Balancing Soil Carbon Quality and Quantity for Sustainable Agriculture

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Abstract

Increasing demand for food will continue to increase pressure on production of crops and pastures. A productive agricultural system requires a relatively stable pool of soil carbon which is turning over at a range of rates. When crop residues or animal manure are returned to the system much of the material needs to break down during the growth of the succeeding crop in order to provide nutrient turnover and labile carbon to maintain, or improve, soil aggregate stability. This is at odds with carbon sequestration. When such materials are removed from the system for the production of biofuels, compost or biochar there is a loss of both nutrients and labile-carbon capital. The carbon management index (CMI) was developed to give weight to both non-labile and labile carbon in agricultural systems and has been shown to be a useful means of monitoring rates of change of carbon in agricultural systems. Data from the Glen Innes, NSW long-term experiment over 60 years shows that total carbon had declined to about half that of the nearby uncultivated reference site but most of this loss occurred in the non-labile carbon fraction such that in the maize/spring oats/red clover rotation the CMI was at 96 compared to the uncultivated reference value of 100. When red clover was omitted from the rotation CMI had declined to 38. The difficulty of accumulating carbon in the agricultural systems is shown in data from the Rothamstead Broadbalk long-term experiment where calculation of total carbon accumulation from manure showed that only some 5% of that added over 155 years and only 12% of carbon added in straw over 11 years was present in the ploughed depth of 23 cm. The difficult task of sequestering carbon in soil whilst maintaining active nutrient cycling is discussed.

Keywords

Soil organic matter, nutrient cycling, aggregate stability, polyphenols, tough leaf cuticle

Introduction

Increasing world demand for food will continue to increase pressure on the production of crops and pastures. This has the potential to reduce soil carbon concentrations and result in soil degradation from soil structural and nutrient decline, and a loss of soil fertility. The application of farmyard manure (FYM) to soil has been practised for many centuries. The addition of organic materials to the soil such as FYM, manures from intensive livestock industries, sewage sludge or the retention of crop residues has the potential to increase soil C concentration. The use of legume pastures as rotations in cropping systems has also been shown to increase soil C concentrations, particularly the more labile fractions (Haynes 2000). A productive agricultural system requires a relatively stable pool of soil C which is turning over at a range of rates. When crop residues or FYM are returned to the system much of it needs to break down during the growth of the succeeding crop in order to provide nutrient turnover and labile C to maintain, or improve, soil aggregate stability. This is at odds with C sequestration. When materials such as straw residues are removed from the system for the production of compost or biochar there is a loss of both nutrients and labile C capital.

Increased awareness of greenhouse-gas emissions and concerns about global warming has led to increased emphasis on sequestering C in the soil (Follett 2001). Swift (2001) suggested that increased soil C concentration was necessary not only for soil C sequestration, but also to alleviate soil degradation by improving soil structure, nutrient cycling and soil fertility to ensure sustainable agriculture production to feed an increasing world population. The problem is to be able to sequester C in the soil while still providing labile C components for nutrient cycling and to maintain or improve soil structure.

A study on the Glen Innes, NSW long-term experiment investigated the effect of different crop rotations on total C (C_T), labile C (C_L) and compared this to on uncultivated reference site. The CMI was also determined for the different rotations. A second study was carried out on two sections of the Rothamsted Broadbalk wheat experiment and investigated the effect of long-term manure applications and straw management under different nitrogen (N) regimes on the accumulation of C in the soil plough layer.

Materials and methods

Glen Innes long-term experiment

In 1982, soil samples were collected and carbon fractions analysed from a limited number of treatments from the long-term experiment at Glen Innes, NSW, which commenced in 1921. Three crop rotations, which differed in the number and type of crops grown, the amount of time in fallow and the amount of time in pasture, were sampled and carbon fractions analysed. The treatments sampled were

- Maize/spring oats rotation (M/SO), (6 maize crops, 6 oat crops and 72 months of fallow in each 12 year cycle).
- Maize/maize/spring oats/red clover rotation (M/M/SO/C), (6 maize crops, 3 oat crops, 45 months clover and 42 months fallow per 12 years).
- Maize/spring oats/red clover rotation (M/SO/C), (4 maize crops, 4 oat crops, 60 months of clover and 36 months of fallow per 12 year cycle)

C_T was determined by catalytic combustion on a Carlo Erba NA1500 CNS analyser (Blair et al. 1995). Since the soils contained carbonates they were pre-treated with 2.5% v/v orthophosphoric acid (85%) (Lefroy et al. 1993). C_L was measured by oxidation with 333 mM $KMnO_4$ according to the method of Blair et al. (1995). Non labile C (C_{NL}) was calculated from the difference between C_T and C_L. The carbon management index (CMI) and Lability Index (LI) derived by Blair et al. (1995) was calculated for each of the treatments using a nearby uncropped pasture area for the reference sample.

Broadbalk experiment

The Broadbalk experiment is located at Rothamsted Research in the United Kingdom. After several centuries in arable cropping, the experiment started in autumn 1843, with the sowing of the first winter wheat (*Triticum aestivum*) crop. The experiment has changed over the years to reflect changes in agricultural practice. This study used results from 5 treatments of the experiment. A detailed explanation of the experiment is given in Blair et al. (2006a).

The treatments studied were

- 35 t ha^{-1} of fresh FYM added each year since 1844 (Fym) straw removed.
- No fertiliser applied since 1844 (Control) straw removed.
- P, K and Mg fertiliser applied since 1852 (N0), straw retained since 1986.
- P, K and Mg fertiliser applied with 288 kg N ha^{-1} since 1985 (N288) straw retained since 1986.
- P, K and Mg fertiliser applied with 288 kg N ha^{-1} since 1985 (N288) straw removed.

The fresh FYM was applied in the autumn and the mean dry matter content of the FYM from 1968 to 1998 was 23%. Tillage was with mouldboard ploughing to a depth of 230 mm. In August 1998, soil samples were collected from each of the above treatments. Sub-samples of the soil were ground to < 500 ?m and C_T determined as for the Glen Innes experiment above. The amount of C added to the soil from either the straw or manure was calculated assuming the manure and straw contained 50% C and that the mean dry matter content of the manure was the same for the period from 1844 to 1998 as it was for the period from 1968 to 1998.

Results

The most exploitative rotation in the Glen Innes experiment was the M/SO, which showed a 54% decline in average maize yield from the 1922-33 12-year cycle to the 1970-81 12-year cycle. This compared to a 17% decline in average maize yield in the M/M/SO/C rotation and a 7% decline in the M/SO/C rotation. These changes in yield are only reflected in differences in the C_T pool between the M/SO rotation and the two rotations with red clover (M/M/SO/C and M/SO/C), whereas, they are clearly reflected in differences in the C_L pool between all three rotations, with the most conservative rotation having a higher C_T, a much higher C_L pool and, concomitantly, a significantly higher LI and CMI (Table 1). The M/SO/C rotation had the highest C_T of all rotations but it was still 56% less than the C_T for the uncropped reference soil while the C_L in this rotation had only been reduced by 20% compared to the reference (Table 1).

Over the 155 years of the Rothamsted Broadbalk experiment, a total of 1248 t of manure (dry weight equivalent) had been added to the Fym treatment. Assuming that the manure contained 50% C, 624 t/ha of C had been added over this time. This resulted in an increase in C_T of 35.4 t/ha above that of the control treatment where no manure had been added (Table 2). These results showed that of the manure added in the 155 years only about 5% had accumulated in the soil (Table 2). These amounts do not take into account the additional C that would have been accumulated from the increased weight of roots added to the system.

Table 1. Effect of crop rotations on C dynamics in the Glen Innes crop rotation experiment.

	Rotation			
	M/SO[1]	M/M/SO/C[1]	M/SO/C[1]	Reference
C_T (mg/kg)	13.7 b[2]	19.7 a	20.7 a	47.2
C_L(mg/kg)	2.8 c	3.8 b	6.3 a	7.9
LI	1.3 b	1.2 b	2.2 a	
CMI	38 c	50 b	96 a	100
% N	0.12 c	0.22 b	0.25 a	

[1] M= maize; SO = spring oats; C = red clover.

[2] Numbers within a row followed by the same letter are not significantly different from each other

Table 2. Manure and carbon (C) added, C_T measured and C accumulated for the control compared with the farmyard manure (Fym) treatments over 155 years.

Treatment	Dry wt. manure added in 155 years (t/ha)	C added in 155 years (t/ha)	C_T (t/ha)	C accumulated (t/ha)	% C accumulated of that added
Control	0	0	26.5		

Fym	1248	624	58.9	35.4	5

During the 11 years of straw retention on the Rothamsted Broadbalk experiment, 82.4 t/ha (dry weight) of straw had been added to the N288 treatment while only 14.7 t/ha had been added to the N0 treatment (Table 3). Assuming that the straw contained 50% C, an additional 67.7 t/ha of straw had been added to the N288 treatment, compared to the N0 treatment over 11 years. After subtracting the additional accumulation of C_T for the roots and stubble using the C_T value for the N288 straw removed treatment, the amount of C accumulated from this additional straw was 4.4 t/ha (Table 3). This shows that although the use of 288 kg/ha of N resulted in the addition of 67.7 t/ha of straw, only 12 % of the C contained in the straw was accumulated in this soil over the 11 year period (Table 3).

Table 3. Straw and carbon (C) added, total carbon (C_T), C accumulated (after allowing for that from the roots, calculated from the C_T values for the 288 kg/ha nitrogen (N288) treatment with straw removed) for the zero nitrogen treatment (N0), straw retained, compared with the N288 treatment, straw retained over 11 years.

Treatment	Straw added in 11 years (t/ha)	Additional straw added (t/ha)	Additional C added in straw (t/ha)	C_T measured (t/ha)	C accumulated allowing for roots (t/ha)	% C accumulated of that added
N0	14.7	0	0	26.5		
N288	82.4	67.7	33.9	36.4	4.4	12

Discussion

The lower reduction in C_L and the CMI, compared to the reference, for the Glen Innes experiment when red clover was used in the rotation and fallow length was reduced, was clearly reflected in the reductions in yields shown over the time period. The lower reduction in C_L but not in C_T for the M/SO/C rotation compared to the M/M/SO/C rotation shows that a longer time under red clover, combined with a shorter fallow period, reduced the decrease in the more labile fractions compared to the non-labile fractions. The increased N resulting from N fixation from the legume could also increase the formation of more labile C compounds from the crop residues (Blair et al. 2006a). C_L drives the nutrient cycling in the system and also provides binding agents for sustained aggregate stability and increased water infiltration (Blair et al. 2006b). Increased nutrient cycling, better soil structure and increased water infiltration along with increased N, can all contribute to higher yields in following crops. Blair et al. (2006b) also showed a lower reduction in C_L and CMI as the result of legumes in a cereal rotation compared to a reference soil and greater reductions of C_L and CMI when fallowing was included in a cereal rotation compared to a reference. The CMI of the system is a sensitive indicator of the sustainability of cropping systems as it takes into account both the changes in C_L and C_{NL} of a cropping system when compared to an uncropped reference.

Disturbance of soils in cropping systems reduces C in the soil and has contributed to the increased CO_2 levels that are leading to global warming. The addition of large quantities of organic matter to soils such as that from FYM or straw return is often suggested as a means of increasing soil C and hence sequestering C in the soil. However it is essential to maintain a balance between the C_L which is required for nutrient cycling and soil structure, and the non-labile fraction which has a longer half life and consequently the potential to be sequestered in the soil. The difficulty of sequestering C from FYM and straw in the soil is shown by the small percentage of the added C from FYM and straw that remained in the soil of the Rothamsted Broadbalk experiment. The 12% of the straw C remaining in the soil over the 11 year period shows that C sequestration is a long-term process. Even with additions of high amounts of

FYM C sequestration remains difficult as only 5% of the C from the FYM added over the 155 year period remained in the soil. This did not take into account the amount of C contributed by the increased amount of roots from the increased yields in the Fym treatment which would likely have reduced even more the percentage of FYM remaining in the soil. FYM contains animal manures, straw and animal urine and can break down rapidly in the soil.

The addition of biochar has been shown to increase soil C_T, however the amounts applied to the soil need to be large, 22 t/ha (Gaskin et al. 2010) and up to 100 t/ha (Chan et al. 2007). The lowest application of 10 t/ha in a 6-week pot trial increased C_T by 25% compared to the control, while the highest application of 100 t/ha increased C_T by 338% over the same period, however losses of C were also high (Chan et al. 2007). The application of such large amounts are only feasible over small areas of cropping lands, thus a different approach is required for large agricultural areas and a more sustainable method for providing a balanced increase in both C_L and C_{NL} to agricultural land is necessary.

A study by Blair et al. (2005) showed that the use of plant residues which breakdown slowly in the soil so that nutrients are released closer to crop demand and labile C compounds are released slowly over extended periods, resulted in a more sustainable system. The addition of organic residues to the soil which were high in N, had a low C:N ratio but were also high in polyphenols and had a tough leaf cuticle inhibited rapid C breakdown and resulted in a continual increase in soil aggregate stability over 200 days (Blair et al. 2005). The organic residue which had the same N concentration and C:N ratio but was low in polyphenols and with a soft leaf cuticle not only broke down more rapidly in the soil but 20% of the N from this treatment was lost in the first 10 days (Blair et al. 2005). These results showed that straw residues and green manures should be selected for high polyphenol contents and tough leaf cuticles to increase the sustainability of the system. This would allow for nutrient release more in line with the demand of the following crop, continual release of labile C compounds to increase aggregate stability and maintain C in the system for extended periods, resulting in some sequestration of C.

Conclusion

A balance is required between the quality and quantity of C added to soils to provide labile C compounds for nutrient cycling and aggregate stability while also allowing for C sequestration. The removal of crop residues for the production of biofuels, compost or biochar could have a detrimental impact on soil C, particularly the labile compounds, which would have a direct impact on the sustainability of the system.

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