Soil Organic Carbon Storage, Nitrous Oxide Emission and Net Climate Benefit of Conservation Agriculture: Insights from Two Long-Term Experiments in Zimbabwe

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The slow increase in grain production in sub-Saharan Africa (SSA) is largely the result of cropland expansion rather than an increase in crop yields, which have been stagnantly low (< 1.5 t ha^{-1}). Sustainable intensification of crop production is therefore needed to feed a growing population whilst minimizing negative impacts on the environment, biodiversity, and climate. Full accounting of the net global warming potential (GWP) of management practices can provide a holistic approach for identifying cropping systems that promote sustainable agriculture intensification to ensure food security whilst mitigating climate change.

SSA is lying in the nexus of rapid population growth (UN, 2022), stagnantly low agricultural productivity and high vulnerability to climate change. Cropland intensification rather than expansion is needed to sustainably increase crop yields per unit area (Aramburu-Merlos et al., 2024; Falconnier et al., 2023) with a minimal negative environmental footprint (Zheng et al., 2023). Conservation agriculture (CA) has been widely proposed as one of the promising approaches to sustainable intensification of food production where it has been shown that CA can improve maize yields by 8.4% in SSA (Corbeels et al., 2020). However, the climate change mitigation potential of CA in terms of greenhouse gas (GHG) emissions and additional soil organic carbon (SOC) storage has not been fully explored in SSA (Corbeels et al., 2019; Li et al., 2023). Additionally, the respective contribution of each CA principle or their different combinations to GHG emissions and SOC storage remains understudied. Therefore, the aim of this research was to determine the net GWP of each of the respective CA principles and/or their different combinations. To evaluate the negative or positive climate impact of a cropping system, it is essential to quantify its net global warming potential (Six et al., 2004; Zheng et al., 2023) given as CO_2 equivalents (CO_2-eq). The net GWP provides an integrated index that allows for comparisons between different cropping systems and is done through accounting of GHG sources and sinks of a cropping system.

In addition, a measure of the intensity of GHG emissions associated with a cropping system is also critical (Zheng et al., 2023). This measure, the greenhouse gas intensity (GHGI), expresses GHG emissions per unit of output (emissions per unit of crop yield). Therefore, the objective of this paper is to share results on the potential climate change mitigation benefits from each CA principle or their combinations under low nitrogen (N) input in sub-humid Zimbabwe.

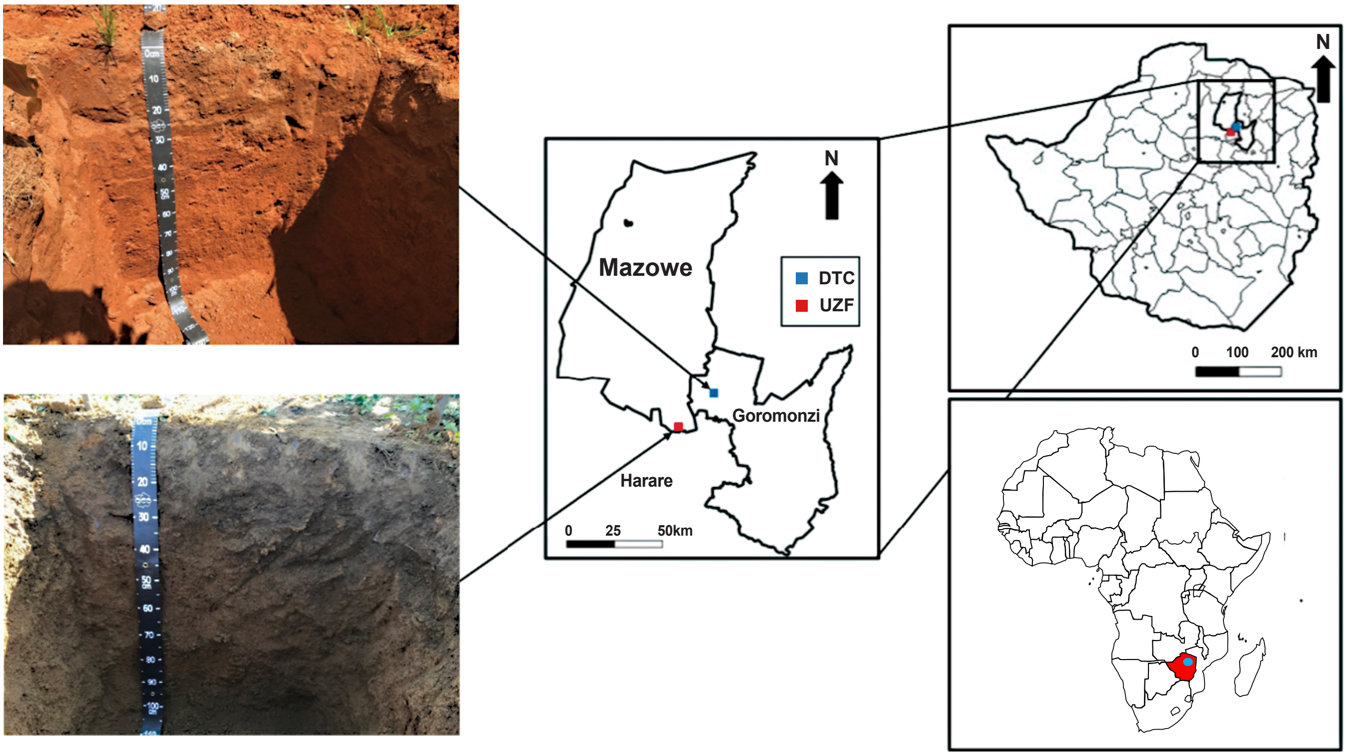

Figure 1. Study sites at Domboshava Training Centre DTC and University of Zimbabwe Farm (UZF).

Study description and methodology

This study was conducted at two long-term experimental sites established by CIMMYT in 2013 in Zimbabwe, on an Abruptic Lixisol at Domboshava Training Centre and a Xanthic Ferralsol at the University of Zimbabwe Farm (**Fig. 1**).

Six treatments replicated four times were investigated: conventional tillage (CT), conventional tillage with rotation (CTR), no-tillage (NT), no-tillage with mulch (NTM), no-tillage with rotation (NTR), no-tillage with mulch and rotation (NTMR). The main crop was maize (*Zea mays* L.) and treatments with rotation included cowpea (*Vigna unguiculate* L. Walp.). Nitrogen was split applied (basal and two top-dressings) at 58 kg N ha^{-1} yr^{-1} on maize rows. GHG samples were regularly collected using the static chamber method in the maize row and inter-row spaces (**Fig. 2a**) during the 2019/20 and 2020/21 cropping seasons and during the 2020/21 dry season (Shumba et al., 2023). SOC and bulk density were determined for samples taken from depths of 0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–50, 50–75, and 75–100 cm from all treatments (Shumba et al., 2024). SOC stocks were calculated using the equivalent soil mass (ESM) approach to account for possible changes in soil bulk density between treatments (Ellert and Bettany, 1995).

Net GWP_{100} (CO_2-equivalent; t CO_2-eq ha^{-1} yr^{-1}) at a 100-year time horizon was calculated for each treatment using **Equation 1**. The CT treatment was used as the reference treatment.

Equation 1:

$$net\ GWP_{100} = \Delta N_2O_{GWP100} + \Delta CH_{4GWP100} - \Delta SOC_{GWP100}$$

The GWP_{100} for nitrous oxide (N_2O), methane (CH_4) and SOC were determined using **Equations 2, 3** and **4**. The net GWP_{100} for this study was calculated at plot scale hence the CO_2-equivalent emissions associated with the manufacture and transportation of fertilizer was not included.

Equation 2:

$$\Delta N_2O_{GWP100} = \Delta\ t\ N_2O\text{-}N\ ha^{-1}\ yr^{-1} \times 44/28 \times 265$$

Equation 3:

$$\Delta CH_{4GWP100} = \Delta\ t\ CH_4\text{-}C\ ha^{-1}\ yr^{-1} \times 44/12 \times 28$$

Equation 4:

$$\Delta SOC_{GWP} = \Delta\ t\ SOC\ ha^{-1}\ yr^{-1} \times 44/12$$

where 265 and 28 are GWP_{100} constants used to give the integrated radiative forcing of N_2O and CH_4, respectively, in terms of their CO_2-equivalence at a 100-

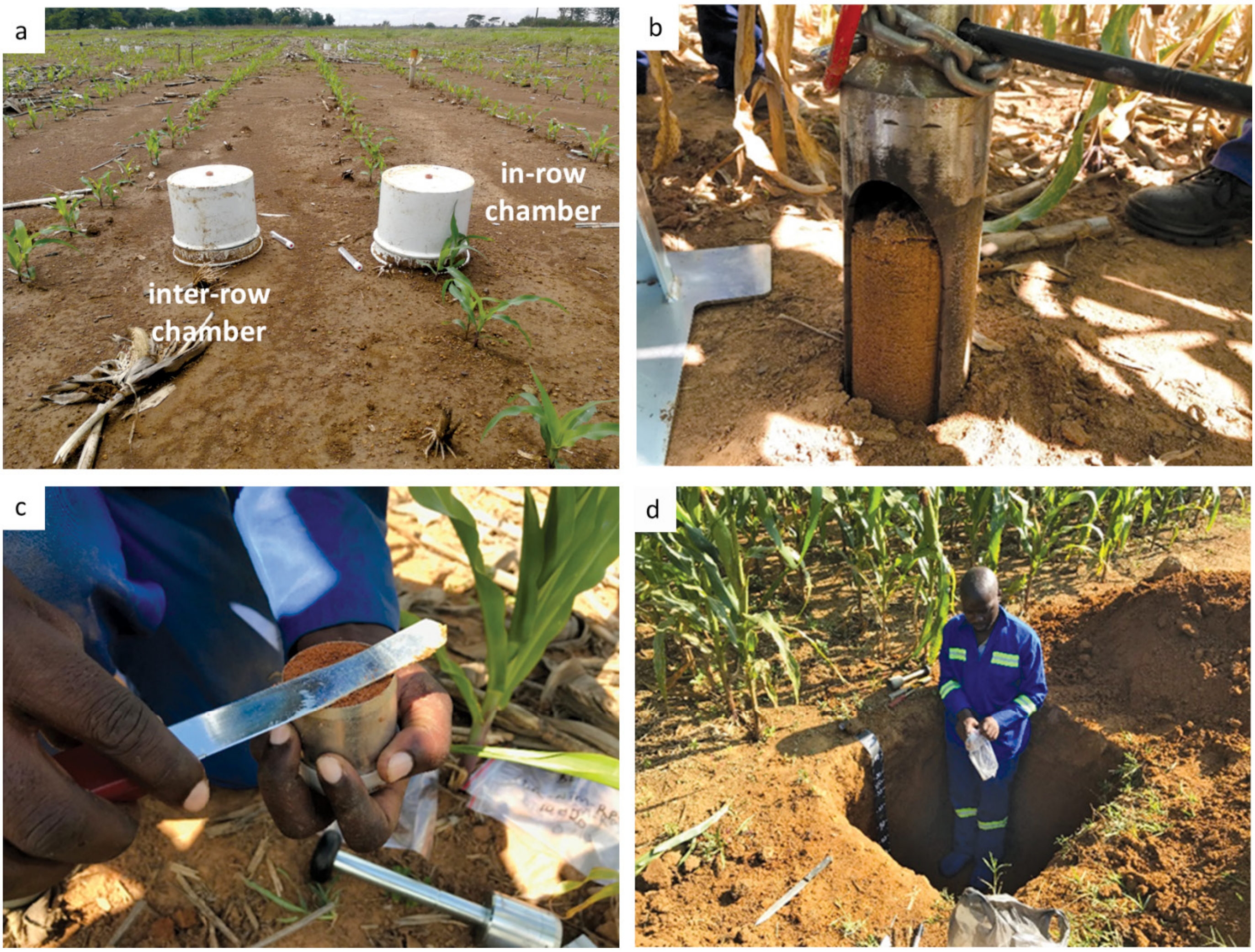

Figure 2. Picture combo showing (a) greenhouse gas sampling in maize rows and inter-rows; (b) soil coring; (c) top soil sampling for bulk density; (d) pits for sub-soil bulk density sampling.

year time horizon (Myhre et al., 2013). ΔN_2O, ΔCH_4 and ΔSOC refers to the observed change of cumulative N_2O and CH_4 and SOC stocks compared to cumulative N_2O and CH_4 and SOC stocks from the reference treatment, CT. For CT, land was tilled using hand hoes, and fertilizer application, weeding and harvesting were all done manually as is typical practice on smallholder farms in Zimbabwe. Thus, the farming system represent very low indirect GHG emissions, hence they were not accounted, compared to mechanized and irrigated high-yielding maize systems in the developed world (e.g., Adviento-Borbe et al., 2007; Huang et al., 2013).

Lastly, the maize grain yield-GHGI (t CO_2-eq t^{-1} yr^{-1}) was calculated to determine the climatic impact of the maize systems by dividing the net GWP by the average maize grain yield (t maize grain ha^{-1} yr^{-1}) for the 2019/20 and 2020/21 cropping seasons.

Cumulative soil N_2O and CH_4 emissions

There were no significant differences in cumulative N_2O emissions between treatments at DTC (average of 2 years), cumulative N_2O emissions ranged from 189-349 g N_2O-N ha^{-1} yr^{-1} **(Fig. 3)**. At UZF, NT in combination with rotation had significantly higher cumulative N_2O emissions. Cumulative CH_4 emissions were not different between treatments at both sites; however, DTC was a net emitter and UZF was a net sink of CH_4 **(Fig. 3)**.

SOC stocks

Results show that maize stover mulching under NT is the overarching factor explaining the increase of SOC in the topsoil (**Fig. 4**). The findings also highlight the importance of considering the entire soil profile where over 50% of the total SOC stocks are stored in the subsoil (30-100 cm).

Net Global Warming Potential (GWP) and Greenhouse Gas Intensity (GHGI)

No tillage alone had a positive GWP at DTC, suggesting a negative impact on climate change mitigation (**Table 1**). However, the combination of NT with at least one other CA component (mulching or rotation or both) where the net GWP is largely negative showed a positive climate benefit except for NTR at UZF. The greenhouse gas intensity (GHGI) followed a similar pattern as the GWP (**Table 1**). At DTC, NT emitted about 0.22 t CO$_2$-eq t^{-1} of maize grain produced. In contrast, NT combined with rotation (NTR) showed the potential to capture between 0.57 to 0.65 t CO$_2$-eq t^{-1} grain. At UZF, NTM had the highest global warming mitigation potential of -0.56 t CO$_2$-eq t^{-1} grain yr^{-1} whilst NTR had a negative impact on global warming with a potential of releasing 0.07 t CO$_2$-eq for every tonne of maize grain produced every year (**Table 1**).

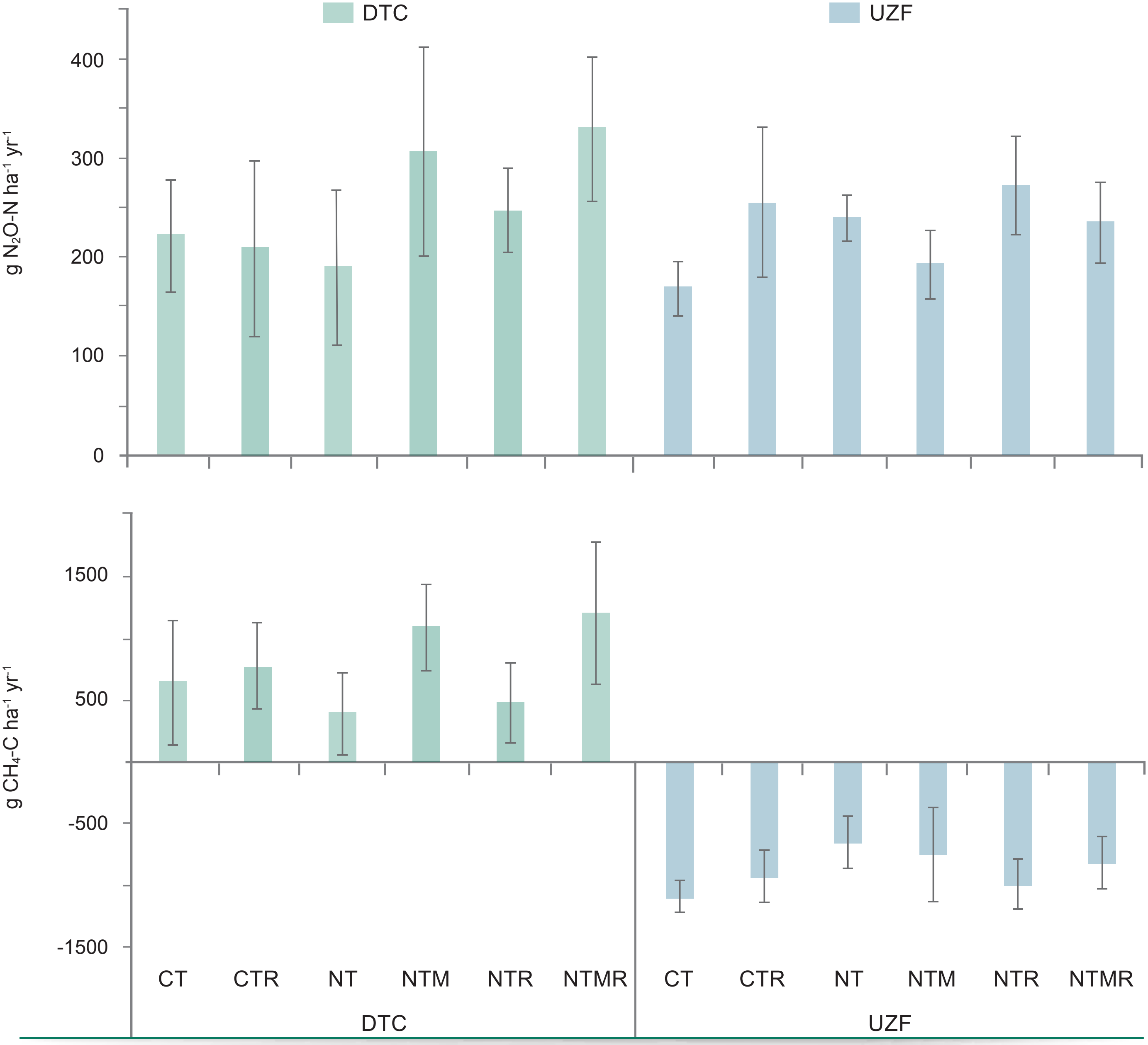

Figure 3. Cumulative N$_2$O (top) and CH$_4$ (bottom) emissions at Domboshava Training Centre (DTC) and University of Zimbabwe farm (UZF) averaged over 2 years. Error bars represent standard errors (N=4). CT: conventional tillage, CTR: conventional tillage with rotation, NT: no tillage, NTM: no tillage with mulch, NTR: no tillage with rotation, NTMR: no tillage with mulch and rotation.

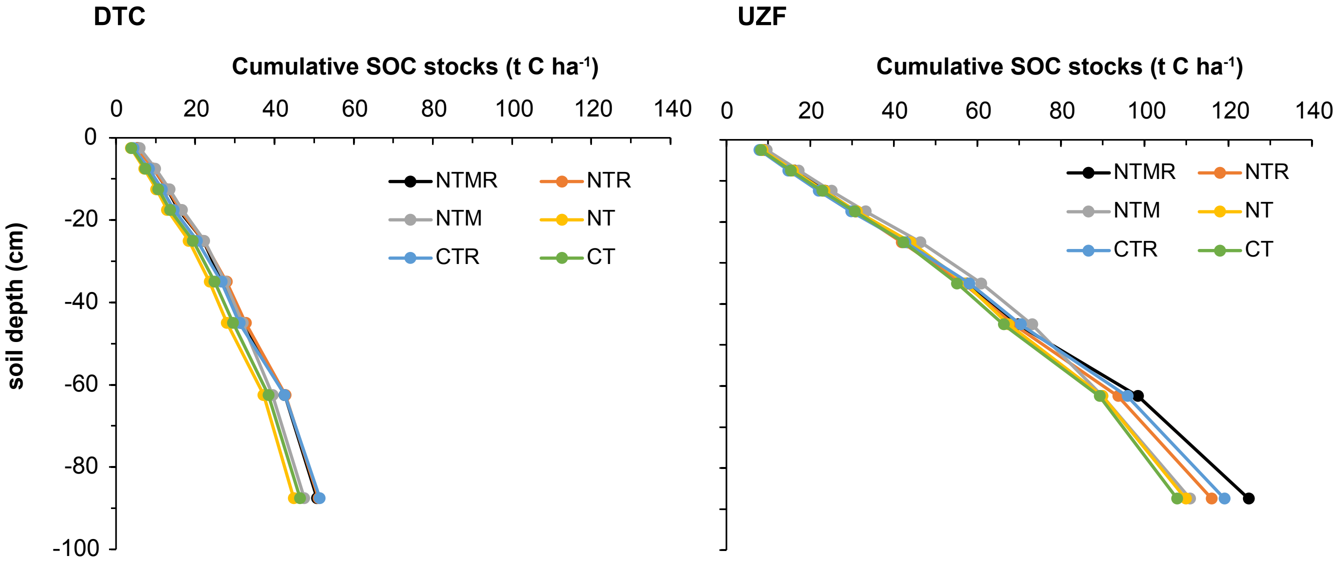

Figure 4. Cumulative SOC stocks profiles at Domboshava Training Centre (DTC) and University of Zimbabwe Farm (UZF) after 8 years of different tillage, residue and crop management systems. CT: conventional tillage, CTR: conventional tillage with rotation, NT: no-tillage, NTM: no-tillage with mulch, NTR: no-tillage with rotation, NTMR: no-tillage with mulch and rotation.

Summary

Despite the high radiative forcing of N_2O and CH_4, their contributions to GWP were negligible compared to the benefits from additional SOC storage, resulting in an overall negative net GWP under NT in combination with at least one CA principle, especially with mulch addition. Moreover, the negative net GWP and GHGI of CA-based cropping systems (except NTR at UZF) were obtained despite an application of 58 kg N ha^{-1} yr^{-1}. This fertilizer rate is more than three times the average rate used in SSA (Falconnier et al., 2023), and it suggests intensification of cropping systems in SSA to levels agreed at the recent Africa Fertilizer and Soil Health Summit in Nairobi (target of 50 kg N ha^{-1} yr^{-1}) could be achieved with a limited impact on climate and with massive benefits on crop production. Providing some safeguards are put in place, this could also decrease pressure on natural ecosystems and reduce emissions related to

Table 1. Global warming potential (GWP_{100}) contributions of N_2O, CH_4 and SOC to net GWP_{100} and greenhouse gas intensity (GHGI) averaged for the two seasons (2019/20 and 2020/21). In brackets are standard errors, N = 4. CTR: conventional tillage with rotation, NT: no-tillage, NTM: no-tillage with mulch, NTR: no-tillage with rotation, NTMR: no-tillage with mulch and rotation.

		*GWP_{100} (t CO_2-eq ha^{-1}yr^{-1})			Net GWP_{100}	Offset	GHGI
Site	Treatments	N_2O	CH_4	SOC	(t CO_2-eq ha^{-1}yr^{-1})	(%)	(t CO_2-eq t^{-1} grain yr^{-1})
DTC	CTR	-0.01 (± 0.03)	0.01 (± 0.03)	-0.49 (± 0.84)	-0.49 (± 0.81)	2.0	-0.17 (± 0.34)
	NT	-0.01 (± 0.02)	-0.03 (± 0.04)	0.46 (± 0.24)	0.42 (± 0.23)	-	0.22 (± 0.14)
	NTM	0.04 (± 0.03)	0.05 (± 0.05)	-1.33 (± 0.35)	-1.25 (± 0.38)	6.8	-0.57 (± 0.18)
	NTR	0.01 (± 0.03)	-0.02 (± 0.03)	-1.18 (± 0.26)	-1.19 (± 0.24)	0.8	-0.62 (± 0.20)
	NTMR	0.05 (± 0.05)	0.06 (± 0.02)	-1.20 (± 0.69)	-1.10 (± 0.66)	9.2	-0.65 (± 0.39)
UZF	CTR	0.04 (± 0.02)	0.02 (± 0.02)	-0.21 (± 0.50)	-0.16 (± 0.50)	28.6	-0.03 (± 0.10)
	NT	0.03 (± 0.03)	0.05 (± 0.03)	-0.80 (± 0.84)	-0.73 (± 0.80)	10.0	-0.24 (± 0.27)
	NTM	0.00 (± 0.02)	-0.02 (± 0.02)	-1.88 (± 0.65)	-1.90 (± 0.66)	-	-0.56 (± 0.25)
	NTR	0.04 (± 0.02)	0.01 (± 0.02)	0.20 (± 0.61)	0.25 (± 0.61)	-	0.07 (± 0.14)
	NTMR	0.03 (± 0.02)	0.03 (± 0.03)	-0.44 (± 0.53)	-0.38 (± 0.52)	15.8	-0.08 (± 0.10)

*Average of the two years of N_2O and CH_4 measurements. GWP_{100} for N_2O and CH_4 is 265 and 28, respectively. Treatments with net negative impact on climate change mitigation have positive net GWP and GHGI. Offset is the percentage climate benefit due to additional SOC storage that is offset by N_2O and CH_4 emissions.

land use change, an additional benefit on climate change mitigation not accounted for in this study. Our study clearly shows that field-based GHGs emissions were offset by additional SOC storage. Therefore, the climate benefit of CA in SSA is mainly driven by an increase in SOC stocks, and the trade-off with non-CO_2 emissions is limited in this context of low N input systems. These findings obtained on two widespread soil types are also characteristic of smallholder farming systems in SSA, where CA practices with low fertilizer application are being promoted, such as the *Pfumvudza/Intwasa* program in Zimbabwe.

In brief, the study suggests that no-tillage systems especially with mulching, can bring some additional benefits in terms of climate change mitigation. ■

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