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Soil Carbon and Phosphorus after 40 Years of Contrasting Tillage and Straw Management in Dryland Wheat Production under Semi-Arid Temperate Climate

Nondumiso Zanele Sosibo [1,2,*], Pardon Muchaonyerwa [1], Ernest Dube [3] and Toi John Tsilo [4]

1 School of Agricultural, Earth and Environmental Sciences, Discipline of Soil Science, University of KwaZulu-Natal, Pietermaritzburg 3201, South Africa
2 Agricultural Research Council—Natural Resources and Engineering (Soil, Climate and Water), Pretoria 0001, South Africa
3 School of Natural Resource Management, Nelson Mandela University, George 6560, South Africa
4 Agricultural Research Council—Small Grain Institute, Bethlehem 9700, South Africa
* Correspondence: sosibon@arc.agric.za

Abstract: The effects of conservation strategies on soil organic carbon (SOC) and phosphorus (P) dynamics in dryland wheat under semi-arid temperate conditions are not well understood. This study quantified the effects of tillage and straw management on SOC concentrations and stocks and P fractions after 40 years of dryland wheat under a semi-arid temperate climate. The treatments were straw management (burned and not burned) combined with tillage methods (conventional tillage (CT), stubble mulch (SM), and no-tillage (NT)). Fertilizer nitrogen (N) and P were applied annually at 60 and 12.5 kg ha^{-1}, respectively. The soils were sampled from 0–50, 50–200, 200–400, 400–600, 600–800, and 800–1000 mm depths, and analyzed using standard methods. The concentration of SOC was not affected by tillage and straw management, except in 200–400 mm where it was higher where the straw was burned rather than retained. The total C stock (0–1000 mm) was higher under NT with straw burning, CT with no burning, and SM, than NT with straw retention and CT with burning. In the topsoil, NT had significantly ($p < 0.05$) higher Bray 1 P, NaOH II Pi, and residual P than SM and CT, while burning straw increased Bray 1 P and $NaHCO_3$ Pi concentrations. The findings imply that while the SOC concentration is not significantly affected by tillage, but is increased by burning in the subsoil only, the total C stock is improved by NT with burned straw, CT with straw retention, and SM, while the labile P fractions are increased by NT with burned straw, relative to CT with burned straw, in the semi-arid dryland wheat region.

Keywords: burned straw; carbon stock; no-till; phosphorus fractions; stubble mulching

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1. Introduction

Soils are the largest reservoir of carbon (C), and C sequestration in soils can help mitigate climate change [1]. Meanwhile, little is known about the magnitude of change in C stocks due to long-term soil conservation strategies in dry areas. According to Sapkota et al. [2], limited work has been done on quantifying the long-term tillage and straw management effects on soil parameters, especially C on marginal soils in dry areas, where there are challenges in generating adequate amounts of biomass. The soil organic C has various pools that differ in decomposability [3,4]. The recalcitrant or passive pool is organic C that is resistant to further biodegradation but is important in C sequestration [3,4]. The active pool is easily decomposable and is an important source of plant nutrients, especially phosphorus (P) [4]. In any given crop production system, the concentration and storage of C can be affected by the tillage intensity and frequency, crop residue management, fertilizer input, and interactions of the aforementioned factors [5,6]. No-tillage is known to reduce losses of sequestered C from tropical soils as it slows down the decomposition rate of soil organic matter (SOM) [7–9]. On the other hand, crop residues accumulate on the surface under no-tillage maintaining higher soil carbon stocks [10]. However, this may increase losses of crop residues to wind erosion on open plains, and consequently, increase C losses when compared to stubble mulched and ploughed systems.

The Eastern Free State of South Africa is a semi-arid temperate area, with dry winter months, summer rainfall, and a high wind erosion hazard [11–13]. In this region, the production of dryland wheat (*Triticum aestivum* L.) during the dry winter months is made possible through the appropriate timing of planting on plinthic soils that have high water tables and high moisture-storage efficiency. The average yields of this wheat that are produced under severely water-limited conditions are low at 2.58 Mg ha^{-1} [14]. To reduce the production costs of the dryland wheat, farmers in the region use a low input production system, which entails reduced fertilizer and pesticide inputs and at times straw burning for plant disease control. Dryland wheat production in the Free State was estimated at approximately 450,000 ha in 2005, contributing to nearly 50% of South Africa's domestic wheat requirements [15]. However, the production area has declined to under 100,000 ha at present [16]. Many farmers lost interest in dryland wheat production due to yield and profitability challenges [14].

Apart from frequent droughts, gradual nutrient depletion is a major threat to sustained dryland wheat production on plinthic soils that are low in soil organic carbon (SOC) and cation exchange capacity (CEC), and are highly susceptible to erosion. Soil acidity (including subsoil) also develops when plinthic soils are cultivated, resulting in aluminium (Al) toxicity and poor root growth. According to Fey [17], the surface horizons of plinthic soils that have low SOC and high iron oxides degrade easily under excessive tillage. Excessive tillage increases the susceptibility of soils to wind erosion, resulting in increased loss of particulate organic matter and other nutrient-rich sediments of the topsoil [12,13]. If nutrient losses from the soil are not abated, fertilizer costs could increase, thus reducing profitability. Suggested strategies for arresting soil degradation in wheat production systems include conservation agriculture (CA) practices, such as crop straw retention and no-tillage (NT) [18–20]. These practices are envisaged to improve the SOC, thus possibly countering the long-term nutrient depletion effects of low-fertilizer input farming as shown elsewhere [9,10,21,22]. However, for dryland wheat farmers who have adopted CA in the Free State, it can be challenging to retain crop residues (wheat straw) as surface mulch because the strong winds blow everything away. Thus, light tillage to incorporate crop residues into the surface soil (stubble mulching) immediately after harvest would be important for crop residue protection against wind erosion.

Phosphorus is the most important nutrient in optimizing wheat growth, grain yield, and quality after N, yet most soils under wheat production in the tropics are P fixing in nature, and deficient in P [23]. The retention of crop residues increases SOC, and potentially decreases the P adsorption capacity of soils through complexation of soluble Al, among other mechanisms [23,24]. Organic P sources favor the build-up of labile P pools at the expense of recalcitrant P when compared to inorganic P sources [25]. However, the magnitude of such effects is likely to be variable depending on the interactions of various factors such as residue type and quantity, tillage intensity, soil and climatic conditions, and the duration of the crop production system. Understanding the effects of CA options on SOC stocks and fractions of P in dryland wheat production systems thus would require long-term, multi-factorial trials.

The only long-term experiment for evaluating the effects of dryland wheat crop management strategies on the soil in semi-arid regions was established in 1979 at the Small Grain Institute (SGI) in South Africa. This trial was originally established to investigate the effects of tillage, crop residue (hereafter referred to as straw), fertilizer application, and weed management on the yield of continuous wheat. Measurements were done on the total SOC changes in the aforementioned trial after 10 [26], 20 [27], 30 [28], and 37 [29–31] years of trial inception. Based on a distillation of research findings that were produced since the trial's inception, it can be noted that in 1989, after 10 years of experimentation, Wiltshire and du Preez [32] showed that the soil N and C did not vary with tillage or straw management treatments although SOC in the trial was lower compared to natural pasture near the trial. In 1999, after 20 years, Du Preez et al. [26] investigated the same treatment effects and reported that the soil quality parameters had declined across all the treatments. After approximately 30 years of the trial, Loke et al. [28] reported that not burning wheat straw resulted in lower extractable P but higher total N, when compared to burning, and that no-tillage (NT) accumulated more SOC in the topsoil (0–50 mm) compared to other tillage practices while both NT and stubble mulching (SM) enhanced the total N, soil pH, and P availability [33], some of these results were in agreement with Motema et al. [30]. All these studies were done with treatments where fertilizer N was applied at 40 kg ha^{-1}, with none done with treatments that were fertilized at 60 kg N ha^{-1}, which could increase biomass input. However, no investigations have yet been done on the sustainability of the various production systems in terms of C stocks, including charcoal-associated C, which could be associated with straw burning.

Soil C and P fractions are pivotal in explaining soil productivity and the quality of SOM being generated by various cropping systems, including in the long-term wheat trial in South Africa. It was, therefore, important to determine the long-term interaction effects of tillage and straw management on SOC stocks, fractions of SOC and P as the conclusion of this long-term trial after 40 years in 2019 approached. The specific objective of this study was to determine the effects of tillage and straw management on SOC stocks and P fractions. It was hypothesized that long-term reduced tillage would significantly increase the SOC fractions, C stocks, and P fractions, with the magnitude of benefit being dependent on the straw management strategy.

2. Materials and Methods

2.1. Description of the Bethlehem Long-Term Trial and Design

The dryland wheat trial was established at the Agricultural Research Council-Small Grain Institute (SGI), near Bethlehem in the Free State Province of South Africa (28°9′ S, 28°17′ E). The area is semi-arid, and temperate with a mean annual rainfall of 743 mm and average monthly temperatures ranging from 7 °C to 20 °C [34]. Bethlehem is a summer rainfall region and dryland wheat is normally planted in the last week of June and harvested in January. The climatic data for the study site during the sampling period (2016–2017) is presented in Figures 1 and 2.

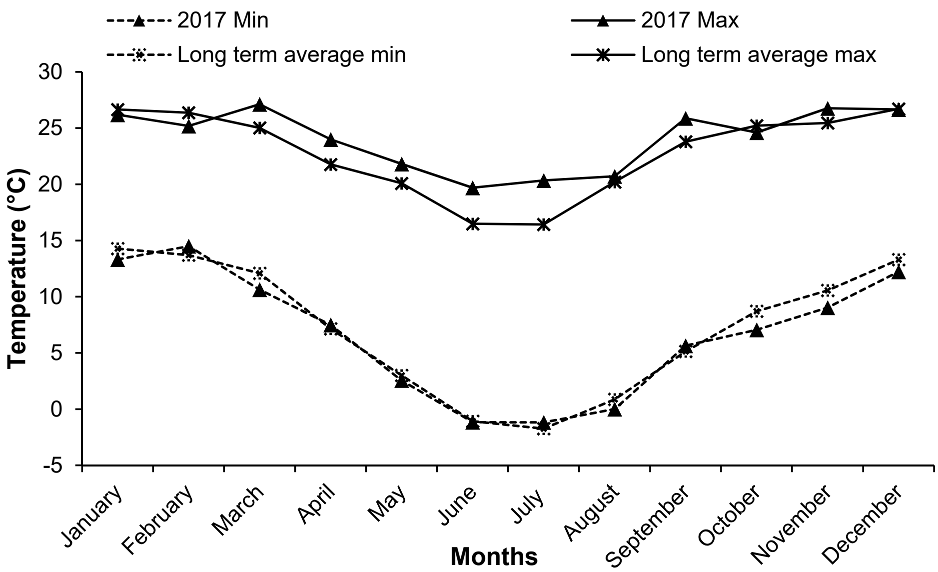

Figure 1. Temperature conditions at the Bethlehem long-term trial site. (source: Agricultural Research Council's agro-climate database; http://155.240.219.9/agromet/Login-Screen-php?btn-Login=CONTINUE, accessed on 20 March 2020).

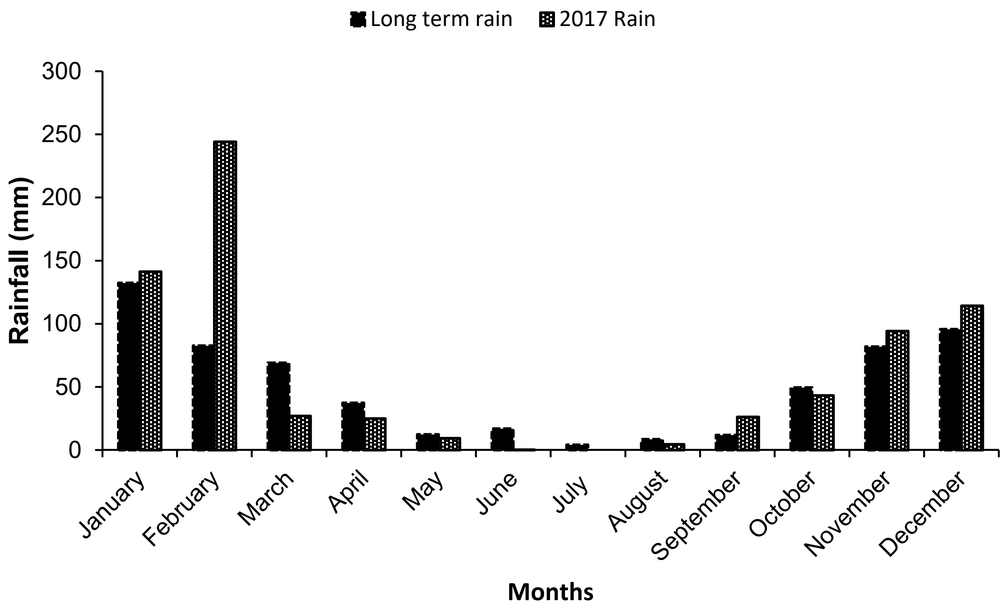

Figure 2. Rainfall conditions at the Bethlehem long-term trial site.

The soil at the trial site was classified as the Mafikeng family of the luvic Avalon soil form [35] and translated to an Acric Plinthosol [36]. Before the commencement of the trial, in 1979, the land was under conventional tillage (mouldboard plough) for at least 20 years [26]. The land surrounding the trial was a natural grassland, with inherent soil P deficiency (12.1 and 10.1 mg kg^{-1} Bray 1 extractable P in 0–50 and 50–200 mm depths, respectively), slight soil acidity (pH 6.0) and low SOC (7.8 and 6.6 g kg^{-1} in 0–50 and 50–200 mm depths, respectively).

The initial objective of the trial was to determine the effects of tillage, straw burning, and N fertilizer application rates on wheat grain yields on the Plinthic soil. These objectives were modified over time to make the trial that was relevant to the wheat producers in the region. At the beginning of this trial, there were two wheat straw management treatments (burned and not burned); three tillage methods (moldboard ploughing, stubble mulch tillage, and no-tillage); two weed control methods (mechanical and chemical); and three N fertilization levels (20, 30, and 40 kg N ha^{-1}) in a factorial arrangement. A computerized Gaspardo (Northmec, South Africa) planter was used to simultaneously apply seed and fertilizer in all the treatments at 200 mm below the soil surface. Various N fertilization levels and a constant amount of P (12.5 kg P ha^{-1}yr^{-1}) were added from Limestone Ammonium Nitrate (28% N) and Single Superphosphate (10.5% P) fertilizers, respectively. The trial was a randomized complete block (RCBD) design on a 2–3% north-facing slope, with 36 treatments and 3 replicates. A hard red winter wheat cultivar *Betta* was planted. In 2002, *Betta* was replaced with a new improved cultivar *Elands*. At the same time, the N fertilizer rate was also increased in synchrony with the higher nutrient requirements of the newly introduced *Elands* cultivar compared to *Betta*. The original 30 and 40 kg N ha^{-1} were replaced with 40 and 60 kg N ha^{-1}, respectively. Each plot was 6 × 30 m with a separation distance of 3 m between the plots. An inter-row spacing of 450 mm was used in all the plots. The intra-row spacing was 30 mm to achieve a seed rate of 74 m^{-2}. Over the years, wheat was consistently planted every year during the last week of June. This planting date was selected to optimize the wheat yield potential for this specific environment. After harvesting the grain, the wheat straw was either burned or retained. In the stubble mulched treatment, a 50 mm wide chisel plough was used to till the soil without much disturbance to the surface mulch. In the ploughed treatment (conventional tillage), wheat ashes, char, or unburned straw were incorporated into the soil using a two-way offset disc up to 150 mm depth. In February of each year, a mouldboard plough further incorporated wheat ashes, char, or wheat straw up to 250 mm depth in the ploughed treatment. The ploughed treatment is referred to as conventional tillage in this paper. For the conventional tillage and stubble mulch treatments, a tine tiller was used to control weeds in March of every year before planting. Additionally, herbicides [glyphosate (N-phosphonomethyl glycine) or paraquat (N, N′-dimethyl-4, 4′-bipyridinium dichloride)] were used to control weeds. The herbicides were alternated to avoid the development of herbicide resistance. The application rate that was used for each herbicide was determined based on the availability and prevalence of weeds.

2.2. Soil Sampling and Analyses

For this study, soil samples were collected from the 0–50, 50–200, 200–400, 400–600, 600–800, and 800–1000 mm layers in the 3 tillage practices [conventional tillage (CT), stubble mulch (SM), and no-tillage (NT)] and 2 straw management strategies (burned and not burned) in June 2016, just before wheat planting in the plots with 60 kg N ha^{-1}. A total of 18 plots were thus sampled. Four random samples that were collected from each plot using a graduated auger and bulked to form a composite sample per soil layer yielding a total of six samples per plot. In total, 108 samples were collected from the selected plots. Likewise, undisturbed soil cores were collected using a soil core sampler for bulk density measurement. The bulk density was calculated based on the mass oven dry soil and the volume of undisturbed cores per soil layer. The samples for other analyses were air-dried after visible debris was removed, and milled (<2 mm). The organic C was analyzed using the Walkley–Black method [37]. Bulk density data were used to calculate C stocks and are, therefore, not presented in this paper. The soil C stock (t ha^{-1}) for each layer was calculated using Equation (1) [38,39].

$$\text{C stock}\left(\text{t ha}^{-1}\right) = \text{SOC} \times \text{BD} \times \text{layer depth} \times 10,000 \times 0.001 \quad (1)$$

where SOC is the content of soil C (g kg^{-1}), BD is the bulk density (kg m^{-3}) of the sampled layer, layer depth was the soil depth (m), 10,000 is the conversion factor from m^{-2} to ha^{-1}, and 0.001 is the conversion factor for kg to tons. The total SOC stock in the top 1000 mm was calculated as the sum of SOC stocks of all the soil layers.

2.3. Soil Carbon Fractions

Macro- and micro-particulate organic carbon (POC) fractions were determined following the procedure by Cambardella and Elliot [40] for soils that were sampled from 0–1000 mm layers. Three sets of each air-dried soil sample (50 g) were suspended in 100 mL of a 5 g L^{-1} sodium hexametaphosphate solution (Calgon) in a tightly sealed bottle. The mixture was shaken on an end-to-end shaker for one hour and poured over a set of 250 and 50 µm sieves. The sieves with soil were then rinsed with distilled water until the water was clear. The soil in the sieves was then back-washed into glass beakers (50–250 and >250 µm POC) for each sample. The samples were dried at 60 °C for 24 h, weighed, milled, and analyzed for organic C using the Walkley–Black method, for the two POC fractions, namely: fine POC ($POC_{50–250}$), hereafter referred to as micro POC, and coarse POC ($POC_{>250–2000}$), hereafter referred to as macro POC. Non-particulate organic carbon (non-POC), hereafter referred to as mineral-associated C, was calculated as the difference between the SOC and total POC (macro POC + micro POC).

Charcoal-associated C was analyzed using a method by Kurth et al. [41], whereby three sets of each dry soil sample (1 g) were digested with 20 mL of 30% H_2O_2 and 10 mL of 1 M HNO_3 in the Erlenmeyer flasks at 100 °C for 16 h. The samples were occasionally removed from the heating plate and swirled to observe for effervescence at 30 min intervals. After 16 h, the samples were filtered through Whatman number 1 filter paper, dried, and finely ground with a mortar and pestle. The total C that remained after digestion (charcoal C) was analyzed using a Leco TruMac CNS/NS analyzer (TruMaC CNS/NS, St. Joseph, MI, USA).

2.4. Soil pH and Phosphorus Fractions

The samples were also analyzed for pH (1:5 soil to 1 M KCl suspension) and plant-available P using the molybdenum blue method [42] after extraction using the Bray 1 method. The fractions of soil P were sequentially extracted following the Hedley et al. [43] method, as modified by Chen et al. [44]. The procedure utilizes extracting reagents of varying ionic strengths and is capable of breaking relevant bonds within the soil colloids, thus solubilising occluded or mineral-bound P into the soil solution. This method determined the inorganic P (Pi) from direct analysis of the extract that was filtered after 16 h of agitation. Some of the filtered extracts following alkaline ($NaHCO_3$ and NaOH) extractants were digested with nitric acid/perchloric acid (HNO_3 + $HClO_4$) mixture to determine the total P (Pt). The organic P (Po) was calculated as the difference between Pt and Pi. A total of three sets of 0.5 g of air-dried soil per sample were initially suspended with 30 mL of 1M NH_4Cl followed, sequentially, by 30 mL of 0.5M $NaHCO_3$, 30 mL 0.1M NaOH I, 30 mL 1M HCl, and 30 mL of 0.1M NaOH II in a test tube. After all the extractions, the remaining soil was also subjected to perchloric (HNO_3 + $HClO_4$) digestion to determine the residual P. After adding each extractant, the mixture was agitated for 16 h on an end to end shaker, centrifuged, filtered, and the extract was analyzed colorimetrically for P using the Seal AA3 HR Phosphate XY-2 auto analyzer (Seal Analytical GmbH, Norderstedt, Germany), which uses molybdenum/ascorbic acid procedure [42] for the fractions NH_4Cl Pi, $NaHCO_3$ Pi, $NaHCO_3$ Pt, NaOH I Pi, NaOH I Pt, HCl Pi, NaOH II Pi, NaOH II Pt, and residual P. The above-mentioned P fractions can be clustered into labile (NH_4Cl Pi, $NaHCO_3$ Pi, $NaHCO_3$ Po), moderately labile (NaOH Pi, NaOH Po), and non-labile (HCl Pi and residual P) pools [45]. Ammonium chloride extractable-P and organic P fractions were not detectable and were, therefore, not reported in this paper.

2.5. Data Analyses

The data were subjected to a general analysis of variance, with tillage and straw management as independent variables and all the soil parameters as dependent variables using Genstat 18th edition. When the null hypothesis (H_o) was rejected at the 95% confidence limit, the means were separated using the Tukey test. The strength and direction of relationships between the labile soil carbon and phosphorus fractions that were significantly affected by treatments in the top 0–50 mm depth were tested using a two-sided correlation between Peason's correlation *r* coefficients and 0 at the 95% confidence limit.

3. Results

3.1. Soil Organic Carbon Fractions and Stocks

The tillage × straw management interaction effects on SOC and its fractions were not significant at all depths except for micro POC in the 0–50 mm soil layer ($p < 0.05$). The main effects of tillage and straw management did not significantly affect the SOC in the top 1000 mm (Table 1), except that the concentration was significantly higher where the straw was burned (9.67 ± 0.94 g kg^{-1}) than not burned (5.76 ± 0.94 g kg^{-1}) in the 200–400 mm soil layer and SM (8.01 ± 0.82 g kg^{-1}) had significantly higher SOC than NT (3.21 ± 0.82 g kg^{-1}) and CT (2.22 ± 0.82 g kg^{-1}) in the 600–800 mm soil layer (Table 1).

The macro POC was higher under NT (0.67 ± 0.05 g kg^{-1}) and SM (0.63 ± 0.05 g kg^{-1}) than under CT (0.30 ± 0.05 g kg^{-1}) in the 0–50 mm, while in the 50–200 mm, the concentration was higher under SM (0.33 ± 0.06 g kg^{-1}) and CT (0.30 ± 0.06 g kg^{-1}) than under the NT (0.13 ± 0.06 g kg^{-1}) treatments. In the 200–400 mm depth, the macro POC was not significantly affected by tillage and straw management. Where straw was burned, the NT and SM resulted in higher micro POC compared to CT (Figure 3), while the tillage did not affect the concentration where straw was not burned (Figure 3) in the top 50 mm.

Table 1. The effect of tillage and straw management on the soil organic carbon in the 0–1000 mm layers.

Factor	Soil Organic C (g kg^{-1})					
	0–50	50–200	200–400	400–600	600–800	800–1000
Tillage practice						
No-tillage	9.10	10.2	7.14	4.79	3.21 [b]	2.90
Stubble mulch	11.5	10.9	8.88	6.55	8.01 [a]	8.00
Conventional tillage	9.10	7.50	7.13	7.72	2.22 [b]	4.70
LSD	7.30	5.98	3.62	4.90	2.60	5.90
Straw management						
Burned	11.3	10.9	9.67 [a]	6.11	3.64	4.10
Not burned	8.40	8.30	5.76 [b]	6.60	5.32	6.30
LSD	5.96	4.88	2.96	4.01	2.12	4.82
***p*-value**						
Tillage	0.700	0.442	0.486	0.438	0.001	0.205
Burning	0.307	0.260	0.015	0.788	0.107	0.322
Tillage × Burning	0.700	0.050	0.901	0.170	0.053	0.196

Means with different letters ([a],[b]) in a column for each factor indicate significant differences at $p < 0.05$ according to the Tukey multiple comparison test, while those means without letters ([a],[b]) in a column for each factor indicate no significant differences. LSD, the least significant difference at a 95% confidence limit. The grassland adjacent to the experiment had 7.80 and 6.60 g C kg^{-1} in the 0–50 and 50–200 mm depths, respectively.

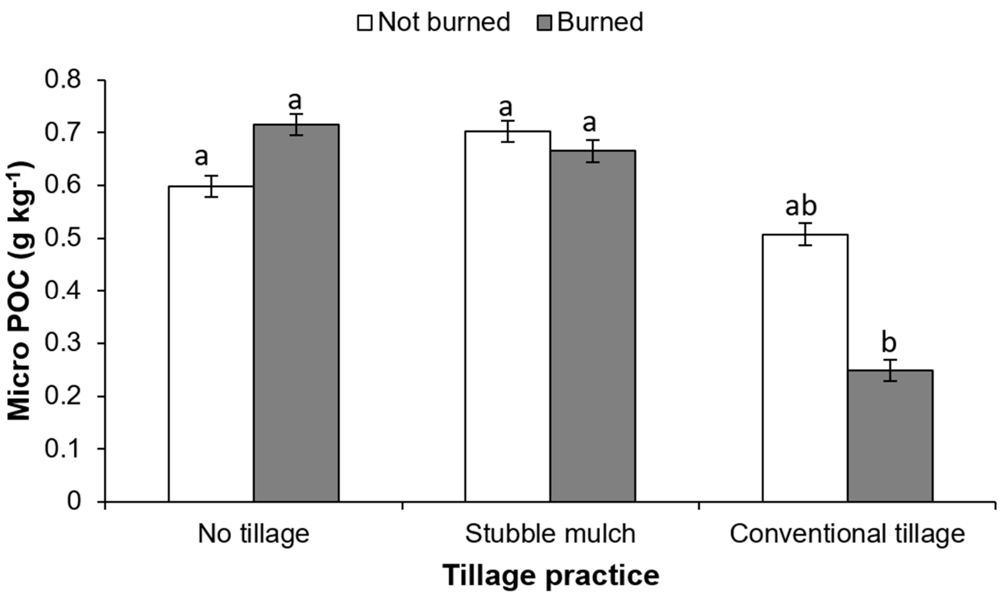

Figure 3. The interaction effect of tillage × straw management on micro POC (g kg^{-1}) in the 0–50 mm soil layer. Error bars represent the standard errors of the mean and different letters (a,b) in the bars represent significant differences at $p < 0.05$ according to Tukey's multiple comparison test.

In the 50–200 mm, micro POC was not significantly affected by tillage and straw management ($p > 0.05$), while in the 200–400 mm, the concentration was higher ($p < 0.05$) under SM (0.35 ± 0.04 g kg^{-1}) and lower under NT (0.24 ± 0.04 g kg^{-1}) than CT (0.30 ± 0.04 g kg^{-1}). Mineral-associated C was not significantly affected by tillage and straw management ($p > 0.05$) in the top 200 mm (Table 2), while in the 200–400 mm straw burning increased the mineral-associated C (9.20 ± 1.30 g kg^{-1}) than when not burned (5.4 ± 1.30 g kg^{-1}). Charcoal C was not significantly affected by tillage and straw management in the top 400 mm (Table 2).

Table 2. The effect of tillage and straw management on carbon that was associated with macro-particulate organic matter, minerals, and charcoal (g kg^{-1}) in the 0–50 and 50–200 mm layers.

Factor	Macro-POC		Mineral-Associate C		Charcoal C	
	0–50	50–200	0–50	50–200	0–50	50–200
Tillage practice						
No-tillage	0.67 [a]	0.10 [b]	7.70	9.50	1.20	0.90
Stubble mulch	0.63 [a]	0.30 [a]	10.2	10.0	1.10	1.20
Conventional tillage	0.30 [b]	0.30 [a]	8.40	6.90	1.50	1.00
LSD	0.11	0.13	7.28	5.86	0.41	0.67
Straw management						
Burned	0.50	0.30	10.2	10.1	1.40	1.00
Not burned	0.50	0.20	7.30	7.60	1.10	1.10
LSD	0.09	0.11	5.94	4.79	0.34	0.54
***p*-value**						
Tillage	<0.001	0.026	0.745	0.461	0.193	0.733
Burning	0.985	0.294	0.296	0.274	0.120	0.650
Tillage × Burning	0.978	0.606	0.679	0.050	0.695	0.578

Means without letters ([a],[b]) in a column for each factor indicate no significant differences at $p < 0.05$ according to the Tukey multiple comparison test. LSD, the least significant difference at a 95% confidence limit.

An analysis of soil C stock per soil layer showed that the tillage × straw management interaction effect was significant in the 50–200 mm soil layer only, where the stock was higher under NT with burned straw, while SM had higher C stocks than both NT and CT in the 600–800 mm soil layer (Table 3). Straw-burning increased the soil C stock in the 200–400 mm soil layer (Table 3). The soil C stocks in the 0–50, 400–600, and 800–1000 mm layers were not significantly affected by tillage or straw management (Table 3).

Table 3. Tillage and straw management effects on the soil carbon stocks (t ha^{-1}) at different soil layers (mm).

Factor	Soil Carbon Stocks (t ha^{-1})					
	0–50	50–200	200–400	400–600	600–800	800–1000
Tillage practice						
No-tillage	7.13	26.8	18.7	13.1	9.67 [b]	9.61
Stubble mulch	8.89	25.0	24.8	18.5	26.4 [a]	27.1
Conventional tillage	7.07	17.0	19.3	24.4	8.07 [b]	18.3
LSD	5.67	13.5	10.8	15.8	10.2	21.1
Straw management						
Burned	8.88	27.2	26.1 [a]	17.4	11.4	12.6
Not burned	6.51	18.6	15.8 [b]	20.0	18.0	24.0
LSD	4.63	11.1	8.79	12.9	8.30	17.3
***p*-value**						
Tillage	0.73	0.28	0.41	0.32	0.004	0.23
Burning	0.28	0.12	0.03	0.66	0.103	0.17
Tillage × Burning	0.67	0.02	0.74	0.15	0.07	0.16

Means with different letters ([a],[b]) in a column for each factor indicate significant differences at $p < 0.05$ according to the Tukey multiple comparison tests, while those means without letters ([a],[b]) in a column for each factor indicate no significant differences. LSD, the least significant difference at a 95% confidence limit.

Tillage × straw management interaction effects on the total soil C stock (0–1000 mm) were significant ($p < 0.05$). The total soil C stock was higher under CT and SM with no burning and NT and SM with straw burning than NT with no burning and CT with straw burning (Figure 4).

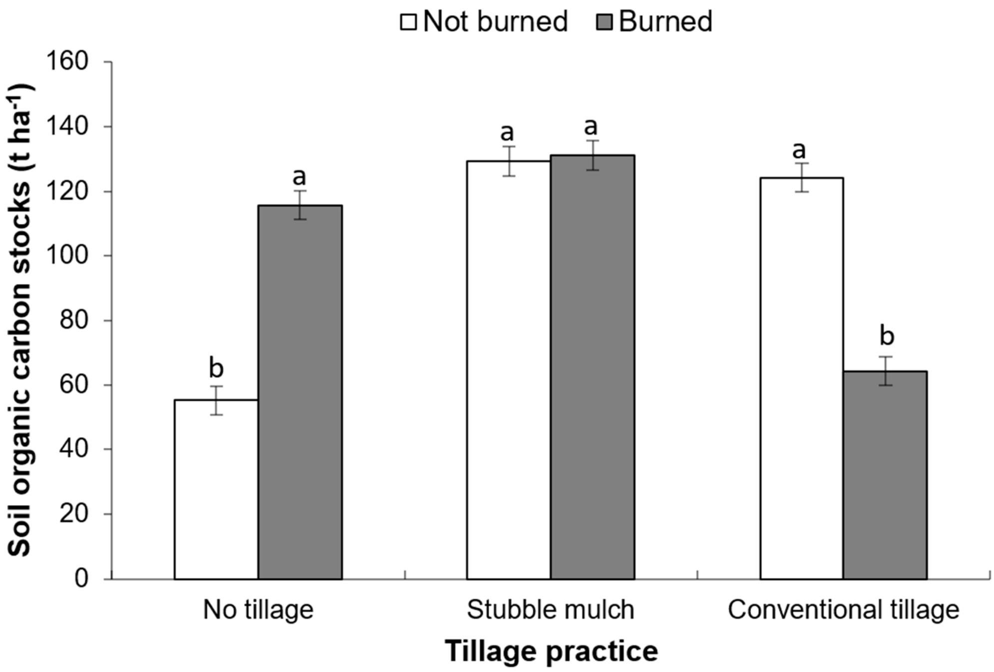

Figure 4. The interaction effect of tillage and wheat straw management on the total carbon stocks (0–1000 mm). Error bars represent the standard errors of the mean and different letters (a,b) in the bars represent significant differences at $p < 0.05$ according to Tukey's multiple comparison test.

3.2. Soil pH and Phosphorus Fractions

The soil pH was higher where the straw was burned only in the top 200 mm (Table 4), while tillage did not affect the soil pH (Table 4). The Bray 1 P concentration was higher under NT than the other two tillage practices (Table 4) and burning straw increased the concentration compared to retention in the top 50 mm (Table 4).

Table 4. The effects of tillage and straw management on soil pH and Bray extractable phosphorus in the 0–50 and 50–200 mm layers.

Factor	Soil pH		Available Phosphorus	
	0–50	**50–200**	**0–50**	**50–200**
Tillage practice				
No-tillage	4.94	4.95	40.3 [a]	31.5
Stubble mulch	4.84	4.95	29.9 [b]	25.4
Conventional tillage	5.10	5.01	23.1 [b]	21.6
LSD	0.289	0.214	8.13	8.38
Straw management				
Burned	5.09 [a]	5.08 [a]	35.4 [a]	27.9
Not burned	4.83 [b]	4.86 [b]	26.8 [b]	24.5
LSD	0.236	0.175	6.64	6.84
***p*-value**				
Tillage	0.165	0.743	0.003	0.069
Burning	0.032	0.023	0.017	0.301
Tillage × Burning	0.273	0.174	0.746	0.612

Means with different letters ([a],[b]) in a column for each factor indicate significant differences at $p < 0.05$ according to the Tukey multiple comparison test, while those means without letters ([a],[b]) in a column for each factor indicate no significant differences. LSD, the least significant difference at a 95% confidence limit. The grassland adjacent to the experiment had a pH of 6.0 at both the 0–50 and 50–200 mm depths, respectively, while the Bray extractable phosphorus was 12.1 and 10.1 mg kg^{-1} in the 0–50 and 50–200 mm depths, respectively.

In the 50–200 and 200–400 mm soil layers, Bray 1 P was not significantly affected by tillage or straw management. The concentration of $NaHCO_3$ Pi was increased by burning straw under CT compared to not burning and all other treatments in the top 50 mm (Figure 5a).

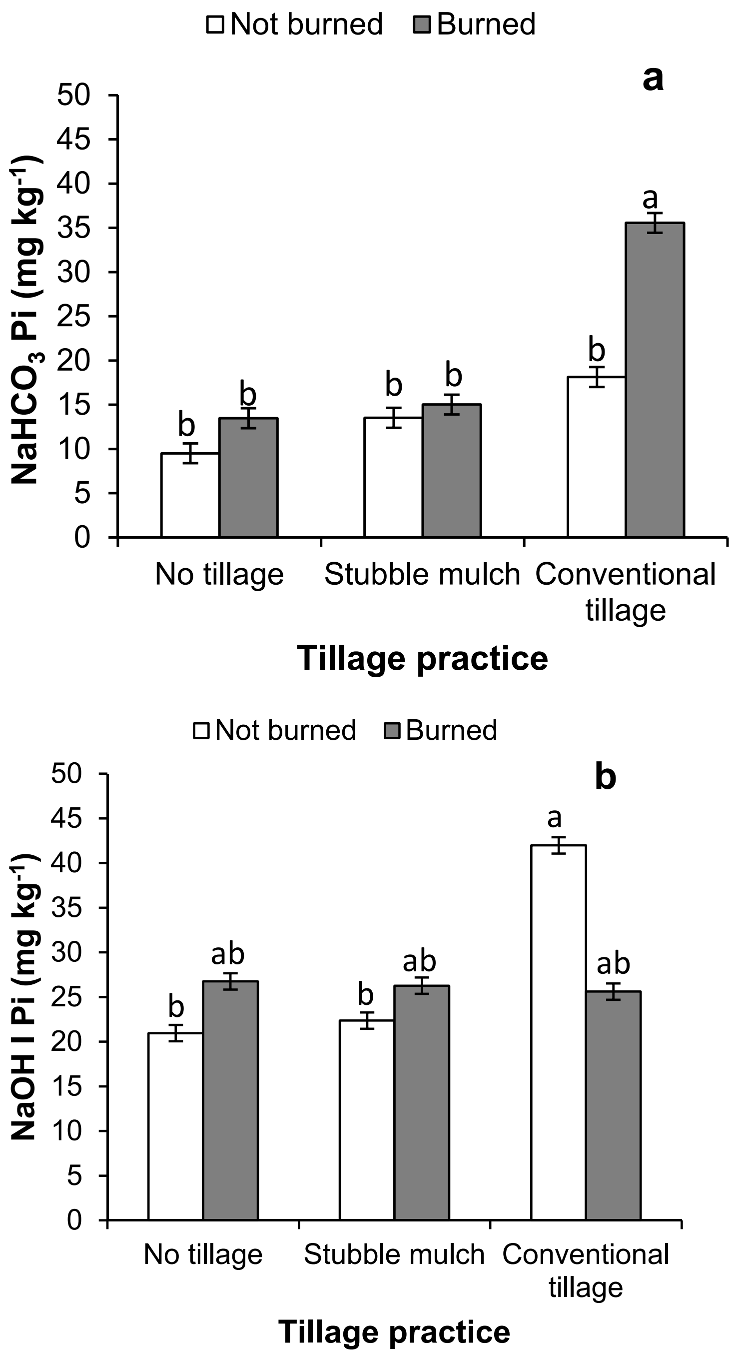

Figure 5. The interaction effect of tillage × straw management on (**a**) $NaHCO_3$ Pi, (**b**) NaOH I Pi, and fractions (mg kg^{-1}) in the 0–50 mm soil layer. The error bars represent the standard errors of the mean and different letters (a,b) in the bars represent significant differences at $p < 0.05$ according to Tukey's multiple comparison test.

The CT (25.7 ± 2.63 mg kg^{-1}) treatment had higher $NaHCO_3$ Pi than SM (14.0 ± 2.63 mg kg^{-1}) and NT (9.2 ± 2.63 mg kg^{-1}) in the 50–200 (Table 5). The trend of $NaHCO_3$ was similar in the 200–400 mm but with lower concentrations (Table 5). Burning (19.7 ± 2.15 mg kg^{-1})

wheat straw increased the $NaHCO_3$ Pi compared to not burning (12.9 ± 2.15 mg kg^{-1}) in the 50–200 mm with no effect in the 200–400 mm depth.

Table 5. The effects of tillage and straw management on soil $NaHCO_3$ Pi and NaOH I Pi (mg kg^{-1}) in the 50–200 and 200–400 mm layers.

Factor	$NaHCO_3$ Pi		NaOH I Pi	
	50–200	200–400	50–200	200–400
Tillage practice				
No-tillage	9.2 ^{b}	6.0 ^{b}	29.1	30.7
Stubble mulch	14.0 ^{b}	8.10 ^{a,b}	27.8	26.9
Conventional tillage	25.7 ^{a}	15.5 ^{a}	28.0	36.5
LSD	5.86	6.76	14.86	15.73
Straw management				
Burned	19.7 ^{a}	12.0	24.0	28.7
Not burned	12.9 ^{b}	7.8	32.6	34.0
LSD	4.79	5.52	12.13	12.84
***p*-value**				
Tillage	<0.001	0.025	0.977	0.425
Burning	0.010	0.124	0.145	0.377
Tillage × Burning	0.120	0.391	0.429	0.933

Means with different letters (^{a},^{b}) in a column for each factor indicate significant differences at $p < 0.05$ according to the Tukey multiple comparison test, while those means without letters (^{a},^{b}) in a column for each factor indicate no significant differences. LSD, the least significant difference at a 95% confidence limit.

Where straw was not burned, the NaOH I Pi was higher under CT than the other tillage systems (Figure 5b) in the top 50 mm. The NaOH II Pi was higher under SM (9.67 ± 0.58 mg kg^{-1}) compared to both NT (7.91 ± 0.58 mg kg^{-1}) and CT (8.02 ± 0.58 mg kg^{-1}) in the top 50 mm. The concentrations of NaOH I Pi and NaOH II Pi in the 50–200 and 200–400 mm depths were not affected by tillage and straw management. The HCl Pi and residual P were not significantly affected by tillage and straw management ($p > 0.05$) in all the depths that were measured (top 400 mm), except that the residual P was higher under NT (6.47 ± 0.41 mg kg^{-1}) compared to SM (5.26 ± 0.41 mg kg^{-1}) in the 50–200 mm depth.

3.3. Correlation of Labile Carbon and Phosphorus Fractions

The soil organic carbon was positively correlated with mineral-associated C (r = 0.99) while macro POC was positively correlated with Bray 1 extractable P (r = 0.73) and negatively correlated with $NaHCO_3$ Pi (r = −0.66) (Table 6). The micro POC was negatively correlated with the mineral-associated C (r = −0.50) and $NaHCO_3$ Pi (r = −0.70). Sodium hydroxide I Pi was not significantly correlated with labile carbon and P fractions (Table 6).

Table 6. Correlations of labile soil carbon and phosphorus fractions in the 0–50 mm soil layer.

Variables	1	2	3	4	5	6	7
1 Organic C	-						
2 Macro POC	0.053 ^{ns}	-					
3 Micro POC	−0.412 ^{ns}	0.703 **	-				
4 Mineral-associated C	0.994 ***	−0.051 ^{ns}	−0.503 *	-			
5 Bray 1 extractable P	0.159 ^{ns}	0.727 ***	0.434 ^{ns}	0.085 ^{ns}	-		
6 $NaHCO_3$ Pi	0.366 ^{ns}	−0.661 **	−0.696 **	0.437 ^{ns}	−0.218 ^{ns}	-	
7 NaOH I Pi	−0.170 ^{ns}	−0.471 ^{ns}	−0.194 ^{ns}	−0.126 ^{ns}	−0.360 ^{ns}	0.0368 ^{ns}	-

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, no significant differences; C, carbon; P, phosphorus; Pi, inorganic phosphorus; POC, particulate organic carbon.

4. Discussion

Conventional farming practices, based on extensive tillage of the soil are reported to be the major cause of land degradation and SOC loss in the Eastern Highveld of South Africa [46]. In the current study, we hypothesised that 40 years of reduced tillage practices (NT and SM) would reduce the loss of C and soil fertility that is associated with conventional tillage practices, with the magnitude of benefit being dependent on the straw management strategy.

The lack of effects of tillage and straw management on soil organic C could be a result of low biomass input from the dryland wheat under semi-arid conditions. The higher C concentration in the 200–400 mm soil layer of the burned plots than in the non-burned plots (Table 1), suggests that straw burning increases C sequestration at deeper soil layers in dryland wheat production systems under semi-arid conditions. This observation could be a result of higher root biomass production under higher pH and labile P (Bray 1 P and $NaHCO_3$ Pi), which are readily available. The reduction of POC in the top 200 mm by CT especially when straw was burned, was explained by excessive soil disturbance, which resulted in the degradation of the labile C fraction in the topsoil. The higher macro POC under NT followed by SM suggested this labile form of soil C accumulated at the surface with less soil disturbance, while CT allowed the burial of material into the soil [47]. The accumulation of POC under NT is in agreement with the findings by dos Reis Ferreira et al. [48]. The increase in this labile form of C under NT and SM, suggests that these tillage treatments encouraged nutrient cycling including P, and these findings are supported by the significant correlations between the labile C and P fractions. The lack of differences in the charcoal C as a result of tillage or straw burning agrees with Rumpel [49], who reported no significant effects of stubble burning in the aromatic and recalcitrant black carbon after 30 years of experimentation in France. The lack of differences was attributed to the low intensity of fire that is used for straw burning [50], which could have resulted in little production of recalcitrant black carbon on the burned treatments. The accumulation of soil organic C and its labile fractions in parts of the soil profile may have affected the total C stocks (0–1000 mm depth).

An unexpected, but significant result from this study was that after nearly 40 years of wheat mono-cropping, the total soil C stocks (0–1000 mm) were higher under CT and SM with no burning as well as NT and SM with straw burning, than NT with no burning or CT with straw burning. A possible explanation for the lower C stocks overall on the NT with no burning treatment is that this treatment had significant losses of C in the form of straw that was blown away by the wind [12]. Strong winds are a major production challenge in the wheat production region around Bethlehem, South Africa [12,13]. The NT without straw burning and CT with burned straw accumulated very little C stocks in t ha^{-1} yr^{-1}, as outlined above due to straw being blown away by the wind under NT as well as a higher aeration rate under CT. As a result, the overall C stock under these management practices was lower compared to NT with straw burning, CT without straw burning, as well as SM. Stubble mulching, which refers to the slight incorporation of the straw into the soil immediately after harvesting grain was probably beneficial for protecting the straw against wind erosion [8,10], hence the higher C stocks on SM treatments with no burning. This also applies to CT without burning, where more biomass that was incorporated in the soil is protected from wind erosion loss. Burning of straw reduced biomass that was incorporated under CT, and with increased aeration of the soil due to the tillage effect, this could have lowered the total soil C stocks on treatments where CT was combined with burning. The higher C stock under NT with burned straw could be explained by the higher SOC in the subsoil, which should have been facilitated by greater available P under less acidic conditions. This reasoning also applies to SM with burned straw.

The aerobic combustion of straw produces alkaline ash, which may be the reason for increased mean pH in the burned systems at both 0–50 and 50–200 mm soil layers. Carbonates that are released after burning increase the soil pH [51,52]. During this process, organic P is converted to inorganic P, making P more available on the burned treatments [53]. Higher P in the surface soil under NT and SM could be explained by the surface accumulation of OM under NT and SM practices. Since the burning of straw increases soil pH compared to no-burning, burning would also increase the availability of some nutrients, particularly P. The higher soil pH and available P where straw was burned in the NT treatment could also have provided more favorable conditions for root growth. The organic matter from roots and their exudates could have significantly contributed to mineral-associated C, which is supported by the strong correlation between the soil organic carbon and the mineral-associated carbon.

The higher Bray 1 P under NT followed by SM suggested that available P accumulated at the surface with less soil disturbance, while CT allowed the burial of material into the soil [47]. Contrary to other parameters, $NaHCO_3$ P (labile) was higher under the burned CT treatments while burning wheat straw increased Al-associated NaOH I Pi, suggesting that straw burning increased the pH and made P more available by reducing P that was bound to Al. This view was supported by higher soil pH where straw was burned. The higher $NaHCO_3$ Pi in the burned CT treatment was in agreement with the findings by Romanya et al. [53], who also reported higher labile P on the burned treatment.

When compared with the grassland soil nearby, all the treatments at least doubled the concentration of available P (Table 3), under the annual input of 12.5 kg P ha^{-1} $year^{-1}$ and 60 kg N ha^{-1}. However, only the NT practices had adequate available P (40 mg kg^{-1}) in the surface soil (Table 3). This is supported by the NaOH II Pi (physically protected P), which was higher under NT and SM. The findings of the current study on $NaHCO_3$ Pi were comparable to Ncoyi et al. [31], who reported 5.07 mg kg^{-1} higher under SM and NT practices than CT, in the plots that were fertilized with 40 kg N ha^{-1}. This suggests that NT is a more sustainable approach for managing P depletion and reducing external P fertilizer requirements. It should be noted that where the soil was less disturbed, nutrient removal in grain was limited as shown by relatively lower yields that were obtained under NT compared to CT [29]. Low nutrient removal rates probably explain why the concentration of available P in the soil remained adequate for dryland wheat after 40 years of continuous cropping, under NT [54]. The lack of tillage effects on HCl Pi in the current study was contrary to those of Ncoyi et al. [31], who reported a 2.16 mg kg^{-1} higher concentration under SM and NT practices than CT, in the plots that were fertilized with 40 kg N ha^{-1}. The results of P fractions in the current study were generally higher than those that were reported by Ncoyi et al. [31] due to the higher biomass production at 60 kg N ha^{-1} than at 40 kg N ha^{-1}.

5. Conclusions

The soil organic C concentration is only increased by straw burning in the subsoil, with no tillage effects while the total soil C stocks (0–1000 mm) is increased by SM, NT with burned straw, as well as CT with no burning, while NT with no burning has no effects when compared to CT with burned straw, after 40 years of dryland wheat under semi-arid conditions. Long-term NT improves the POC, available P (Bray 1 P, $NaHCO_3$ Pi), and NaOH I Pi concentrations more than SM and CT in the top soil regardless of the straw management strategy. Straw burning improves the soil pH and available P concentrations within the 0–200 mm soil layer. The SM is recommended over NT with retained straw and CT with burned straw for increasing soil C storage, while NT with burned straw would be preferred for improving both soil C storage and available P in dryland wheat systems under windy conditions of the temperate region. Although the burning of straw appears beneficial in improving the soil pH and P availability across all the treatments, the harmful effects of straw burning on C emissions cannot be overlooked. Further studies are recommended to understand the effects of SM on soil properties, where the dryland wheat is rotated with legumes such as soyabean, to improve biomass input and nutrient cycling towards refining conservation agriculture for the dryland wheat production systems.

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