Long-term carbon mitigation potential of no-till, nitrogen application and stubble retention practices in a subtropical cereal cropping system

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Abstract

The long-term carbon mitigation potentials of no-till (NT) *vs.* conventional till (CT), stubble retention (SR) *vs.* stubble burning (SB) and N fertilisation (NF) *vs.* no N application (N0) as well as their interactions were examined on a Vertisol in semi-arid subtropical Queensland, Australia by taking into account their impacts on soil organic C (SOC) content, crop residue C storage, on-farm fossil fuel consumption and CO_2 emissions associated with N fertiliser application. The experimental site has been cropped with wheat or barley with a summer fallow period each year (except in 1982, 1991 and 1994) for 33 years. Where NT, SR or NF treatment was applied alone, no significant effect on SOC was found in the 0 – 10, 10 – 20 and 0 – 20 cm depths. However, the treatment effects in the 0 – 10 cm depth were interactive and maximum SOC sequestration was achieved under the NT + SR + NF treatment. Carbon storage in crop residues ranged from 0.10 Mg C/ha under the CT + SB + NF treatment to 0.64 Mg C/ha under the NT + SR + N0 treatment. The cumulative fossil fuel CO_2 emission in 33 years was estimated to be 0.61 Mg C/ha less under the NT systems than under CT systems. Cumulative CO_2 emissions from N fertiliser application added up to 0.85 Mg C/ha. A full C accounting indicated that maximum CO_2 mitigation was achieved under the NT + SR + NF treatment, which was, for example, 2.26 Mg C/ha higher than under the CT + SB + N0 treatment after 33 years (0.07 Mg C/ha.yr on average).

Key Words

Greenhouse, global warming, carbon sequestration

Introduction

Concerns over the increasing concentration of CO_2 in the atmosphere and global climate change have prompted increasing interest in assessing the potential of carbon sequestration in agricultural land and the measures that can be used to achieve this potential (Cole *et al*. 1997; Lal *et al*. 1999; Bruce *et al*. 1999; Swift 2001). It has been estimated that through improved management the 1.3 billion ha cultivated soils in the world may potentially sequester 0.4 – 0.6 Pg C/yr over the next 50 years, which is about 13 – 19% of the net annual atmospheric CO_2 increase in 1990s (Paustian *et al*. 1997; Cole *et al*. 1997). To maximise agricultural carbon mitigation, farming strategies that promote carbon sequestration and/or suppress CO_2 emission must be practised. Such strategies may include, but are not limited to, no-till, N fertiliser application and stubble retention (Paustian *et al*. 1997; Bruce *et al*. 1999).

Many studies have been undertaken to examine the effects of tillage, fertiliser application and stubble management on soil organic C (SOC) content (Rasmussen and Collins 1991; Fettell and Gill 1995; Dalal and Chan 2001). These studies were generally initiated in recognition of the importance of soil organic matter in the maintenance and improvement of soil fertility. Indeed, the results obtained in such studies provide a valuable database for assessing the potential of carbon sequestration in soil by different land management practices under a diversity of climatic and edaphic conditions. However, knowledge of the changes in SOC alone may not be sufficient for carbon accounting purposes. In situations where crop residues accumulate, considerable amounts of carbon can be locked in this reservoir. The amount of carbon stored in crop residues should be taken into account in carbon inventories (IPCC 1996), but scarce data can be found in the literature. Moreover, fossil fuel consumption may vary under different farming practices such as conventional till compared with no-till, which may offset in the long term the carbon benefit indicated by SOC changes (Kern and Johnson 1993). Schlesinger (1999) pointed out that CO_2 emission in the process of ammonia production should be taken into account in assessing the net C sink resulted from N fertiliser application. Therefore, a complete understanding of the impacts of different farming practices on the mitigation potential of atmospheric CO_2 requires field-level analysis of all aspects of C sources, sinks and fluxes in the system.

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In the present study, we attempted to carry out a full carbon accounting to assess the CO_2 mitigation potentials of no-till (NT) *vs.* conventional till (CT), stubble retention (SR) *vs.* stubble burning (SB), and N fertiliser application (NF) *vs.* nil N application (N0) on a Vertisol in subtropical Queensland, Australia. The long-term carbon mitigation potentials were estimated by including SOC, crop residue C and CO_2 emission from energy consumption and N fertiliser use. Wheat or barley has been grown on this site under a combination of tillage, stubble management and N fertiliser application for the last 33 years.

Materials and methods

The field trial

The experiment was conducted at Hermitage Research Station (28^o 12' S, 152^o 06' E), Queensland, Australia. Mean annual temperature at the site is 17.5 ^oC and mean annual rainfall is 685 mm. The soil is a Vertosol (Isbell 1996) or Udic Pellustert (Soil Survey Staff 1999) containing 65% clay, 24% silt, and 11% sand.

The field trial was established in 1968. Wheat (*Triticum aestivum* L., cv.) or barley (*Hordeum vulgare* L., cv.) was grown generally from June to November/December each year except 1982, 1991 and 1994, when there was insufficient rainfall for sowing. Detailed descriptions of this experiment were given by Marley and Littler (1989) and Dalal (1989). In the present study, eight treatments were selected, which consisted of a 2 × 2 × 2 factorial combination of tillage (CT or NT), stubble management (SR or SB), and N fertilisation (N0 or NF) arranged in a randomised block design with four replicates. The treatments under CT involved on average five tillage operations with a chisel plough to approximately 10 cm depth during the fallow period each year (approximately December to June), while the plots under NT were sprayed with herbicide to control weeds. Crop residues with the SB practice were burnt shortly after harvest. The treatments with NF received urea at 46 kg N/ha.yr during the first eight years, then at 69 kg N/ha.yr until 1996 and at 90 kg N/ha.yr thereafter. The fertiliser was applied at 4 – 5 cm depth at sowing.

Collection, processing and analysis of soil and stubble samples

Soil was sampled in July 2001 at the end of a fallow period. The samples were randomly taken from four points in each plot at 0 – 10 and 10 – 20 cm depths with a 7-cm dia. auger, the soil from each depth was bulked and mixed. After removal of large plant pieces (rare in the 10 – 20 cm soil), the soil samples were air-dried, ground to < 2 mm, and then sub-sampled and fine-ground to < 0.25 mm.

Crop residues above and in the top 10 cm soil were sampled from three points in each plot during the early and late fallow period by pushing a 20 cm × 24 cm open-end stainless steel enclosure into soil. The crop residues enclosed were manually picked up and mixed to obtain a composite sample for each plot. Separation of crop residues from soil was conducted with similar procedure to soil sample processing to avoid significant double-accounting. The samples were washed, dried at 60 ^oC, cut into about 2 cm pieces, sub-sampled and then ground to < 0.25 mm. Total C content in the fine-ground soil and crop residue samples was determined by dry-combustion with a LECO CNS-2000 analyser (LECO Corporation, MI, USA). No significant carbonate was detected in the soil. The amounts of SOC per unit area of land under different treatments were compared in an equivalent soil mass, based on a standard or reference bulk density of 1.0 Mg/m^3 (average of all plots). This method eliminates the potentially erroneous comparisons that might result from calculating the C storage as the product of concentration, bulk density and depth (Ellert and Bettany 1995).

Statistical analysis

The treatment effects were assessed using the Analysis of Variance procedure of Genstat Release 6.1 (Payne 2002), treating depths as sub-plots in a split-plot design for soil samples. Treatment means were compared using the least significant difference (l.s.d) test at $P < 0.05$.

Results and discussion

Carbon sequestration in soil

The mean SOC content in the top 10 cm soil was 20.5 ± 0.7 Mg/ha (Fig. 1 a). On average, NT, SR and NF treatments increased SOC content in the top 10 cm depth by 0.35, 0.29 and 0.97 Mg/ha in comparison to CT, SB and N0 treatments, respectively ($P < 0.05$ for the NF effect; $P > 0.05$ for the NT and SR effects). However, there were significant interactions between tillage, N fertiliser application and stubble management practices (Fig. 1). For example, NT resulted in significantly higher SOC content than CT only when SR and NF were implemented (1.7 Mg/ha). Significant effects of N application on SOC were observed under NT, with magnitudes of 1.2 and 1.8 Mg/ha under SB and SR, respectively. In comparison to SB practice, SR increased SOC content only when practised in combination with NT and NF (1.2 Mg/ha). Among all the management practices, the NT + NF + SR treatment resulted in the highest SOC level (22.0 Mg C/ha) in the surface 10 cm depth.

SOC contents in the 10 – 20 cm depth were consistently lower than in the top 10 cm of soil, with an average value of 19.6 ± 0.4 Mg/ha. The SOC contents at this depth were not significantly different under different cropping practices ($P > 0.05$). Therefore, the relative treatment effects on SOC in the 0 – 20 cm soil (Fig. 1 c) were similar to those in the top 10 cm soil except that the stubble retention effect under NT + NF became statistically insignificant.

The ineffectiveness of a single conservation farming practice in raising SOC level on the studied site appeared to differ from the general notion that no-till, N application and stubble retention can effectively increase C sequestration in soil (Paustian *et al*. 1997; Smith *et al*. 2000). According to a review of West and Post (2002) using a global database of long-term experiments, a change from CT to NT can, on average, sequester 2.9 Mg C/ha over 12 yr under continuous wheat. Smith *et al.* (2000) estimated annual SOC accumulation rates through straw incorporation as opposed to burning ranging from 0.42 to 1.31% of the SOC concentration per year. Fertiliser application enhances biomass production and C input and many experiments showed a positive effect of N additions on SOC content (Paustian *et al*. 1997; Campbell *et al*. 2000).

The insignificant response of SOC to NT under N0 or SB, to SR under N0 or CT, and to NF under CT were consistent with the results from many long-term (mostly < 20 yr) field trials under continuous cereal crops in Australia (Carter and Mele 1992; Ladd *et al*. 1994; Fettell and Gill 1995; Dalal and Chan 2001). Changes in SOC under a farming practice is a function of the rates of C input and decomposition, which are affected by the climate, soil properties, cropping system and productivity, length of fallow period, and other farming practices. The modest effects of NT, SR or NF and their strong interdependence on raising soil organic level in this study might be attributed to the low productivity of plant biomass C (average grain yield is 2.7 Mg/ha.yr) under continuous wheat/barley and the rapid mineralisation of soil organic matter since the field trial is located in a semi-arid subtropical region with a long fallow period from December to June.

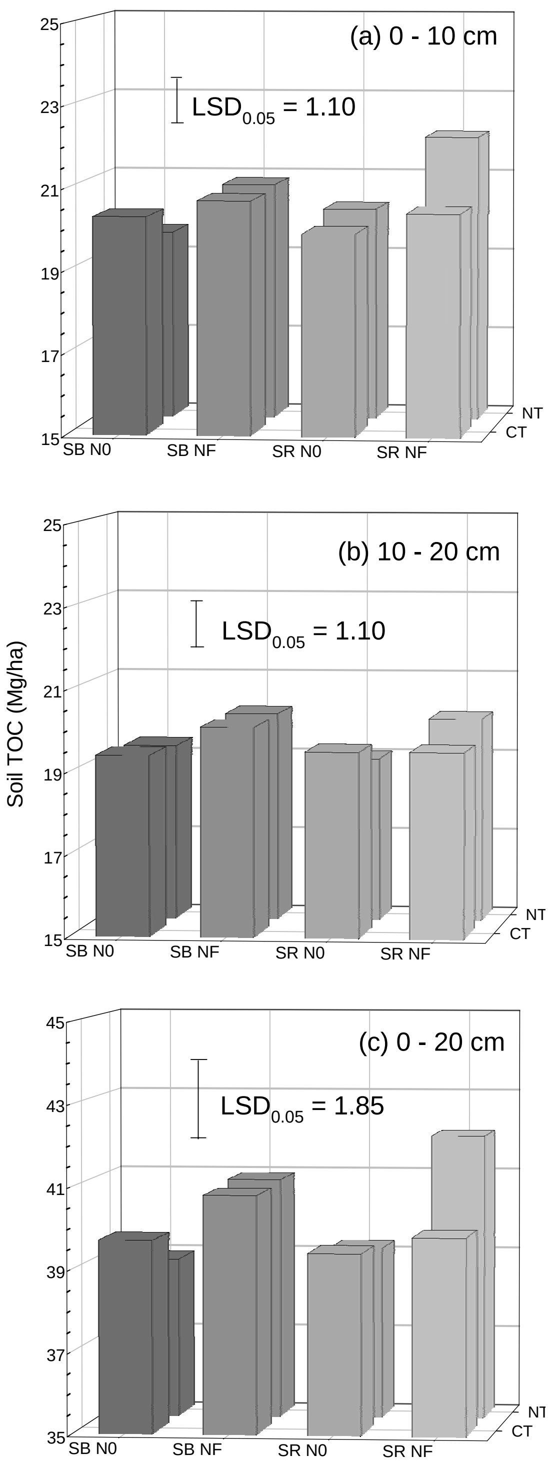

Figure 1. Organic carbon contents in the top 20 cm soil under different farming treatments (NT: no-till; CT: conventional till; SB: stubble burnt; SR: stubble retained; N0: no fertiliser N application; NF: N fertiliser applied).

Carbon storage in crop residues

The crop residues collectable at the time of sampling were largely derived from the recent crop-growing season but also included a part of old remnants. The crop residues stored 0.3 t C/ha on average. As expected, significantly higher amount of C was found under SR (0.42 t C/ha) than under SB treatment (0.15 t C/ha; Fig. 2). Under the SB treatment, C storage in the litter was not significantly affected by tillage and fertiliser application. Where the stubble was retained, however, significantly higher amount of crop residue C was found under the NT + N0 treatment (0.64 t C/ha) than others ($P < 0.05$). This could, at least in part, be attributed to the slower decomposition rate under this treatment in comparison to the other three treatments, due to the combined effects of less contact with soil under NT and poor quality of the litter under N0. The C/N ratios of the crop residues were consistently higher under N0 (61 ± 21) than under NF (33 ± 6; $P < 0.05$).

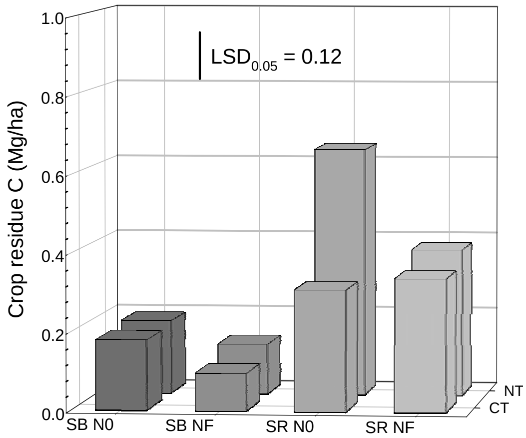

Fig. 2. Carbon storage in the crop residues at the end of a fallow period under different treatments (NT: no-till; CT: conventional till; SB: stubble burnt; SR: stubble retained; N0: no fertiliser N application; NF: N fertiliser applied).

CO_2 emission from energy consumption

In the present study, we compared the relative C benefit of different agricultural practices at the farm level only. Energy consumption associated with operations common to all treatments (e.g. sowing and harvesting) was not taken into account in the comparison. Diesel consumption rate for a tillage operation per unit of area is affected by factors such as the horsepower of the tractor, the size of the plough and the depth of tillage. According to French (1997), the average diesel consumption rates in this area were 7 L/ha for each tillage operation under CT and 2 L/ha for each herbicide spray under NT. Using a typical density of No. 2 diesel fuel of 0.852 kg/L and a C content of 873 g C/kg (Kern and Johnson 1993), CO_2-C emission from fossil fuel usage since the establishment of this field trial (33 yr) was estimated as:

CO_2-C from tillage = 7 L diesel/ha.operation × 0.852 kg/L diesel × 873 g C/kg diesel × 5 operations/yr × 33 yrs × 10^{-6} = 0.86 Mg C/ha

CO_2-C from herbicide spray = 2 L diesel/ha.operation × 0.852 kg/L diesel × 873 g C/kg diesel × 5 operations/yr × 33 yrs × 10^{-6} = 0.25 Mg C/ha.

CO_2 emission from N fertiliser application

After application in soil, urea can be hydrolysed by urease to form CO_2:

$4CO(NH_2)_2 + 4H_2O \rightarrow 8NH_3 + 4CO_2$

The CO_2 formed in the above process can be stored in soil as carbonate and/or emitted into the atmosphere, depending on the environmental and soil conditions such as pH. In this study, N fertiliser application resulted in significant decline in pH in the top 10 cm of soil, being 6.7 ± 0.3 (mean ± SD) under NF compared to 7.7 ± 0.2 under N0 treatments. Assuming that all the CO_2 from urea hydrolysis has been released into the atmosphere, the total amount of CO_2 emission from fertiliser application in the last 30 years (no fertiliser applied in 1982, 1991 and 1994) would be:

CO_2-C from urea application = (46 kg N/ha.yr × 8 yrs + 69 kg N/ha.yr × 17 yrs + 90 kg N/ha.yr × 4 yr) × 0.43 kg C/kg N = 0.82 Mg C/ha

Net carbon balance

The C benefits for different farming practices were assessed using the CT + SB + N0 treatment as the reference system. Increases in SOC (0 – 20 cm depth) or stubble C stock relative to that under CT + SB + N0 were reflected by positive values, and decreases by negative values (Table 1). Savings of fossil fuel C emission by NT were credited, and the additional C emissions from herbicide spray or urea decomposition were deducted from the overall C balance.

Table 1. Carbon benefits (Mg C/ha) of different treatments relative to those under CT + SB + N0 after 33 years

Farming Treatments[a]			SOC (0-20 cm) benefits[b]	Stubble C benefits[c]	Fossil fuel C savings		CO_2 emission from urea	Net C balance[d]
					Tillage	Herbicide		
CT	SB	N0	0	0	0	0	0	0
CT	SB	NF	1.05[ns]	-0.08[ns]	0	0	-0.85	0.12[ns]
CT	SR	N0	-0.32[ns]	0.13*	0	0	0	-0.19[ns]
CT	SR	NF	0.10[ns]	0.16*	0	0	-0.85	-0.59[ns]
NT	SB	N0	-0.80[ns]	0.01[ns]	0.86	-0.25	0	-0.18[ns]
NT	SB	NF	1.24[ns]	-0.05[ns]	0.86	-0.25	-0.85	0.95[ns]
NT	SR	N0	-0.49[ns]	0.46*	0.86	-0.25	0	0.58[ns]
NT	SR	NF	2.31*	0.19*	0.86	-0.25	-0.85	2.26*

[a] CT: conventional tillage; NT: no-till; SB: stubble burnt; SR: stubble retained; N0: no N fertiliser application; and NF: N fertiliser applied.
[b] $LSD_{0.05}$ = 1.85; *: the difference to the reference is significant at $P < 0.05$; ns: not significant.
[c] $LSD_{0.05}$ = 0.12.
[d] $LSD_{0.05}$ = 1.84.

The results of full C accounting showed that SOC changes, fossil fuel emission, C stock in crop residues, and CO_2 release from urea hydrolysis all affected net C fluxes from this cropping system considerably. The maximum difference among all treatments was 3.11 Mg C/ha in SOC content (0 – 20 cm depth), 0.54 Mg C/ha in crop residue C stock, 0.61 Mg C/ha in fossil fuel emission and 0.85 Mg C/ha in fertiliser emission. Averaged across treatments, the C mitigation potential was 1.07 Mg C/ha higher under NT than under CT ($P < 0.05$), while the difference was not significant between NF and N0 (0.63 Mg C/ha) and between SR and SB practices (0.30 Mg C/ha; $P > 0.05$). Fertiliser application or stubble retention alone could not result in higher C benefit than their counterpart treatments, irrespective of the other farming practices. The effect of NT was significant only under SR + NF practices, being 2.85 Mg C/ha higher than under CT. Overall, maximum C benefit was achieved with SR and NF under NT systems, which is 2.26 Mg C/ha (0.07 Mg C/ha.yr on average) higher than under CT + SB + N0 and also significantly higher than under other treatments except NT + SB +NF and NT + SR + N0. Compared to the observations or predictions in some other areas (Paustian *et al.* 1997; Smith *et al.* 2000; West and Post 2002), the CO_2 mitigation potentials of the conservation farming practices are low in this agricultural system.

It is recognised that, in addition to CO_2 sequestration and emissions, fluxes of non-CO_2 greenhouse gases such as N_2O and CH_4 may also be significantly affected by tillage, N fertiliser application and stubble management. Further research is required to assess the full greenhouse impact of different farming practices by including non-CO_2 greenhouse gas emissions and under different crop and crop/pasture rotation systems.

Conclusions

At this experimental site, no-till, stubble retention or N fertiliser application had little effect on SOC stocks if applied alone, which differed from the observations in other areas of the world. The treatment effects were interactive in the top 10 cm soil but not significant in the 10 – 20 depth interval. Maximum SOC sequestration was achieved under the NT + SR + NF treatment, which was 2.26 Mg C/ha higher than under the CT + SB + N0 treatment in the surface 20 cm depth. Reduced fossil fuel C emission associated with no-till practice was estimated to be 0.61 Mg C/ha in 33 years. Carbon stocks in crop residues at the end of the fallow period ranged from 0.10 to 0.64 Mg C/ha. To evaluate the atmospheric CO_2 mitigation capacity by different farming practices, C sequestration in soil, C storage in crop residues and CO_2 emission from fossil fuel consumption and N fertiliser application should be considered together. A full C accounting indicated that maximum C mitigation was achieved with crop residue retention and N fertiliser application under no-till systems.

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