CHAPTER 3

A SURVEY OF THE FERTILITY STATUS OF SOILS USED FOR COTTON PRODUCTION IN AUSTRALIA

3.1. INTRODUCTION

Cotton is grown in several identifiable areas in Eastern Australia (Figure 1.1). The cropping systems used in each region varies considerably. In the regions studied in this survey, there are substantial differences in rotations. In Emerald, most of the cotton is grown on 250 ha blocks in state government developed irrigation scheme areas, some of which are close to town. About 90 - 95 % of farmers grow continuous cotton with 50 % of the cotton grown on 1 m permanent beds. There has been a decline in the area of rotational cropping with about 50 - 60 % of the farmers pulling and burning cotton stubble after harvest. On the Darling Downs, about 66 % of the farmers grow continuous cotton with up to 60 % of the cotton grown on permanent beds (Marshall, 1995). About 50 % of the farmers pull and burn stubble after harvest. In the Macintyre Valley, 70 % of the farmers grow continuous cotton, though rotations and fallowing are on the increase. Most of the area is on permanent beds and over 80 % of farmers pull and burn stubble after harvesting. In Namoi and Gwydir Valleys, most cotton growers are gradually adopting farming systems based on some form of 1or 2 m permanent beds, with width depending on preference and circumstances. Almost all farmers are now using some form of rotation to ameliorate adverse soil conditions. The rotation cycle for Namoi is, on average, 2 years cotton/1 year rotation crop, and for Gwydir valley, 3 to 4 years cotton/1 year rotation crop (Shaw, 1993). The main rotation crop is wheat, although other crops such as safflower, faba beans, and chickpeas are sometimes included. In the Macquarie valley, a survey by Kay and Holden (1993) found that 26 % of farmers slash and incorporate stubble, 50 % pull, rake and burn the stubble, while 24 % practice both. About 80 % of the farmers grow cotton on permanent beds. In recent years there has been a marked reduction in stubble burning in all areas.

The soils used for cotton production in Australia are known to have a high chemical fertility status (McKenzie *et al.*, 1995), with responses only to nitrogen. However, data regarding the chemical properties of these soils are scattered or uncoordinated. Also, information relating the chemical fertility status of soils that are currently under cotton production to that of the same soil type in a native state is scarce. Such information will be useful in predicting the trends in soil fertility after extended periods of growing cotton. Most studies on soil fertility under cotton were mainly concerned with nitrogen status (Constable and Rochester, 1988). Some work has been done on soil potassium

in cracking clay soils under cotton (Wright, 1994) with a major focus on premature senescence of cotton. Reports describing the general fertility of these soils are rare. The specific objectives of the study reported in this chapter are to:

1. Provide information on the soil test values in the soils used for cotton production in Australia
2. Examine differences in soil test values between cropped and uncropped soils
3. Determine nutrients likely to limit the growth of cotton seedlings, and
4. Determine possible relationships between soil test values and early seedling growth of cotton.

3.2. MATERIALS AND METHODS

3.2.1. Soil Sampling

The soil samples used for this study were collected at a depth of 0 - 20 cm from seven of the main cotton growing regions of New South Wales (NSW) and Queensland (Qld) to give a total of 65 samples ranging widely in cropping histories (Table 3.1). A more detailed description of the sampling sites is given in Appendix 3.1. The soil samples collected represent the main soil types used for cotton production in Australia, notably red, brown and grey cracking clays, together with some red brown earths, black earths, and alluvial soils (Stace *et al.*, 1972). All samples were collected between late winter and early spring (August to September) after the field has been ploughed prior to the next cotton crop. All the cropped sites sampled had cotton grown on them in the previous summer. The samples were collected such that for each cropped site, an adjacent uncropped sample was collected as a reference. Across all sites, samples were collected using a stratified random sampling scheme as described by Crépin and Johnson (1993). Each site was divided into two strata and samples were collected from several points randomly selected in each of these strata. The samples collected from each site were bulked in clean bins and taken to a potting shed in preparation for a double-pot nutrient omission trial. The bulk samples were thoroughly mixed, sieved through a 2 mm sieve, and then sub-sampled for carbon and nutrient analyses.

3.2.2. Soil Nutrient Analyses

All chemical analyses were carried out at the INCITEC Analytical Laboratories (Brisbane) using the methods described as follows: Soil pH was determined using a combination electrode in a 1:5 soil:water ratio stirred for 1 hr. Nitrate-N was extracted in a 1:5 soil:water ratio and determined colorimetrically using a segmented flow analyser. Sulfur was extracted as SO_4-S by 0.01M $Ca(H_2PO_4)_2$ in a 1:5 soil:solution ratio for 16 hr and measured on an Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP-AES). Phosphorus was extracted for 16 hr in a 1:100 soil:solution of 0.05 M $NaHCO_3$ and determined in a segmented flow analyser. Exchangeable cations

were measured by ICP-AES in 1:10 neutral normal ammonium acetate extracts, and the CEC was calculated as the sum of exchangeable cations. Electrical conductivity was measured in a 1:5 soil:water ratio, stirred and allowed to stand for 1 hr before read by a conductivity meter. Chlorides were extracted in 1:5 soil:water ratio for 1 hr, centrifuged and measured colorimetrically in a segmented flow analyser. Micronutrients (Zn, Mn and Fe) were extracted in 1:10 soil:solution ratio using DTPA (diethylenetriaminepentaacetic acid) for 1 hr and then measured on ICP-AES. Boron was extracted in a 1:2 soil:solution ratio of 0.01M $CaCl_2$ for one hour and measured on ICP-AES. Aluminium was extracted in a 1:10 soil:solution ratio of 1M KCl for 1 hr and measured on an Atomic Absorption Spectrophotometer. Organic carbon (C_{WB}) was determined by the method of Walkley and Black (1934) as modified by Sims and Haby (1971).

Table 3.1: Distribution of samples by region and period under cultivation. Soil of the same type occurring more than once in a region indicate different locations

		Number of samples					
Region	Soil type	Reference	< 5 yrs	5-10 yrs	11-20 yrs	21-30 yrs	> 30 yrs
Gwydir	Red clay	1	-	1	1	-	-
Valley	Brown clay	1	-	1	1	-	-
(NSW)	Grey clay	1	-	1	1	-	-
Emerald	Grey clay	1	-	-	1	-	-
(Qld)	Black earth	1	-	-	-	2	-
	Alluvial	1	-	-	2	-	-
Macintyre	Red earth	1	-	-	1	-	-
Valley	Black earth	1	-	1	-	-	-
(Qld)	Grey clay	1	-	1	-	-	-
	Grey clay	1	1	-	1	-	-
Bourke	Red earth	1	-	-	-	1	-
(NSW)	Grey clay	1	-	1	-	-	-
	Grey clay	1	1	-	-	-	-
	Grey clay	1	1	-	1	-	-
Macquarie	Red brown earth	1	-	-	-	-	1
Valley	Red brown earth	1	-	1	-	-	-
(NSW)	Grey clay	1	1	-	1	-	-
	Alluvial	1	1	2	-	-	-
Darling	Grey clay	1	-	-	-	-	1
Downs (Qld)	Grey clay	1	-	-	-	-	1
	Black earth	1	-	-	-	-	1
	Grey clay	1	-	-	-	-	1
	Black earth	1	-	-	-	-	1
Namoi	Grey clay	1	-	-	-	1	-
Valley	Grey clay	1	-	-	-	-	1
(NSW)	Grey clay	1	1	-	-	-	-
	Grey clay	1	-	1	-	1	-

3.2.3. Double-pot Experiment

(a) Background

The double-pot technique employed in this study closely follows that described by Janssen (1974, 1990). The method was developed in the 1970s (Janssen, 1974; Muller, 1979) as a follow-up to the technique used by Bouma and Dowling (1966) for the assessment of nutritional stress in plants. The double-pot technique consists of two pots (15 cm diameter) with one pot containing a known weight of the soil sample to be investigated and the second pot containing a nutrient solution. The pot containing the soil sample is placed on top of the pot containing the nutrient solution. The soil sample in the top pot is connected to the nutrient solution in the lower pot by means of an absorbent uncut cigarette filter passed through a hole in the bottom of the upper pot.

The principle of this technique is that plants can take up nutrients simultaneously from the nutrients already present in the soil under investigation and from nutrients absorbed into the soil from the nutrient solution below. When a nutrient is omitted from the solution, plants can take up that nutrient only from the soil. The difference between plants on a deficient and on a complete nutrient solution gives an indication of the availability of the omitted nutrient in that soil. The method can serve as a guide to reduce the number of field trials and as an aid to laboratory and field studies.

(b) Experimental Design and Treatments

For each soil, the experiment was set up in a randomised complete block design with seven treatments replicated three times. The treatments consisted of seven nutrient solutions as summarised in Table 3.2. Nutrient solutions were prepared separately for each of the treatments using reagent grade chemicals (Appendix 3.2). The final concentrations of all nutrients in the various solutions are summarised in Table 3.3. The response of cotton to N in the soils studied is now well recognised (Constable and Rochester, 1988; Hearn, 1986) and thus no minus N treatment was included.

Table 3.2: Nutrient solutions used in the double-pot trial

Solution	Description
+ All	All major nutrients (N, P, K, S, Ca, Mg) and micronutrients (Cu, Zn, Fe, Mn, Mo, B)
- All	Distilled water only
- P	All nutrients as in +All except P
- S	All nutrients as in +All except S
- K	All nutrients as in +All except K
- Mg	All nutrients as in +All except Mg
- Trace	All nutrients as in +All except micronutrients

Table 3.3: Final Concentration of Macro- and Micronutrients in Nutrient Solutions

Nutrient	+All	-All	-P	-S	-K	-Mg	-Trace
				Concentration (mM)			
N	10.00	0	10.00	10.00	10.00	10.00	10.00
P	2.00	0	0	2.00	2.00	2.00	2.00
S	0.75	0	0.75	0	0.75	0.75	0.75
K	4.00	0	4.00	4.00	0	4.00	4.00
Ca	3.00	0	3.00	3.00	3.00	3.00	3.00
Mg	0.75	0	0.75	0.75	0.75	0	0.75
				Concentration (μM)			
Fe	150	0	150	150	150	150	0
Mn	15.0	0	15.0	15.0	15.0	15.0	0
Zn	1.50	0	1.50	1.50	1.50	1.50	0
Cu	1.00	0	1.00	1.00	1.00	1.00	0
B	0.50	0	0.50	0.50	0.50	0.50	0
Mo	0.07	0	0.07	0.07	0.07	0.07	0

(c) Growing conditions

From each of the sieved (< 2 mm) bulk samples, 450 g was weighed separately into 21 plastic pots (15 cm diameter) with an absorbent cylindrical filter through the base. These 21 pots served as the upper pots for the three replicates of the seven treatments. The lower pots were half filled with distilled water and covered with aluminium foil to prevent algal growth. The pots containing the 450 g soil sample were then placed on top of the lower pots such that the filter coming from the upper pot touched the base of the lower pot. In this way, water or nutrient solution was continuously being drawn through the filter into the soil above keeping the soil moist and supplying nutrients to the growing seedling.

Seeds of cotton (*Gossypium hirsutum;* variety Siokra V15) were then planted (three per pot) to a depth of approximately 1 cm. After emergence, the seedlings were thinned to one per pot and allowed to establish for two weeks. During this period, the distilled water in the lower pot refilled as necessary. Two weeks after sowing the cotton seeds, when all the seedlings were well established, the distilled water in the lower pots was discarded and replaced by the appropriate nutrient solutions. The solution in the lower pots was monitored daily and the nutrient solutions were replenished to ensure a continuous supply to the growing seedlings. The pots were re-randomised every week. The minimum and maximum temperature of the glasshouse was recorded daily throughout the growing period (Figure 3.1). The seedlings were allowed to grow for another four weeks after applying the nutrient solutions. At six weeks after sowing, the seedlings were harvested by cutting at the cotyledon

node level, placed in paper bags and dried in an oven at 80°C for one week. The dried seedlings were then weighed and the dry weight recorded.

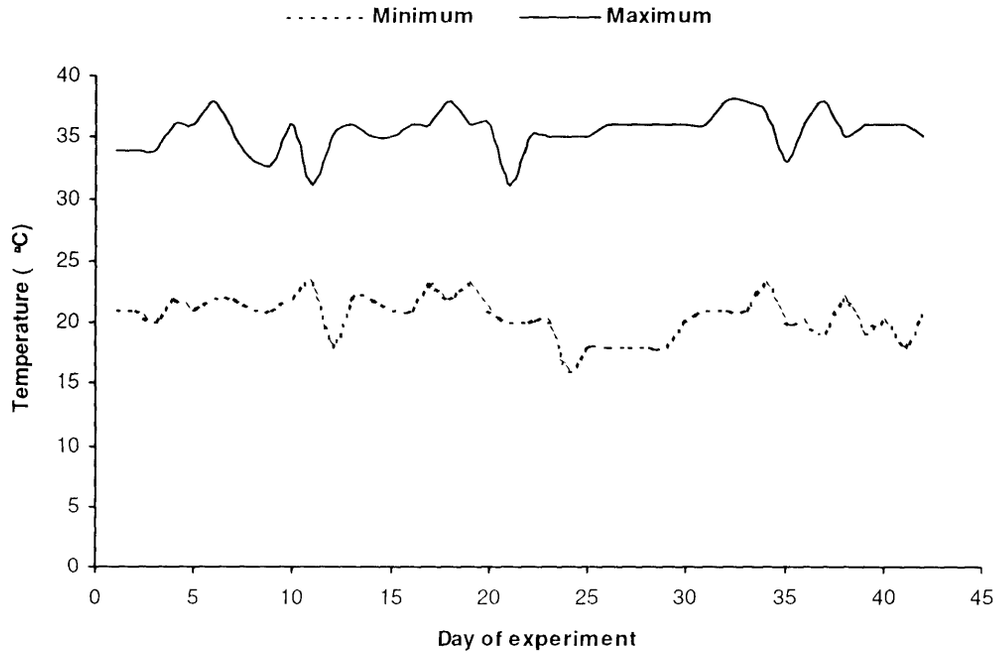

Figure 3.1. Fluctuations in glasshouse temperature during six weeks of cotton growth

3.2.4. Data analysis

Analysis of variance was carried out on the seedling dry matter yields using the NEVA (Version 3.3) analysis of variance program (Burr, 1980). Mean separation was determined using the Duncan's Multiple Range Test. Responses to a particular nutrient were considered to be significant when the dry matter yield was significantly reduced relative to the '+ All' as a result of omitting that nutrient from the nutrient solution. Linear correlation coefficients between soil chemical properties and dry matter yield were calculated using the SYSTAT (Version 5.0) Multivariate General Linear Hypothesis (MGLH) program (Wilkinson 1990). Relative dry matter yields in a deficient solution (dry matter yield in a deficient solution as a percentage of dry matter yield in the complete solution) were plotted against the nutrient level in the soil and then fitted to a Mitscherlich-Bray function. The basic form of this function as described by Melsted and Peck (1980) and Nelson and Anderson (1980) is as follows:

$\log (100 - RY) = \log 100 - c_1x_1$, where RY = relative dry matter yield with all nutrients, except nutrient being studied, at adequate level, c_1 = a constant which relates nutrient level to relative yield, and x_1 = soil test value of the nutrient (eg P, S, K) for the soil under consideration.

3.3. RESULTS AND DISCUSSION

3.3.1. Soil nutrient status

The soil chemical properties varied widely between regions and between sites in the same region. The soil pH ranged from a minimum of 5.8 to a maximum of 8.8, with the lowest pH observed in a sample from the Darling Downs and the highest pH in a sample from the Namoi Valley (Table 3.4). Detailed chemical properties of all sites sampled are presented in Appendices 3.3 - 3.9. Despite the variability in pH values, mean values of samples from all regions fall within a narrow range (7.2 - 8.0). Over 80 % of the samples have pH values in the range 6.5 - 8.8, with more than 60 % above pH 7.5. Fageria *et al.* (1997) mentioned that the critical pH for most annual crops is about 5.5 - 6.0. Although most of the soils used for cotton production in Australia, as observed in this study, have pH values above this range, the extent to which pH limits cotton yields under Australian conditions has not been determined.

The organic carbon content (C_{WB}) in all the regions ranged between 3.0 mg/g and 25.0 mg/g. Generally, organic carbon concentration of these soils is low (Table 3.4) with most of the soils, especially the cropped soils, having an organic carbon concentration below 10 mg/g. Nitrate levels varied widely, but since the response of cotton to N applications in these soils is well recognised (Constable *et al.*, 1992; Constable and Rochester, 1988; Hearn, 1981; Hodges, 1992), only limited discussion on nitrate will be included in this study.

Soil test P values across all sites ranged between 5 and 78 mg/kg (Table 3.4), with the lowest values observed in soils from the Darling Downs and Emerald. Interpretation of these values with respect to sufficiency levels is made difficult by the lack of specific soil test calibrations for cotton under Australian conditions. In an earlier review by Hearn (1981), soil P values (0.5 M $NaHCO_3$ extracts) above 10 mg/kg are considered adequate for cotton. These estimates were based on studies carried out elsewhere, mostly on crops other than cotton, and their applicability to cotton grown under Australian conditions is unclear. For instance, Barber (1982) reported the results of phosphate trials conducted by the NSW Department of Agriculture in the cotton growing regions of Namoi Valley in 1969/70, 1970/71, and 1979/80. The results showed that there was no relationship between lint yield and soil test P level (Olsen test). Similar trials conducted in the same years at Auscott, Warren, in the Macquarie Valley showed that despite low soil test P on some soils, responses to applied P up to 50 kg/ha were variable or nil. It was therefore concluded that available soil P alone was insufficient for determining the extent to which cotton growth will be limited by P. The report of Barber (1982) was preceded by a study by Harris (1974, pers. comm.) which also showed that the common bicarbonate extractable P did not show any relationship with cotton yield. With regards to sulfur nutrition of cotton, much less has been done as compared to P. Hodges (1992) reported that S deficiency is more common on acidic, highly weathered soils low in organic matter.

Table 3.4: Variability in some chemical properties of samples from all regions

Chemical property		Region						
		Gwydir Valley	Emerald	MacIntyre Valley	Bourke	Macquarie Valley	Darling Downs	Namoi Valley
pH	Minimum	6.8	6.8	6.9	7.0	6.0	5.8	5.9
	Maximum	8.3	8.6	8.5	8.6	8.5	8.5	8.8
	Mean	7.5	7.8	7.7	8.0	7.2	7.6	7.5
C_{WB}	Minimum	6.9	7.0	4.9	1.5	5.0	6.3	5.5
(mg/g)	Maximum	20.6	29.1	13.5	4.9	12.8	16.1	23.6
	Mean	10.9	11.4	7.8	2.7	8.9	9.7	10.6
Total N	Minimum	1.4	0.7	0.6	0.4	0.7	0.5	0.8
(mg/g)	Maximum	2.5	2.7	1.4	0.8	1.6	1.6	2.2
	Mean	1.3	1.1	1.1	0.5	1.1	0.9	1.3
NO_3-N	Minimum	6.4	3.3	4.6	3.3	2.2	1.4	4.4
(mg/kg)	Maximum	29.8	18.5	60.0	32.7	60.0	18.2	53.4
	Mean	13.9	9.0	17.8	16.9	29.2	6.0	16.8
S	Minimum	10.0	6.0	5.0	2.0	3.0	2.0	4.0
(mg/kg)	Maximum	56.0	16.0	65.0	25.0	23.0	9.0	22.0
	Mean	19.1	9.9	16.0	11.9	12.1	4.9	12.4
P	Minimum	24.0	7.0	15.0	8.0	5.0	8.0	19.0
(mg/kg)	Maximum	67.0	49.0	76.0	34.0	62.0	40.0	78.0
	Mean	42.2	27.3	32.7	19.2	33.9	17.9	42.5
Exchangeable cations (cmol (+)/kg)								
K	Minimum	0.6	0.3	0.7	0.9	0.5	0.2	1.0
	Maximum	1.5	0.8	1.5	2.2	2.2	1.7	2.0
	Mean	1.1	0.6	1.0	1.3	1.1	0.8	1.4
Ca	Minimum	9.3	14.1	11.0	5.7	4.0	14.1	14.3
	Maximum	25.5	40.6	24.6	23.6	30.6	31.3	29.4
	Mean	16.4	29.1	16.3	15.0	15.5	22.9	20.7
Mg	Minimum	4.0	6.8	5.5	2.2	1.3	8.3	8.7
	Maximum	11.6	20.3	12.0	9.8	8.9	21.6	15.5
	Mean	7.7	12.5	8.6	7.1	5.6	15.1	12.5
Na	Minimum	0.3	0.3	0.7	0.1	0.0	0.4	0.3
	Maximum	2.8	1.5	1.4	4.4	1.3	3.5	5.2
	Mean	0.8	0.6	1.1	1.9	0.6	1.7	1.6
CEC	Minimum	14.8	22.9	20.3	9.2	6.3	27.0	25.1
	Maximum	39.6	62.1	34.0	34.2	39.4	58.0	47.4
	Mean	26.0	42.8	27.0	25.4	22.8	40.5	36.3

According to critical levels recommended for various nutrients by Daniells and Larsen (1991) and Hearn (1981), most of the sites sampled had soil test levels within or above the critical range (Table 3.5). Available P appears adequate in over 80 % of the samples examined. All samples from the Gwydir valley had soil test P levels above the recommended critical levels. Soil test S appears

adequate in most of the sites, except for some soils from Darling Downs (Table 3.5). Potassium levels were adequate in all soils except for some soil types in the Emerald and Darling Downs regions. All soils contain adequate amounts of Ca and Mg for cotton growth. All samples studied had Fe and B levels above the recommended critical level (Table 3.5). Cu and Zn are found below the critical level in a substantial number of samples. However, Constable *et al.* (1988) reported that cotton grown in these soils did not appear to be deficient in Cu, Zn, Fe, Mn or B, and that there is little justification for an expansion of micronutrient fertiliser use on cotton grown in these environments. Constable *et al.* (1988) also concluded that the common soil tests had not shown any correlation with the high levels of these nutrients normally found in cotton. It thus appears that levels of micronutrients determined through plant tissue testing may be a better indicator of their requirement than the levels found in the soil.

Table 3.5: Number of samples from each region falling below, within and above the recommended critical ranges for cotton

			Number of samples						
Soil Test	Critical Range[1]		Gwydir Valley	Emerald	Macquarie Valley	MacIntyre Valley	Darling Downs	Namoi Valley	Bourke
P	10 - 20	Above	9	5	7	5	5	7	3
mg/kg		Within	0	2	2	4	1	2	4
		Below	0	1	2	0	4	0	2
S	5 - 10	Above	7	2	5	6	0	6	3
mg/kg		Within	2	6	6	5	5	2	3
		Below	0	0	0	0	5	1	3
K	0.2 - 0.4	Above	9	7	11	9	8	9	9
cmol/kg		Within	0	1	0	0	1	0	0
		Below	0	0	0	0	1	0	0
Mg	1.0 - 1.2	Above	9	8	11	9	10	9	9
cmol/kg		Within	0	0	0	0	0	0	0
		Below	0	0	0	0	0	0	0
Fe	2	Above	9	8	11	9	10	9	9
mg/kg		Below	0	0	0	0	0	0	0
Mn	2	Above	9	6	9	8	9	9	5
mg/kg		Below	0	2	2	1	1	0	4
Cu	2	Above	1	0	1	0	0	2	0
mg/kg		Below	8	8	10	9	10	7	9
Zn	0.5	Above	4	1	5	9	0	5	9
mg/kg		Below	5	7	6	0	10	4	0
B	0.4	Above	9	8	11	9	10	9	9
mg/kg		Below	0	0	0	0	0	0	0

[1] Critical ranges are based on reports in Daniells and Larsen (1991) and Hearn (1981)

3.3.2. Effects of cropping

The soil properties most affected by cropping were pH, organic carbon, nitrate-N, sulfur, and Fe. While organic carbon and Fe levels declined with cropping, the levels of nitrate-N, sulfur and pH increased with cropping as evidenced by the differences in the reference and cropped soils (Table 3.6). The changes in the various organic carbon fractions in these soils will receive a more extensive coverage in the following chapter (Chapter 4). The Fe extracted by DTPA probably includes Fe associated with organic matter as well as exchangeable Fe (Dalal and Mayer, 1986c)

The increase in pH with cropping could be partly due to losses in organic matter, but most likely the result of deep ploughing bringing up calcium carbonate nodules from depth. In high organic matter soils, hydrogen ions released from carboxyl and other acidic groups present in soil organic matter help to regulate the pH levels by neutralizing the hydroxyl groups responsible for the high pH. Thus, losses in organic carbon with cultivation tend to be accompanied by an increase in pH. Applications of sulfur fertilisers is not a common practice in cotton growing in Australia. However, analysis of irrigation water from several cotton farms have revealed substantial quantities of sulfur in irrigation water, as much as 10 to 13.5 kg S/ML (Conteh, 1996, unpublished data). The higher sulfur content in the cropped soils relative to the reference soils could have resulted from sulfur applied to the soil through irrigation. There is no clear effect of cropping on the soil test P and exchangeable cations (Table 3.6).

3.3.3. Correlations between soil variables

The correlation matrix between soil variables was calculated and examined for useful relationships amongst soil variables (Table 3.7). A strong association between pH and organic carbon, nitrate, P, Ca and CEC can be seen from the significant correlation coefficients. The strong negative correlation between pH and organic carbon agrees with the observations presented earlier (Table 3.6). What was not immediately clear was the observation that both pH and nitrate levels increased with cropping (Table 3.6), yet pH and nitrate are negatively correlated (Table 3.7). It is known that high nitrate levels can reduce soil pH (Constable, 1988), thus the negative correlation. However, it is probable that the reduction in pH caused by increased nitrate levels was not sufficient to offset the increases in pH caused by reductions in soil organic matter and increase in carbonates. Therefore, even though both nitrate and pH increased with cropping, these two soil variables remain negatively correlated. The negative correlation between pH and soil P is most likely due to the high Ca^{2+} ions normally associated with high pH which have the effect of converting water-soluble P into less soluble forms (Hodges, 1992; Tisdale *et al.*, 1985). It is also seen that availability of P and K is favoured by high organic matter levels (Table 3.7).

Table 3.6: Variability in soil chemical properties between reference and cropped soil

Statistic	Cropping history	Chemical property															
		pH	C_{WB} mg/g	NO_3	S mg/kg	P	Exchangeable cations (cmol(+)/kg)						Trace elements (mg/kg)				
							K	Ca	Mg	Al	Na	CEC	Cu	Zn	Mn	Fe	B
Minimum	Reference	5.8	4.0	1.4	2.0	5.0	0.28	3.96	1.34	0.01	0.04	6.34	0.40	0.10	1.00	3.00	0.65
	Cropped	6.0	3.0	1.7	2.0	8.0	0.18	4.30	1.90	0.01	0.23	7.18	0.40	0.10	1.00	2.00	0.67
Maximum	Reference	8.5	25.0	52.2	22.0	78.0	2.21	40.61	21.11	0.01	4.37	62.12	2.50	3.70	46.00	92.00	2.99
	Cropped	8.8	16.0	60.0	65.0	77.0	2.17	38.56	21.57	0.01	5.16	58.04	1.80	2.70	49.00	22.00	2.98
Mean	Reference	7.4	12.9	11.4	8.0	29.8	1.02	18.39	9.77	0.01	1.32	30.52	1.08	0.71	11.22	15.26	1.48
	Cropped	7.8	8.9	19.3	16.1	31.4	1.07	19.78	9.79	0.01	1.09	31.74	0.93	0.59	9.32	7.89	1.44
Median	Reference	7.4	12.0	7.8	8.0	30.0	0.95	16.99	8.70	0.01	1.09	27.45	0.90	0.40	6.00	10.00	1.40
	Cropped	7.9	8.5	13.5	13.5	28.5	1.02	19.96	9.51	0.01	0.85	32.31	0.80	0.40	5.00	6.00	1.31

C_{WB} = Walkley-Black organic carbon

Table 3.7: Linear correlation coefficients between selected soil chemical properties

	pH	C_{WB}	NO_3^-	S	P	K	Ca	Mg	EC	CEC	Ca/Mg
pH	-	-0.45**	-0.27*	ns	-0.34*	ns	0.62***	ns	ns	0.54***	0.31*
C_{WB}	-0.45**	-	ns	ns	0.47***	0.39**	ns	ns	ns	ns	ns
NO_3	-0.27*	ns	-	ns	ns	0.32*	-0.35**	-0.38**	0.52***	-0.39**	ns
S	ns	ns	ns	-	ns	ns	ns	ns	0.63***	ns	ns
P	-0.34*	0.47***	ns	ns	-	0.40**	-0.27*	ns	ns	ns	ns
K	ns	0.39**	0.32*	ns	0.40**	-	ns	ns	0.34*	ns	ns
Ca	0.62***	ns	-0.35**	ns	0.27*	ns	-	0.69***	ns	0.95***	ns
Mg	ns	ns	-0.38**	ns	ns	ns	0.69***	-	ns	0.88***	0.56***
CEC	0.54***	ns	-0.39**	ns	ns	ns	0.95***	0.88***	ns	-	ns

ns = not significant, * significant at $P < 0.05$, ** significant at $P < 0.01$, *** significant at $P < 0.001$

3.3.4. Nutrient responses

The dry matter yield of cotton seedlings for all soils are presented in the Appendices 3.10 to 3.16. The nutrients found to be most limiting to the early seedling growth of cotton in the soils studied were P and S (Table 3.8). From a total of 65 sites studied, significant responses to each of P and S were found in 41 sites. The total number of sites showing responses to K, Mg, and Trace nutrients was much smaller, being 11, 10, and 17, respectively (Table 3.8). There was no significant difference between the reference and the cropped sites in the total number of sites showing significant responses to P, S, K, and Trace nutrients. The total number of reference sites showing responses to Mg was more than double that of the cropped sites. Samples found to be most responsive to P and S were those from Darling Downs and Macintyre Valley, while the least responsive samples were those from Gwydir Valley (Table 3.8). For most of these sites, the total number of responses do not agree with the number of samples showing soil test values below the generally accepted critical levels (Table 3.5). For instance, despite soil test P values above the critical limits for all samples from Gwydir Valley (Table 3.5), significant responses to P were still obtained in some of these samples (Table 3.8). Similar results were observed for samples from all the other sites examined.

To be able to identify any relationship between soil test levels and nutrient responses, relative yields were plotted againts soil test values for P, S, and K, and the resulting scatter plots fitted to a Mitscherlich-Bray function (Figure 3.2). Actual yields do not usually correlate well with soil test results because they contain variations due to soil texture, structure, CEC, source of charge and organic matter content (Melsted and Peck, 1980).

Table 3.8: Significant responses to P, S, K, Mg, and Trace nutrients by region

Region	Cropping history	Total No. of samples	Number of Significant Responses				
			P	S	K	Mg	Trace
Darling	Reference	5	5	4	1	1	1
Downs	Cropped	5	5	4	2	0	0
	Total	*10*	*10*	*8*	*3*	*1*	*1*
Gwydir	Reference	3	2	2	0	0	0
Valley	Cropped	6	1	1	0	1	0
	Total	*9*	3	*3*	*0*	*1*	*0*
Namoi	Reference	4	1	3	0	1	0
Valley	Cropped	5	2	4	1	0	1
	Total	*9*	*3*	*7*	*1*	*1*	*1*
Emerald	Reference	3	3	1	1	0	1
	Cropped	5	1	2	0	0	0
	Total	*8*	*4*	3	*1*	0	*1*
Macquarie	Reference	4	2	2	1	0	0
Valley	Cropped	7	4	2	1	2	1
	Total	*11*	*6*	*4*	*2*	*2*	*1*
MacIntyre	Reference	4	4	4	1	3	4
Valley	Cropped	5	5	5	1	0	5
	Total	*9*	*9*	*9*	*2*	*3*	*9*
Bourke	Reference	4	4	4	1	2	3
	Cropped	5	2	3	1	0	1
	Total	*9*	*6*	*7*	*2*	*2*	*4*
Total	Reference	27	21	20	5	7	9
	Cropped	38	20	21	6	3	8
	Total	**65**	**41**	**41**	**11**	**10**	**17**

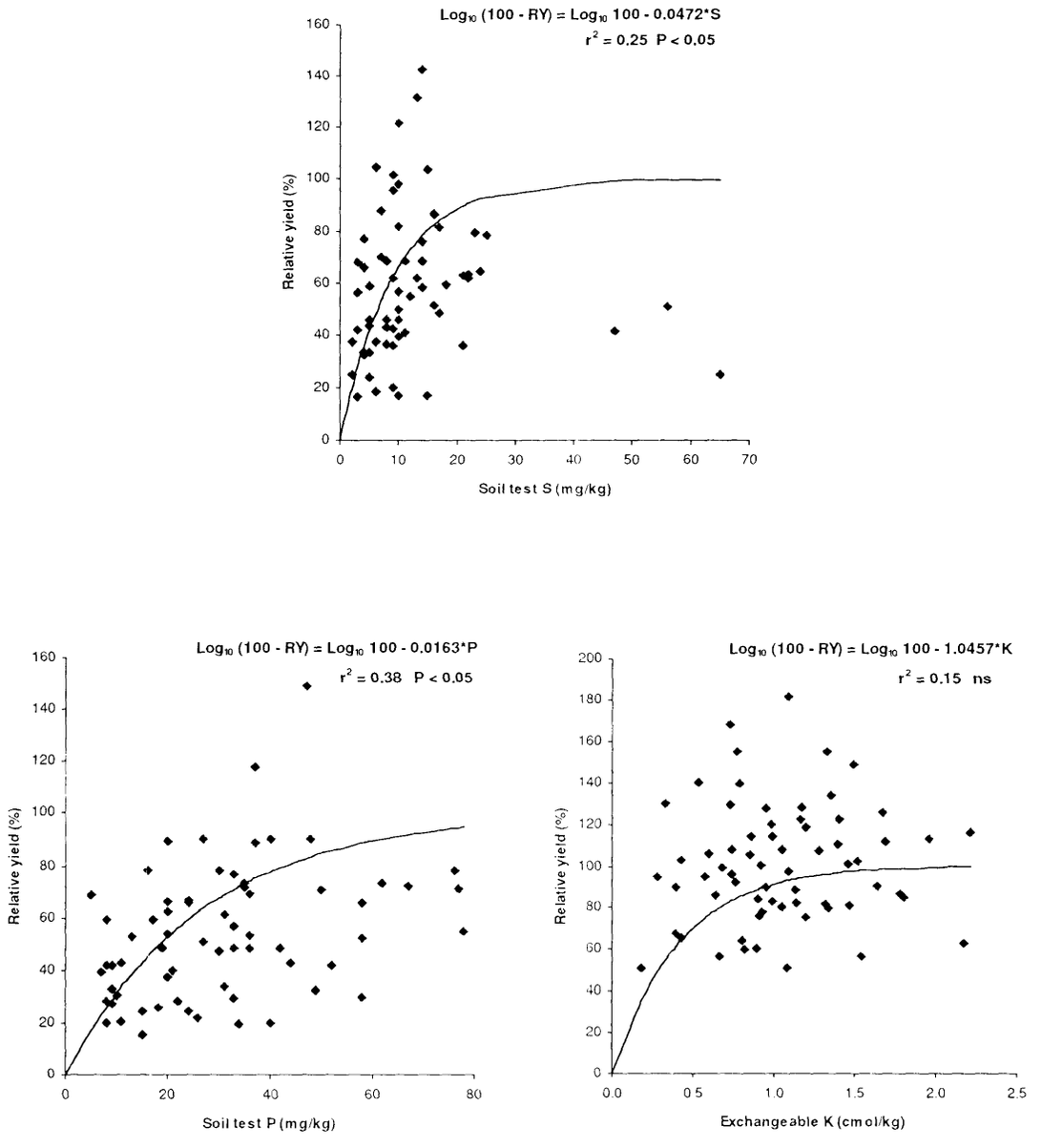

Figure 3.2: Relationship between soil test and relative yield of cotton seedlings using the modified Mitscherlich-Bray growth function. ns = not significant

The results for Mg have not been included because removal of Mg from nutrient solutions resulted in increased growth in a substantial number of samples. Trace elements are also not examined in this relationship because of the difficulty in separating the effects of individual trace elements. Despite the significant r^2 values for soil test P and S, the proportion of the variation accountable by the relationship is too small to be considered satisfactory (Figure 3.2). Soil test K showed no significant relationship to relative dry matter yield.

Although the extent to which responses under glasshouse conditions relate to growth of the cotton plant under field conditions is not precisely known, the results obtained in this survey provide a useful indication of the soils capability to supply nutrients to the developing seedlings. Also, the extent to which the differences in seedling growth observed in this study relate to lint yield and quality is not known.

3.4. CONCLUSIONS

The results from the survey reported in this chapter show that most of the soils used for cotton production in Australia are alkaline in reaction, with a considerable variability in soil test values. The ranges observed for most soil tests indicate adequate chemical fertility in these soils, but no significant relationships were found between soil test levels and nutrient responses under glasshouse conditions. The large number of significant responses to P and S under glasshouse conditions, inspite of the adequate soil test levels, suggests the need for future field studies to examine the role of these nutrients in cotton cropping systems.

CHAPTER 4

CHANGES IN SOIL ORGANIC CARBON UNDER COTTON AS STUDIED BY ORGANIC CARBON FRACTIONATION

4.1. INTRODUCTION

Most of Australian cotton production is carried out in cracking clay soils, most of which have been developed by opening up new land to cultivation. Initially, productivity was supported through the utilisation of nutrients released from accumulated organic matter reserves (Blair, 1993). This high level of organic matter (see Chapter 3) was also a contributor to the physical fertility of these soils. In their native state, these soils are at equilibrium and this equilibrium is disturbed when the soil is brought into cultivation due to the reduced accumulation of fresh organic materials and the accelerated breakdown of already existing organic matter (Nardi *et al.*, 1996).

The prevailing temperatures under which cotton production occurs, accompanied by the repeated wetting and drying cycles resulting from irrigation and rainfall, and the regular application of inorganic nitrogen suggests that cultivation of these soils has generally involved exploitation of soil organic matter reserves (Jenkinson, 1981; Amato *et al.*, 1984 ; Van Gestel *et al.*, 1993). Some growers chisel-plough furrows under dry conditions during the cotton season in an attempt to improve water penetration at the next irrigation. Short-term water entry may occur, but repeated pulverisation of the soil usually creates serious damage due to organic matter loss and dust formation (McKenzie *et al.*, 1995). The effects of low soil organic matter on nutrient availability and soil physical condition emphasise the need for management systems that can monitor and stabilise, at high steady-state, the soil organic matter levels consistent with the prevailing environment.

The complex nature of organic matter in soils, coupled with its association with the soil mineral matrix, has led to the development of a wide range of approaches used for monitoring organic management changes under different soil management systems. Most of these approaches were reviewed in Chapter 2. Since soil organic matter exists in a wide diversity of forms with considerable variability in decomposition rates (Duxbury *et al.*, 1989; Bonde *et al.*, 1992), the loss of the 'labile' fraction could be greater than the loss of total organic carbon upon cultivation. The lability

of any organic carbon fraction could be due to either chemical composition (Skjemstad *et al.*, 1996) or protection within the soil aggregates (Theng *et al.*, 1989; Christensen, 1996). Many workers believe that all soil organic matter is readily decomposable and that only associations with the soil, at both the molecular and aggregate levels, prevent decomposition from occurring rapidly (Duxbury *et al.*, 1989; Piccolo, 1996). The distribution of organic carbon among the labile and non-labile pools is affected by many factors including the type of tillage and length of cultivation (Tiessen and Stewart, 1983; Camberdella and Elliott, 1994). The greatest effects of cultivation on soil organic carbon have been reported to occur in the macroaggregate (250 - 2000 μm) fraction (Camberdella and Elliott, 1993).

This chapter examines the potential value of a simple measurement of labile and non-labile carbon fractions to provide a widely applicable monitoring indicator of organic matter changes in soils under cotton production. Since the rate of organic carbon loss from soils under cultivation is both a function of the chemical nature and location within soil aggregates, this chapter also examines and compares the distribution and relative losses of the different organic carbon fractions in various aggregate size fractions of soils.

4.2. MATERIALS AND METHODS

4.2.1. Soil sampling

The 65 samples described in Chapter 3 were used in this study. The bulk samples, collected from the field, were first air-dried, thoroughly mixed, and then sub-sampled for carbon fractionation. Each of the 65 sub-samples was then sieved through a 2000 μm sieve to remove all litter material. The sieved soil was then further ground, sieved to less than 500 μm, and stored in plastic pet pottles at room temperature prior to analysis.

4.2.2. Determination of total carbon (C_T)

The total carbon (C_T) in each sample was determined using an Automatic Nitrogen and Carbon Analyser by Mass Spectrometry (ANCA-MS). This instrument is usually used for the determination of ^{15}N and ^{13}C in plant and soil samples but can also determine % N and % C on weighed samples. The basic principle of operation of the ANCA-MS has been described in detail by Barrie (1991), Grewal *et al.* (1991), and Barrie and Prosser (1996). Essentially, the sample is subjected to flash combustion in a Carlo-Erba (NA 1500) Dumas-type combustion unit during which all carbon is converted to CO_2 which is then measured by a thermal conductivity detector in a mass spectrometer (Europa Scientific Stable Isotope Analyser). A more detailed description of this equipment has been presented earlier in this thesis (Section 2.5.2).

Each 500 μm sieved sample, containing approximately 350 μg carbon, was weighed into tin capsules (8 x 5 mm). Estimation of sample containing 350 μg C was based on earlier determinations of organic carbon by the Walkley - Black procedure (Chapter 3). The use of the ANCA-MS for measurement of total carbon in preference to the use of the Walkley-Black procedure was because of the known incomplete recovery of carbon by the Walkley-Black procedure (Nelson and Sommers, 1982). Because many of these soils contain carbon in the form of carbonates, each weighed sample was treated with two drops of a 5 % solution of ortho-phosphoric acid prior to ANCA-MS determination. This was added into the tin cups containing the weighed soil and then allowed to dry overnight in an oven at 30°C.

The choice of two drops of ortho-phosphoric acid was based on earlier trials which showed that two drops were enough to remove all carbonates from the small amounts of soil weighed. These earlier trials were carried out on ten high-pH (7.8 - 8.8) samples selected from the set of 65 samples already described. The total carbon on each of these ten samples was measured in triplicate without acid treatment and after one, two and three drops of 5 % ortho-phosphoric acid. Four drops were found to saturate the soil in the tin cups and therefore were not included in the acid treatment trial. The total carbon measured in these soils by ANCA-MS showed no significant difference between two and three drops but both were lower than the one drop and the untreated soil. Therefore, two drops of ortho-phosphoric acid solution were considered to satisfactorily remove carbonates without significantly affecting the organic carbon content.

4.2.3. Determination of labile carbon (C_L)

The labile carbon in each sample was determined using the procedure described by Blair *et al.* (1995b). The procedure is based on the supposition that the oxidative action of a 333 mM solution of potassium permanganate ($KMnO_4$) on soil organic matter is comparable to that of enzymes produced by soil micro-organisms (Loginow *et al.*, 1987). A pre-weighed soil sample containing approximately 15 mg of total carbon (C_T) was treated with an excess of 333 mM $KMnO_4$ for one hour. The amount of carbon oxidised was determined spectrophotometrically from the amount of $KMnO_4$ remaining. This represents the labile carbon (C_L) which was considered as the most readily decomposable fraction of soil organic matter. The unoxidised fraction was referred to as the non-labile carbon (C_{NL}), and was calculated as the difference between C_T and C_L.

(a) Preparation of standard solutions

The 333 mM solution of $KMnO_4$ was prepared by dissolving 263.4 g of reagent grade $KMnO_4$ in 4.5 L of deionised water and made to volume in a 5 L volumetric flask. The solution was then filtered through acid-washed glass wool, transferred into acid-washed bottles and stored in the dark. From the 333 mM stock solution, seven standard solutions needed for the calibration curve were prepared as outlined in Table 4.1. The top standard was the same as the stock solution. To obtain

the exact concentration of each of these standard solutions, they were titrated against a primary standard. A primary standard substance is usually one that is easy to obtain, purify and dry at high temperatures (110 - 120°C) without altering its pure state. It should be readily soluble under the conditions in which it is employed and must have a high equivalent weight so that the weighing errors may be negligible. The reaction with the standard solution should be stoichiometric and practically instantaneous. The titration error should be negligible, or easy to determine accurately by experiment. In this study, the primary standard used was arsenic oxide, As_2O_3.

Table 4.1: Standard solutions used for calibration curve

Solution No.	Concentration (mM)	Volume of 333 mM $KMnO_4$ used (mL)	Volume of deionised H_2O used (mL)
1	333.0	10.0	0.0
2	329.7	9.9	0.1
3	326.3	9.8	0.2
4	323.0	9.7	0.3
5	319.7	9.6	0.4
6	316.5	9.5	0.5
7	313.0	9.4	0.6

(b) Fractionation procedure

Each soil, containing approximately 15 mg C_T, was weighed into 30 mL plastic centrifuge tubes followed by addition of 25 mL of 333 mM $KMnO_4$ stock solution using a dispenser at room temperature. Each batch included at least two blank solutions (333 mM $KMnO_4$ without soil) and a laboratory standard soil of known C_L. Because of small variations in the volume of $KMnO_4$ dispensed, the exact weight of $KMnO_4$ added was recorded rather than the volume. This was done by placing the centrifuge tubes containing the weighed soil on a balance (Mettler PM 6100) before adding the $KMnO_4$ solution. The centrifuge tubes were then firmly capped and tumbled for 60 minutes at a speed of 12 rpm on a tumbler with a radius of 15 cm. At the end of the 60 minutes, the centrifuge tubes were transferred to a centrifuge (Jouan CR412) and centrifuged at 2000 rpm (RCF = 815 g) for 5 minutes.

After centrifuging, all the solutions (standards, unknowns, standard soil and blanks) were diluted by a factor of 250 with deionised water and mixed thoroughly. Caution was taken to ensure that the solution to be diluted was devoid of any particulate matter by taking the aliquot from just below the surface of the solution. Dilution of all solutions was accomplished by the use of a Hamilton automatic diluter (MICROLAB 500 Series) in two steps. The first step consisted of a 1 in 25 dilution (9.6 mL H_2O + 0.4 mL solution) which was followed by a 1 in 10 dilution (4.5 mL H_2O + 0.5 mL

solution). All solutions were thoroughly mixed between dilution steps. The absorbance of the diluted solution was then measured in a split-beam spectrophotometer (Spectronic GENESYS 5) at a wavelength of 565 nm using the top standard as a reference.

(c) Calculations of carbon fractions

The absorbance of the standard solutions was used to prepare a standard curve from which the concentrations of the $KMnO_4$ remaining in the various solutions was calculated. From the concentration of the remaining $KMnO_4$, the labile carbon (C_L) was calculated as follows:

$$C_L \text{ (mg/g)} = \frac{(\text{mM Blank} - \text{mM Unknown}) \times 9 \times \text{weight of KMnO4 added (g)}}{1000 \times \text{Soil weight (g)}}$$

This calculation is based on the assumption that 1 mM $KMnO_4$ oxidises the labile carbon to produce 0.75 mM CO_2 (9 mg C). This corresponds to a valency change of 3 for the Mn ($MnO_4^- \rightarrow MnO_2$) and an assumed average valency change of 4 in the carbon compounds. The C_{NL} was calculated as the difference between C_T and C_L.

Using the C_L and C_{NL} contents obtained, the following indicies were calculated as described by Blair *et al.* (1995b):

Carbon Pool Index (CPI) : The loss of carbon from a soil with a large pool size is of less consequence than the loss of the same amount of C from a soil already depleted of carbon. Similarly it is more difficult to rehabilitate a soil depleted of carbon than one with a large pool. To account for this a carbon pool index is calculated taking into consideration the total carbon content (C_T) of a sample as compared to the carbon content of a nearby uncropped reference soil.

$$\text{CPI} = \frac{C_T \text{ in sample (mg/g)}}{C_T \text{ in reference (mg/g)}}$$

Lability of soil carbon: The lability of soil carbon expresses the amount of C_L present in a soil relative to the amount of C_{NL} in the same soil and is given by:

$$\text{Lability}(L) = \frac{C_L \text{ in sample (mg/g)}}{C_{NL} \text{ in sample (mg/g)}}$$

Lability Index (LI): Losses occurring in C_L of a soil and its impact on sustainability can be estimated from the lability index as follows:

$$\text{Lability Index (LI)} = \frac{\text{Lability of sample}}{\text{Lability of reference soil}}$$

Carbon Management Index: Based on these indicators, an index of carbon status was calculated as follows:

$$\text{Carbon Management Index (CMI)} = \text{Carbon pool index} \times \text{Lability index} \times 100$$

$$= \text{CPI} \times \text{LI} \times 100$$

4.2.4. Aggregate-size separation

From the total of 65 samples, 5 pairs were selected to represent paired cropped/uncropped soil from five sites. A description of the location of these sites, the soil type (Stace *et al.* 1972), the length of cropping and the dominant vegetation at each of the sites is given in Table 4.2. Air-dried soil was first gently crushed by hand and sieved through a 2000 μm sieve. The less than 2000 μm sieved soil was further crushed and passed through a 500 μm sieve and particles greater than 500 μm were discarded. Separation of the various aggregate sizes was done in duplicate using a method similar to that described by Camberdella and Elliott (1994), except that dry sieving was used and only size fractions less than 500 μm were studied. Four sieves were arranged from top to bottom in decreasing order of size of 450 μm - 250 μm - 150 μm - 50 μm. A 50-g subsample from each of the soils was placed on the top sieve and gently shaken until soil had stopped passing through the sieve, generally after 30 - 40 seconds. The top sieve was then detached from the others and the fraction greater than 450 μm was removed, weighed and stored in a glass vial. The procedure was repeated until all five sieves had been used. This gave five aggregate size fractions in duplicate: < 50 μm, 50 - 150 μm, 150 - 250 μm, 250 - 450 μm, and 450 - 500 μm. A similar approach was used by Christensen (1986) to study straw incorporation in soil aggregate fractions.

4.2.5. Isolation of the light fraction

The light fraction was isolated from each aggregate fraction using a procedure similar to that described by Golchin *et al.* (1994) and Whitbread (1996). The separation medium was prepared by dissolving reagent-grade sodium polytungstate, $Na_6(H_2W_{12}O_{40}).H_2O$, (SOMETU, IMBROS P/L, Moonah, TAS 7009), in deionised water and the density adjusted to 1.6 Mg/m^3 using a hydrometer. Each size fraction was weighed (10 g) in a 250-mL plastic centrifuge tube and 100 mL of sodium polytungstate gently added using a dispenser. Some of the size fractions obtained from some soils were less than 10 g, and in such cases all of the fraction was used and the polytungstate added to give a soil:solution ratio of 1:10. After gentle mixing for a few seconds, the particles which adhered to

the stopper and tubes were washed into the suspension using the sodium polytungstate solution. The suspension was allowed to stand for 30 minutes and then centrifuged at 2000 rpm (RCF = 815 g) for 30 minutes in a centrifuge (Sorvall RC-5B, Du Pont Instruments). The supernatant with the floating particles was poured into a Buchner funnel fitted with a glass-fibre filter paper (Whatman GF/A) and filtered under vacuum. The floating material was then washed with deionised water to remove the remaining polytungstate and then dried at 60°C for 12 hours before being scrubbed off the filter paper using a soft brush. This material, considered as the light fraction, was then weighed and stored for analysis.

4.2.6. Chemical analysis of aggregate fractions

Each of the aggregate size fractions and the light fraction obtained from the ten samples was analysed for total carbon (C_T), and $\delta^{13}C$ by ANCA-MS as described earlier for the whole soil (Section 4.2.2). The $\delta^{13}C$ gives the ratio of ^{13}C to ^{12}C expressed relative to a laboratory standard calibrated against the PDB standard (Boutton 1996). The PDB is a carbonate from the fossil of a Cretaceous bellemnite, *Bellemnitella americana*, from the Pee Dee formation in South Carolina. The labile carbon (C_L) in each aggregate fraction was determined using the same procedure described earlier (Section 4.2.3). Relative losses (% decline) of each carbon fraction were calculated from the difference between values in a reference (uncropped) and cultivated soil as follows:

$$\text{Relative Loss (\%)} = \frac{\text{Amount in reference soil - Amount in cropped soil}}{\text{Amount in reference soil}} \times 100$$

Analysis of variance (ANOVA) was performed on the data using the NEVA (Version 3.3) ANOVA program for complete factorial experiments (Burr, 1980). Mean separation was determined using the Duncan's Multiple Range Test (DMRT).

Table 4.2: Description of samples selected for aggregate size fractionation

[A]All of the cropped sites (except for Site 3 with only 6 years cropping) had been under continuous cotton production for at least 10 years.

Site no.	Region	Soil type	Cropping history[A]	Property name	Site location	Dominant vegetation
1	Gwydir Valley (NSW)	Grey Cracking Clay	Native/Reference	"Norwood"	Shed	*Panicum queenslandicum* (Domin) *Eucalyptus microtheca* F. Muell. *Paspalidium constrictum* (Domin)
	"	"	Cropped; 18 years	"	Field 14	Under cotton cropping
2	Emerald (Qld)	Grey Cracking Clay	Native/Reference	"Waterways"	South of Field 1	*Paspalidium caespitosum* *Acacia doratoxylon* *Acacia cambagei* *Acacia harpophylla*
	"	"	Cropped; 21 years	"	Field 1	Under cotton cropping
3	MacIntyre Valley (Qld)	Black Earth	Native/Reference	"Warendi south"	Treeline west of Field 1	*Codonocarpus sp.* Open woodland
	"	"	Cropped; 6 years	"	Field 4	Under cotton cropping
4	Darling Downs (Qld)	Grey Cracking Clay	Native/Reference	"Kupunn"	Not recorded	Mainly Brigalow (*Acacia sp.*)
	"	"	Cropped; 40 years	"	Not recorded	Under cotton cropping
5	Darling Downs (Qld)	Grey Cracking Clay	Native/Reference	"Dalby Agric. College"	Not recorded	Treeless plain; mainly native grasses
	"	"	Cropped; 50 years	"	Not recorded	Under cotton cropping

4.3. RESULTS

Since soil management practices under cotton production tend to vary between regions rather than between soil types, the results are presented by regions. Detailed information on the previous management histories of the specific sites sampled was not available, therefore the results were examined on the basis of existing knowledge of soil organic matter dynamics. Relative changes were expressed based on differences in each carbon fraction between the reference and the cropped soils.

4.3.1. Changes in carbon fractions in soils from the Gwydir Valley

There has been a general decline in the total carbon (C_T) of all the cropped sites in the Gwydir Valley when compared to the reference sites (Table 4.3). Among the three soil types examined from this region, the red clay had the lowest carbon concentration both for the reference and the cropped soil. The greatest decline in C_T was observed on the brown clay which showed a loss of 61% after 14 years of cropping. The greatest loss of C_T occurred in the first five years of cropping, with the greatest loss in the grey clay (56%) followed by the brown clay (49%). Losses of C_T from the red clay after the first five years of cropping were relatively small (3%) compared to the other soil types. Although similar trends were observed in the labile carbon (C_L), the relative changes in C_L were greater than the relative changes in C_T and C_{NL}, especially in the early periods of cultivation (Table 4.3). The Carbon Management Index showed a general decline across all soils with the greatest loss observed in the brown clay.

Table 4.3: Carbon fractions in soils from the Gwydir Valley

Cropping history[A]	C_T (mg/g)	C_L (mg/g)	C_{NL} (mg/g)	Lability (C_L / C_{NL})	CPI	LI	CMI
			Red clay (Norwood)[B]				
Reference	9.9	1.5	8.4	0.17	1.00	1.00	100
5 years	9.6	1.1	8.5	0.13	0.97	0.76	74
14 years	7.7	1.2	6.5	0.18	0.78	1.06	83
			Brown clay (Norwood)				
Reference	21.7	4.2	17.6	0.23	1.00	1.00	100
5 years	11.1	1.4	9.7	0.14	0.51	0.61	31
14 years	8.3	1.2	7.2	0.16	0.38	0.70	27
			Grey clay (Norwood)				
Reference	22.4	3.6	18.7	0.19	1.00	1.00	100
5 years	9.8	1.3	8.5	0.16	0.44	0.84	37
18 years	9.4	1.3	8.1	0.16	0.42	0.84	35

[A]Cropping history refers to length of time under cultivation; [B]Names in parenthesis indicate property sampled

4.3.2. Changes in carbon fractions in soils from the Namoi Valley

An appropriate comparison of the relative changes in the various fractions between regions was made difficult by the differences in cropping histories of the soils from the various sites. Although cultivation resulted in a general decline in C_T, C_L and C_{NL}, the relative losses in the C_{NL} were greater than the relative losses in C_T and C_L, and this is reflected in an increase in the lability index (LI) of the soils from Oakville and Myola (Table 4.4). However, the CMI declined generally.

Table 4.4: Carbon fractions in soils from the Namoi Valley

Cropping history	C_T (mg/g)	C_L (mg/g)	C_{NL} (mg/g)	Lability (C_L / C_{NL})	CPI	LI	CMI
			Grey clay (Kilmarnock)				
Reference	28.0	6.6	21.4	0.31	1.00	1.00	100
40 years	14.6	3.3	11.3	0.30	0.52	0.97	50
			Grey clay (Myola)				
Reference	11.7	1.9	9.8	0.19	1.00	1.00	100
1 year	7.2	1.5	5.6	0.27	0.61	1.42	87
			Grey clay (Oakville)				
Reference	13.4	2.3	11.1	0.21	1.00	1.00	100
10 years	8.5	1.9	6.6	0.28	0.63	1.33	84
30 year	7.2	1.8	5.4	0.33	0.59	1.44	84

4.3.3. Changes in carbon fractions in soils from the Macquarie Valley

The red brown earth soils from two sites in Macquarie Valley showed similar losses in the various carbon fractions inspite of differences in the periods of cultivation. However, the relative losses in C_L were higher than the relative losses in C_T and C_{NL} (Table 4.5). While no significant changes were observed in C_T and C_{NL} in the grey clay, the C_L showed an increase of 20 % in the first four years of cropping, and this is reflected in an increase in the CMI (Table 4.5). The CMI of the grey clay after 12 years of cropping has not changed much when compared to the reference soil. In the alluvial soil, all carbon fractions declined with cropping, with the C_L showing the greatest losses as compared to C_T and C_{NL}.

4.3.4. Changes in carbon fractions in soils from Bourke

All samples from Bourke had very low levels for all carbon fractions (Table 4.6). This is in contrast with the report of Russel (1984) which indicated that cracking clay soils in Australia generally have relatively high organic matter content in the virgin state, whether under grassland or forest. The red earth had the highest C_T level of 6.5 mg/g in the reference soil and 4.8 mg/g in the cropped soil. These values are also out of the range (7.7 mg C/g to 41.0 mg C/g) reported by Spain *et al.* (1983). This region also has the lowest level of total nitrogen (Chapter 3). The reductions in C_T during

cropping ranged from 3% to 40%, while reductions in C_L and C_{NL} range from 0 to 44% and 0 to 23% respectively.

Table 4.5: Carbon fractions in soils of Macquarie Valley

Cropping history	C_T (mg/g)	C_L (mg/g)	C_{NL} (mg/g)	Lability (C_L / C_{NL})	CPI	LI	CMI
			Red Brown Earth (Elengerah)				
Reference	14.9	2.6	12.2	0.22	1.00	1.00	100
10 years	11.0	1.85	9.2	0.20	0.74	0.91	67
			Red Brown Earth (Allambie)				
Reference	11.4	2.0	9.4	0.21	1.00	1.00	100
50 years	8.2	1.4	6.8	0.21	0.72	1.01	72
			Grey Clay (New Tereweena)				
Reference	10.8	1.0	9.8	0.10	1.00	1.00	100
4 years	10.7	1.2	9.7	0.12	0.99	1.25	125
12 years	7.8	0.9	6.9	0.14	0.73	1.39	101
			Alluvial Soil (Kilowen)				
Reference	11.7	1.9	9.7	0.20	1.00	1.00	100
2 years	6.0	0.8	5.2	0.16	0.51	0.80	41
10 years	10.9	1.7	9.2	0.19	0.93	0.95	88

Table 4.6: Carbon fractions in soils from Bourke

Cropping history	C_T (mg/g)	C_L (mg/g)	C_{NL} (mg/g)	Lability (C_L / C_{NL})	CPI	LI	CMI
			Red earth				
Reference	6.5	0.9	5.6	0.16	1.00	1.00	100
25 years	4.8	0.5	4.3	0.11	0.74	0.69	51
			Grey clay (site 1)				
Reference	3.9	0.5	3.4	0.15	1.00	1.00	100
5 years	3.8	0.4	3.4	0.13	0.97	0.87	84
			Grey clay (site 2)				
Reference	3.6	0.4	3.1	0.14	1.00	1.00	100
1 year	3.1	0.4	2.7	0.13	0.86	0.93	80
16 years	3.2	0.4	2.8	0.14	0.89	1.00	89
			Grey clay (site 3)				
Reference	4.7	0.5	4.2	0.12	1.00	1.00	100
27 years	2.8	0.3	2.5	0.12	0.60	1.00	60

4.3.5. Changes in carbon fractions in soils from the MacIntyre Valley

The greatest loss in C_T and C_{NL} was observed in the grey clay while the greatest loss in C_L was observed in the black earth. Although a general reduction in the various carbon fractions was observed in all the samples from this region, the relative losses in C_L from the red clay and black

earth were greater than the relative losses in C_T and C_{NL} (Table 4.7). In the grey clay, the relative losses in C_T, C_L and C_{NL} were 57%, 30% and 64% respectively. The greater loss in C_{NL} relative to the C_L resulted in an increase in the lability index (LI). In all the samples however, the CMI declined with cropping.

Table 4.7: Carbon fractions in soils from MacIntyre Valley

Cropping history	C_T (mg/g)	C_L (mg/g)	C_{NL} (mg/g)	Lability (C_L / C_{NL})	CPI	LI	CMI
			Red clay (Koarlo)				
Reference	10.1	2.1	8.0	0.27	1.00	1.00	100
20 years	8.7	1.3	7.4	0.18	0.86	0.67	58
			Black earth (Warendi South)				
Reference	16.1	4.0	12.1	0.33	1.00	1.00	100
6 years	12.8	2.1	10.7	0.19	0.80	0.57	46
			Grey clay (Mundine)				
Reference	15.1	3.0	12.1	0.25	1.00	1.00	100
8 years	6.5	2.1	4.4	0.47	0.43	1.83	79

4.3.6. Changes in carbon fractions in soils from the Darling Downs

The samples collected from five sites on the Darling Downs include grey clays from three sites and black earths from two sites. The grey clay from Dalby Agricultural College had the highest concentration of C_T, C_L and C_{NL}. While there has been a decline in all carbon fractions with cropping, the relative losses in C_L were higher than the relative losses in C_{NL} in samples from most sites. The relative losses in C_L, C_T and C_{NL} ranged from 19 to 40 %, 7 to 54 %, and 7 to 37 %, respectively (Table 4.8). The black earth from Dalby Agricultural College had the lowest decline in CMI inspite of the large losses observed in the C_T after 60 years of cropping. This is mainly a result of the relatively smaller losses in C_L, as compared to the losses in C_T and C_{NL}.

4.3.7. Changes in carbon fractions in soils from Emerald

There has been a general decline in all carbon fractions in soils from Emerald. The relative losses in C_T, C_L and C_{NL} ranged from 12 to 73%, 5 to 82%, and 13 to 72% respectively (Table 4.9). The greatest decline in C_T, C_L and C_{NL} was in the grey clay after 21 years of cropping. The losses in the C_L in the black earth after 15 years of cropping were relatively small compared to the losses in the C_T and C_{NL}, and this is reflected in an increase in LI. Similarly, losses in the C_L in the alluvial soil after 10 years of cropping were relatively smaller than the losses in the C_T and C_{NL}. After 12 years of cropping however, the C_L in the alluvial soil had declined by as much as 50% while the relatively losses in C_T and C_{NL} for the same period were 29 and 23% respectively. In all the soils there has been a general decline in the CMI, with the greatest decline occurring in the grey clay after 21 years of cropping (Table 4.9).

Table 4.8: Carbon fractions in soils from the Darling Downs

Cropping history	C_T (mg/g)	C_L (mg/g)	C_{NL} (mg/g)	Lability (C_L / C_{NL})	CPI	LI	CMI
			Grey clay (Kupuun)				
Reference	13.6	2.9	10.7	0.27	1.00	1.00	100
40 years	9.3	1.8	7.5	0.24	0.68	0.88	60
			Grey clay (Daandine)				
Reference	10.0	1.3	8.7	0.14	1.00	1.00	100
50 years	8.1	1.1	7.0	0.16	0.80	1.10	88
			Black earth (Dalby Agric. College)				
Reference	13.2	1.5	11.7	0.13	1.00	1.00	100
60 years	8.8	1.4	7.3	0.18	0.67	1.37	92
			Grey clay (Dalby Agric. College)				
Reference	18.8	3.8	15.0	0.25	1.00	1.00	100
50 years	11.2	1.8	9.4	0.20	0.59	0.78	47
			Black earth (Waco)				
Reference	14.1	2.8	11.3	0.25	1.00	1.00	100
50 years	10.7	1.3	9.4	0.14	0.75	0.55	42

Table 4.9: Carbon fractions in soils from Emerald

Cropping history	C_T (mg/g)	C_L (mg/g)	C_{NL} (mg/g)	Lability (C_L / C_{NL})	CPI	LI	CMI
			Grey clay (Water ways)				
Reference	33.1	3.3	29.8	0.11	1.00	1.00	100
21years	8.8	0.6	8.2	0.08	0.27	0.67	18
22 years	10.7	1.1	9.6	0.11	0.32	1.01	33
			Black earth (Tyson Downs)				
Reference	13.4	1.7	11.7	0.15	1.00	1.00	100
15 years	11.3	1.6	9.7	0.17	0.85	1.15	97
			Alluvial soil (Killara)				
Reference	12.2	1.8	10.4	0.17	1.00	1.00	100
10 years	10.7	1.7	9.0	0.19	0.88	1.12	98
12 years	8.7	0.9	8.0	0.12	0.73	0.70	51

4.3.8. Distribution of aggregate size fractions in selected soils

The distribution of aggregate size fractions varied between sites (Figure 4.1). The effects of cropping on the relative proportion of the different aggregate size fractions also varied between sites. In most of the sites, fractions in the 250 - 450 μm range made up the highest proportion of the total soil weight while fractions < 50 μm made up the lowest proportion of the total soil weight. The relative proportion of the different aggregate fractions ranged from 5.6 to 14.9% for the < 50 μm fraction, 10.9 to 21.7% for the 50 -150 μm fraction, 14.2 to 24.7% for the 150 - 250 μm fraction, 21.8 to 40.9% for the 250 - 450 μm fraction, and 5.6 to 35.4% for the 450 - 500 μm fraction.

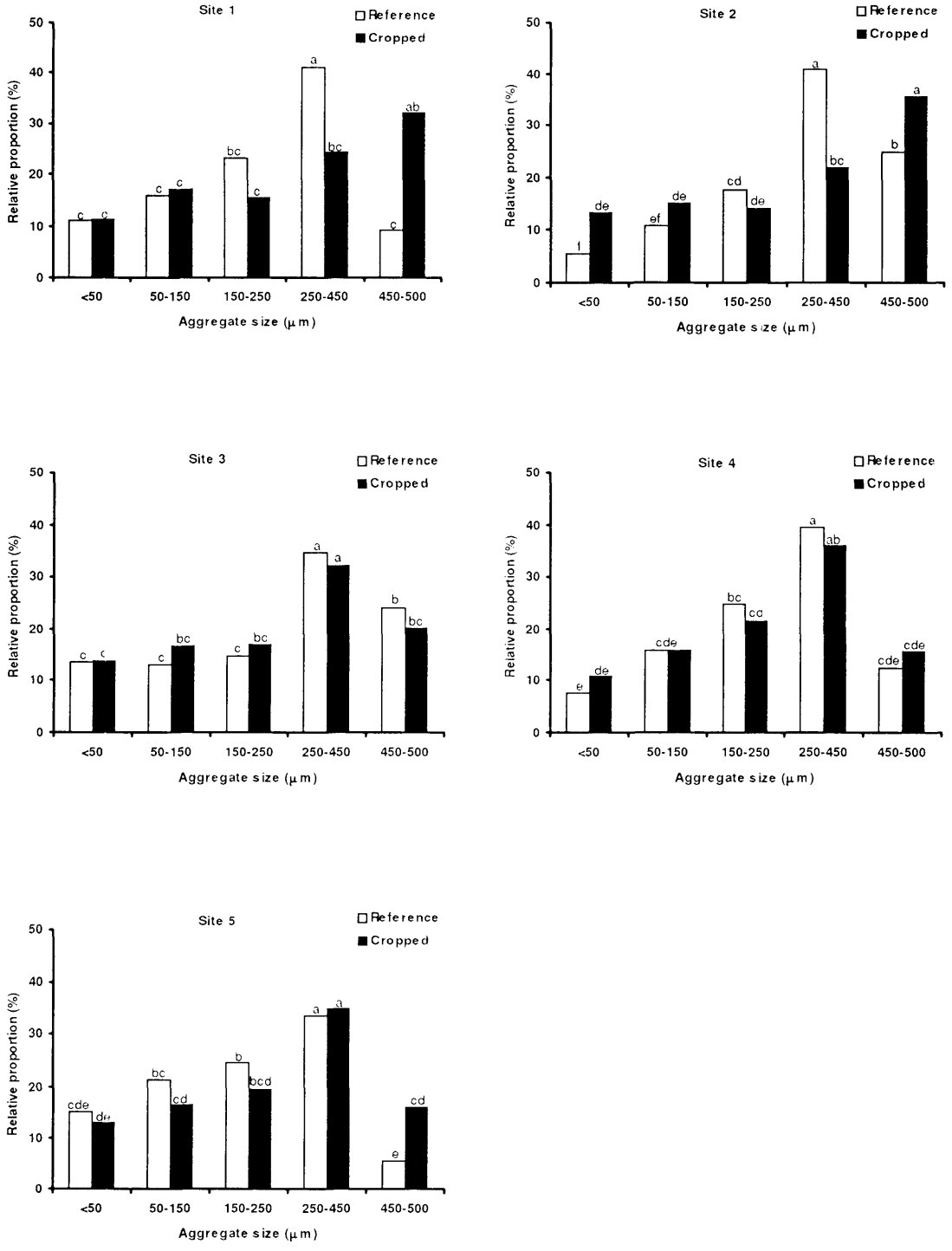

Figure 4.1: Distribution of aggregate size fractions in cropped and reference soils from the various sites. Columns within a site headed by the same letter are not significantly different ($P < 0.05$ DMRT)

4.3.9. Distribution and losses of total and labile carbon in different aggregate sizes

The total carbon concentration (C_T) in the reference soils was significantly higher than that in the cropped soils in all aggregate sizes (Table 4.10), indicating that significant losses of carbon due to cropping have occurred in all size fractions. There was a general decrease in C_T as aggregate size increased for most of the sites, except for the reference soil in Site 1. Generally, the relative losses of C_T were higher in the larger aggregates than in the smaller aggregates, although this was not the case for soils from all sites. For instance, the soils from Site 5 had a higher loss in the < 50 μm fraction than in the 450 - 500 μm fraction. Relative loss in C_T across all sites due to cropping ranged from 0 to 65.3%.

Table 4.10: Distribution and relative losses of total carbon (C_T mg/g) in aggregate fractions

History	< 50 μm	50 - 150 μm	150 - 250 μm	250 - 450 μm	450 - 500 μm
			Site 1		
Reference	23.9b	24.9a	23.9b	24.3ab	22.3c
Cropped	12.9d	12.5d	11.2e	10.9e	9.1f
% decline	46.0	49.8	53.1	55.1	59.2
			Site 2		
Reference	34.5a	32.5b	32.2b	29.6c	25.9d
Cropped	12.5e	11.4f	11.4f	10.4g	9.0h
% decline	63.8	64.9	64.6	64.9	65.3
			Site 3		
Reference	21.2a	20.3b	15.5c	14.2e	14.2e
Cropped	15.5c	14.9d	11.6f	10.5f	8.5g
% decline	26.9	26.6	25.2	26.1	40.1
			Site 4		
Reference	14.0a	14.0a	12.5b	12.1c	12.1c
Cropped	14.0a	11.1d	10.1e	8.9f	8.4g
% decline	0.0	20.7	19.2	26.4	30.6
			Site 5		
Reference	20.5a	20.5a	19.6b	19.6b	18.9c
Cropped	12.4d	12.4d	12.4d	12.4d	11.5e
% decline	39.5	39.5	36.7	36.7	39.2

Means within a site followed by the same letter are not significantly different (P < 0.05 DMRT)

As with C_T, there were been losses in the labile carbon (C_L) due to cropping in all the aggregate size fractions (Table 4.11). The relative losses in C_L during cultivation were generally higher in the larger aggregates than in the smaller aggregates. The trend observed in C_L with respect to aggregate size was not consistent across all sites. However, in soils from most of the sites, C_L in the smaller aggregates was higher than that in the larger aggregates. An exception to this trend was the reference soil from Site 4 where the C_L concentration was higher in the larger aggregates than in the smaller aggregates.

Table 4.11: Distribution and relative losses of labile carbon (C_L mg/g) in aggregate fractions

History	< 50 μm	50 - 150 μm	150 - 250 μm	250 - 450 μm	450 - 500 μm
			Site 1		
Reference	6.4a	6.6a	5.4b	4.9c	4.9c
Cropped	2.2d	2.2d	1.8e	1.4f	1.4f
% decline	66.3	66.8	66.4	71.6	72.1
			Site 2		
Reference	7.6a	7.1b	6.1d	6.3cd	6.1d
Cropped	2.0e	1.6ef	1.5f	1.5f	1.1g
% decline	74.1	72.9	75.3	75.8	82.3
			Site 3		
Reference	3.9a	3.1b	1.9c	1.9c	1.8c
Cropped	3.0b	2.1c	1.3d	1.1d	1.0d
% decline	22.1	30.2	30.6	41.0	41.8
			Site 4		
Reference	1.8d	2.5b	2.0c	2.8a	2.7ab
Cropped	1.3e	1.2e	0.9f	1.0f	0.6g
% decline	21.7	50.5	54.7	64.5	77.6
			Site 5		
Reference	3.4a	3.4a	2.8b	3.0b	2.9b
Cropped	2.3c	2.0d	1.6e	1.2f	1.1f
% decline	31.9	41.8	40.7	59.0	62.7

Means within a site followed by the same letter are not significantly different (P < 0.05 DMRT)

4.3.10 Distribution and losses of light fraction (LF) and light fraction carbon (LF-C) in different aggregate size fractions.

The amount of gross light fraction (LF) isolated from the aggregate size fractions across all sites ranged from 19.2 to 39.9 mg/g and 9.5 to 26.9 mg/g in the reference and cropped soils respectively (Table 4.12). Gross LF in this thesis refers to the total mass of LF material isolated per unit mass of sample. Generally, the amount of LF recovered increased as the size of the aggregates increased for both the reference and cropped soils. No consistent trend was observed in the relative losses in LF concentration with increase in aggregate size fraction. The carbon concentration of the LF ranged from 13.8 to 44.0% for the LF isolated from the reference soils, and from 8.9 to 23.0% for the LF isolated from the cropped soils (Table 4.13). Across all sites, the carbon content of the LF obtained from all aggregate fractions show little variability, and no consistent trend was observed with increasing aggregate fraction. While most other carbon fractions have declined with cropping, the carbon concentration of the LF increased in some aggregate sizes (Table 4.13).

As with the gross LF content, the proportion of total soil carbon present as LF (LF-C) increased as the size of the aggregates increased for both the reference and the cropped soils (Table 4.14). A higher proportion of soil carbon was present in the LF of the reference soils than in the LF of the cropped soils in all aggregate size fractions. Across all sites studied, the LF-C ranged from 18.2 to 57.8% in the reference soils, and from 10.3 to 42.7% in the cropped soils. The relative losses in the total soil carbon through the LF in different aggregate size fractions varied between sites (Table 4.14). The mean values across all sites showed that the amount of total soil carbon lost

through the LF increased with decreasing aggregate size. The relative losses in LF carbon during cultivation ranged from a mean of 29.6% in the 450 - 500 μm aggregates to a mean of 47.4% in the < 50 μm aggregates.

Table 4.12: Distribution and relative losses of light fraction (mg/g) between aggregate fractions

History	< 50 μm	50 - 150 μm	150 - 250 μm	250 - 450 μm	450 - 500 μm
			Site 1		
Reference	19.2d	20.2d	26.1c	28.5b	32.2a
Cropped	9.5h	11.0g	11.0g	15.4f	16.9e
% decline	50.4	45.7	58.1	45.9	47.5
			Site 2		
Reference	20.9d	23.6c	27.0b	38.5a	39.9a
Cropped	10.9f	11.0f	16.1e	20.5d	26.9b
% decline	47.5	53.6	40.3	46.6	32.5
			Site 3		
Reference	29.6b	24.6e	26.1d	28.7c	32.6a
Cropped	12.3h	12.5gh	12.6gh	12.9fg	13.2f
% decline	58.3	49.3	51.7	55.0	59.4
			Site 4		
Reference	26.3c	24.6d	26.1c	29.0b	32.6a
Cropped	12.4f	12.5f	12.6f	12.8f	13.2e
% decline	52.9	49.5	51.7	55.7	59.4
			Site 5		
Reference	22.3e	24.6d	26.6c	29.0b	32.3a
Cropped	12.1h	12.4gh	12.6gh	12.9fg	13.3f
% decline	45.7	49.4	52.4	55.5	58.9

Means within a site followed by the same letter are not significantly different (P < 0.05 DMRT)

Table 4.13: Carbon concentration (%) of light fraction in aggregate fractions

History	< 50 μm	50 - 150 μm	150 - 250 μm	250 - 450 μm	450 - 500 μm
			Site 1		
Reference	33.0d	35.7c	31.6e	37.1b	37.7a
Cropped	17.9i	18.1h	20.0g	20.5g	23.0f
% decline	45.7	49.3	36.7	44.7	39.0
			Site 2		
Reference	44.0a	40.2b	37.8c	29.8d	30.5d
Cropped	19.8f	21.7e	15.5g	12.3h	8.9i
% decline	55.0	46.0	59.0	58.7	70.8
			Site 3		
Reference	15.6e	21.4a	18.0b	17.2c	15.5e
Cropped	13.0h	13.6g	14.7f	17.3c	16.5d
% decline	16.7	36.4	18.3	-0.6	-6.4
			Site 4		
Reference	20.7e	24.6b	25.9a	24.1b	21.4d
Cropped	13.3g	18.9f	19.2f	22.8c	23.1c
% decline	35.7	7.3	25.9	5.4	-7.9
			Site 5		
Reference	16.7a	16.9a	16.3b	14.9d	13.8f
Cropped	13.1g	14.2e	15.6c	16.3b	16.8a
% decline	21.5	16.0	4.3	-9.4	-21.7

Means within a site followed by the same letter are not significantly different (P < 0.05 DMRT). Negative changes imply increase with cropping.

Table 4.14: Total soil carbon present as light fraction (LF-C) from different aggregate fractions (mg C/g soil). Values in parenthesis indicate percent of total soil carbon.

History	< 50 µm	50 - 150 µm	150 - 250 µm	250 - 450 µm	450 - 500 µm
			Site 1		
Reference	6.4e *(26.6)*	7.2d *(29.0)*	8.3c *(34.6)*	10.6b *(43.6)*	12.1a *(54.4)*
Cropped	1.7g *(13.3)*	2.0g *(15.9)*	2.2g *(19.6)*	3.2f *(29.0)*	3.9f *(42.7)*
% decline	73.4	72.2	73.5	69.8	67.8
			Site 2		
Reference	9.2d *(26.6)*	9.5cd *(29.3)*	10.2c *(31.7)*	11.4b *(38.7)*	12.2a *(47.0)*
Cropped	2.2e *(17.3)*	2.4e *(20.9)*	2.5e *(22.0)*	2.5e *(24.4)*	2.4e *(26.6)*
% decline	76.1	74.7	75.5	78.1	80.3
			Site 3		
Reference	4.6c *(21.8)*	5.3a *(26.0)*	4.7bc *(30.3)*	4.9b *(34.6)*	5.1a *(35.7)*
Cropped	1.6f *(10.3)*	1.7ef *(11.4)*	1.9e *(16.0)*	2.2d *(21.2)*	2.2d *(25.7)*
% decline	65.2	67.9	59.6	55.1	56.9
			Site 4		
Reference	5.5c *(38.9)*	6.1b *(43.3)*	6.8a *(54.2)*	7.0a *(57.8)*	7.0a *(57.7)*
Cropped	1.6f *(11.7)*	2.3e *(21.2)*	2.4e *(24.0)*	3.0d *(33.3)*	3.1d *(36.4)*
% decline	70.9	62.3	64.7	57.1	55.7
			Site 5		
Reference	3.7c *(18.2)*	4.1b *(20.2)*	4.3a *(22.0)*	4.3a *(22.0)*	4.5a *(23.7)*
Cropped	1.6e *(12.8)*	1.7e *(14.2)*	2.0d *(16.0)*	2.1d *(17.0)*	2.2d *(19.4)*
% decline	56.7	58.5	53.5	51.2	51.1

Means within a site followed by the same letter are not significantly different (P < 0.05 DMRT).

4.3.11. Variations in the soil and light fraction $\delta^{13}C$ values between aggregate fractions

The $\delta^{13}C$ values of the soil range from -26.27 to -18.18 ‰ in the reference soils, and from -23.93 to -16.22 ‰ in the cropped soils (Table 4.15). With the exception of the cropped soil from Site 4 and soils from Site 5, the ranges in the $\delta^{13}C$ of the soil indicate that the organic matter in most of these soils is derived mainly from C3 vegetation. The ranges in $\delta^{13}C$ of the light fraction (Table 4.16) also suggest that the organic matter is mainly derived from C3 vegetation in all sites except for Site 5. In all sites and all aggregate fractions, the $\delta^{13}C$ values are higher in the cropped soils than in the reference soils. Generally, $\delta^{13}C$ values decrease with increasing aggregate size for both the reference and the cropped soils (Table 4.15).

The $\delta^{13}C$ values of the LF also indicate that the organic matter in most soils from these regions is derived mainly from C3 vegetation (Table 4.16). However, values of $\delta^{13}C$ in the LF are generally lower than those of the corresponding soil fraction. As with the $\delta^{13}C$ of the soil aggregate fractions, the $\delta^{13}C$ of the LF decreases as the size of the aggregate from which it was isolated increases. The $\delta^{13}C$ values of the LF from the cropped soil are generally higher than those of the LF from the reference soil.

Table 4.15: Variations in $\delta^{13}C$ (‰) between aggregate fractions of reference and cropped soil

History	< 50 µm	50 - 150 µm	150 - 250 µm	250 - 450 µm	450 - 500 µm
			Site 1		
Reference	-25.03g	-24.51f	-24.26e	-25.50i	-25.34h
Cropped	-20.02a	-20.01a	-20.68b	-21.37d	-21.07c
			Site 2		
Reference	-23.63c	-25.01e	25.09e	-26.08f	-26.27g
Cropped	-21.91a	-23.06b	-23.62c	-23.65c	-23.93d
			Site 3		
Reference	-20.31a	-21.94c	-21.95c	-23.32e	-23.72f
Cropped	-20.94b	-21.00b	-21.06b	-22.50d	-23.29e
			Site 4		
Reference	-24.93d	-25.14e	-25.29f	-25.46g	-25.15e
Cropped	-19.68ab	-20.91c	-19.60a	-19.79b	-21.04c
			Site 5		
Reference	-18.79f	-18.18e	-18.77f	-19.11g	-19.96h
Cropped	-16.22a	-17.69c	-17.10b	-17.99d	-19.78h

Means within a site followed by the same letter are not significantly different (P < 0.05 DMRT)

Table 4.16: Variations in $\delta^{13}C$ (‰) of the light fraction isolated from aggregate fractions of reference and cropped soil

History	< 50 µm	50 - 150 µm	150 - 250 µm	250 - 450 µm	450 - 500 µm
			Site 1		
Reference	-25.12e	-25.38f	-25.92g	-26.24h	-26.40i
Cropped	-20.72a	-20.73a	-21.41b	-21.82c	-22.13d
			Site 2		
Reference	-27.20f	-27.00f	-25.90e	-25.98e	-24.47c
Cropped	-24.78d	-24.46c	-24.49c	-23.88b	-22.69a
			Site 3		
Reference	-21.03a	-22.72c	-24.15e	-22.73c	-24.56e
Cropped	-21.68b	-21.74b	-23.30d	-21.81b	-24.11e
			Site 4		
Reference	-25.81c	-26.04f	-26.03f	-26.19g	-26.36h
Cropped	-20.38a	-21.79d	-21.65c	-20.29a	-20.49b
			Site 5		
Reference	-19.46e	-19.43e	-19.79f	-18.82d	-20.67g
Cropped	-16.79a	-17.71b	-18.63d	-18.32c	-20.48g

Means in a site followed by the same letter are not significantly different (P < 0.05 DMRT)

4.4. DISCUSSION

4.4.1. Changes in carbon fractions in the whole soil from different cotton growing regions

In all of the sites examined, cultivation of the soil has led to a significant decline in all the carbon fractions determined. These soils are predominantly clayey in texture, and Wallace (1994) has pointed out that generally the more clay in a soil, the greater the need for organic matter.

Continuous decline in carbon levels in these soils therefore may threaten long-term sustainability of their productivity. Severe slaking may occur when these soils are wetted if there is low organic matter in the top soil (McKenzie *et al.*, 1995). A practical implication of these changes to the cotton producer is the need to develop management strategies that will increase or maintain SOM levels during cotton production. It is worth noting that the impact of low SOM on the physical condition may vary between soils. For instance, on some soils such, as the red brown earths where illite may comprise 50 to 60 % of the clay fraction, declining SOM can have drastic effects. On the other hand, on soils such as the self-mulching black earths where montmorillonite may comprise 50 to 60% of the clay fraction, physical properties are much less affected by SOM decline (Russel, 1984).

The effect of breaking a virgin soil and cultivating it has received considerable attention in earlier studies (Dalal and Mayer 1986a; Oades *et al.*, 1988). Although it is well understood that cultivation accelerates the rate of decomposition of soil organic matter, there has been neither an accepted measure of organic matter quality nor has there been consensus on whether the quality of organic matter has changed with cultivation. For instance, Preston *et al* (1994) reported that despite a carbon loss of more than 50% as a result of cultivation, changes in the nature of organic carbon in the size fractions were generally small. It is in this regard that the carbon fractions determined in this study potentially find useful applications. For instance, in most of the soils examined, the relative changes in the labile carbon as a result of cultivation were higher than the relative changes in the total carbon and non-labile carbon, especially in the early periods of cultivation. For example, in the red clay from Gwydir valley (Table 4.3), while a decline of only 3% was observed in the C_T level after five years of cultivation, the C_L had dropped by 27% of its original value while the C_{NL} has not shown any significant change. This trend was also observed in the brown clay (Table 4.3) where the C_L has dropped by 67 % in five years of cultivation while the changes in C_T and C_{NL} were 49 % and 45 % respectively. This indicates that when the soil is brought into cultivation from its native state, those organic matter components that are readily oxidisable are lost more rapidly than the recalcitrant components.

In the red-brown earth from Elengerah in Macquarie valley (Table 4.5), while the C_T and C_{NL} have declined by 26% and 25% respectively, the decline in the C_L was 29% after 10 years of cultivation. In the alluvial soil, the decline in the carbon fractions during the first two years of cultivation was 49% for the C_T, 58% for the C_L, and 46% for the C_{NL} (Table 4.5). After 10 years, however, the losses were only 7% for C_T, 10% for C_L and 5% for the C_{NL}. This implies a rapid loss of all the carbon fractions in the early stages of cultivation, and then an improvement in the subsequent stages. This could have been due to the adoption of land management practices which minimise losses of organic carbon during cropping. For instance, in a survey of cotton land management practices in the Macquarie valley, Kay and Holden (1993) showed that 26% of cotton farmers slashed and incorporated cotton residues into the soil after harvesting while 50% raked and burnt the residues, and 24 % of cotton farmers carried out both practices. This is an improvement to the initial

practice of burning residues at the early stages of cotton production, and this could have reduced the rate of decline of soil organic carbon.

Organic carbon in soils under cultivation is in a dynamic state in which the net content is a balance between rate of breakdown and rate of addition. The rate of breakdown is often more important than the rate of addition (Nardi *et al*,. 1996). In their native state, soils are in equilibrium and tend to have characteristic SOM content. This equilibrium is disturbed when the soils are brought into cultivation by the reduced accumulation of fresh material and the acceleration of SOM breakdown. Given optimal time and soil conditions, the labile components can be rapidly and completely mineralised and the non-labile components accumulate. Under sub-optimal conditions (eg lack of moisture or poor aeration), decomposition is much slowed and modified materials, which are potentially mineralisable accumulate. Usually, simple sugars are most easily broken down followed by starch, simple proteins, complex proteins, pectins, hemicellulose, cellulose, lignin, waxes, resins and tanins, in that order (Piccolo, 1996). The relative distribution of these compounds in the labile and non-labile carbon reported in this study are yet to be evaluated.

The relative changes in the ratio of C_L to C_{NL} of the cropped soils relative to the reference soils are reflected in the lability index (LI). Results from the soils analysed in this study show a wide variation in the changes occurring in the LI of the soil carbon during cropping. Unlike the general decreases observed in the C_T, C_L, and C_{NL}, some increases in the LI were observed in a number of soils, such as the red clay from Gwydir valley (Table 4.3), the grey clay from Myola and Oakville in Namoi valley (Table 4.4), the grey clay from Macquarie valley (Table 4.5), the grey clay from McIntyre valley (Table 4.7) and the grey clay and alluvial soil from Emerald valley (Table 4.9). This is mainly due to an increase in the ratio of C_L to C_{NL} during cropping which can happen in situations where resistant SOM components are microbially broken down into simple labile fractions and thus increasing the C_L fraction. Lability index can also increase by the incorporation of organic matter with low C/N ratio or high plant residue quality index (Tian *et al.*, 1995).

In situations where the LI declines with cropping, the implications are that the ratio of C_L to C_{NL} has decreased during cultivation of the soil. This could have resulted from soil management systems which lead to either (i) a rapid decomposition of the readily available carbon while maintaining the resistant carbon fractions, (ii) a rapid transformation of the readily decomposable carbon into a stable form, or (iii) though increasing both the C_L and C_{NL}, the conversion from C_L to C_{NL} occurs at a much faster rate than the rate of increase in C_L. For instance, Nardi *et al.* (1996) indicated that during SOM decomposition, lignin, a recalcitrant component, can be produced from microbial metabolism. Also, Insam (1996) described possible pathways which include hydroxylation, decarboxylation, and various oxidative mechanisms which may lead to the formation of resistant organic matter from simple phenolic units.

Organic matter assessments should not only take into account the total organic carbon present at any given time, but should also consider the amount of readily mineralisable fractions in relation to the less-mineralisable and total carbon content, and this should be related to what exists in the native state. The carbon pool index (CPI) and carbon management index (CMI) used in this study are useful measures in this direction. The general changes occurring in the CPI and CMI of all the 65 soils in relation to the length of cropping are represented in a polynomial relationship (Figure 4.2). The relationship shows a rapid decline in both the CPI and CMI of all soils cropped in the first 30 years. As the cropping period extends beyond 30 years, both indices gradually improve. Since the CPI expresses the total carbon of a cultivated soil as a proportion of the total carbon in a reference soil, the initial rapid decline in the CPI is a direct result of the reductions in the total soil carbon during initial cultivation. The gradual increase observed in those soils that have been cropped for more than 30 years demonstrate the potential for the development of cotton cropping systems that will improve the carbon status of soils.

An examination of the available cropping histories of all sites showed that out of the 65 sites studied, only seven of these sites have been cropped for more than 30 years, five of which are from the Darling Downs in Queensland. Background information on these sites show that the dominant cropping systems carried out in these sites are traditional mixed cropping in which legumes and cereals have been rotated with cotton. The incorporation of residues from these rotation crops could have resulted in the increases in the CPI. Although similar trends were observed in the CMI as in the CPI, the CMI show higher rates of change with length of cropping than the CPI (Figure 4.2), and since the CMI incorporates not only the C_T of the cultivated and reference soil, but also the C_L and C_{NL}, it can provide a more useful indicator of the carbon status of soils. It is still not clear what organic compounds are present in the C_L and C_{NL} fraction Long-term organic matter dynamics may be better understood by taking into consideration the transformations taking place between the easily decomposable components and the very stable components.

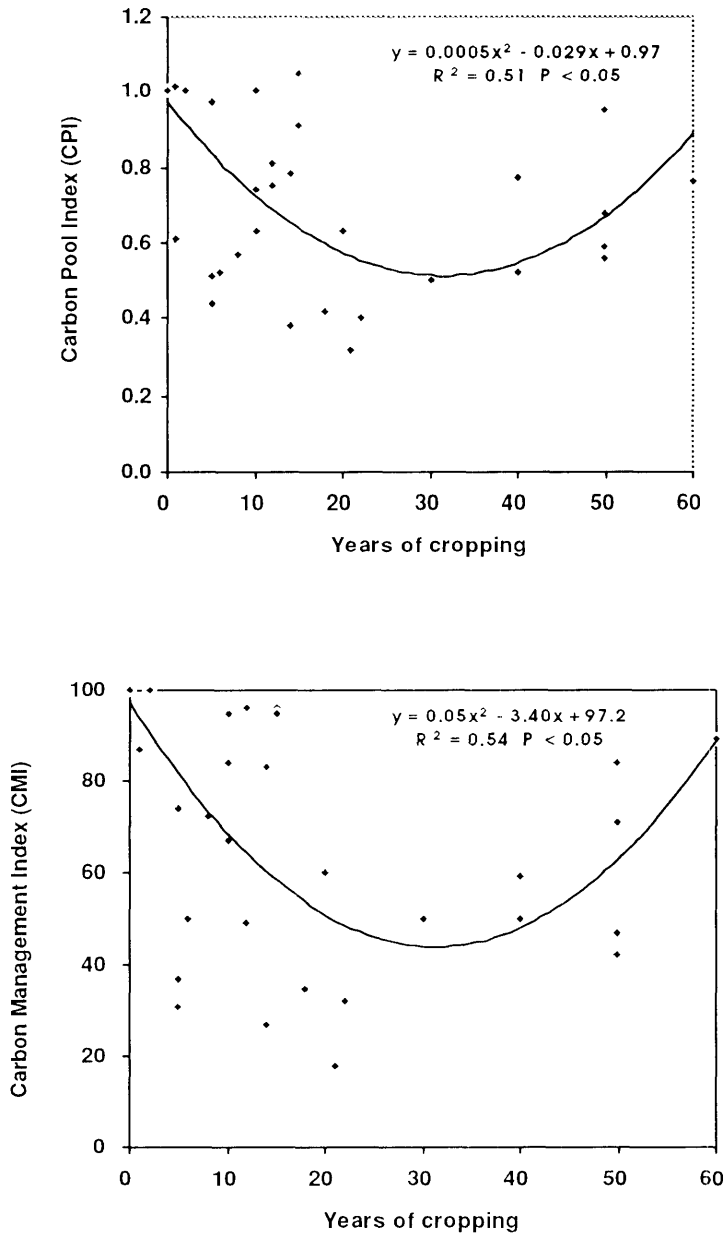

Figure 4.2: Changes in carbon pool index and carbon management index in relation to years of cropping

4.4.2. Distribution and losses of carbon fractions in different aggregates sizes

The distribution of organic carbon in soil aggregates has been the subject of controversy in previous reports. This study shows that both total and labile carbon tend to occur in higher concentrations in smaller aggregates (< 250 μm) than in the larger aggregates (> 250 μm). While Gupta and Germida (1988) and Elliott *et al.* (1991) found no clear trend in carbon concentration between aggregate size fractions, Baldock *et al.* (1987) observed that both organic carbon and carbohydrate contents increased with decreasing aggregate size. Conversely, Haynes and Swift

(1990) and Camberdella and Elliott (1993) generally found that organic carbon content decreased with a decrease in size of aggregates. A striking observation in this study is that while both C_T (Table 4.10) and C_L (Table 4.11) increased with a decrease in aggregate size, the total light fraction (LF) content decreased with a decrease in aggregate size (Table 4.12). This suggests that the relative contribution of the LF to the C_T declines as the size of the aggregates reduces, and is supported by data reported in Table 4.14 which shows that the proportion of total carbon present in the LF decreases as the aggregate size decreases. This is primarily because most of the total carbon present in the small aggregates consists of organic matter that has undergone extensive humification, and such material is normally not included in the LF. This observation is supported by the report of Baldock *et al.* (1992) which suggested that organic matter in smaller aggregates is more decomposed than organic matter in larger aggregates. The LF mainly consists of plant debris, both fresh and partially decomposed, although other materials may be present in significant amounts. Charcoal, for example, may be an important constituent of the LF in some soils (Skjemstad *et al.*, 1990).

The range in carbon concentration of the LF found in this study (Table 4.13) is wider than the range reported by Janzen *et al.* (1992). Skjemstad *et al.* (1986) reported that LF accounted for 9% of organic carbon in a virgin soil, but only 1% of organic carbon in a cultivated soil. On the other hand, Tiessen and Stewart (1983) found that LF accounted for 20 - 30% of organic carbon in virgin soil but only 8 - 14% in cultivated soil. The differences observed between the ranges reported in this study and other studies could be due to variation in methodology, soil type, cropping systems, or standing vegetation.

The trend observed in the $\delta^{13}C$ of both the soil (Table 4.15) and the LF (Table 4.16) showed that the $\delta^{13}C$ values decrease as the aggregate size increases. The $\delta^{13}C$ gives an indication of the ratio of ^{13}C to ^{12}C in the soil organic matter, and has been used extensively in understanding the dynamics of soil organic matter (Skjemstad *et al.*, 1990; Balesdent and Mariotti, 1996; Conteh *et al.*, 1997b). The $^{13}C/^{12}C$ ratios of soil organic matter corresponds closely to that of the native vegetation from which it was derived. Based on these carbon isotope ratios, organic matter is said to be either C4-derived (high $\delta^{13}C$, *ca.* -16 to -19‰) or C3-derived (low $\delta^{13}C$, *ca.* -32 to -22‰).

The increase in $\delta^{13}C$ with decrease in aggregate size also suggests that organic matter in smaller aggregates is more decomposed than organic matter in larger aggregates, as was observed for the LF distribution. Because organic matter decomposition in soil is usually a slow and lengthy process, there is little direct evidence for evaluating the potential for isotope fractionation as plant carbon is incorporated into the soil organic matter (Boutton, 1996). However, Balesdent *et al.* (1993) showed that the $\delta^{13}C$ of soil organic matter is greater than the $\delta^{13}C$ of current above-ground inputs, indicating that $\delta^{13}C$ values increase as organic matter is decomposed. Also, Balesdent and Mariotti (1996) showed that $\delta^{13}C$ values increase with decreasing particle size, and that coarse plant debris

are lower in $\delta^{13}C$ relative to finer organo-mineral fractions. Lignin in soil organic matter normally decomposes at a significantly slower rate than cellulose, hemicellulose, or simple sugars. Since lignin often comprises a significant proportion of the total mass of plant tissue and is 5 to 6 ‰ lower in $\delta^{13}C$ than bulk tissue (Boutton, 1996), its slower rate of decomposition has the potential to alter the $\delta^{13}C$ of plant material as it is incorporated into the soil organic matter pool. It is therefore not surprising that the $\delta^{13}C$ values of the cultivated soil are higher than those of the reference soil (Table 4.15), and the $\delta^{13}C$ values of the light fraction (Table 4.16) lower than those of the corresponding bulk soil (Table 4.15).

Generally, carbon was lost from all aggregate fractions, showing that decomposable organic matter is present in all aggregate sizes. Bonde *et al.* (1992) used ^{13}C natural abundance to show that individual aggregate size fractions contained at least two organic matter pools with different turnover times. The relative losses of both C_T (Table 4.10) and C_L (Table 4.11) due to cultivation are higher in the larger aggregates than in the smaller aggregates. These differences in rates of loss of C_T and C_L between aggregate sizes suggest a higher degree of protection of the organic matter in the smaller aggregates than in the larger aggregates. This can be seen from the fact that even though the labile carbon content increases as aggregate size decreases (Table 4.11), losses of both C_T (Table 4.10) and C_L (Table 4.11) decrease as aggregate size decreases. This agrees with the conclusion of Skjemstad *et al.* (1986) that the major mechanism responsible for the relative stability of organic matter in soil is a physical association with the inorganic components, rather than an inherent chemical or biochemical inertness.

However, in all the aggregate fractions examined, the relative losses in the C_L due to cultivation (Table 4.11) were higher than the losses in C_T (Table 4.10). Lability of organic carbon, as defined in this study, is due to ease of oxidation which is more of a chemical property, and, as Piccolo (1996) pointed out, the labile organic carbon in soil is believed to be composed of cellular biopolymers such as carbohydrates, amino acids, peptides, and amino sugars. From the results of this study, it appears that the mechanisms responsible for the loss of organic carbon in soil are, first, chemical structure, which can then be enhanced or inhibited by physical protection. The results obtained in this study also agree with the report of Elliott (1986) who fractionated soil organic matter into decomposable and recalcitrant fractions on the basis of its location within aggregates of different sizes. He demonstrated that organic matter associated with macroaggregates (> 250 μm) was more readily mineralised than that associated with microaggregates (< 250 μm) and was the primary source of nutrients lost during cultivation.

The LF has been used extensively as a measure of labile organic matter in soil (Dalal and Mayer 1986b; Skjemstad *et al.* 1986; Janzen *et al.* 1992) because these materials are known to decompose more quickly than total organic matter (Gregorich *et al.*, 1989; Bonde *et al.*, 1992).

However, Gregorich and Janzen (1996) indicated that although the sensitivity of the LF to management effect is well established, its usefulness as a predictor of organic matter changes has not been verified. Also, various reports on the use of LF have not indicated which component of the LF is the most sensitive indicator of organic matter change. A comparison of the losses of the gross LF (Table 4.12) to the losses of C_T (Table 4.10) and C_L (Table 4.11) showed wide variation between sites. The mean values however indicated that losses of C_T, C_L and gross LF due to cultivation are in the order C_L > LF > C_T. This shows that the labile carbon determined by ease of oxidation is a more sensitive indicator of organic matter changes due to cultivation than the gross LF even though the LF is more sensitive than the C_T. This is probably due to the fact that the gross LF contains organic materials that are recalcitrant (Skjemstad *et al.*, 1990). However, the total soil carbon present in the light fraction (Table 4.14) appears to be more sensitive to cultivation than the gross LF (Table 4.12). The differences between the rate of loss of the LF-C and the C_L are not clear in soils from Sites 1 and 2. Losses in both these fractions appear to have occurred at similar rates in these two sites. At Site 3, the rate of loss of LF-C was higher than the loss of the C_L whereas in Sites 4 and 5, the differences depend on aggregate size. These results show that both the C_L and the LF-C are sensitive indicators of organic matter changes brought about by cultivation, since the loss of these two fractions occur at a much higher rate than the loss of total organic carbon.

A comparison of the rate of loss of various components of the LF show that the carbon content of the LF (Table 4.13) is not as sensitive to cultivation as the gross LF (Table 4.12) and the LF-C (Table 4.14). It can be seen that while most of the carbon fractions have declined during cultivation, the carbon content of the LF increased in some cases (Table 4.13). Such increases could be misleading because they probably only indicate that fresh organic material, with high carbon content, has been added to the soil rather than an actual increase in total soil carbon. Gregorich and Janzen (1996) indicated that such increases in the LF only signal enhanced levels of labile organic matter, but the eventual conversion of that transient carbon to stable organic matter has not been adequately described. Therefore, such an increase may not indicate an increase in organic matter beyond the accumulation of the LF probably arising from leaf drop from the cotton plants during defoliation which precedes harvesting of cotton.

4.5. CONCLUSIONS

Cultivation of soils has led to a decrease in the organic carbon status of the cracking clay soils used in cotton production. The effects of cultivation was more pronounced in C_L and CMI than in C_T and C_{NL}. The effects of cultivation on the ratio of C_L to C_{NL} (LI) was not as clear, since both increases and decreases were observed as a result of cultivation. The CMI generally declined during cultivation with the exception of a few soils, and since the CMI incorporates the changes taking place in the C_T, C_L and C_{NL}, the use of this index can provide very useful results in the monitoring of organic matter status of soils. There is still a need for further investigation into the chemical composition of

the C_L and C_{NL} so as to understand which specific organic compounds are present in both of these fractions.

From the results of the distribution and losses of carbon fractions in aggregate fractions, it can be concluded that the organic matter present in the cracking clay soils used for cotton production is highly decomposed, and most of it is concentrated in the microaggregates of the soil. This could probably be due to the intensive tillage operations involved during cultivation coupled with the high prevailing temperatures and moisture levels required for cotton production. Most of the organic matter in the macroaggregates is dominated by undecomposed or partially decomposed plant materials probably arising from leaf drop during defoliation which precedes harvesting of cotton. The rate of loss of organic carbon from these soils during cultivation can be appropriately studied by both ease of oxidation and the proportion of total carbon present in the light fraction. The carbon content of the light fraction from these soils is not a useful indicator of organic matter changes occurring under cultivation.