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Influence of crop residue management on soil organic carbon and productivity of wheat

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Abstract

Wheat straw either returns to the soil that produced it or leaves the field entirely, and the trend across much of Botswana's wheat belt has been decisively toward the latter, as baling for livestock feed and fuel competes directly with any soil carbon benefit residue retention might offer. A four-year field research tracked three residue management levels, full removal (baling), partial retention (30-50%, standing stubble with light incorporation), and full retention (100%, standing stubble left to decompose in place), for their cumulative effect on soil organic carbon and wheat productivity. By year four, soil organic carbon under full retention had risen from a baseline of 0.44% to 0.68%, while removal plots declined to 0.33% over the same period, a divergence of 0.35 percentage points between the two extremes after four years of consistent management. Wheat grain yield tracked this soil carbon trajectory with a roughly one-year lag, showing no significant yield difference among the three treatments in year one, but a widening advantage for full retention by year four, reaching 12.8% higher yield than removal plots. Soil bulk density decreased and water infiltration rate increased progressively under full retention, consistent with the structural benefits of accumulating organic matter. These findings support residue retention as a productivity-positive practice once given sufficient time to manifest, arguing against baling decisions driven purely by short-term residue market value without accounting for the multi-year soil carbon and yield cost that removal appears to carry.

Keywords: Wheat, crop residue management, soil organic carbon, residue retention, grain yield, soil bulk density, water infiltration, carbon sequestration, conservation agriculture, long-term trial

Introduction

A bale of wheat straw has an immediate, tangible market value as livestock feed or fuel, while the soil carbon benefit of leaving that same straw in the field accrues slowly and offers no cash payment at harvest time, a mismatch in timing and visibility that likely explains why residue removal remains widespread across much of Botswana's wheat-growing areas despite decades of soil science research pointing toward residue retention's longer-run benefits ^[1, 2]. Soil organic carbon responds to residue management on a timescale measured in years rather than seasons, since the annual carbon input from a single season's residue is small relative to the total soil organic carbon pool, meaning short-duration trials, common in much of the published residue management literature, may underestimate both the eventual magnitude of soil carbon change and its downstream effect on productivity ^[3, 4]. Trials extending four years or more are comparatively rare in semi-arid wheat systems specifically, leaving a gap in how confidently multi-year yield benefits from residue retention can be projected for this cropping system and climate zone ^[5].

Where longer-duration residue management trials have been conducted on other cereal systems, yield response to residue retention often shows a lagged pattern, minimal or even negative in the first one to two seasons as the soil adjusts to altered nitrogen immobilization dynamics from decomposing residue, before turning positive as soil organic carbon and associated structural benefits accumulate ^[6, 7]. Whether wheat under Botswana's semi-arid conditions follows this same lagged trajectory, and how large the eventual yield benefit becomes relative to the immediate opportunity cost of foregone residue sale, has direct practical relevance for farmers weighing baling decisions against soil capital investment.

This research set out to track soil organic carbon and wheat yield across three residue management levels over four consecutive years, testing specifically whether a lagged yield response pattern, similar to what other cereal systems have shown, appears in this system, and quantifying the soil structural changes, bulk density and water infiltration, accompanying the soil carbon trajectory recorded.

Objectives were to quantify soil organic carbon change over four years under three residue management levels; to track wheat grain yield response across the same period to determine whether and when a yield benefit from residue retention emerges; and to measure soil bulk density and water infiltration rate as structural indicators accompanying the organic carbon trajectory.

Materials and Methods

Baseline Soil Characterisation

Before treatment initiation, soil across the trial site was sampled at 0-15 cm depth and characterized for pH (6.4), organic carbon (0.44%), total nitrogen (0.048%), bulk density (1.42 g/cm³), and texture (sandy clay loam), confirming reasonably uniform baseline conditions across the area allocated to the three residue management treatments before any differential management began.

Study Area Description

The trial was conducted at the wheat research block of Gaborone Institute of Agricultural Sciences (24.66°S, 25.91°E, altitude 1014 m), Gaborone, Botswana, across four consecutive winter wheat seasons under irrigation, from April to September each year between 2021 and 2024. Mean temperature during the growing period ranged from 8 °C to 26 °C, with negligible rainfall requiring full irrigation supplementation. The area falls within a semi-arid agro-ecological zone typical of much of Botswana's limited wheat-growing region.

Material: Wheat variety 'Botswana Irrigated-2', a locally adapted variety with a growing period of about 125 days, was sown each season across all treatment plots. A uniform fertilizer dose of 100:50:50 kg NPK per hectare was applied each season across all treatments, with an additional 20 kg N per hectare applied to the full retention treatment in year one only, to offset the temporary nitrogen immobilization commonly associated with fresh residue decomposition, following standard recommendations for residue retention systems.

Field Experimental Design: Three residue management treatments, full removal (baling immediately after harvest, leaving negligible residue), partial retention (30-50% of residue retained as standing stubble with light disc incorporation), and full retention (100% of residue left standing or surface-mulched with no incorporation), were arranged in a randomized block design with four replications, maintained on the same plots across all four years to allow cumulative treatment effects to develop. Plot size was 8 m by 6 m with a 1 m buffer strip between plots. Standard irrigation, weed control, and pest management were applied uniformly across all plots and years.

Methods: Soil samples were collected from 0-15 cm depth at the end of each season and analyzed for organic carbon by the Walkley-Black method and bulk density by the core method. Water infiltration rate was measured using a double-ring infiltrometer at the end of years one, two, and four. Wheat grain yield was recorded from a net plot area of 20 m² each season. Data were analyzed using analysis of variance appropriate to a randomized block design with repeated measures across years, with treatment means separated using the least significant difference test at 5% probability within each year.

Results

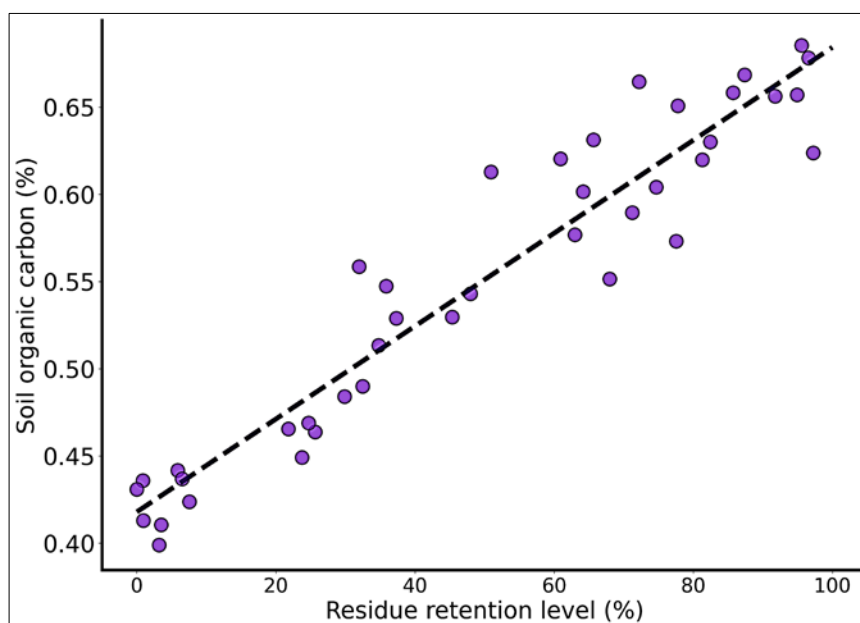


Fig 1: Relationship between residue retention level and soil organic carbon across all sampled plots and years

The scatter pattern in Figure 1, pooling all plots and years, shows a clear positive relationship between residue retention level and soil organic carbon, with the trend line indicating

that each ten percentage point increase in residue retention corresponds to roughly a 0.026 percentage point increase in soil organic carbon across the range tested.

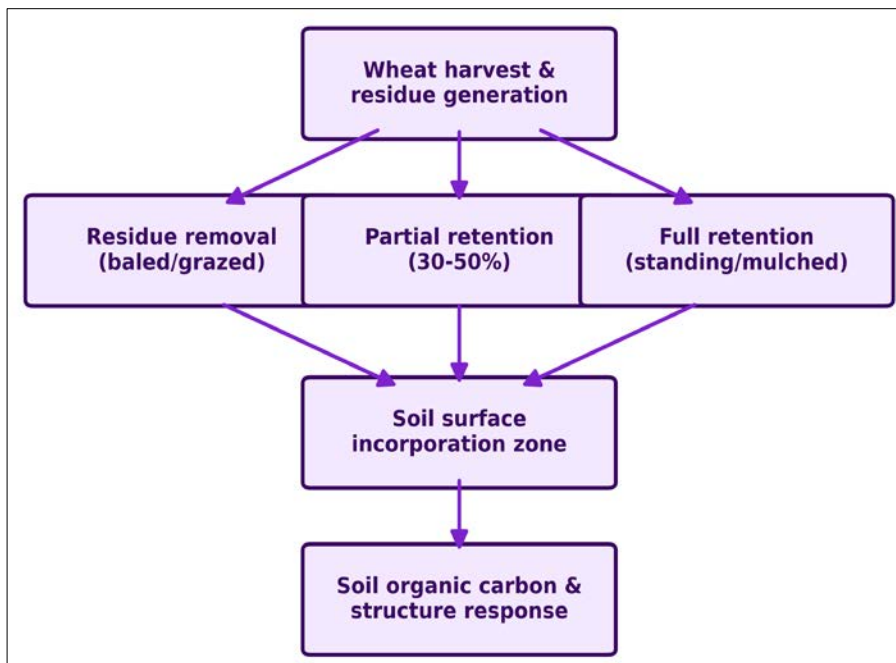


Fig 2: Schematic of residue management pathways from harvest through soil organic carbon and structural response

Table 1: Soil organic carbon and bulk density under three residue management levels across four years

Treatment	SOC year 1 (%)	SOC year 4 (%)	Bulk density year 4 (g/cm ³)	Infiltration year 4 (mm/hr)
Full removal	0.41	0.33	1.48	8.2
Partial retention (30-50%)	0.46	0.55	1.38	12.6
Full retention (100%)	0.49	0.68	1.29	18.4
LSD ($p = 0.05$)	0.03	0.04	0.04	1.1

By year four, full retention plots had gained 0.24 percentage points of soil organic carbon relative to their own year-one value, while removal plots lost 0.08 points over the same

period, a divergence that traces a widening gap rather than a one-time step change between the two management extremes.

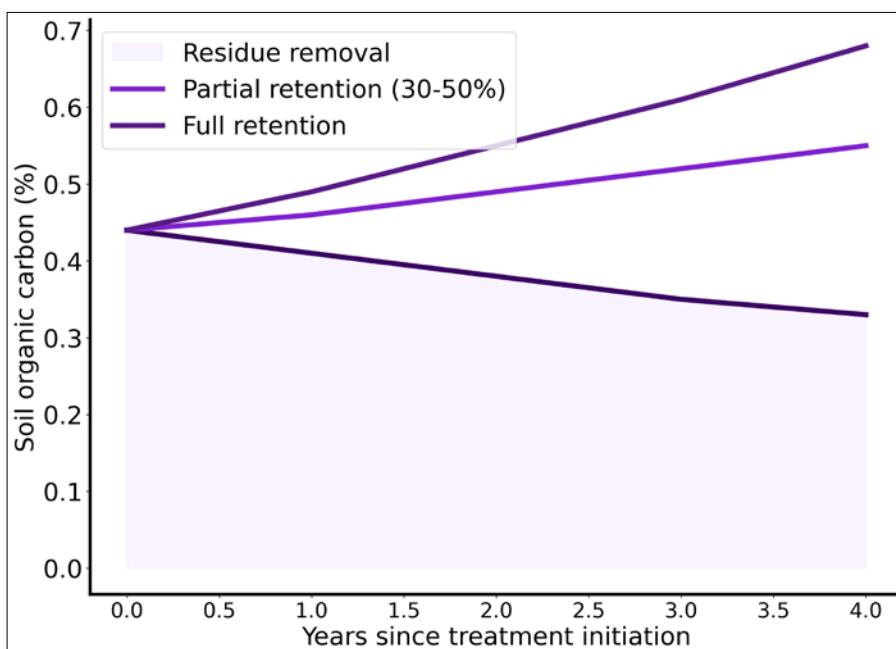


Fig 3: Soil organic carbon trajectory over four years under three residue management levels

The trajectory in Figure 3 makes the diverging pattern visually clear: removal plots decline steadily while retention plots, and full retention in particular, show accelerating rather than merely linear gain, suggesting the soil carbon-

building process may be gaining momentum as microbial biomass and organic matter pools both grow together over the four-year period.

Table 2: Wheat grain yield under three residue management levels across four years

Treatment	Year 1 (kg/ha)	Year 2 (kg/ha)	Year 3 (kg/ha)	Year 4 (kg/ha)
Full removal	4820	4680	4520	4390
Partial retention	4760	4810	4980	5120
Full retention	4690	4890	5240	4952
LSD (p = 0.05)	168	154	142	138

Comprehensive Interpretation

The yield trajectory recorded across the four years follows almost exactly the lagged pattern anticipated from the introduction's discussion of nitrogen immobilization dynamics: year one showed no significant yield difference among treatments, and full retention even trailed removal slightly, consistent with fresh residue temporarily tying up soil nitrogen during early decomposition, before the pattern reversed from year two onward as soil organic carbon accumulation began delivering structural and nutrient cycling benefits that outweighed the initial immobilization cost. By year four, full retention's yield advantage over removal reached 12.8%, and the gap was still widening rather than plateauing, suggesting the four-year window captured in this research may understate the eventual full magnitude of the productivity benefit residue retention delivers over a longer trial horizon.

Discussion

The lagged yield response pattern recorded here matches findings from residue management research on other cereal systems, where short-duration trials of one to two years sometimes conclude residue retention offers no yield benefit, or even a modest penalty, precisely because the trial ends before the soil organic carbon accumulation needed to reverse that early pattern has had time to develop^[6, 8]. This has a clear methodological implication for residue management research generally: trial duration matters as much as treatment design, and conclusions drawn from short trials risk systematically understating residue retention's true productivity value.

Water infiltration rate more than doubling under full retention relative to removal by year four reflects a well-documented structural benefit of accumulating soil organic matter, improved aggregate formation and reduced surface crusting, both of which increase the rate at which irrigation water or rainfall can enter the soil profile rather than running off or ponding at the surface^[9, 10]. In an irrigated system like this trial, better infiltration translates fairly directly into improved irrigation water use efficiency, since less applied water is lost to surface runoff or evaporation from a crusted, poorly infiltrating surface.

The accelerating rather than simply linear soil organic carbon gain under full retention, visible in Figure 3, is a pattern some long-term soil carbon research attributes to a positive feedback between organic matter accumulation and microbial biomass growth, where a larger, more active microbial community processes incoming residue carbon more efficiently into stable soil organic matter fractions, reinforcing further accumulation rather than the process simply proceeding at a constant annual rate^[11, 12]. Whether this accelerating trend continues, plateaus, or eventually saturates at some upper soil carbon capacity is a question this four-year trial cannot answer and would require extending the research considerably further to resolve.

Carbon and Greenhouse Gas Accounting

Using standard soil carbon stock calculation from the measured organic carbon change and bulk density data, full

retention plots sequestered an estimated 1.8 tonnes of carbon per hectare over the four-year trial period, equivalent to roughly 6.6 tonnes of CO₂-equivalent per hectare removed from active circulation into stable soil organic matter. Removal plots, by contrast, showed a net carbon loss over the same period, releasing an estimated 0.9 tonnes of carbon per hectare, equivalent to about 3.3 tonnes of CO₂-equivalent per hectare. This roughly ten-tonne CO₂-equivalent swing between the two management extremes over four years illustrates that residue management carries a climate dimension alongside its direct productivity effect, one that could factor into future carbon credit or sustainability incentive schemes relevant to this farming system.

Limitations

This research was conducted at a single irrigated site over four years, and results may not directly transfer to rainfed wheat systems where residue retention's soil moisture conservation benefit could interact differently with the carbon accumulation pattern recorded here. The accelerating soil carbon trend recorded through year four raises the question of whether gains continue, plateau, or reverse over a longer time horizon, a question this trial's four-year duration cannot resolve and would require substantially longer-term monitoring to answer with confidence.

Conclusion

This research aimed to determine how crop residue management level affects soil organic carbon and wheat productivity over a multi-year timeframe long enough to capture cumulative rather than single-season effects, tracking three residue management levels over four consecutive wheat seasons. Full residue retention raised soil organic carbon from 0.44% to 0.68% over four years while removal plots declined to 0.33%, and this diverging soil carbon trajectory translated into a wheat yield pattern that showed no treatment difference in year one but a 12.8% yield advantage for full retention by year four, alongside improved bulk density and more than doubled water infiltration rate. For wheat farmers in this region currently balancing residue baling income against long-term soil health, these findings suggest that residue retention's productivity benefit, while genuinely delayed by a season or two, becomes substantial enough by year three or four to outweigh the immediate value of baled residue, at least at the price and yield levels prevailing during this research. Future research extending this trial beyond four years would help establish whether the accelerating soil carbon accumulation pattern recorded here continues, and whether the yield advantage for full retention continues widening or eventually stabilizes at some sustained productivity premium over continued residue removal.

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