the soil. It is not known whether maize-based systems involving desmodium, bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* (L.) Walp.), green gram (*Vigna radiata* (L.) R. Wilczek) or groundnut (*Arachis hypogaea* L.) enhance carbon stocks in the soil or simply prevent the loss of carbon. This study compares push-pull technology with non-push-pull cropping systems in low, medium and high rainfall conditions in Western Kenya. The authors hypothesized that: (1) carbon held in plants and soil is higher in push-pull farms than in conventional maize systems, (2) carbon stocks increase with the duration over which push-pull has been practiced on a farm, (3) carbon stocks in the systems vary depending on climatic conditions, and (4) aboveground biomass carbon is positively correlated with SOC and grain yield.

Materials and methods

Study sites

This study was conducted in three sites in western Kenya: Bondo and Siaya in Siaya county and Vihiga in Vihiga county. These sites represent regions with contrasting agro-climatic conditions: high rainfall (Vihiga, 1800–2000 mm), medium rainfall (Siaya, 1200–1800 mm), and low rainfall (Bondo, 750–1200 mm). The study sites also vary in elevation, with a gradient from low elevation in Bondo (1100–1350 m) to medium elevation in Siaya (1140–1400 m) and high elevation in Vihiga (1300–1800 m). The climate in the area is sub-humid tropical in Vihiga and Siaya and semi-arid in Bondo. Rainfall in western Kenya is bimodal. Long rains (LR) are received between April and July while short rains (SR) occur between September and November. Due to climate variability/irregular and unreliable rainfall, the onset of corresponding LR and SR seasons varies from one year to the next. Soils in the study area are mainly Acrisols, Ferralsols and Nitisols [42]. Soil texture varies from sandy loam in Bondo to loamy sand in Siaya and Vihiga.

Agriculture, particularly farming and livestock keeping, is the main source of livelihood in western Kenya. Agricultural production is predominantly smallholder-rainfed for subsistence [43, 44]. Land holdings are generally small due to fragmentation in the process of passing the land from parents to offspring. Farms are relatively larger in Bondo (3.0 ha) than in Siaya (1.02 ha) and Vihiga (0.41 ha) [45, 46]. Land preparation is mainly done by oxen or tractors in Bondo and Siaya and hand hoeing in Vihiga [45, 46]. Cereals (e.g. maize, sorghum, millet and wheat) are traditionally intercropped with legumes such as bean, groundnut, cowpea or green gram [47]. Other food crops common in smallholder farms include sweet potatoes (*Ipomoea batatas* (L.) Lam.), cassava (*Manihot esculenta* Crantz) and vegetables [34]. Soil infertility, irregular and unreliable rainfall, pests (weeds such as striga and insect pests such as stem-borers and fall armyworm) are major constraints to crop production in the region [48]. Push-pull technology is widely practiced in western Kenya and has received much attention because of its contribution to improving soil fertility and to the control of striga, stemborer and fall armyworms [36, 49].

Experimental design, and establishment and management of crops

A factorial design was employed with site (Bondo, Siaya and Vihiga) as the main factor. In each site, farmers who use push-pull were categorized according to how long they had practiced the technology; less than 2 years, 2 to 5 years and more than 5 years. Four farms were randomly selected in each category (push-pull age), giving a total of 12 farms per site and 36 farms across the three sites. Each push-pull farm was assigned a control farm on which maize was practiced either as a monoculture or with a companion legume crop. Control farms were as physically close to push-pull farms as possible to minimize intra-farm soil fertility and management gradient or time for land use change to cropland. The plot size varied between 13 m × 11 m and 42 m × 26 m for push-pull farms. Control farms were approximately the same size as their respective push-pull farms. The study covered three cropping seasons: 2017 LR, 2017 SR and 2018 LR.

Push-pull plots were established by intercropping maize with *D. intortum* in a 1:1 row arrangement and planting *brachiaria* on the border of the plot. Maize was planted at 0.75 m × 0.30 m inter- and intra-row spacing. Desmodium was planted at an equal distance between rows of maize (0.375 m from a row of maize). Desmodium seeds were drilled when the plots were established at the beginning of the first season, and gap-filling was done regularly to replace seedlings that had not geminated. At the beginning of subsequent seasons, desmodium was trimmed before planting maize and was left to grow throughout the season to control striga, stem-borers and fall armyworm and to improve soil fertility. Three rows of brachiaria were planted at the farm border with 0.50 m between rows and 0.50 m within rows at the start of the first season. Brachiaria was harvested depending on farmers' need for fodder; at least one row of fully grown brachiaria was always retained around the border to maintain the "pull" function (to trap insect pests) of the push-pull. On control farms (maize monocrop, maize–bean, maize–cowpea, maize–green gram and maize–groundnut), maize was planted at 0.75 m × 0.30 m. Legumes in control farms (beans, cowpea, green gram or groundnut) were planted in a 1:1 maize–-legume row arrangement. The intercropped legume was planted at approximately 0.30 m in the row. Land preparation was done using a hand hoe for both push-pull and control plots. In push-pull plots, the soil was worked in strips between desmodium rows leaving approximately 60% of the farm undisturbed. In control farms, the totality of the land was worked. Mineral fertilizers were applied in push-pull and control farms at a rate of 60 kg di-ammonium phosphate (DAP) ha^{-1} at planting and 60 kg calcium ammonium nitrate (CAN) ha^{-1} at 6 weeks after planting, equivalent to 27 kg N, 12 kg P and 4.8 kg Ca ha^{-1}. Weeding was done manually, twice in a season. There was no pesticide application in either push-pull or control farms during the study period. Crop residues were removed from farms. Regular visits and interactions between farmers and the research team ensured that farmers applied management activities uniformly in the push-pull and respective control plots.

Estimation of biomass carbon and SOC

Biomass carbon was estimated as the total amount of carbon contained in aboveground biomass (shoots, grains and cobs) of crops grown on a farm. A four-step approach was used: (1) estimation of the dry matter of the shoot, grain and empty cobs of the crop grown on a farm; (2) estimation of the amount of carbon contained in each of these components using the carbon content value identified from published literature; (3) estimation of the total amount of carbon per crop grown on a farm by adding the amount of carbon stored in its different parts; and (4) estimation of the amount of carbon stored aboveground on a farm by adding the amount of carbon for each crop grown on the farm. Maize plants were harvested from randomly selected 3 m × 3 m quadrats in push-pull and control plots. Cobs were separated from stovers and the plant cut at 5 cm above the ground. Cobs and stovers were immediately weighed in the field using a spring balance. A random sample of five cobs with grains and five stovers was taken and weighed immediately using a 6000 g 0.1 g portable balance with rechargeable batteries (6.0 kg weighing balance). The samples (stover and cobs) were transported to the laboratory and oven-dried at 65 °C to a constant weight and their dry weight was determined using a 6.0 kg weighing balance. The ratio of the dry weights of the stover, cobs and grain to the respective sample fresh weight was multiplied with the fresh weight of the components determined in the field to obtain component dry weight. The amount of carbon contained in maize components was estimated by multiplying their dry matter with their respective carbon content (stover: 22.2%, grain: 13.9% and cobs: 4.3%) reported in Ma *et al.* [50].

Shoots of desmodium, brachiaria, beans, cowpea, green gram and groundnut were harvested from randomly selected 1 m long quadrats along their respective rows. Harvested material was stacked in a tared sack and the fresh weight was determined in the field. The crop materials were transported to the laboratory and oven dried at 65 °C to a constant weight and their dry weight was determined. The amount of carbon in these materials was estimated by multiplying their dry matter yield by a carbon fraction of 42.3% [50].

The amount of carbon stored in soils was estimated for the 0–15 cm topsoil layer. Soil sampling was done from the inner two thirds of each plot between the maize rows. Nine random cores were

Table 1. Summary of analysis of fixed effect in 2017 long rain (LR), 2017 short rain (SR) and 2018 LR in western Kenya on biomass carbon stock (aboveground), soil carbon content, soil bulk density, soil carbon stock and maize grain yield.

	Biomass carbon stock		Soil carbon content				Soil carbon stock		
Source of variation	2017 SR	2018 LR	2017 LR	2017 SR	2018 LR	Soil bulk density	2017 LR	2017 SR	2018 LR
Site	.495	.165	**.016**	.094	**.010**	.843	**.018**	.118	**.022**
Age of push-pull on a farm (age)	.950	.175	.761	.669	.359	.702	.632	.455	.158
Cropping system	**< .001**	**< .001**	.998	.921	.117	**< .001**	**< .001**	**< .001**	**< .001**
Site × age	.954	.726	.744	.901	.645	.115	.229	.704	.350
Site × cropping system	.464	.179	.054	.369	.850	**.013**	.508	.192	.845
Age × cropping system	.941	.344	**.005**	.888	.789	.392	.067	.353	.903
Site × Age × cropping system	.756	.755	.288	.656	.685	.576	.505	.915	.962
Bondo									
Age	.786	.078	.989	.775	.364	.193	.477	.360	.140
Cropping system	**< .001**	**< .001**	.206	.246	.409	**.002**	**.016**	.105	**.025**
Age × cropping system	.863	.546	.130	.451	.999	.902	.173	.748	.990
Siaya									
Age	.992	.693	.676	.537	.663	.487	.656	.363	.481
Cropping system	**< .001**	**.001**	.058	.878	.486	**< .001**	.097	**.008**	**< .001**
Age × cropping system	.568	.744	**.036**	.537	.264	.186	.284	.396	.874
Vihiga									
Age	.997	.687	.113	.987	.458	.184	**.014**	.920	.902
Cropping system	**< .001**	**.002**	.688	.327	.252	**< .001**	**< .001**	**.003**	**< .001**
Age × cropping system	.645	.331	.702	.863	.485	.815	.737	.784	.448

Numbers in the table are P values. P values $\leq$ .05 are printed in bold.

taken from each of the push-pull and control plots immediately after harvesting maize. Visible plant debris deposited on the soil surface was removed and soil cores were collected using a 2 cm diameter soil auger. The nine subsamples were bulked to a composite sample and transferred to the laboratory, where they were air-dried and ground; visible organic debris was removed and they were sieved through a 2 mm sieve. The soil samples were analyzed for total organic carbon content using the Walkley and Black wet oxidation method together with the colorimetric method using ultraviolet visible spectroscopy (UV-Vis). The analysis was done in the laboratory of the International Centre for Insect Physiology and Ecology (icipe), Mbita station, Kenya. At the end of the 2018 LR season, five random samples from undisturbed soil were collected from push-pull and control farms for determination of bulk density at 0–15 cm depth. The volume of soil in the 0–15 cm topsoil layer (1500 m^3) per hectare together with soil bulk density (g/cm^3) and soil carbon content (g of carbon per kg of soil) was used to estimate the amount of carbon stored in the 0–15 cm layer per hectare in both push-pull and control farms.

Statistical analysis

A mixed-effect model run by restricted maximum likelihood was used to determine differences between push-pull and control farms, and to test the effects of the length of time that push-pull had been practiced on a farm, of sites and their interaction. The farm was fitted in the model as a random effect. The analysis was done per season. Linear regression analysis was done to assess correlations between SOC stock, biomass carbon stock, SOC content, soil bulk density and maize grain yield. The level of significance was set at $\alpha = 0.05$. All statistical analysis was done in R version 3.6.1 [51].

Results

Biomass carbon

The amount of biomass carbon was higher in push-pull farms than non-push-pull farms in all the two seasons in the three sites (Table 1). In 2017 SR, biomass carbon in push-pull farms was 3.5 ± 0.3, 3.6 ± 0.3 and 3.5 ± 0.2 t ha^{-1} in Bondo, Siaya and Vihiga, respectively. The corresponding values for non-push-pull farms were 1.2 ± 0.3 t/ha^{-1} in Bondo, 1.1 ± 0.3 t ha^{-1} in Siaya and 1.7 ± 0.2 t ha^{-1} in Vihiga. This represents an increase of 2.3 ± 0.4 (183.3%), 2.4 ± 0.4 (205.0%) and 1.8 ± 0.3 (106.3%) t of biomass carbon ha^{-1} compared to non-push-pull farms in 2017 SR in Bondo, Siaya and Vihiga, respectively (Figure 1).

Similarly, in 2018 LR, biomass carbon in push-pull farms was 4.0 ± 0.4 t ha^{-1} in Bondo, 3.0 ± 0.3 in Siaya and 3.2 ± 0.2 t ha^{-1} in Vihiga compared to 1.8 ± 0.4, 1.5 ± 0.3 and 2.1 ± 0.2 t ha^{-1} in non-push-pull farms, respectively (Figure 1). Similar to 2017 SR, the amount of biomass carbon in push-pull farms in Bondo, Siaya and Vihiga was higher than that found in non-push-pull farms (Figure 1). The duration over which push-pull had been practiced on a farm and climatic conditions (represented by sites) and their interaction did not affect the amount of biomass carbon stored on the farms (Table 1).

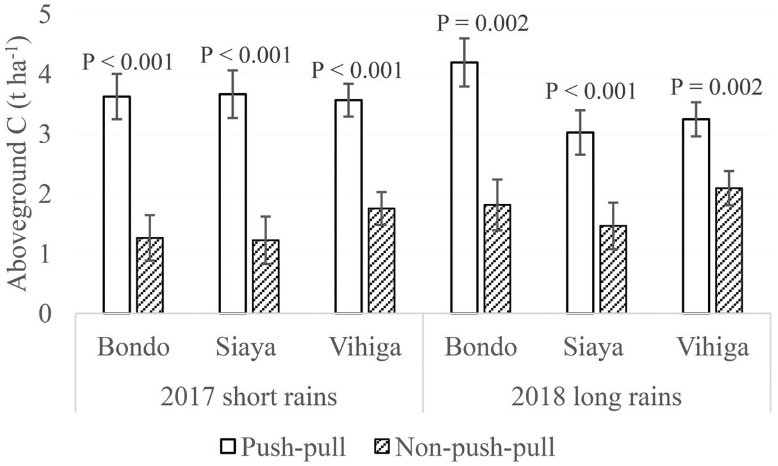

Figure 1. Aboveground biomass carbon estimated in push-pull and non-push-pull farms in Bondo, Siaya and Vihiga in 2017 short rain and 2018 short rain seasons.

SOC concentration and stocks

SOC concentration

The concentration of SOC in push-pull and non-push-pull farms was influenced by the length of time that push-pull had been practiced on a farm. This phenomenon was observed in one of the three seasons: 2017 LR (Table 1). In 2017 LR, the concentration of SOC on farms where push-pull had been practiced for more than 5 years was higher than that for non-push-pull farms by 1.4 ± 0.6 g kg^{-1} (df = 11, t ratio = 2.2, $p = 0.048$). In contrast, no significant difference was observed between push-pull and non-push-pull farms where push-pull had been practiced for less than 5 years (Figure 2a).

In the same season (2017 LR) in Siaya, a large but not significant difference was observed in the concentration of SOC in non-push-pull farms compared to farms where push-pull had been practiced for less than 2 years (7.8 ± 2.3 g kg^{-1}), and the gap narrowed for farms where push-pull had been practiced for 2 years and above (Figure 2b; Table 1). There was no significant evidence of changes in SOC concentration due to the duration of push-pull on farms when push-pull and non-push-pull farms were compared.

In the three study seasons, the concentration of SOC was lower in Siaya compared to Bondo, while Vihiga had intermediate values for SOC concentration (Figure 3; Table 1). In fact, for the three consecutive seasons – 2017 LR, 2017 SR and 2018 LR – the mean concentration of SOC for Bondo site was higher than that for Siaya site, by 4.5 ± 1.3, 5.3 ± 2.0, and 4.4 ± 1.2 g kg^{-1} in the three respective seasons (Figure 3).

SOC stock

Soil bulk density was higher in push-pull than non-push-pull farms in all three sites (Table 1; Figure 4). The mean for push-pull farms was 1.0 g/cm^3 in Bondo and Vihiga and 1.1 g/cm^3 in Siaya, compared to the average of around 0.8 g/m^3 observed in non-push-pull farms across the three sites. This shows that the mean soil bulk density for push-pull farms was higher than that for non-push-pull farms, by 0.1, 0.3 and 0.2 g/cm^3 (or t per m^3) in Bondo, Siaya and Vihiga, respectively (Figure 4).

The mean SOC stored in push-pull farms was consistently higher than that for non-push-pull farms, but the magnitude of difference depended on sites and seasons (Table 1). During the study period (three seasons) in all the sites, the mean SOC stock for push-pull farms was higher than that for non-push-pull farms by between 5.2 ± 2.1 t ha^{-1} (estimated in Siaya in 2017 LR) and 9.4 ± 2.6 t ha^{-1} (observed in Vihiga in 2017 SR). The exception to this was the 3.8 ± 1.7 t SOC ha^{-1} difference observed in Bondo in 2017 SR (SOC stock being higher in push-pull than non-push-pull farms; Figure 5b).

The mean SOC stock for Siaya was lower than that for Bondo in the three seasons, and lower than that of Vihiga in one out of three seasons: 2017 LR (Figure 6a). The mean SOC stock for Bondo was higher than that for Siaya by 6.5 ± 2.0, 7.6 ± 3.0 and 6.1 ± 2.0 t ha^{-1} in 2017 LR, 2017 SR and 2018 LR, respectively (Figure 6a), while the mean SOC stock for Vihiga was higher than that for Siaya by 4.7 ± 1.8 and 7.0 ± 2.8 t ha^{-1} in 2017 LR and 2017 SR, respectively ($p = .053$ for 2017 SR).

In Vihiga in 2017 LR, farms where push-pull had been practiced for more than 5 years had more SOC stock than those where push-pull had been practiced for less than 2 years. Moreover, farms where push-pull had been practiced for a period between 2 and 5 years had a mean SOC intermediate between that of farms that had practiced

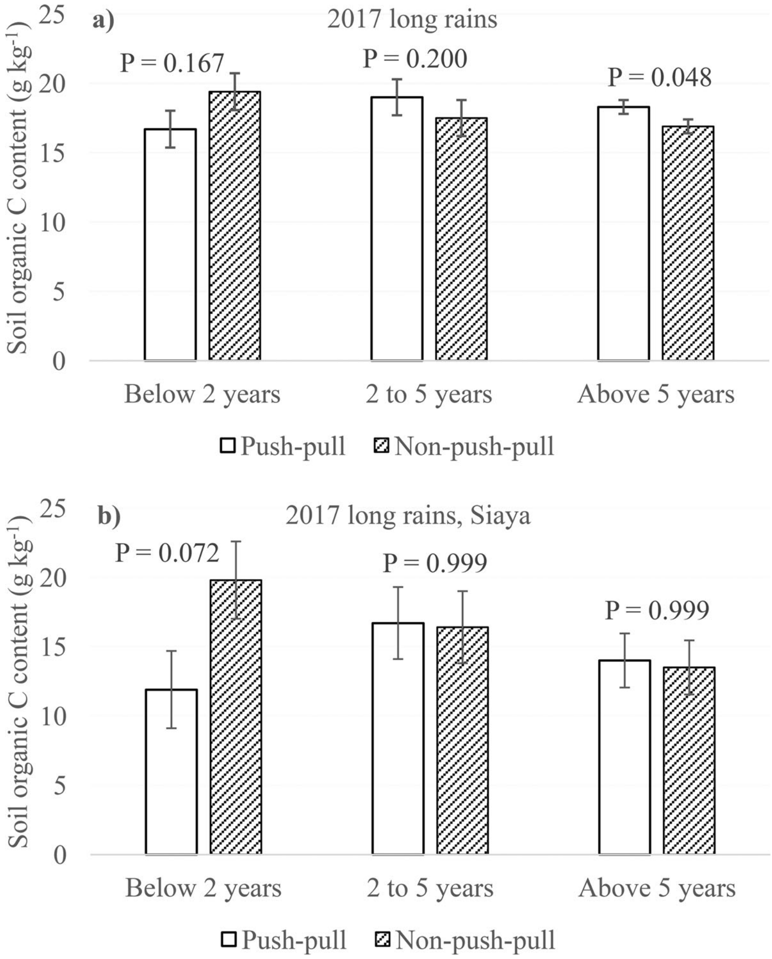

Figure 2. Effect of push-pull practice duration on the concentration of organic carbon in farm (a) as average of the three study sites; Bondo, Siaya and Vihiga in 2017 long rains, and (b) effect of push-pull practice duration in Siaya in 2017 long rains. Sampling was carried out on farms where push-pull had been practiced for less than 2 years, for 2–5 years, and for more than 5 years, and on their control farms. Bars show standard errors.

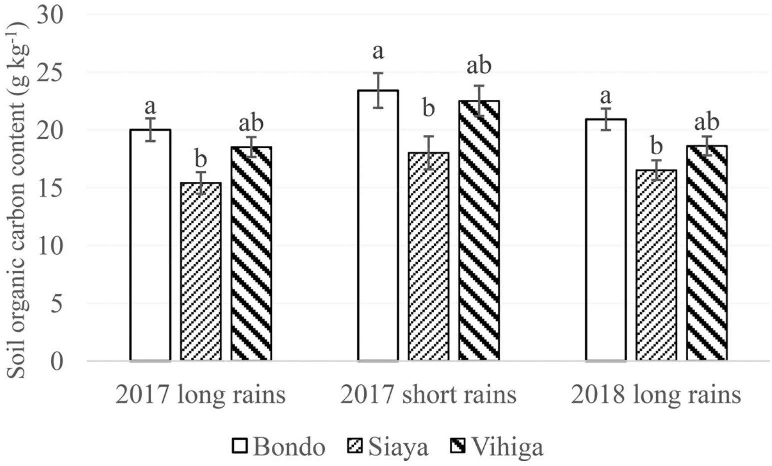

Figure 3. Concentration of soil organic carbon in Bondo, Siaya and Vihiga during the 2017 long rains, 2017 short rains and 2018 long rains. Bars show standard errors. Means with different letters are significantly different at $\alpha = 0.05$.

push-pull for more than 5 years and that of farms that had practiced it for less than 2 years (Figure 6b). In fact, farms where push-pull had been practiced for more than 5 years had 5.5 ± 1.7 t more SOC ha^{-1} than those that had had push-pull for less than 2 years ($p = 0.027$). Additionally, farms that practiced push-pull for 2 to 5 years had 4.6 ± 1.8 t more SOC ha^{-1} than those that had practiced push-pull for less than 2 years ($p = 0.078$).

Relationship between biomass carbon, SOC and maize grain yield

There was no significant relationship between biomass carbon and SOC stocks in push-pull and non-

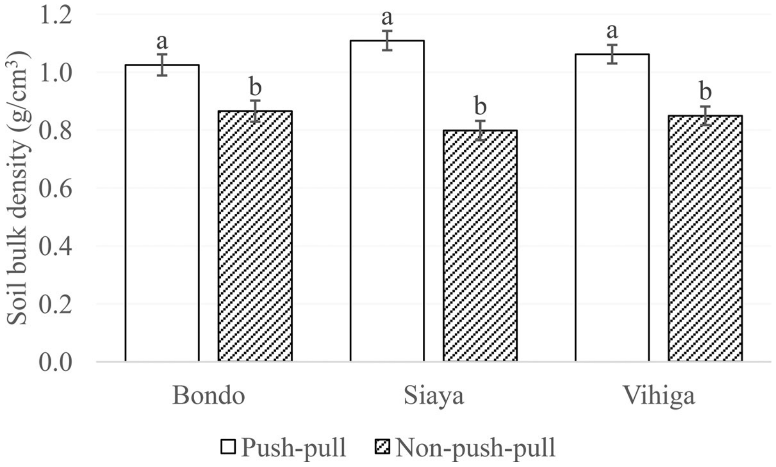

Figure 4. **Effect of push-pull on soil bulk density in Bondo, Siaya and Vihiga. Sampling was carried out after harvesting maize in the 2018 long rain season. Bars represent standard errors. Means with different letters are significantly different at $\alpha = 0.05$.**

push-pull farms (Table 2). Push-pull and non-push-pull farms that had higher SOC concentration (content) also had higher SOC stocks, but this was more pronounced in push-pull than non-push-pull farms (slope or β value of 1.4 for push-pull against 1.2 for non-push-pull, and adj. R^2 of 0.819 for push-pull vs. 0.776 for non-push-pull; see Table 2). On the other hand, non-push-pull farms that had higher bulk density also had higher SOC stock, contrary to what was observed in push-pull farms (Table 2). In push-pull farms, there was a slight negative relationship between SOC concentration and soil bulk density (5.6% total variation), contrary to what was observed in non-push-pull farms (no significant relationship). In both push-pull and non-push-pull farms, those that had relatively high SOC concentration and SOC stock tended to have relatively low maize grain yield, but that relationship too was small: 5.6% variation for push-pull farms (for both SOC content and stock), and 5.7 and 3.7% variation for non-push-pull farms for SOC concentration and SOC stock, respectively (Table 2).

Discussion

Push-pull farms had higher biomass carbon. This can be attributed to the higher biomass produced in push-pull farms [34]. High biomass production in push-pull is due to its relatively high level of intensification as maize is grown with desmodium (additive intercrop) and brachiaria in the same plot. Their combined biomass (maize, desmodium and brachiaria) outperforms that for maize, or maize and a legume, grown on non-push-pull farms [34]. Production of biomass in agriculture is paramount in managing soils for increased land productivity, rehabilitating degraded lands, reducing losses of SOC and increasing SOC stored in soils [52]. The observed increase in biomass carbon in push-pull farms compared to non-push-pull farms suggests that the adoption of push-pull can increase carbon inputs into soils relative to non-push-pull cropping systems and help to attain the 2050 global target of 55 t C ha^{-1} in the 30 cm topsoil [14, 17, 18, 53]. To achieve this goal, plant residues should be retained on the farm or recycled through livestock feeding and returning manure to the farms.

The concentration of SOC was higher in push-pull than non-push-pull farms when push-pull was practiced for more than 5 years (Figure 2a). Moreover, the SOC concentration for non-push-pull tended to be higher than that for farms where push-pull had been practiced for less than 2 years, and yet no difference was observed between non-push-pull farms and farms where push-pull had been practiced for 2 years and above (Figure 2b). This suggests that push-pull is able to build SOC concentration and outpace non-push-pull maize-based cropping systems. However, there was no clear positive trend of SOC concentration based on the period of time push-pull had been practiced on a farm. This is because farm management varies from farmer to farmer.

Additionally, soils were not assessed for SOC concentration before they were turned into push-pull farms. This (assessing the initial SOC concentration) might have made it possible to monitor changes over time in push-pull and non-push-pull farms alike. It might therefore be necessary to observe changes on a particular farm (push-pull and non-push-pull) over time to substantiate the claim that push-pull builds SOC concentration more over time than non-push-pull maize-based

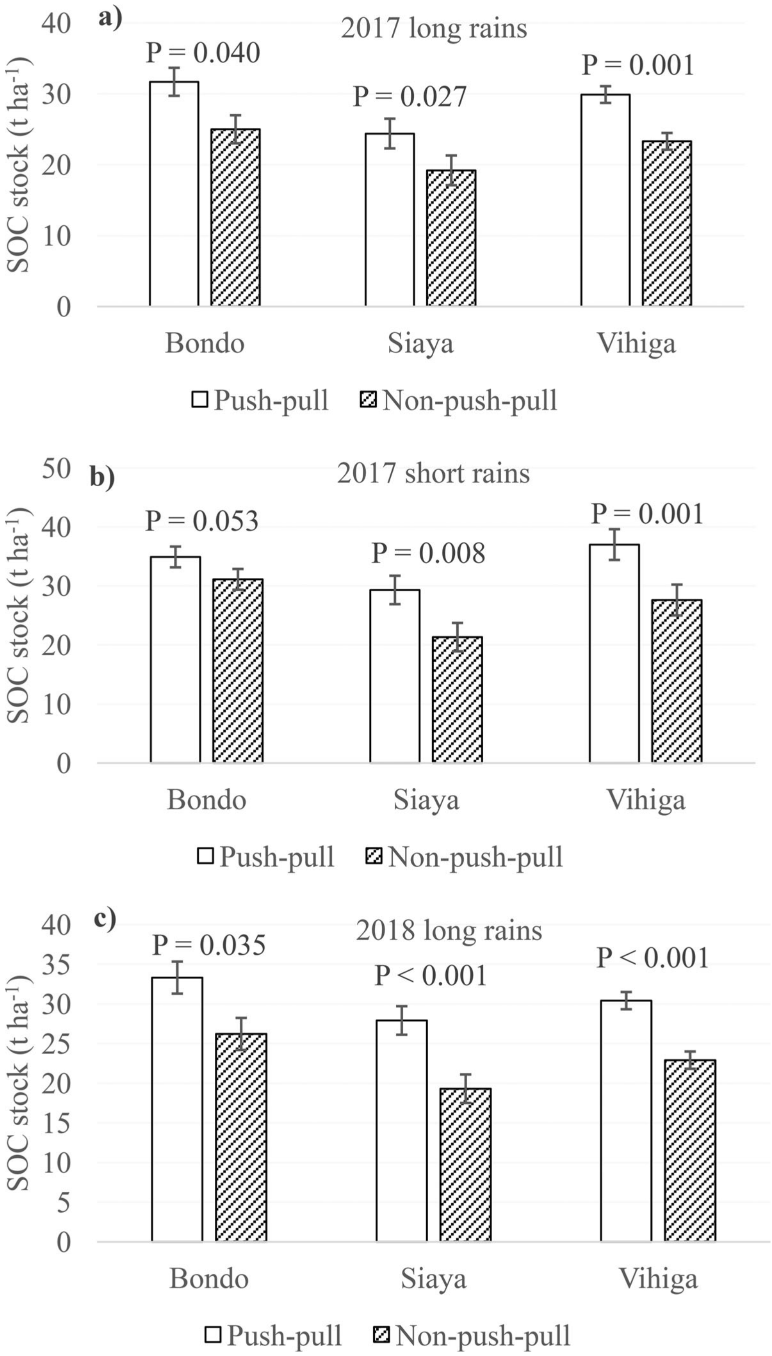

Figure 5. Effect of push-pull technology on soil organic carbon (SOC) stock in Bondo, Siaya and Vihiga during the (a) 2017 long rains, (b) 2017 short rains and (c) 2018 long rains. Bars represent standard errors.

cropping systems do. This claim is based on the fact that when soils are less disturbed and covered, soil particles bind together in micro- and macro-aggregates and protect against SOC losses [54]. Likewise, push-pull technology is a combination of reduced tillage and permanent live mulch (desmodium). In fact, soil tillage in push-pull happens in strips between desmodium rows to plant maize, leaving around 60% of soils undisturbed [55]. The combination of these conditions would increase SOC concentration over time, and it may be more than two decades before saturation is reached [18]. Monitoring SOC concentration on farms is necessary to gauge the progress in achieving the 4 per mille per annum increase in SOC concentration on farms [18]. It is therefore advisable to regularly analyze changes in SOC concentration in push-pull and other cropping systems as well, to track changes over time.

Likewise, care should be taken to cooperate with farmers who are adopting push-pull for the first time on their farms in order to assess the initial SOC concentration that will be used for further evaluation of push-pull technology vis-à-vis carbon dynamics over time relative to their counterpart maize-based cropping systems. A clear difference was not observed in SOC concentration between push-pull and non-push-pull farms in all three sites

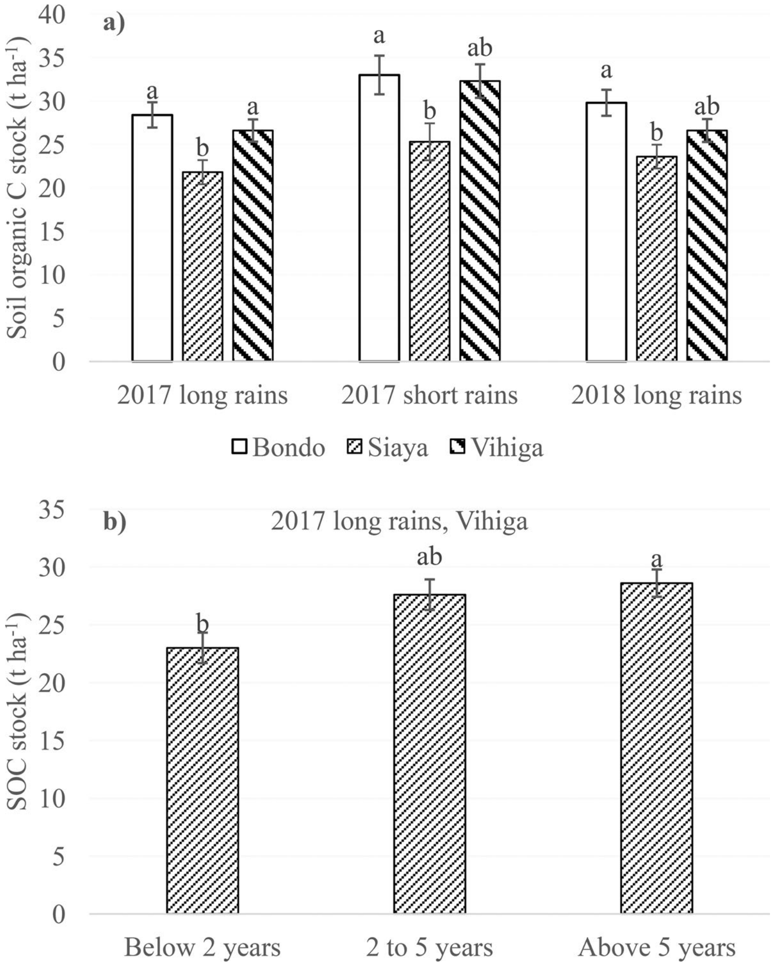

Figure 6. Soil organic carbon (SOC) stock in Bondo, Siaya and Vihiga (a) during the 2017 long rains, 2017 short rains and 2018 long rains and (b) on push-pull farms in Vihiga during the 2017 long rains, where push-pull farming had been practiced for different lengths of time. Bars represent standard errors. Means with a different letter in a season are significantly different at $\alpha = 0.05$.

Table 2. Relationship between abovegrounda dn belowground carbon stock, soil organic carbon (SOC) content, soil bulk density and maize grain yield from push-pull and non-push-pull farms.

		Push-pull				Non-push-pull			
Response variable	Predictor variable	Intercept	B	Adj. R^2	P value	Intercept	B	Adj. R^2	P value
SOC stocks (t ha^{-1})	Biomass carbon	30.304	0.272	−0.008	.674	24.221***	−0.205	−0.009	.868
	SOC content	3.015*	1.432	0.819	< .001	−0.193	1.265	0.776	< .001
	Soil bulk density	20,996**	9351	0.012	.137	498.800	27939.4	0.197	< .001
SOC content (g kg^{-1})	Biomass carbon	18.600***	0.378	−0.001	.355	19.316***	−0.171	−0.009	.841
	Soil bulk density	31.290***	−11.052	0.066	.004	19.060***	−0.043	−0.009	.992
Soil bulk density (g/cm^3)	Bomass carbon	1.102***	−0.015	0.012	.137	0.842***	−0.004	−0.009	.816
	SOC content	1.199***	−0.006	0.066	.004	0.837***	−0.000	−0.009	.992
Maize grain yield (t ha^{-1})	Soil bulk density	1.408	0.062	−0.009	.964	1.408	0.062	−0.009	.964
	SOC content	3.848***	−0.108	0.056	.009	3.050***	−0.083	0.057	.008
	SOC stock	3.855***	−0.068	0.056	.009	2.628***	−0.048	0.037	.028

The level of significance of intercept is shown with asterisks: *, ** and *** indicate significance at $p = 0.05$, 0.001 and < 0.001, respectively. The level of significance of B values (slopes) is indicated by P values. P values $\leq .05$ are printed in bold.

in the three study seasons (direct effect). Similarly, a study over five seasons in Siaya and Vihiga reported no change in SOC over time in push-pull plots compared to other maize-based cropping systems [56], suggesting that changes might take more than 2 years to happen. A long-term study is therefore needed to track changes in SOC concentration over time. Additionally, returning the biomass on farms would accelerate the build-up of SOC concentration.

Push-pull farms increased soil bulk density. This might have been due to an improvement in soil aggregation compared to non-push-pull farms. Soils with high bulk density are likely to limit the growth of roots for crops due to compaction, thus reducing the growth of shoots and the yield [57]. This is, however, not the case for push-pull as observed values of its soil bulk density are lower than critical values associated with compaction [40, 58, 59]. Furthermore, push-pull promotes better crop growth and yields than conventional cropping systems [34, 37, 60].

Push-pull farms increased SOC stock in all the three sites. This is due to the relatively higher soil bulk density observed in push-pull than non-push-pull farms (Figure 4), suggesting better soil aggregation and aggregate stability in push-pull than non-push-pull farms. In push-pull farms, the input rate of organic matter might have been relatively higher compared to non-push-pull farms thanks to higher biomass production aboveground [34] and higher root turnover belowground; and, because of better soil aggregation (better soil bulk density), SOC might have been protected physically by aggregates, hence reducing the rate of its decomposition (SOC) [22]. Other studies have shown that changing land use from native forest or pasture to crops leads to the loss of SOC by 42% and 59%, respectively [40, 61]. Ways to mitigate these losses include conservation tillage, reduced tillage and cover cropping [1], and these are characteristics of push-pull technology (reduced tillage and cover cropping). Such practices are known to reverse the negative trend of SOC over time in croplands to positive trends [1]. SOC stocks observed in this study are in the range reported in the central highlands of Kenya [28]. However, no till and reduced till have been reported to alter the distribution of SOC in the soil profile, with high SOC accumulation in 10 cm uppermost soil layer and reduced SOC with increasing depth. In addition to this, the overall SOC stock in the profile remains similar to that for conventional practices [62]. Even though push-pull technology is a reduced-till technology, it might be an exception in terms of conserving SOC and in SOC distribution in the profile. This is because, unlike reduced-till technologies, with push-pull organic matter is buried deep in the profile through tilling the maize strips between rows of desmodium. Additionally, unlike reduced till where the soil is covered by mulch, a perennial desmodium is used in push-pull technology. Thanks to the desmodium roots that go deep, as well as their exudates and turnover, it is suggested that SOC in the profile for push-pull farms might be higher than that for non-push-pull maize cropping systems, but this needs to be assessed for clarity.

Site and seasonal variations in soil carbon content and SOC stock were found, with lower quantities in Siaya. This could be attributed to differences in the amount and distribution of rainfall and its effect on microbial activity in soils and the loss of dissolved organic carbon through erosion and deep percolation below the 0–15 cm depth sampled in this study [63, 64]. The downward movement of dissolved SOC in the profile referred to as deep percolation is, however, not a loss as the carbon that moves deep in the soil profile is preserved from the adverse effects of farming activities and seasonal changes. An increase in SOC was observed with the length of time push-pull had been practiced in Vihiga (one of three sites) in one of three study seasons (2017 LR). This suggests that SOC stock increases with time in push-pull farms. However, because it was not consistent across sites and seasons, this is not sufficient evidence to conclude that push-pull increases SOC stock with time. Further studies are needed to explore the effect of the duration of push-pull on a farm on its SOC.

The amount of SOC stock was not correlated with amount of biomass carbon, probably because the biomass was removed. However, even when residues are added, they contribute less to SOC stock compared to roots. Normally, shoots contribute less to SOC; some estimates indicated a 2:1 ratio between the contribution from roots and that of shoots to SOC [13]. While 45% of carbon contained in roots is stabilized as SOC, only 8% of carbon in shoots is [63]. Further, the residence time in soils of carbon derived from roots is 2.5 times greater than that for carbon derived from shoots, due partly to the higher amount of recalcitrant carbon compounds in roots than in shoots, the relatively higher physical protection of carbon in roots than in shoots, and the continuous addition of carbon from root exudation and small root turnover [10, 65]. Therefore, the build-up of SOC stock depended much on roots and less on shoots, given that crop residues were removed. Soil bulk density in push-pull farms was negatively affected by SOC content relative to non-push-pull farms (Table 2), as expected [66, 67]. This implies a relatively higher level of organic matter on push-pull compared to non-push-pull farms. Both SOC content and stock were negatively related to maize grain yield, although the relationship explained only a small portion of the variation (Table 2). This suggests that maize grain yield was partially supported by mineralization of SOC into crop nutrients and that unless SOC is replenished through the addition of organic matter (retaining crop residues, for example), SOC will be lost over time.

This study gives the first report comparing push-pull and conventional maize cropping systems in western Kenya in terms of biomass and SOC stocks, showing that push-pull stores more carbon in biomass and 15 cm topsoil. Because push-pull is a combination of reduced till and a perennial legume cover crop, the authors posit that it is different from and superior to no till/reduced till and conservation agriculture in terms of SOC distribution in the profile. For example, reasons why SOC stocks of no till and plow till are similar when the entire profile is examined are: the mixing and burying of crop residues in plow till, in contrast to ,no till which increases SOC in the layers below 30 cm; and the rooting habits under no till and plow till, the latter favoring deeper rooting than the former [6, 13]. This is crucial especially because farmers in western Kenya use tractors and oxen for land preparation, while push-pull is worked using a hand hoe to maintain the desmodium, a perennial legume cover crop with a tap root that can reach 0.6 to 1.2 m [68] even under grassland conditions (no till). Additionally, soils under perennials have been reported to have more SOC in their profile (up to 2 m) than soils under annual crops [13]. Contrary to no till, the inter-desmodium rows are tilled, offering a mix and burial of organic matter in the profile, adding to the organic matter derived from desmodium roots and translocation of organic matter from the soil surface to the deep layers following the tap root of desmodium (facilitated by percolating water). In light of this, this study suggests that the improvement in SOC observed in push-pull is not altered by the depth throughout the entire profile (compared to non-push-pull) due to the presence of desmodium and the tillage of inter-desmodium rows, and thus the SOC stock in the entire profile is greater in push-pull than in non-push-pull farms. Studies of the entire profile are recommended, to characterize the ability of push-pull to mitigate climate change through carbon sequestration relative to conventional maize-based cropping systems in the region.

Conclusions

Farms with push-pull store higher amounts of carbon in biomass and soils than farms without push-pull, due to the relatively higher level of crop intensification in push-pull farms and the lower level of soil disturbance in push-pull farms compared to non-push-pull. SOC concentration and stock increases with the length of time that push-pull is practiced on a farm, but this effect was site specific. Push-pull increases soil bulk density but in a range below critical values associated with compaction. Differences in soil conditions are responsible for variations in the amount of biomass and SOC found in the three sites. There was no relationship between biomass carbon and SOC because crop residues were removed. Adoption of push-pull offers the opportunity to store more carbon both above and below ground, in different climatic conditions. We did not assess emissions of greenhouse gases such as carbon dioxide, methane and nitrogen oxides from push-pull and non-push-pull farms, especially due to changes in wet or dry conditions and temperatures. Studies that take into account emission of these gases are recommended to fully understand the comparative ability of push-pull in mitigating climate change also through reducing emissions. In addition, long-term studies involving farm-specific SOC dynamics over time in the entire soil profile would shed more light on the contribution of push-pull technology to the mitigation of climate change through carbon sequestration. We recommend studies of the entire soil profile and greenhouse gas emissions to increase the knowledge of push-pull's potential for climate change mitigation.

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Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the International Centre for Insect Physiology and Ecology (icipe). Data are available from the authors at http://www.icipe.org with the permission of icipe management.

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