IMPACT OF CROPPING ON THE SOIL C AND N, AND THE POTENTIAL FOR C SEQUESTRATION UNDER HARDWOOD FOREST PLANTATIONS IN SUBTROPICAL QUEENSLAND, AUSTRALIA

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Abstract
Cropping has been extensively practiced in the Kingaroy district of southeast Queensland for more than 30 years. This cropping has resulted in such a serious decrease in soil fertility that hardwood plantations are being established on the crop soils. To quantify the magnitude of carbon (C) and nitrogen (N) decline, samples of soil to 90 cm were taken under 3 treatments; natural subtropical rainforest (Natural), continuously cropped (Crop), and cropped then pasture (Pasture). The Natural soil had a greater total carbon (TC, 8.9%) and total nitrogen (TN, 0.7%) than both the adjacent Crop (2.2% and 0.2% for TC and TN, respectively) and Pasture (3.8%, 0.3%) in the top 5 cm of soil. This trend was repeated with depth down the soil profile; Natural TC and TN were always greater than both Crop and Pasture soil TC and TN, and the Pasture soil TC and TN were greater than those of the Crop soil. The delta ^{13}C ($\delta^{13}C$) value for soil under Natural vegetation was -25.9‰ in the top 5 cm, while the Crop and Pasture soils had values of -23.4‰ and -22.1‰, respectively. The increase in $\delta^{13}C$ with the clearing of the natural C_3 vegetation for crop and pasture in the surface soil indicates the increasing presence of C_4 vegetation. Soil $\delta^{13}C$ decreased with depth for both Crop and Pasture treatments to a value similar to that for the Natural treatment. Sampling over the next 20 years will quantify C sequestration in soils under the hardwood forest plantations that have been established on the Crop and Pasture treatments.

Additional Keywords: stable isotopes, natural abundance, soil carbon, hardwood forestry, soil organic matter.

Introduction
Soil organic matter (SOM) is an important indicator of soil fertility, and closely associated with many critical soil chemical, physical and biological processes (Fisher and Binkley, 2000). The role of SOM in the global climate has become important with suggestions by the Kyoto protocol that soils may act as a potential sink for carbon dioxide (CO_2) (Krull and Skjemstad 2003). Changes in climate and land-use will have a significant effect on the carbon (C) budget, particularly soil C, as soil fertility is strongly dependent upon the accumulation and turnover of soil organic C and nitrogen (N) (McColl and Gressel, 1995; Fisher and Binkley, 2000). SOM quality and fertility can decline rapidly with the introduction of agricultural practices, such as cropping and grazing of pastures where many of the nutrients are removed in produce from the ecosystem. This decline is enhanced without the addition of fertilizers. However, it is becoming increasingly common for farmers to plant native forest trees on ex-farmland to improve the soil structure and SOM quality. Forests store 20-100 times more C per unit area in aboveground biomass and soils than croplands (Sanchez et al. 2003), while acidic forest soils have a particularly high potential to sequester large amounts of C, and thus become a significant sink for atmospheric CO_2 (Hagedorn et al. 2001; Sanchez et al. 2003). Harvesting of the forest will lead to greenhouse gas emissions, but CO_2 will then be taken out of the atmosphere again if the forest is replanted or encouraged to regenerate naturally (Australian Greenhouse Office 2001).

The application of stable isotope analyses to SOM studies has become an increasingly used tool to assess SOM decomposition and transformations, vegetation and climate changes, and land-use change or management (Balesdent *et al.* 1987; Nadelhoffer and Fry 1994; Ehleringer *et al.* 2000). The delta ^{13}C ($\delta^{13}C$) and $\delta^{15}N$ values of SOM reflect contributions from plant foliage and stems, roots, and the consequences of the subsequent processes occurring within the soil (Boutton *et al.* 1999; Ehleringer *et al.* 2000), while the photosynthetic contribution to SOM from C_3 and C_4 vegetation can also be easily distinguished using stable isotope analyses (Ehleringer *et al.* 2000). Woody plants possess the C_3 photosynthetic pathway with a $\delta^{13}C$ range of –27 to -32‰, while plants with the C_4 pathway have $\delta^{13}C$ range from –13 to -17‰ (Smith and Epstein 1971). Fractionation dynamics of N in soils are commonly assumed to progress towards ^{15}N enrichment due to SOM decomposition as the proportion of ^{15}N-enriched microbial biomass increases (Nadelhoffer and Fry 1994; Krull and Skjemstad 2003) and most soils show

^{13}C enrichment with depth (and degree of decomposition) despite an assumed increase in ^{13}C-depleted lignin (Benner *et al.* 1987). Carbon isotope dynamics do not follow a simple pattern but seem to be influenced by a combination of environmental, chemical and mineralogical factors (Krull and Skjemstad 2003).

In the lowland soils supporting sugarcane (C_4 species) that was grown on soil previously under tropical rainforest (C_3) in northeastern Queensland, Spain *et al.* (1990) used stable ^{13}C isotopes to study the source of SOM consumed by the pantropical earthworm species *Pontoscolex corethrurus* (Muller). They demonstrated that it was unlikely that much of its tissue C would be assimilated from the more complex fractions of SOM derived from the original C_3 tropical forest vegetation. The $\delta^{13}C$ value of the earthworm tissues was -9‰ compared with -12‰ in the plant tissue and -15‰ in the soil, suggesting that *P. corethrurus* may derive much of its tissue C from an intimate association with the sugarcane roots (Spain *et al.* 1990). In a preliminary study Saffigna (2000) compared the C and $\delta^{13}C$ values for plant and surface soil samples from a *Paspalum* (C_4 grass with a $\delta^{13}C$ value of -13‰) site with an adjacent 4-year-old *Eucalyptus pellita* (C_3 tree with $\delta^{13}C$ of -31‰) hardwood plantation site established on agricultural land in tropical north Queensland. The limited sampling intensity precluded statistical analysis. However, the soil $\delta^{13}C$ (-22‰) for the hardwood plantation site showed a trend of being 2 units more negative than the $\delta^{13}C$ (-20‰) for the grass site. This may reflect C sequestration in the soil due to the presence of the C_3 tree species.

The objective of this study was to evaluate the impact of cropping and pasture for over 30 years on the C and N status of soils at Kingaroy, as compared with the natural vegetation. These results will provide a baseline for quantification of C sequestration by the trees that have now been planted onto the crop and pasture sites. Soil sampling will take place over a 20-year period to quantify the extent of C sequestration in the soil.

Materials and Methods

Site and Soil Description

The field site is located at Coolabunia, near Kingaroy (26°35'S, 151°50'E) in southeast Queensland where cropping has been extensively practiced for over 30 years. There were 3 adjacent sampling sites at Coolabunia. The Crop site had been cropped to maize (*Zea mays*) and peanuts (*Arachis hypogaea*) for over 30 years. The Pasture site had initially been cropped, and then was a predominantly green panic (*Panicum maximum*) and Rhodes grass (*Chloris gayana*) pasture for over 20 years. The Natural site was sub-tropical dry vine forest.

Kingaroy is situated approximately 215 km north west of Brisbane and some 130 km inland from the coast. Elevation at Kingaroy is 441 m above sea level. The climate is classified as sub-tropical, with long summers and mild winters. Annual rainfall varies from 339 to 1430 mm, with an average of 781 mm, and is summer-dominant with about 70% falling between October and March. Frosts also occur during winter, with low-lying areas having the highest number of and severest frosts. June, July and August are the coldest months and on average Kingaroy has 24 heavy and 22 light frosts each year. Occasional frosts can also occur in May and September. Kingaroy does not have the high summer temperatures of many other regions in Queensland with December and January - the hottest months – averaging only 10 days between them over 32°C and usually only one day over 38°C (100°F). The yearly average maximum temperature is 24.7°C, while the yearly average minimum is 11.4°C.

The soil is classified as a Red Ferrosol according to the Australian Soil Classification of Isbell (1996), or a Tropeptic eutrustox (Oxisol) by the Soil Survey Staff (2003). Three replicate soil samples to 90 cm were taken from under the 3 treatments; natural vegetation (Natural), continuously cropped (Crop), and cropped then pasture (Pasture).

Total Carbon, Total Nitrogen and ^{13}C and ^{15}N Natural Abundance

The total C (TC), total N (TN), ^{13}C natural abundance ($\delta^{13}C$) and ^{15}N natural abundance ($\delta^{15}N$) analyses were determined in triplicate on each soil sample on an Isoprime isotope ratio mass spectrometer coupled to a Eurovector elemental analyser (Isoprime-EuroEA 3000). Briefly, soils containing approximately 50 μg N were weighed into 8 × 5 mm tin (Sn) capsules and analysed against a known set of standards. Samples were combusted, and reaction products separated by gas chromatography to give TC and TN content together with stable isotope ratios. The isotope ratios were expressed using the 'delta' notation (δ), with units of per mil or parts per thousand (‰), relative to the marine limestone fossil Pee Dee Belemnite (PDB) (Craig 1953) and atmospheric N_2 standards (Mariotti 1983) for $\delta^{13}C$ and $\delta^{15}N$ respectively, using the following relationship:

$$\delta\ (‰) = (R_{sample} / R_{standard} - 1) \times 1000,$$

where R is the molar ratio of the heavy to light isotope (i.e. $^{13}C/^{12}C$ or $^{15}N/^{14}N$) of the sample or standard (Ehleringer *et al.* 2000). Samples that contain more of the heavy isotope are referred to as 'enriched' and are 'heavier' than other samples, while those that contain less of the heavy isotope are 'depleted' and are 'lighter' than other samples (Lajtha and Michener 1994).

Statistical Analysis

The STATISTICA software package (StatSoft 2001) was used for analysis of all data by one-way ANOVA. Least significant difference (l.s.d.) was used to separate the means when differences were significant.

Results and Discussion

Soil Carbon

Cropping has been extensively practiced in the Red Ferrosols in the Kingaroy district of southeast Queensland for more than 30 years. Table 1 displays the chemical properties for the 0-5 cm soil depth under the adjacent Natural, Crop and Pasture sites. The Natural soil had a significantly greater total C (TC, 8.9%) than both the adjacent Crop (2.2%) and Pasture (3.8%) soils in the top 5 cm of soil ($p<0.001$). This trend continued with depth; Natural soil TC was always greater than both the Crop and Pasture soil, and the Pasture soil TC was greater than that of the Crop soil (Figure 1).

Table 1. Chemical properties of the 0-5 cm soil depth under the Natural, Crop and Pasture sites at Kingaroy, southeast Queensland, Australia. Data in a column are means (n = 3); data in parentheses are standard errors of the means. Means within a column followed by the same letter are not different at the 5% level of significance.

Treatment	Total C (%)	Total N (%)	C/N Ratio	Delta ^{13}C (‰)	Delta ^{15}N (‰)
Natural	8.92 (0.24)a	0.66 (0.014)a	13.5 (0.3)a	-25.9 (0.10)a	7.1 (0.3)a
Pasture	3.78 (0.04)b	0.31 (0.002)b	12.3 (0.2)b	-22.1 (0.10)b	7.0 (0.1)a
Crop	2.15 (0.06)c	0.18 (0.004)c	11.7 (0.1)b	-23.4 (0.07)c	7.8 (0.3)a

At a depth of 90 cm, the TC of the Natural soil was 2.2% compared with 0.5% in the Crop soil and 0.8% in the Pasture soil. TC of the Natural soil was significantly greater ($p<0.001$) than both the Crop and Pasture soils at all depths, while that of the Pasture soil was significantly greater than the Crop soil at most depths ($p<0.01$) with the exception of the 10-20 and 20-30 cm depths. This indicates that soil C has declined with the removal of natural vegetation and the establishment of crop and pasture production. This is in contrast to other studies reporting greater TC values in the top 5 cm of pasture soils after conversion from forest (Desjardins *et al*. 2004; Fearnside and Barbosa 1998). However, the establishment of trees on ex cropping or pasture land can help to improve soil quality and fertility, whilst providing a sink for atmospheric CO_2 (Australian Greenhouse Office 2001).

Soil Nitrogen

Total N follows similar dynamics as TC down the soil profile (Figure 2), with the Natural soil displaying a greater TN (0.7%) in the 0-5 cm soil depth as compared with the Crop (0.2%) and Pasture soil (0.31%). Again this trend continued with depth, with the Natural soil TN always greater than that of the Crop or Pasture soil ($p<0.001$), while the Pasture soil TN was consistently greater than that of the Crop soil ($p<0.01$; $p<0.05$ at 90 cm). At a depth of 90 cm, the TN of the Natural soil was 0.13% compared with 0.03% in the Crop soil and 0.04% in the Pasture soil, yet all means were significantly different at all depths using one-way ANOVA and l.s.d. to separate means at the 5% significance level.

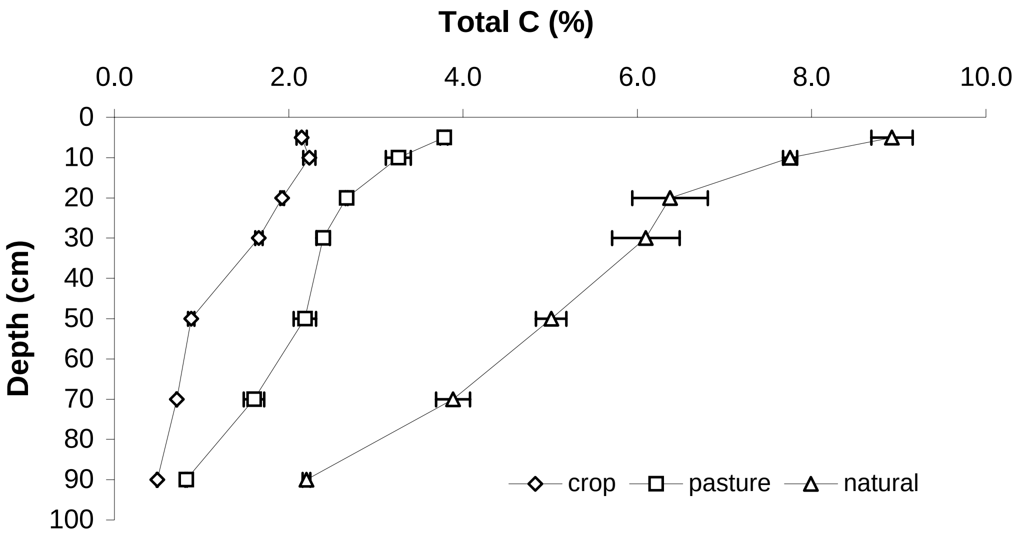

Figure 1. Total C (%) down the soil profile for adjacent Natural, Crop and Pasture sites at Kingaroy, southeast Queensland, Australia.

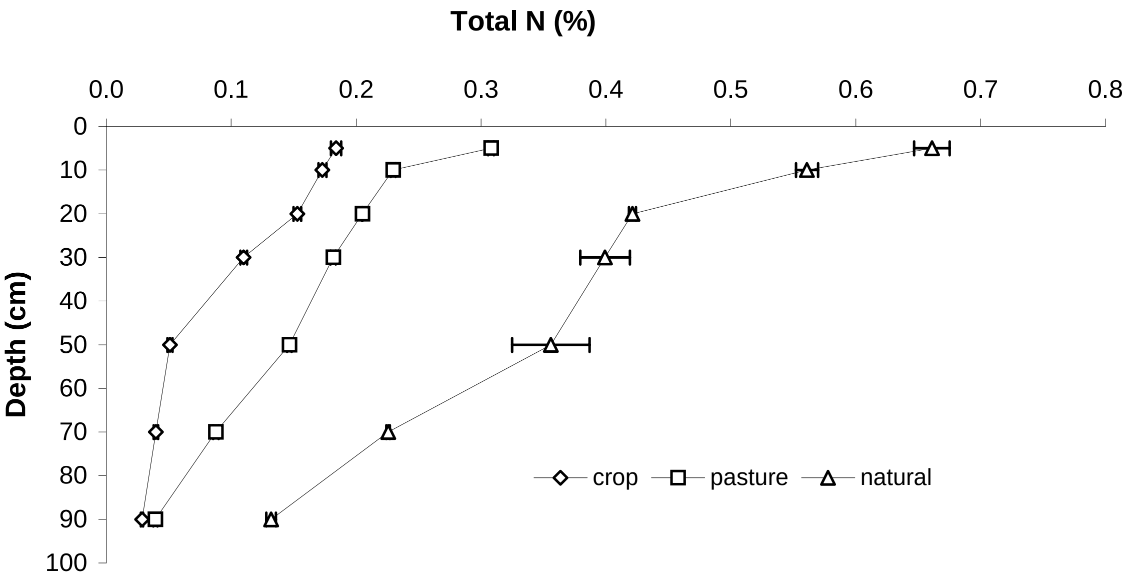

Figure 2. Total N (%) down the soil profile for adjacent Natural, Crop and Pasture sites at Kingaroy, southeast Queensland, Australia.

^{13}C Natural Abundance

The δ^{13}C value for soil under the Natural treatment (-25.9 ‰) was significantly less ($p<0.001$) in the top 5 cm soil (Figure 3) than the Crop (-23.4‰) and Pasture soils (-22.1‰). The δ^{13}C for the Pasture soil was significantly greater ($p<0.001$) than that for the Crop soil in the top 5 cm. The increase in δ^{13}C with the clearing of the C_3 vegetation for crop (2.5 unit increase) and pasture (3.8 unit increase) production in the surface soil indicates the increasing presence of C_4 vegetation, which has an average δ^{13}C value of –13 to -17‰. The smaller increase for the Crop site is most likely due to the influence of the C_3 (δ^{13}C of -27 to -32‰) peanut crop.

Delta ^{13}C decreased with depth for both Crop and Pasture to a similar value as that for the Natural site (Figure 3). The δ^{13}C values reached –25.1‰ at 90 cm in the Crop soil and –24.5‰ in the Pasture, while the Natural soil remained at –25.6‰. Enrichment of δ^{13}C with depth has been observed in a number of forest soil studies

(Nadelhoffer and Fry 1988; Ehleringer *et al.* 2000; Bekele and Hudnall 2003) and Figure 3 indicates that the introduction of pasture and crops at Kingaroy has resulted in an enrichment of ^{13}C at the soil surface due to the presence of C_4 vegetation. Using one-way ANOVA, $\delta^{13}C$ of the Pasture soil at 90 cm was significantly greater than both the Crop ($p<0.01$) and Natural ($p<0.001$) soils, while $\delta^{13}C$ of the Crop soil was significantly greater than that under Natural ($p<0.05$).

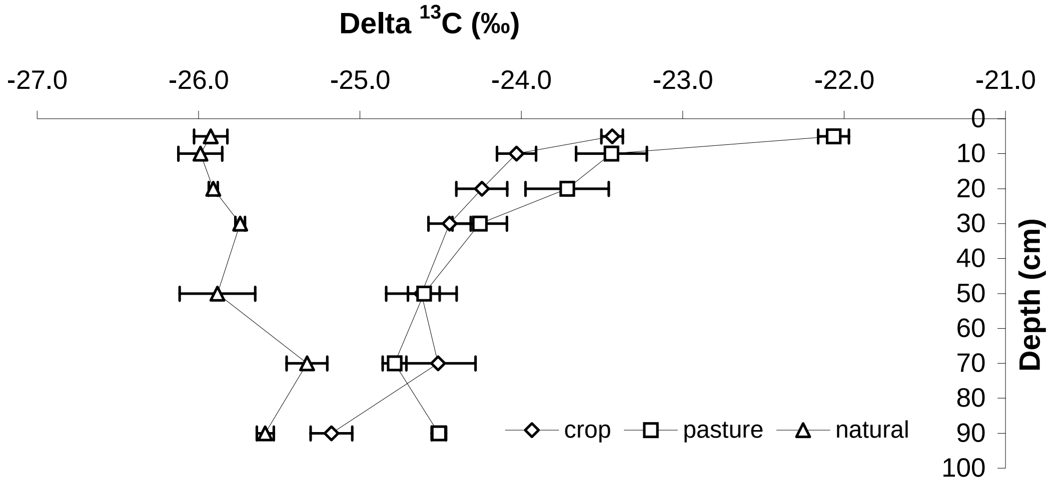

Figure 3. Delta ^{13}C (‰) down the soil profile for adjacent Natural, Crop and Pasture sites at Kingaroy, southeast Queensland, Australia.

Conclusions

This study has demonstrated the major impact of cropping and pasture on reducing the soil C and N content to a depth of 90 cm. Thus there is considerable potential for C sequestration in soil under hardwood forest plantations. Stable carbon isotope analysis of these 3 adjacent soils indicated that differences due to the introduction of C_4 crop and pasture species were evident down the soil profile to 90 cm. The major effect was in the top 50 cm of the soil profile.

Although C had disappeared from the soil, a portion of this C_3 derived C from the original subtropical rainforest was replaced by C_4 derived C from the crop and pasture species. Thus, the gross loss of soil C may be larger than the net loss reported above.

The next phase of this proposed 20-year duration experiment will quantify the magnitude of C sequestration in soil following the establishment of hardwood forest plantations on the crop and pasture sites.

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