THE EFFECT OF VARIOUS AMENDMENTS ON C AND N DYNAMICS OF ACTIVE ORGANIC MATTER AND AGGREGATE STABILITY IN DIFFERENT SOILS

by

Robert Abram Janzen

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
Master of Science
in the
Department of Soil Science

Winnipeg, Manitoba

ISBN 0-315-44095-3

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ABSTRACT

This short-term incubation study was undertaken to determine the influence of the characteristics of the soil and of the materials added to the soil on the incorporation of C and N into active soil organic matter (SOM) and on the stabilization and size distribution of soil aggregates. Three Manitoba soils containing varying amounts of clay and soil organic matter (SOM) were studied: (1) Newdale clay loam from the bottom of a knoll (NB); (2) Newdale clay loam from the top of the same knoll (NT); and (3) Red River Clay (RRC). These soils were subjected to four amendment treatments: (1) control where no plant or fertilizer materials were added (C); (2) ^{14}C- and ^{15}N-labelled wheat straw (S); (3) labelled wheat straw and ^{15}N-labelled KNO_3 (SF); and (4) labelled prebloom alfalfa residue (Af). The amended soils were incubated at 20°C and 75% field capacity.

Soil samples were collected at 0, 7, 30, and 90 days of incubation. Two humic acid fractions were obtained from the amended soils. Fraction A (Fr-A) was extracted by $Na_4P_2O_7$ and Fraction B (Fr-B) was recovered from the remaining residue by sonication. The levels of ^{14}C and ^{15}N in these fractions were measured. Wet sieving and dispersibility parameters were determined for the soils after 90 days of incubation.

Significant ($P<0.05$) differences in the incorporation of ^{14}C and ^{15}N into Fr-A and Fr-B attributed to soil and treatment effects were observed. The effect of clay content on C and N incorporation was most marked in Fr-B: C incorporation in all treatments tended to be higher in the RRC soil than in the NB soil: N incorporation in the S and Af

treatments was usually higher in the RRC soil, but in the SF treatment N incorporation tended to be higher in the NB soil. The effect of the form of C and N in the residue was most apparent in the incorporation of N into Fr-B: in all soils the level of ^{15}N in the Af treatment was higher than that in the SF treatment. The effects of SOM content and of C:N ratio of the residue on incorporation dynamics were noticeable but not as pronounced.

The soil aggregate stability studies also revealed soil and treatment effects. The wet sieving analysis determined significant ($P<0.05$) differences in the log geometric mean diameter (LGMD) and in the size distribution of aggregates among treatments. The most profound effects were observed in the SF treatment, with the decrease in LGMD increasing with increasing cation exchange capacity of the soil. The turbidimetrically measured dispersibility of the soils in water prior to and after $NaIO_4/Na_2B_4O_7$ treatment indicated significant ($P<0.05$) differences among soils. The NT soil was found to be the most dispersible in the water, and the RRC soil had the highest dispersibility following the $NaIO_4/Na_2B_4O_7$ treatment.

ACKNOWLEDGEMENTS

In carrying out this investigation I have relied heavily upon the ideas and support of others. I here must express my gratitude to:

Dr. T.B. Goh, Assistant Professor, Department of Soil Science, whose congenial inspiration and judicious counsel ensured that my work was both enjoyable and effective.

Dr. C.F. Shaykewich, Professor, Department of Soil Science, whose consistent concern for the welfare of his students "made a difference" in the quality of education I received.

Dr. C.M. Cho, Professor, Department of Soil Science, Dr. G.G. Choudhry, Associate Professor, Department of Soil Science, and Dr. R.D. Hill, Professor, Department of Plant Science, who served on the examining committee and generously made their expertise available to me.

Dr. G.J. Racz, Professor and Head, Department of Soil Science, whose administrative efforts provided a productive work environment.

Hildred Thould and Helen Nemeth, whose cheerful competence was a continual source of encouragement and support.

Val Huzel and Gregg Morden, who provided technical support and who patiently suffered my "scrounging" sprees.

Fellow graduate students who provided encouragement and inspiration by their example of dedicated effort.

Natural Sciences and Engineering Research Council of Canada (NSERC) and Economic and Regional Development Agreement (ERDA) for financial assistance.

Finally, - family, friends, and church community, who continually help me to recognize that:

> God has created the world as a place where righteousness and beauty will be established. But this involves a system of relationships-- among God, his people, and the land -- which are included in the covenant God has established with the earth. There is every encouragement to use wise methods of stewardship,.... But these are a part of a larger response to God's covenanting love. When we respond in obedience, we will enjoy the fruit of the earth, and the poor will be cared for. When we turn from God, we can expect ecological disaster and social oppression.
>
> --- Dyrness (1987)

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1. INTRODUCTION

Soil organic matter (SOM) dynamics must be considered in the development and implementation of sound soil management practices. These dynamics consist of the transformation and transfer of materials within and between the various compartments (or "pools") of the SOM and include many competing processes. Nutrients are concurrently mineralized and immobilized. Microbial products (amino acids, polysaccharides, etc.) are concurrently produced, stabilized, and decomposed. The more vigorous these dynamics, the larger is the proportion of the SOM which is in an active or labile form. The larger this labile pool of SOM, the more effective is the contribution of SOM to the maintenance of soil physical and chemical fertility. Thus, management practices designed to maintain SOM dynamics help to ensure the efficient and sustainable utilization of the soil resource.

Management practices which maximize the addition of organic materials to the soil are most effective in maintaining and enhancing SOM dynamics. Since the processes are primarily microbially mediated, the added organic materials provide substrate for microbial growth. The decomposition products of the added materials as well as microbial wastes and remains are relatively labile. They thus participate in SOM dynamics by increasing the size of the active pool. Crop rotations which prevent erosion, minimize tillage, conserve crop residues, include sodforming forages, and/or utilize green and animal manures are therefore examples of management practices which contribute to the long-term fertility of the soil.

Effective soil resource management takes into account the effect of soil type on SOM dynamics. The soil pH, the nature and amount of clay minerals, the organic matter content, and the soil moisture regime are examples of soil factors which influence SOM dynamics. In developing management practices the properties of the soil must be considered.

This study grew out of the conviction that the maintenance of active SOM dynamics is crucial to the sustainable productivity of the soil, and that these dynamics vary with soil type. The primary objective of this study was to describe the incorporation of C and N into the relatively labile SOM pool of soils differing in organic matter and clay contents using several residue treatments varying in C/N ratios, form of N, and availability of C and N. The second objective was to relate the effects of these short-term treatments to a more concrete aspect of soil quality; namely, the aggregate stabilities of the amended soils.

2. LITERATURE REVIEW

The soil organic matter (SOM) contributes significantly to the long-term chemical and physical fertility of the soil by providing nutrients to plants and microorganisms as well as by stabilizing soil aggregates, thereby improving the tilth, the moisture holding capacity, and the aeration status of the soil. However, the nature of the SOM (i.e. its quality) is influenced by the type of soil within which it develops and by the management practices to which the soil is subjected. The resulting characteristics of the SOM determine the extent of its benefits to soil productivity. Soil management practices which enhance the quality of SOM are thus important to the sustainable utilization of the soil resource (cf. McGill et al. 1986).

The following literature review will consider SOM quality within the context of the influence of management practices and of soil properties on SOM dynamics.

2.1. Quality of the Soil Organic Matter

2.1.1. Evaluation of Quality

The quality of the SOM is evaluated in terms of its ability to contribute to the chemical and physical fertility of the soil. The SOM is a heterogeneous system, consisting of compartments or pools of materials which differ in their rates of cycling (Sauerbeck and Gonzalez 1977; McGill et al. 1981; Woodmansee et al. 1981; Parton et al. 1983; Tiessen and Stewart 1983; Paul 1984; Anderson and Coleman 1985) and

hence in their ability to contribute to the maintenance of soil fertility. An evaluation of SOM quality is therefore concerned with the relative sizes of the various pools.

Many researchers have emphasized the importance of the actively cycling pool of the SOM in contributing to soil productivity. This pool is most effective in providing nutrients for microbial and plant growth (Floate 1981; Paul and Juma 1981; Woodmansee et al. 1981; Janssen 1984) and is crucial to the maintenance of aggregate stability (Tisdall and Oades 1979; Foster 1981; Reid and Goss 1981; Tisdall and Oades 1982; Cheshire et al. 1983; Cheshire et al. 1984; Elliott and Lynch 1984; Lynch 1984; Oades 1984; Chapman and Lynch 1985; Metzger and Robert 1985; Chaney and Swift 1986). Thus, the larger the proportion of young or actively cycling SOM, the higher the quality of the SOM.

The active SOM pool may consist of several fractions. Paul and Juma (1981) developed a model simulating the microbial mineralization and immobilization of N which contained four distinct types of active SOM: (1) biomass; (2) metabolite-N; (3) active-N; and (4) stabilized-N (half-life of 27 years). They concluded that these fractions contributed 24%, 4%, 32%, and 40%, respectively, of the N entering the mineral-N pool. Paul (1984) continued the discussion of the multifraction character of active SOM, providing a detailed description of the relationship of active SOM to SOM quality and to soil productivity and identifying those aspects of active SOM dynamics which require further research.

A point of clarification is necessary here. The term "stabilization" or "stability" is used in two ways in the discussion of

active SOM dynamics. First, organic materials are said to be stabilized into the active SOM pool. Stabilization in this context refers to the slowing of the humification of materials after their incorporation into the active SOM. One school of thought understands humification as the "multistep process involving the decomposition of residues to more simple units and the subsequent condensation of these units into complex structures" (Anderson and Coleman 1985). In this context the active SOM pool includes materials which have been stabilized between the decomposition and condensation steps of the humification process. Second, the active SOM is said to participate in the stabilization of soil aggregates. Stabilization here denotes the increased resistance to dispersion and/or disruption of aggregates attributed to the binding action of active SOM.

2.1.2. Cycling of Nutrients from Active Soil Organic Matter

The active SOM contributes to the efficient cycling of nutrients because it consists of materials of intermediate availability. According to the model of Paul and Juma (1981), these materials might have half-lives of six months to 27 years. These materials are quite readily utilized for microbial growth and/or mineralized for plant uptake. Yet, the nutrients are not available rapidly enough to promote a flush of microbial activity. The active SOM thus acts as a short- to medium-term storehouse of nutrients (Anderson et al. 1974; Ladd et al. 1977; Paul and McGill 1977; Paul and Voroney 1980; Anderson and Paul 1984; Anderson and Coleman 1985; Christensen and Sorensen 1985), gradually but relatively rapidly releasing nutrients for microbial and

plant use.

The ability of the active SOM to serve as a storehouse of nutrients is characteristic of its immobilized or stabilized situation. The active SOM consists of materials immobilized by incorporation into microbial tissue and stabilized by association with soil minerals (McGill and Paul 1976; Paul 1984). These materials (e.g. amino acids, proteins, simple carbohydrates, polysaccharides) have a labile chemical structure but their physical position prevents immediate decomposition. Nutrients immobilized in the biomass are released into the soil when the microbes die and their cells lyse (McGill et al. 1975; Paul and Voroney, 1980; Van Veen et al. 1984). Plant and microbial metabolites adsorbed to the mineral surfaces are continually recycled, but at a rate slower than that of free metabolites (Van Veen and Paul 1981). This regulated release of nutrients from the active SOM maintains the nutrient supplying capacity of the SOM and is thus central to SOM quality.

Clearly, the active SOM is crucial to the efficient cycling of C and N within the soil. Therefore, soil management practices which maintain and increase the size of this pool should be developed and implemented. However, in order to evaluate the impact of management factors on the active SOM, an effective approach to the study of this pool must be determined.

The fine clay fraction is frequently identified in the literature as a locus of active SOM. The SOM associated with this particle size fraction exhibits a relatively rapid turnover rate and a high degree of mineralizability (Anderson et al. 1974; Young and Spycher 1979; Amato and Ladd 1980; Anderson and Coleman 1985). Anderson et al. (1981)

concluded that up to 20% of the SOM in grassland soils is complexed with the fine clay and that this material is rich in readily mineralized nutrients. Chichester (1969) fractionated soils by particle size and found that ppm N, % C, and mineralizable N increases with decreasing particle size. The labile nature of this pool of the SOM has been explained on the basis of the role of the fine clays in the stabilization of microbial and plant cell lysate and metabolites. Campbell et al. (1981) found a corelation between CEC and potentially mineralizable N and concluded that this was "consistent with the theory that expanding lattice clays adsorb and protect aliphatic N and N of microbial origin against rapid decomposition". Tiessen et al. (1984) point out that clay-adsorbed material remains relatively labile because microorganisms are preferentially associated with the stabilizing clay surfaces. The turnover of the organic materials associated with the fine clay fraction thus reflect active SOM dynamics.

McGill et al. (1975) developed an approach to the study of the active SOM which recognizes the importance of the fine clay associated material. This method can be modified to produce two humic acid fractions. The first humic acid (HA) fraction, Fraction A (Fr-A), is obtained by extraction with $Na_4P_2O_7$. This fraction consists of humic material associated with polyvalent cations in the soil (McGill and Paul 1976; McKeague et al. 1971), having a relatively low susceptibility to hydrolysis and a high proportion of aromatic components (Anderson et al. 1974). Some labile materials (extracellular metabolites) of the active SOM pool, however, are adsorbed to the surface of the HA colloids. The second HA fraction, Fraction B (Fr-B), is collected by sonicating the

$Na_4P_2O_7$-extracted residue. This treatment disperses microaggregates and disrupts microbial cells, thereby releasing occluded or "protected" active SOM and intracellular metabolites. The sonicated suspension is centrifuged in order to remove all particles larger than 0.04 μm (equivalent spherical diameter). The Fr-B fraction thus consists primarily of active SOM, including microbial intracellular metabolites, free in solution and adsorbed to the fine clay colloids. This method of extracting some of the active SOM is useful for studying nutrient cycling on a short term basis (Paul and McGill 1977) and therefore appropriate for determining the effects of management factors on the active SOM.

2.1.3. Stabilization of Soil Aggregates by Active Soil Organic Matter

The interaction between active SOM materials and soil minerals which facilitates effective nutrient cycling is also crucial to the stabilization of soil aggregates by active SOM. The labile SOM adsorbed to mineral surfaces and trapped within microaggregates acts as a bridge between discrete clay particles or tactoids and as a nucleus or matrix for microaggregate formation (Marshall 1976; Foster 1978; Turchenek and Oades 1978; Tisdall and Oades 1982; Metzger and Robert 1985; Emerson et al. 1986). Thus, as well as regulating the sustained release of nutrients, the active SOM-mineral complexes also contribute significantly to the maintenance of the long-term physical fertility of the soil.

The active SOM participating in aggregate stabilization is of both microbial and plant origin. Mucilages are polysaccharide gels which are

produced by microorganisms wherever organic debris is being decomposed and by plant roots growing through the soil matrix. The carbohydrate gels secreted by bacteria, fungi, or roots are collectively termed extra-cellular polysaccharides -- ECP (Emerson et al. 1986). Oades (1984) lists the evidence for the role of these polysaccharides in aggregate stabilization: correlations of aggregate stability and polysaccharide content; stabilization of aggregates by additions of microbial and soil polysaccharides; degradation of aggregates by oxidation of polysaccharides with periodate; and identification of polysaccharides *in situ* in thin sections of soils. Living plant roots and fungal hyphae form a stabilizing net around soil aggregates, but here also contact with the soil minerals is achieved by means of the associated mucilage (Emerson et al. 1986). Based on work with periodate treatment, Cheshire et al. (1983) determined that the stability of >45 μm diameter aggregates depends more upon microbial than upon plant polysaccharides. Thus, although plant polysaccharides certainly play a role, those of microbial origin likely represent the active SOM most important to aggregate stability.

Soil minerals and many microbial polysaccharides are polyanions and therefore the interaction between them can be mediated by polyvalent cations. The cations (usually Ca^{2+}, Mg^{2+}, Al^{3+}, or Fe^{3+}) form a bridge between the mineral and the polyanions (Edwards and Bremner 1967; Mortland 1970; Schnitzer and Kodama 1977; Theng 1979; Stevenson 1982). These cations are therefore necessary to the stabilization of aggregates by polyanionic humic material through the formation of organo-mineral complexes (Oades 1984; Goh et al. 1987). Indeed, extractants (e.g. Na-

pyrophosphate; acetylacetone in benzene) or chelating agents which remove these di- and trivalent cations have been shown to decrease the water stability of soil aggregates (Hamblin and Greenland 1977; Reid et al. 1982; Oades 1984).

The amount and influence of polyvalent cations in the soil is a function of soil type, but the amount of microbial polysaccharide in the soil can be influenced by soil management practices. Soil aggregate stability is thus dependent both upon soil type and soil management factors. Therefore, in order to describe the effect of soil type on, and to evaluate the suitability of management factors for, the maintenance of aggregate stability, the study of the interaction of these polycations and polysaccharides is useful. In the present work, the analysis of the effect of organo-mineral complexes and polysaccharides on soil aggregate stability will be emphasized.

Cheshire et al. (1983) have developed an approach amenable to the study of the effect of polysaccharides on soil aggregate stability. This method determines the difference in water dispersible stability between aggregates with and without periodate/Na-tetraborate treatment. The periodate ($NaIO_4$) cleaves the bond between carbon atoms which both have at least one -OH or =O group (cf. Bobbitt 1956). The tetraborate ($Na_2B_4O_7$) degrades the partially oxidized polysaccharides (i.e. ring opened to form polyaldehydes) which are unstable under alkaline conditions (Mehta et al. 1960; Theng 1979). Cheshire et al. (1983) found that carbohydrate material remaining after periodate treatment is

enriched in plant sugars[1], and they therefore suggested that microbial carbohydrates are preferentially oxidized. This method thus represents a means of quantifying the contribution of the active SOM of microbial origin to aggregate stability, and therefore a means of evaluating the benefit of given management practices to soil physical properties.

2.2. Effects of Soil and Management Factors on Nutrient Cycling

In different soils under different management regimes the incorporation of material into the active SOM proceeds differently, resulting in active SOM which varies in amount and in ability to provide nutrients to microbes and plants.

2.2.1. Effect of Soil Type

The type of soil affects the cycling of nutrients from the active SOM by determining the stabilization of materials into the active SOM. The complement of minerals unique to each soil type provide dissimilar amounts of polyvalent cations, offer different opportunities for chemical and physical protection of SOM, and exert distinct chemical influences on the formation and further humification of active SOM. Indeed, Herman et al. (1977) proposed that "the effect of soil in controlling decomposition may be as great as the effect of the

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[1]Soil microbes synthesize mainly galactose, glucose, mannose, rhamnose, and fucose, but very little arabinose and xylose (Cheshire et al. 1984). Plant tissue, however, contains substantial quantities of arabinose and xylose. The ratio of galactose + mannose/arabinose + xylose is therefore low (<0.5) for plant and high (>2.0) for microbial polysaccharides (Turchenek and Oades 1979; Oades 1984).

substrate."

The formation of complexes with metal cations which are adsorbed to, or are structural components of, soil minerals protects active SOM from rapid degradation (Theng 1979; Martin and Haider 1986). This associated SOM is chemically less accessible to agents of decomposition. Schnitzer and Kodama (1977) reported that >75% of the fulvic acid (FA) adsorbed to Cu^{2+}-montmorillonite was retained after heating the complex to 1273°K. Olness and Clapp (1975) showed that the oxidation of SOM was prevented by adsorption to montmorillonite, likely because periodate anions were excluded from the clay surface (Emerson et al. 1986). In the associated situation the functional groups of the SOM are occupied, thereby inactivating the SOM with respect to microbial extracellular enzymes (Theng 1979). Further, the complexed SOM may be physically inaccessible to microbial attack (Foster 1981). Many investigators have found that it is possible for some SOM (i.e. small molecules) to be protected by adsorption between the lattice sheets of expanding clays (Schnitzer and Kodama 1977; Goh and Huang 1986; Martin and Haider 1986; Schnitzer 1986). This interlayer adsorption more effectively stabilizes SOM than does surface adsorption (Martin and Haider 1986). Theng (1979) asserted that where interlayer adsorption is not possible (i.e. SOM polymer too large) the SOM may be protected by penetration into intercrystalline and interdomain pores of clay/water systems and into the pores and channels between the spherical silico-alumina particles of allophane soils. The largest SOM particles (i.e. fragments of microbial or plant material) may be protected by serving as nucleation points onto which a coating of mineral particles adsorb (Foster 1981; Tisdall and

Oades 1982; Oades 1984; Tiessen et al. 1984). The polyvalent metal cations in the soil thus make possible the organo-mineral interactions which facilitate the stabilization of labile materials into the active SOM pool.

The stabilization effect of these interactions, however, varies with the type of mineral participating in the complex. Martin and Haider (1986) found that montmorillonite began to retard $^{14}CO_2$ evolution from amino acid derived C only after the first 90 days of incubation. In their study minerals with higher CEC were found to exhibit more marked stabilization effects, with kaolinite having no effect on the rate of amino acid C evolution. Theng (1979) reported that only fulvic acids (FA's) and humic acids (HA's) were stabilized in allophane soils since fresh organic residues generally rapidly decomposed. Wada and Inoue (1967) compared the decomposition of a water extract from rotting clover leaves in montmorillonite- and allophane-containing soils. They found that the rate of loss of material by migration down the soil profile or by mineralization was lower in the allophane soil. They also extracted humic substances (HS's) which were darker in color and richer in HA's from the montmorillonite than from the allophane soil. Sen (1961) concluded that the addition of montmorillonite and illite decreased the rate of decomposition of HA's, but that a much greater reduction in the mineralization rate was achieved when Al^{3+} ions were added to the clay-humate system. Table 2.1 summarizes the stabilization effects attributed to interaction with various minerals.

Soil minerals help to preserve active SOM by chemically and physically protecting it from degradative influences. It appears,

however, that the organo-mineral interaction also participates in the transformation of materials within the active SOM pool.

Various investigators have found that soil minerals catalyze the oxidative polymerization of smaller adsorbed organic molecules into larger, chemically more complex ones (Wang et al. 1978a; Wang et al. 1978b; Shindo and Huang 1982; Schwertmann et al. 1986; Wang et al. 1986). This random abiotic polymerization complicates enzymatic degradation (Theng 1979) and thereby ensures that this material is gradually mineralized.

Many soil minerals have been shown (in the laboratory) to possess

Table 2.1. Stabilization characteristics of various soil minerals (from Duchaufour 1976)

Mineral	Stabilization Dynamics
Active $CaCO_3$	Sequesters fresh organic material with carbonate film in Rendzina soils -- humified compounds precipitated without transformation -- humification impeded at relatively early stage and HS's easily extracted once $CaCO_3$ removed
Alumina	Stabilizes FA's and HA's in allophane soils -- fresh materials decompose rapidly -- HS's more transformed and condensed than in Rendzina (mean residence time older)
Active Fe	Clay-bound stabilizing agent, but not as effective as $CaCO_3$ and alumina -- strongly insolubilizes (i.e. precipitates) SOM so that extraction resisted (much humin formed)
Swelling clay	In acid soils in temperate climates illites and vermiculites act like bound Fe -- stabilization not efficient In wet/dry alternating pedoclimates Chernozems and Vertisols stabilize SOM to form mature, polymerized HS's

this catalytic capability. Shindo and Huang (1982) demonstrated the

ability of Mn(IV) oxide to catalyze the abiotic browning (i.e. formation HS's) of hydroquinone. Wang et al. (1978a) found that clay minerals and quartz catalyzed the oxidative polymerization of various phenolic compounds, with catalytic efficacy decreasing in the order, 2:2 > 2:1 > 1:1 > quartz. A most complete review of the catalytic activity of various soil minerals has been presented by Wang et al. (1986). These authors document abiotic polymerization of phenolic compounds (and subsequent formation of HS's) catalyzed with varying capability by oxides , hydroxyoxides, and short-range ordered minerals, by clay-sized layer silicates, by primary minerals, and by whole soils.

Soil minerals also influence the stabilization of materials into active SOM by altering microbial dynamics. Martin and Haider (1986) reported that in the presence of clays: (1) microbial numbers and activity may be increased; (2) the uptake of O_2 and evolution of CO_2 may increase and decrease, respectively (increased efficiency in the conversion of C to biomass); and the proportion of residual ^{14}C and ^{15}N retained in the biomass may be increased. Theng (1979) documented increased amounts of organic matter production and higher incorporation of N into microbial cells in a system amended with montmorillonite. Thus, the presence of clay minerals may modify microbial growth toward the incorporation of a larger proportion of added materials into the active SOM.

Soil minerals, including clay minerals, thus influence active SOM dynamics. Sorensen (1981) summarized the importance of soil clays to the stabilization of active SOM: "The effect of clay in increasing the organic matter in soil is possibly caused by newly synthesized matter,

extracellular metabolites, as well as cellular material, forming biostable complexes and aggregates with clay. The higher the concentration of clay the more readily the interactions take place." In a study of Saskatchewan soils, Campbell and Souster (1982) found that the losses of SOM and of potentially mineralizable N increased with decreasing clay content. A study of the active SOM, then, must recognize the potential contribution of the soil clay to the maintenance of this pool.

2.2.2. Effect of Type of Management Practices

According to Russell (1973), "The level of organic matter in an agricultural soil is determined by the rates of addition and oxidation of plant residues and of soil humus." Recent work has established that SOM quality is also dependent upon these factors (Sauerbeck and Gonzalez 1977; Janssen 1984; McGill et al. 1986). Since these rates of addition and oxidation are strongly influenced by soil management practices, the amount of SOM, as well as its quality, can be modified. The challenge, then, is to understand the effect of management practices on the active SOM pool in order to efficiently and sustainably utilize the soil resource (Bacon 1982; Paul 1984).

Uncultivated soils, because of the perennial growth habit of their indigenous vegetation, have a higher level of addition of organic residues than do cultivated soils. For this reason soils almost always contain less active SOM in the cultivated than in the native state (Campbell and Souster 1982; Parton et al. 1983; Tiessen and Stewart 1983; Anderson and Coleman 1985). Lynch (1984) reported that the

microbial biomass of grassland soils may be twice that of cultivated soils. The degree to which cultivation negatively affects the active SOM, however, can be moderated by responsible management of the soil.

Two aspects of soil management which affect the active SOM dynamics are (1) the residue and fertilizer management practices, and (2) the type of crops grown. These management practices determine the amount and type of residue which is incorporated into the soil.

Cropping practices which maximize the return of organic materials to the soil minimize the deleterious effect of cultivation on the active SOM. McGill et al. (1986) showed that a soil cropped for 50 years to a wheat-oats-barley-forage-forage rotation contained 117% more (i.e. > twice) microbial N than did the same soil under wheat-fallow. Janzen (1987) demonstrated increased relative N mineralization potential in continuous wheat and wheat-wheat-fallow rotations with adequate N fertilization. Janssen (1984) found that added farmyard manure could replace the active SOM decomposed during the crop year. Biederbeck et al. (1984) concluded that the loss of active SOM due to frequent fallow could be reversed with the use of longer rotations, fallow-substitute crops, and N and P fertilizers. Dormaar et al. (1979) found that the frequent burning of crop residues generally reduced organic C, polysaccharides, and % water-stable aggregates. Thus, rotations which employ adequate fertilization, include forages, periodically incorporate manure, and exclude fallow are beneficial to the active SOM pool.

The composition of added residues influences their decomposition and therefore affects active SOM dynamics. The amount of available C in the residue appears to control both the rate of decomposition and the

amount of microbial biomass produced in cultivated soils (Reinertsen et al. 1984; Jawson and Elliott 1986). Kassim et al. (1981a; 1981b) found that most residual glucose C is incorporated into biomass while that of the less readily degradable phenolic C is primarily found in less hydrolyzable SOM material (Stott et al. 1983). Martin et al. (1980) proposed that lignin (highly phenolic) C is primarily incorporated into the aromatic components of SOM, while polysaccharide C is preferentially used for energy and for synthesis of intracellular polymers (Murayama et al. 1979). Management practices determine the nature of residues added to the soil and thus influence active SOM dynamics by determining the input of available C (McGill et al. 1986).

The influence of available N content of residues on active SOM dynamics in cultivated soils appears to be controlled by several factors. First, the N status of the soil is important. In undisturbed grassland or forest soils C inputs are high and N is the nutrient limiting decomposition (Paul and Juma 1981). In cultivated soils, however, C is also usually deficient so that N added in or with residues will be immobilized into microbial biomass but may not alter decomposition rates (Bacon 1982). Second, the stage of decomposition seems significant. Knapp et al. (1983a; 1983b) found that the initial rate of wheat straw decomposition was governed by both C and N availability, but that after 240 hours of incubation microbial activity responded to the addition of C but not to that of N. Finally, the form of N in the residue appears to influence decomposition dynamics. Till et al. (1982) proposed that young plant materials contain nutrients in forms which can be much more rapidly recycled than those in mature

plants. Azam et al. (1985) showed that more $(NH_4)_2SO_4$-N was incorporated into microbial biomass when it was added to the soil with a legume residue than when added alone. Other investigators have found that fertilizer N does not increase microbial activity as much as other amendments (Biederbeck et al. 1984; McGill et al. 1986). Thus, in order to effectively manage the soil resource, practices must be developed which recognize the possible influences on active SOM dynamics of the N in added residues.

2.3. Effects of Management Factors on Aggregate Stabilization

The efficacy of the stabilization of soil aggregates by active SOM depends upon the nature of the SOM, the attachment of this material to soil particles, and the integrity of soil microaggregates. Thus, management practices can affect aggregate stabilization by influencing the amount of polysaccharide material (Lynch 1984) in the active SOM and by modifying soil surface chemistry (Goh et al. 1987).

The effect of soil management practices on the stabilization capability of the active SOM is exerted primarily through their influence on microbial dynamics. "The types and numbers of microorganisms, metabolites, cellular components after death, and different substrate for microorganisms all affect the aggregation process" (Elliott and Lynch 1984). Chapman and Lynch (1985) developed a coculture of cellulolytic fungi with non-cellulolytic polysaccharide-producing organisms which was more effective in achieving stabilization than was a natural mixed flora. They proposed that straw could be

inoculated with these organisms in order to produce a stability-enhancing compost. Swincer et al. (1968) found that a pasture soil contained four times as much microbial polysaccharide as did a soil under wheat-fallow. Dormaar et al. (1979) observed decreased levels of polysaccharide in Southern Alberta soils where the burning of crop residues was practiced on a long-term basis. The increased aggregate stability under ryegrass is attributed by Tisdall and Oades (1979) largely to the association of polysaccharide-producing filamentous fungi with the fine roots of the ryegrass. Knapp et al. (1983b) proposed that, when the available N content of decomposing plant residues is limiting to microbial growth, excess available C is immobilized as polysaccharide. The effect of management practices on aggregate stability thus reflect the influence of these practices on the character of the active SOM produced by microbial processes.

Management practices can undermine aggregate stability by perturbing the polymer-particle and the particle-particle interactions in the soil. The influence of management practices on both the SOM dynamics and the soil solution chemistry are implicated in this effect.

Although it is predominantly beneficial to aggregate stability, under some conditions the SOM contributes to aggregate instability. Organic anions produced by living roots and rhizosphere organisms and by the decomposition of organic soil materials can decrease aggregate stability. These anions decrease macroaggregate stability by chelating polyvalent cations, thereby disrupting the organo-(Al, Fe, Ca)-particle linkages and reducing soil solution polyvalent cation concentrations (Reid et al. 1982; Oades 1984). The sorption of the organic anions

promotes dispersion by increasing the negative charge of the clay surfaces, thereby compromising the stability of microaggregates (Oades 1984). According to Oades (1984) these negative effects of SOM on soil structure can become significant when the SOM is allowed to deteriorate. Oades warns that excessive cultivation and low additions of organic materials will result in a more highly oxidized SOM (i.e. more soluble and more acidic functional groups per unit weight) and consequently in a decrease in soil structural stability.

Management practices can also affect aggregate stability by directly altering the cation balance of the soil. Goh et al. (1987) concluded that the addition of high levels of NH_4^+ fertilizers may result in the replacement of Ca^{2+} and Mg^{2+} by NH_4^+ on the exchange and thus an increase in the water-dispersible clay of the soil. Grant (1986) showed that the addition of NH_4NO_3 increased the concentration of Ca and Mg in the soil solution. Grant proposed that, as well as displacing cations on the exchange, the NH_4^+ could have been rapidly converted to NO_3^-, thereby increasing the anion concentration and shifting the equilibrium among solid, exchangeable, and solution phases toward increased cation concentration in the soil solution. Whatever the mechanism, then, the addition of some types of N fertilizers can decrease aggregate stability by increasing the dispersive interaction between clay particles.

In summary, this review has described some aspects of active SOM dynamics and has elucidated the importance of the active SOM pool to the sustainable utilization of the soil resource. The influence of soil

management practices and of soil properties on active SOM dynamics and consequently on soil productivity has been demonstrated. The challenge to further research is thus to evaluate the relative benefits of various management practices in different soils in order to nurture active SOM dynamics.

3. INCORPORATION OF C AND N FROM VARIOUS AMENDMENTS INTO THE ORGANIC MATTER OF DIFFERENT SOILS

3.1. Introduction

Plant residue management practices influence soil organic matter (SOM) quality (Dormaar et al. 1979; Biederbeck et al. 1984; Anderson and Coleman 1985; Janzen 1987), because the amount and type of organic residues added to the soil determine the proportion of the SOM which is actively cycling (Janssen 1984; McGill et al. 1986). The effects of management practices on the active SOM are cumulative, becoming more pronounced in long-term applications (McGill et al. 1986). However, because of the rapid turnover rate of the active SOM, short-term effects may also be relevant to SOM quality.

The short-term effects of management practices on SOM quality may be readily observed in the SOM associated with the fine clay fraction. These organic materials exhibit a relatively rapid turnover rate and a high degree of mineralizability (Amato and Ladd 1980; Anderson and Coleman 1985). The labile nature of this pool has been explained on the basis of the role of the fine clays in the stabilization of microbial and plant cell lysate and metabolites (McGill et al. 1975; Campbell et al. 1981; Tiessen et al. 1984). Influences noted in the fine clay-associated material may thus reflect the effects of management practices on the active SOM.

The importance of fine clays in stabilizing labile materials serves to emphasize the significance of soil factors for active SOM dynamics. Van Veen et al. (1984) concluded that differences in C and N dynamics in

different soils could be explained according to the ability of the respective soils to preserve SOM and microorganisms. Indeed, Herman et al. (1977) postulated that the influence of soil factors on plant residue decomposition was as great or greater than that of residue composition. This study was undertaken in order to demonstrate the interrelation of soil factors and residue composition in influencing the incorporation of amendment C and N into the active SOM.

3.2. **Materials and Methods**

3.2.1. Soils

Three different soils, chosen to provide varying levels of SOM and clay content, were collected in the spring of 1986 from the 0-100 mm depth of cultivated fields. One Newdale soil (Rego Black Chernozem)--designated NT -- was obtained from the top of a knoll near Rivers, Manitoba (legal description NW 18 - 12 - 20 W). A second Newdale soil (Gleyed Eluviated Black Chernozem) -- NB -- was collected from the foot of the same knoll. A sample of Red River Clay soil (Gleyed Rego Black Chernozem) -- RRC -- from the Glenlea Research Station in Glenlea, Manitoba was also used. The NT and NB soils were ground to pass a 2 mm sieve, while the RRC was ground to pass through a 4 mm sieve. Representative chemical and physical characteristics of the soils are listed in Table 3.1.

Table 3.1. Chemical and physical characteristics of the soils used (Soils: NB = Newdale clay loam bottom of knoll; NT = Newdale clay loam top of knoll; and RRC = Red River Clay)

Characteristic	NB	NT	RRC
Organic matter (%)	8.9	3.4	6.7
Total N (%)	0.43	0.20	0.31
Field capacity (% w/w)	34.7	27.4	51.5
pH	7.0	7.2	7.1
CEC (cmol + kg^{-1})	30.32	18.32	38.78
Reaction with HCl	none	strong	none
Clay (%)	33.8	30.6	73.9
Silt (%)	28.4	26.9	22.87
Sand (%)	37.9	42.5	3.16

3.2.2. Plant Materials

The plant materials used were wheat (Triticum aestivum c.v. Neepawa) straw and alfalfa (Medicago sativa c.v. Beaver). The plants were grown in a soil to which micro- (Cu and Zn) and macro-nutrients (P, K, and S) were added. Labelled $(NH_4)_2SO_4$, 50% ^{15}N enrichment, was also added. The plants were periodically isolated during their growth in a clear acrylic chamber in which $^{14}CO_2$ was evolved by the addition of 1.0 $mol \cdot L^{-1}$ Na_2CO_3 (61.83 kBq mg^{-1} C) to 85% lactic acid. Sufficient Na_2CO_3 was added to provide 15 μmol of CO_2 s^{-1} m^{-2} of leaf area. The plants were subjected to this labelling treatment 6 times (for a total of 20 hours). The alfalfa was harvested after 30 days (480 hours of light) at the budding/preblooming stage. The wheat reached maturity at 70 days (1120 hours of light). The shoot portions of the plants (the grain was removed from the wheat) were dried at 60°C, ground to pass a 20 mesh screen, and stored at room temperature until they were incorporated into the soils used for the incubation study. Table 3.2. lists some

pertinent characteristics of the plant materials.

Table 3.2. Characteristics of the wheat straw and alfalfa

Characteristic	Alfalfa	Wheat straw
Carbon (%)	48.11	52.72
Nitrogen (%)	4.05	2.00
C:N ratio	11.88	26.35
^{14}C (kBq mg^{-1} C)	2.62	0.56
Atom % ^{15}N excess	20.654	28.956

3.2.3. Treatments

Four treatments were applied in duplicate to each of the three soils . These consisted of (1) a control where no fertilizer or plant material was added to the soil (treatment C), (2) wheat straw (treatment S), (3) alfalfa (treatment Af), and (4) wheat straw with sufficient KNO_3 -- 46.772 atom % ^{15}N excess -- to reduce the C:N ratio to 11.70 (treatment SF). A total of 7.5 g of plant materials (plus 1.36 g of KNO_3 in SF treatment) were added to 2500 g of air-dried soil in plastic bags. The contents were thoroughly mixed by closing the bags and manually rotating them for one minute. The bags containing the amended soils were placed into plastic pots. The soils were then compacted by dropping the pots from a height of 5 cm 50 times onto a table. The resulting layer of amended soil was approximately 10 cm deep. The soil-plant residue mixtures were wetted to field capacity with distilled water and then incubated at 20°C in a temperature-controlled chamber.

A second set of soil-plant residue mixtures, representing the initial condition (Day 0 extraction/fractionation), was prepared. The

same four treatments were applied in duplicate to the NT, NB, and RRC soils, but only 0.75 g plant material (plus 0.136 g **unlabelled** KNO_3 in the SF treatment) and 250 g soil were used. The plant material (and fertilizer where required) and soil were placed in 250 mL plastic sample jars. Stirring of the mixture and then shaking of the capped jars were used to achieve thorough mixing of the contents. This set of mixtures was not wetted and was stored at -5°C until extraction.

3.2.4. Sample Preparation

Soil samples were collected from the pots for analysis after 7, 30, and 90 days of incubation. About 250 g (air dry basis) of soil were collected from each pot. Care was taken to ensure that the sample removed represented a column from the top to the bottom of the layer of soil in the pot. Further, effort was made to minimize the mechanical disturbance of soil remaining in the pot. These subsamples were dried at room temperature and then stored at -5°C.

3.2.5. Extraction and Fractionation

The procedure described by McGill et al. (1975) to extract and fractionate organic matter using sodium pyrophosphate and ultrasonic dispersion was used in a slightly modified form. Figure 3.1. presents this modified procedure as a flow chart. One sample from each of the unincubated mixtures (i.e. Day 0 extraction/fractionation) and two subsamples of each of the incubated samples (i.e. Day 7, Day 30, and Day 90 extraction/fractionation) were extracted and fractionated by this method. Fraction A (Fr-A) and Fraction B (Fr-B) from each soil sample

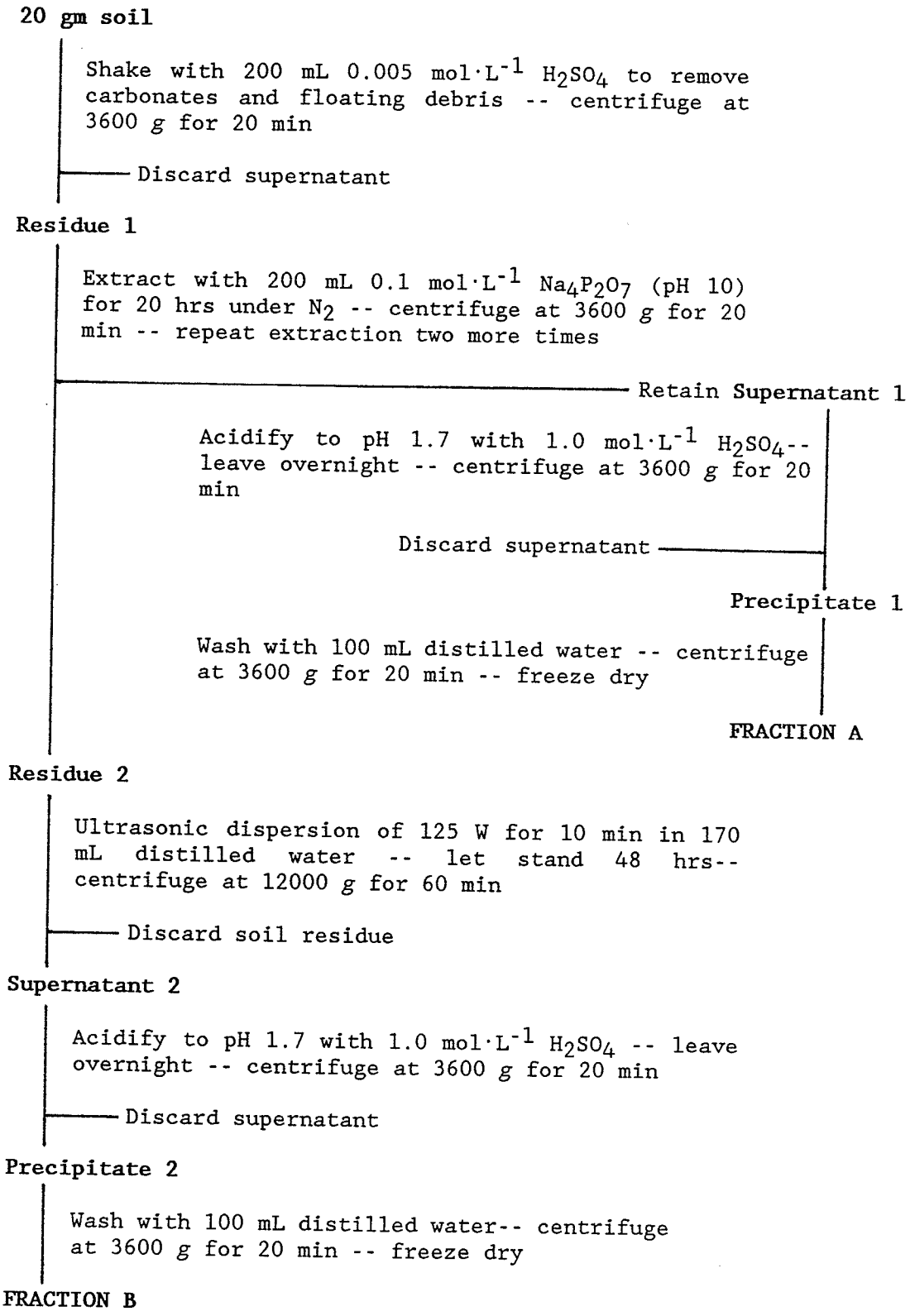


Figure 3.1. Flow chart of extraction and fractionation procedure.

were stored in closed 15 mL centrifuge tubes at room temperature.

3.2.6. Fractions

The organic matter fractions obtained by the above procedure were analyzed.

The total weights of Fr-A and Fr-B extracted per each 20 g soil sample were calculated. Aliquots of either 180 or 200 mL (600 mL were collected in total, but only these aliquots were retained) of Supernatant 1 (see Fig. 3.1.) were acidified to produce the precipitate which was freeze dried to obtain Fr-A. Therefore,

Total Wt. Fr-A = Wt. of ppt. from aliquot x (600 / Vol. of aliquot).

Fr-B was obtained from the acid precipitates of 125 mL aliquots (170 mL were collected in total) of Supernatant 2. Thus,

Total Wt. Fr-B = Wt. of ppt. from aliquot x (170 / 125).

The organic carbon content (%C) of Fr-A and Fr-B from all soil samples was measured. Expressed as a percentage of the weight of Fr-A and Fr-B analyzed (ranging from 10 to 100 mg), this value was used to calculate the total amount of C extracted in each fraction per each 20 g soil sample as follows:

Total Wt. C = % C x Total Wt. Fr-A (or Fr-B).

The ^{14}C activity of Fr-A and Fr-B from all soil samples was measured (procedure described below). The values obtained were expressed as kilo Bequerels (kBq) mg^{-1} C. Describing the results with respect to the percent of added ^{14}C incorporated (i.e. $\%C_{INC}$) into the extracted fractions, removed this confounding effect of the organic matter content of the soil:

$$\%C_{INC} = \frac{\text{kBq in fraction}}{\text{DPM in plant material added to 20 g soil}} \times 100.$$

The organic nitrogen content (%N) of Fr-A and Fr-B of all soil samples was measured. These values were used to calculate the total amount of N extracted in each fraction per 20 g soil sample as follows:

$$\text{Total Wt. N} = \%\ \text{N} \times \text{Total Wt. Fr-A (or Fr-B)}.$$

The ^{15}N enrichment of Fr-A and Fr-B from all soil samples was measured by mass spectrometer as described below. By determining the factor by which the plant-derived ^{15}N had been diluted, it was possible to calculate 1) the weight of plant-derived N (N_{INC}) and 2) the percent of added N which was incorporated into the respective fraction ($\%N_{INC}$) as follows:

$$N_{INC} = \frac{\text{Atom \% } ^{15}N \text{ excess in fraction}}{\text{Atom \% } ^{15}N \text{ excess in plant}} \times \text{Total N; and}$$

$$\%N_{INC} = \frac{N_{INC}}{\text{N from plant in 20 g soil}} \times 100.$$

3.2.7. Analytical Procedures

(1) Particle size analysis: The standard pipette method was used as described in McKeague (1978). The dispersing agent used consisted of 35.70 g of sodium hexametaphosphate and 7.94 g of sodium carbonate in 1.00 L of distilled water.

(2) Field capacity moisture content: Soil, ground as described in section 3.2.1., was placed into acrylic cylinders 4.5 cm in diameter by 20.5 cm in height with perforated bottoms. Water was added until the wetting front extended about two thirds of the way down the cylinder. The column was then covered with a plastic film and allowed to equilibrate for 48 hours. At that time the moist soil was sampled and the gravimetric field capacity moisture content determined from the loss in weight upon drying for 24 hours at 105°C. The field capacity determination was carried out in triplicate for each of the three soils.

(3) Total organic carbon: Total organic C was determined by the Walkley-Black procedure as outlined in McKeague (1978). The organic matter fractions (or plant material or soil) were oxidized with excess potassium dichromate (0.1667 $mol \cdot L^{-1}$). The resulting solutions were back-titrated (to endpoint of 750 mV) with ferrous sulphate (0.05 $mol \cdot L^{-1}$) using an automatic titrator. Organic matter content was calculated by multiplying organic C (%) by a factor of 1.724.

(4) Cation exchange capacity (CEC): CEC (and exchangeable cations) was determined by NH_4^+ displacement (NH_4OAc at pH 7) and micro-Kjeldahl distillation according to the method of Chapman (1965) as described in McKeague (1978).

(5) ^{14}C activity: The ^{14}C content of the organic matter fractions and plant material was measured (in kBq mg^{-1} C). A Packard 306 Sample Oxidizer was used to ignite the samples, to trap the evolved CO_2 in 4.0 mL of 2-methoxy-ethylamine (trade name Carbo-sorb -- Packard Instruments; Downers Grove, Illinois), and to mix the trap with 14.0 mL of scintillation fluid (PCS -- Amersham; Oakville, Ontario) in a scintillation vial. The activity of the material was then measured in a Beckman LS 7500 scintillation counter.

(6) Total N: Total N, which in this experiment refers to total NH_4^+-N, was determined by Kjeldahl digestion. The organic matter fractions (or plant material or soil) were digested with 25 mL of concentrated sulfuric acid and 2 Kelpak tablets (5.0 g K_2SO_4 and 5.0 mg Se per tablet) for 1.0 hour. The digested residues were distilled with 50.0 mL of 50% NaOH and the distillate captured in 50.0 mL of 0.01 $mol \cdot L^{-1}$ H_2SO_4 containing mixed indicator. The excess acid was back-titrated to the color-indicated endpoint (pH 7.0) using 0.01 $mol \cdot L^{-1}$ NaOH. The N content was calculated according to the amount of base used in the back-titration. The solutions were then acidified with the addition of a few drops of 0.01 $mol \cdot L^{-1}$ H_2SO4 in order to prevent the gaseous escape of NH_3. The solutions were dried to about 10 mL and retained for ^{15}N

analysis as described below.

(7) Atom % ^{15}N excess: The ^{15}N content of the acidified titres (dried to 10 mL) was determined. The NH_4^+-N in the solutions was converted to N_2 gas in a vacuum apparatus by treatment with sodium hypobromite (NaOBr). The N_2 gas was analyzed for mass to charge ratio (m/e) of 28, 29, and 30 as described by Cho and Sakdinan (1978), using a micromass 602 mass spectrometer (V.G. Micromass Ltd., Winsford, England). Atom % ^{15}N excess was calculated as follows:

$$\text{Atom \% } ^{15}N \text{ excess} = \frac{100}{(100 \,/\, (2R+1)) - B)} \times 100,$$

where R is the ratio of the peak heights of m/e 28 and 29, and B represents the measured background abundance of ^{15}N in the atmosphere.

The N content of the Fr-A and Fr-B samples was found to be too low to provide sufficient pressure in the mass spectrometer. Therefore, these samples were "spiked" with 1.0 mL of 0.1 mol·L^{-1} $(NH_4)_2SO_4$-- 1.356 mg N -- after their N content had been determined. The atom % ^{15}N excess of the Fr-A and Fr-B samples were calculated accordingly:

$$\text{Atom \% } ^{15}N \text{ excess} = (\text{Diluted atom \% } ^{15}N \text{ excess}) \times \frac{\text{mg N in sample} + 1.356 \text{ mg N}}{\text{mg N in sample}}$$

(8) pH: Supernatant 1 (Spt-1) and Supernatant 1 (Spt-2) were acidified

to pH 1.7 in the fractionation procedure (Fig. 3.1.). The pH of these solutions was measured with a digital pH meter fitted with a glass and calomel electrode (Fisher Accumet pH meter, Model 620). Soil pH values were measured with the same instrument, using 25 g soil (air dry) in 50 mL of 0.01 $mol \cdot L^{-1}$ $CaCl_2$.

Soils were classified as calcareous or noncalcareous on the basis of their reaction with dilute HCl. The soil which effervesced strongly upon addition of HCl was considered calcareous. The soils which did not effervesce were classified as noncalcareous.

(9) Centrifugation: A refrigerated centrifuge was used in the extraction/fractionation procedure. An IEC B-20A centrifuge, fitted with a 6-pot rotating head (IEC No. 872), was used. Polycarbonate centrifuge bottles (250 mL capacity) were used both as extraction vessels and in the centrifuging operations.

(10) Freeze drying: A LABCONCO Model Freeze Dry-5 freeze drying apparatus was used to dry the organic matter fractions.

3.3. **Results and Discussion**

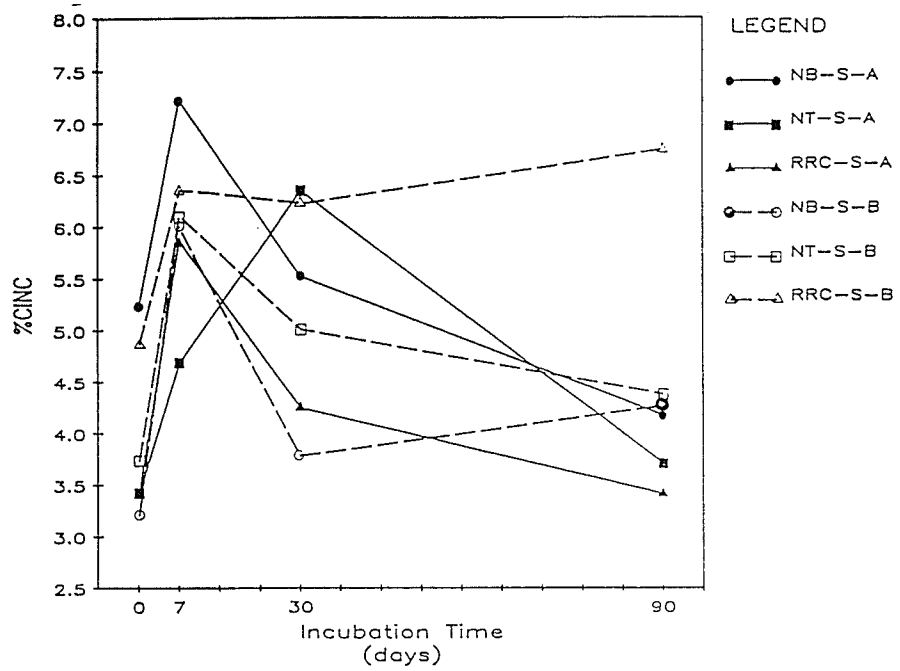
The extraction and fractionation scheme used in the present investigation (see Fig. 3.1.) was designed to isolate relatively distinct active SOM fractions. The results of this study show that labelled C and N are incorporated into both Fr-A and Fr-B (Fig. 3.2. and Appendix 1.).

Sodium pyrophosphate is effective in extracting humic substances

(HS's) complexed with polyvalent cations (McKeague et al. 1971; Schnitzer and Khan 1978). Fr-A thus contains humic acids (HA's) of relatively high C:N ratio and of predominantly aromatic structure (Anderson et al. 1974; Schnitzer and Kodama 1978). To these relatively recalcitrant HA's, however, are adsorbed more aliphatic organic molecules (McGill et al. 1975) which are likely extracellular microbial proteins. Indeed, McGill et al. (1975) found that up to 70% of the ^{14}C associated with Fr-A is held in these adsorbed substances. In this study levels of incorporated C and N in Fr-A were quite similar to those in Fr-B in the Newdale soil, but were lower ($P<0.05$) than those in Fr-B of the RRC soil (Fig. 3.2. and see Appendix 1. for a table including levels of significance). Thus, the active SOM material extracted in Fr-A could play an important role in the cycling of nutrients in soils with low clay content.

Ultrasonic dispersion (i.e. sonication) disrupts soil microaggregates and microbial cells, thereby exposing SOM which was occluded within the microaggregates and releasing microbial cytoplasm. Fr-B therefore consists of very fine clay particles (<0.04 μm) which remain suspended after centrifugation, labile organic materials adsorbed to this clay (including microbial lysate), as well as HA's which "escaped" the initial Na-pyrophosphate extraction. According to the literature Fr-B contains a larger proportion of more readily hydrolyzable materials than does Fr-A (Anderson et al. 1974; Amato and Ladd 1980; Anderson and Paul 1984). The data obtained here, however, indicate that the turnover rate of newly incorporated C and N may be slower in Fr-B in the RRC soil than in the Newdale soils (i.e. levels of

(a).



(b).

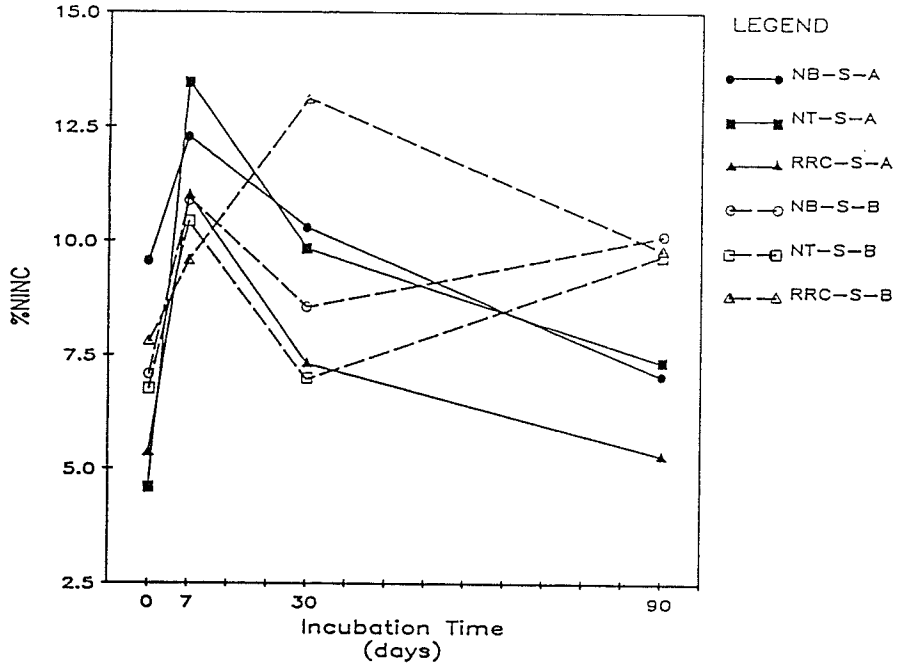


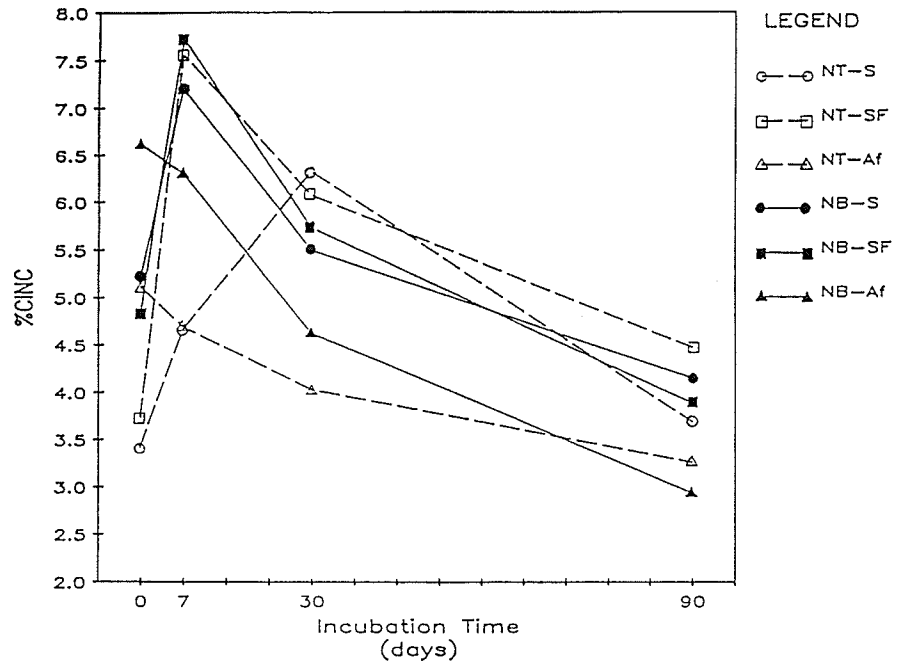
Figure 3.2. Comparison of incorporation dynamics of (a) ^{14}C and (b) ^{15}N from the straw treatment (S) into Fraction A and Fraction B of the soils. Soils: NB = Newdale clay loam from bottom of knoll; NT = Newdale clay loam from top of knoll; and RRC = Red River Clay.

$\%C_{INC}$ and $\%N_{INC}$ tend to be higher in Fr-B than in Fr-A after 90 days of incubation -- Fig. 3.2.). The role in nutrient cycling of the Fr-B materials may thus vary with the type of soil.

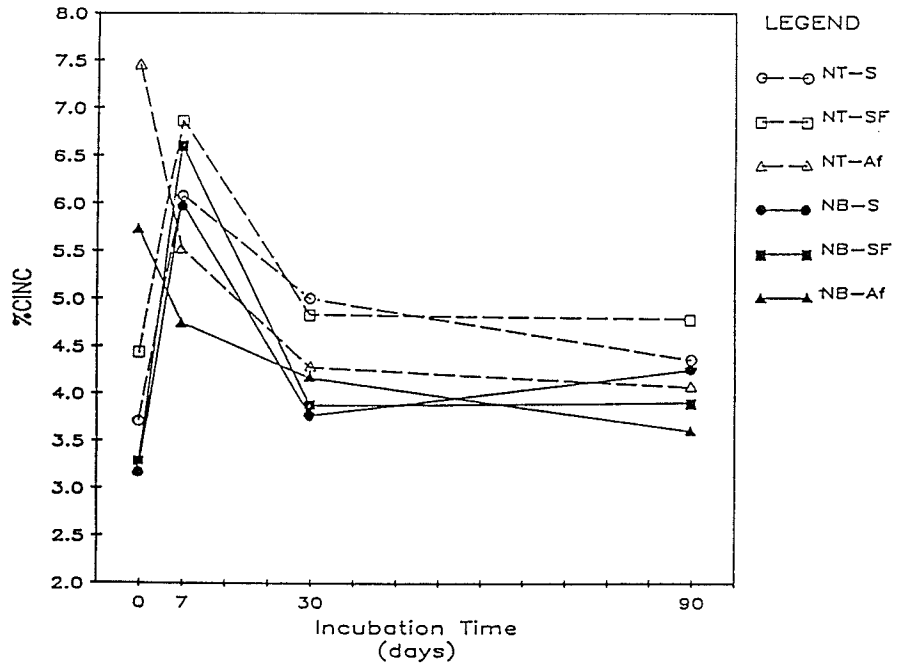
3.3.1. Effect of Soil Organic Matter Content

The charged surfaces of the SOM colloids interact with other organic molecules in the soil (Schnitzer and Khan 1978; Choudhry 1984). Biederbeck and Paul (1973) concluded that HA's contain an adsorbed "humoprotein" moiety. Hydrogen bonds between phenolic hydroxyl groups of the HA and oxygens of the peptide linkage of polyamides attach the humoprotein to the HA colloids. The NB soil, having a SOM content higher than that of the NT soil, would be expected to contain more newly added materials interacting with SOM surfaces and thus to have higher $\%C_{INC}$ and $\%N_{INC}$ values in Fr-A. This was generally found to be the case in this study. The higher ($P<0.05$) level of $\%C_{INC}$ at 0 and 7 days in Fr-A of the S treatment of the NB soil as compared to that of the same fraction and treatment in the NT soil showed the expected difference most profoundly (Fig. 3.3.a. and see Appendix 2. for a table including levels of significance). In the Af treatment the $\%C_{INC}$ in Fr-A was also higher in the NB soil at 0 and 7 days (Fig. 3.3.a.). The $\%C_{INC}$ in the SF treatments, however, were similar in the two soils. Fewer significant ($P<0.05$) differences between $\%N_{INC}$ values in Fr-A of the two Newdale soils were found, but where these occurred the values in the NB soil were higher (Fig. 3.4.a.).

Even though more labelled C and N was incorporated from treatment Af into the NB soil than into the NT soil from that treatment,



(a).



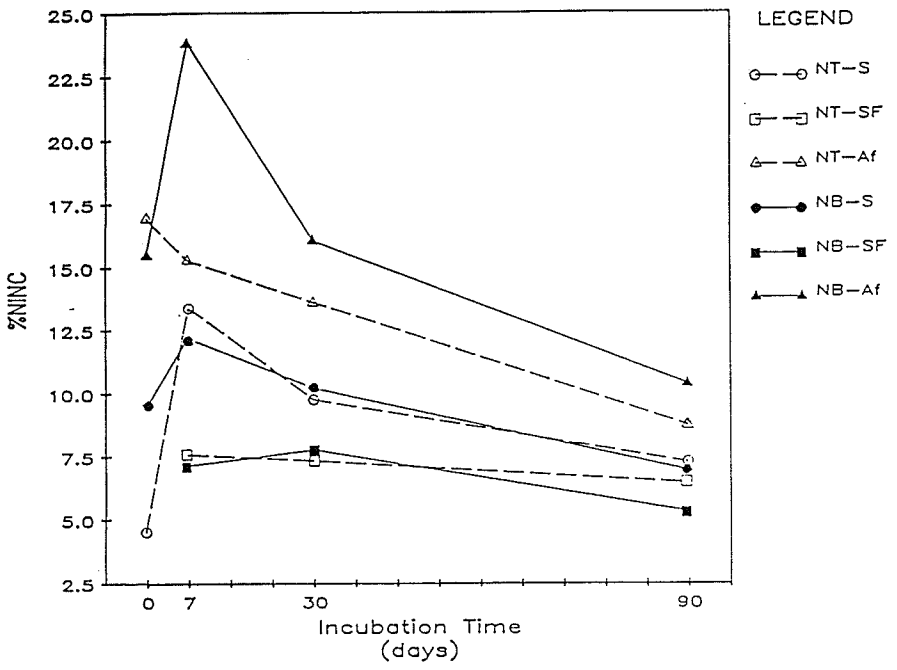
(b).

Figure 3.3. The incorporation of ^{14}C from different amendment treatments into (a) Fraction A and (b) Fraction B of soils containing different amounts of soil organic matter (SOM). Soils NB and NT are as explained in Fig. 3.2. Treatments: S = wheat straw; SF = wheat straw + KNO_3 fertilizer; and Af = alfalfa.

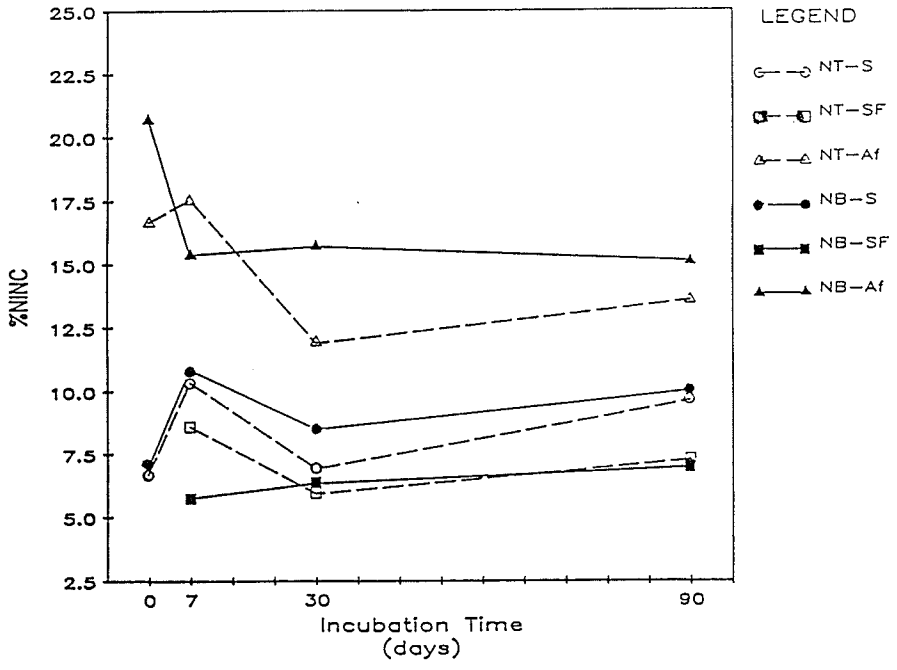
differences in incorporation into Fr-A of the Newdale soils were smaller than might have been expected on the basis of the amount of SOM colloids in the two soils. This may be a reflection of differences in the capacities of the SOM in the two soils to adsorb materials. Oades (1984) stated that SOM in a regularly cultivated soil receiving low organic matter inputs contains more acidic functional groups per unit weight than that in a soil having a higher SOM content. The surfaces of the SOM colloids in the NT soil may be more reactive than those in the NB soil and therefore able to incorporate more labelled C and N into Fr-A per unit weight of SOM.

The SOM content of the soil also has implications for the amount of interactions between newly added materials and mineral surfaces. Since the Newdale soils contain similar amounts of clay, the NB soil would likely have a larger proportion of the clay surface area saturated with SOM than would the NT soil. The NT soil might therefore be expected to incorporate more labelled C and N into Fr-B than would the NB soil. The incorporation of labelled C into Fr-B was consistent with this prediction. The level of $\%C_{INC}$ in Fr-B of the NT soil was usually higher (sometimes significantly -- $P<0.05$) than that in the NB soil (Fig. 3.3.b.). N incorporation dynamics, however, did not follow the predicted pattern. Where significant ($P<0.05$) differences in $\%N_{INC}$ between the two Newdale soils occurred (only in the Af treatment), the levels in the NB soils were higher (Fig. 3.4.b.).

Some quantitative and qualitative differences in microbial populations and dynamics might be expected between the two Newdale soils. Given the methodology of this work, however, these can be



(a).



(b).

Figure 3.4. The incorporation of ^{15}N from different amendment treatments into (a) Fraction A and (b) Fraction B of soils containing different amounts of soil organic matter (SOM). Soils NB and NT are as explained in Fig. 3.2. Treatments S, SF, and Af are as explained in Fig. 3.3.

studied only indirectly by observation of the levels of $\%C_{INC}$ and $\%N_{INC}$ in HA-B (cf. Paul and McGill 1977). Differences in microbial factors between the two soils did not seem to dramatically affect incorporation dynamics since the $\%C_{INC}$ and $\%N_{INC}$ values in Fr-B were remarkably similar for the Newdale soils at the top (NT) and bottom (NB) of the knoll (e.g. Fig. 3.2.).

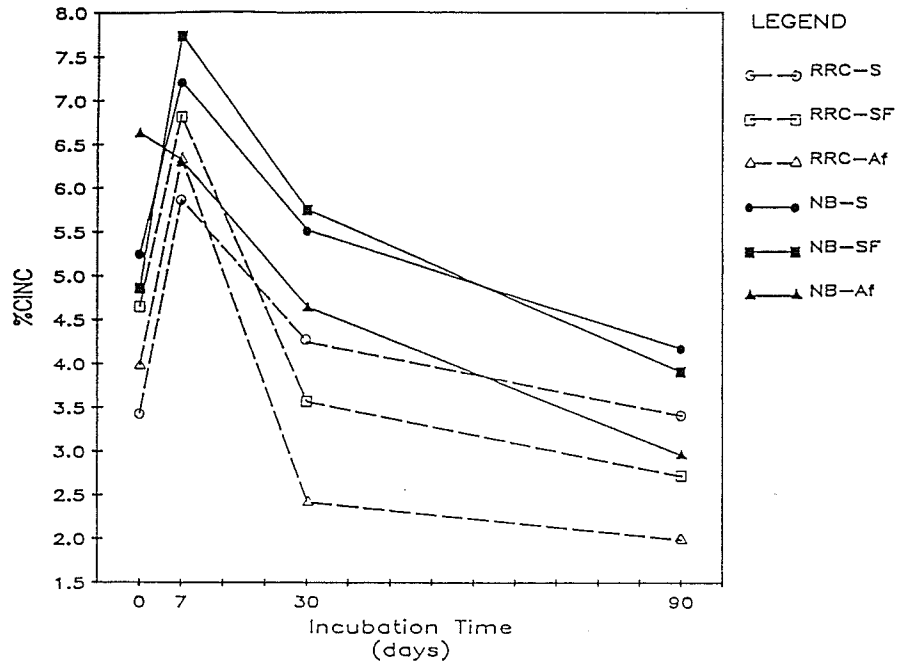
3.3.2. Effect of Soil Clay Content

The interaction of soil minerals with the decomposition products of recently added residues slows their further humification and thus serves to retain these labile materials in the active SOM (Paul 1984). Sorensen (1981) asserted that the interaction of clay minerals with labile decomposition products takes place more readily as clay content increases.

The RRC soil, having higher clay content and lower SOM content, would therefore be expected to have levels of $\%C_{INC}$ and $\%N_{INC}$ which are higher than those in Fr-B and lower than those in Fr-A of the NB soil which contained a higher SOM and a lower clay content. The incorporation of labelled C and N into Fr-A was observed to proceed as expected (See Appendix 3. for a table including levels of significance). In Fr-A the levels of $\%C_{INC}$ and $\%N_{INC}$ in the same treatments were usually greater (sometimes significantly -- $P<0.05$) in the NB soil than in the RRC soil (Fig. 3.5.a, 3.6.a.). The level of C incorporated into Fr-B of the RRC soil was consistently higher than into that of the NB soil (Fig. 3.5.b.). Indeed, the $\%C_{INC}$ of RRC-S had not declined from its peak level by the end of the incubation period and was still

significantly higher ($P<0.05$) than that in NB-S. Further, the $\%C_{INC}$ in Fr-B from the Af and SF treatments appeared to decrease less over the course of the incubation in the RRC soil when compared to the NB soil. Van Veen and Paul (1981) achieved the best fit in a simulation of SOM decomposition by assuming that soil amino acids adsorbed to soil minerals decomposed 0.01-0.005 times as fast as free metabolites. The RRC soil may thus have demonstrated a slower decline of incorporated C because of the large amount of very effective stabilizing surfaces available for interaction with the decomposition products of added residues.

N incorporation dynamics were more complex (See Appendix 3. for a table including levels of significance). Where significant differences ($P<0.05$) in $\%N_{INC}$ were observed between soils for the same residue treatment, the levels of N incorporation in the Af and S treatments were found to be higher ($P<0.05$) in the RRC soil than in the NB soil, but the situation was reversed in the SF treatment where fertilizer was added to the straw (Fig. 3.6.). The level of incorporated N was therefore observed to have increased with higher clay content in the Af and S treatments, but to have declined with higher clay content in the SF treatment. This could be due to lower microbial utilization of the nitrate-N. Aleynikova and Utrobina (1973) postulated that ammonium fertilizers more intensely stimulate the activity of ammonifying bacteria and fungi than do nitrate fertilizers. Paul and Juma (1981) present the preferential utilization of ammonium by microorganisms as a well documented fact. Nitrate-N which was not metabolized by microorganisms (i.e. converted to ammonium-N) would not be recovered in



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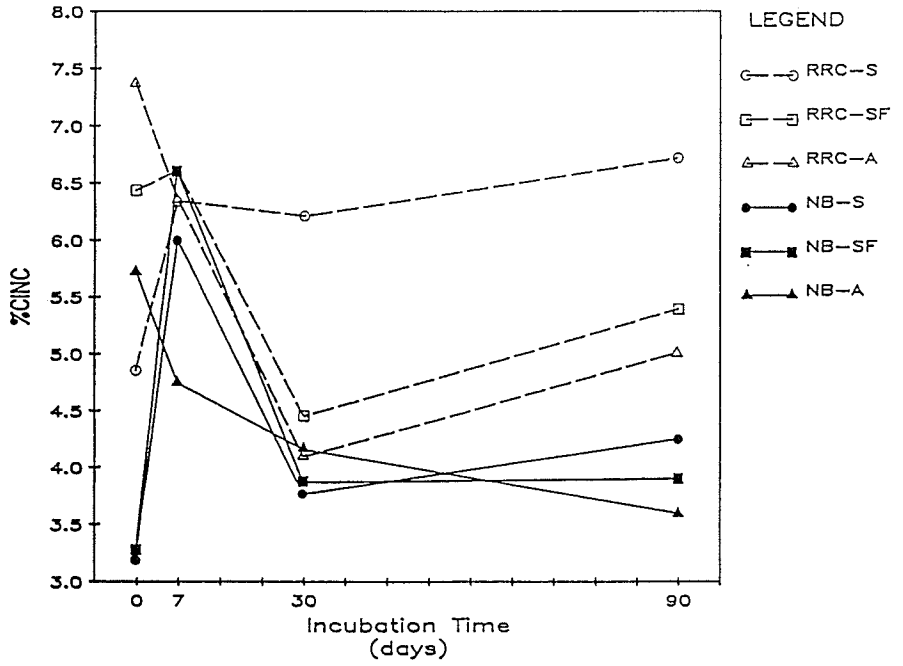
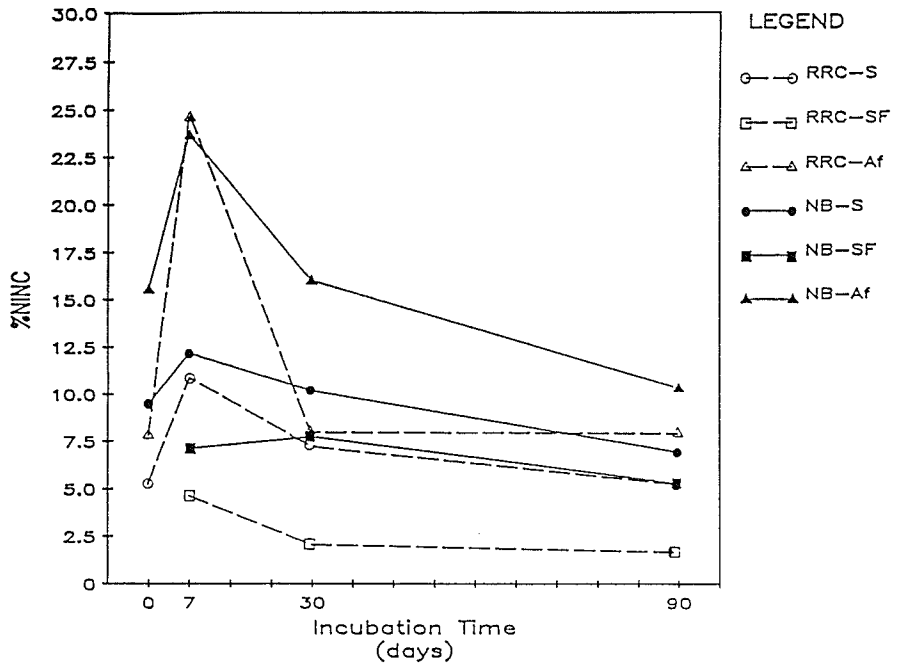


(b).

Figure 3.5. The incorporation of ^{14}C from different amendment treatments into (a) Fraction A and (b) Fraction B of soils containing different amounts of clay. Soils NB and RRC are as explained in Fig. 3.2. Treatments S, SF, and Af are as explained in Fig. 3.3.



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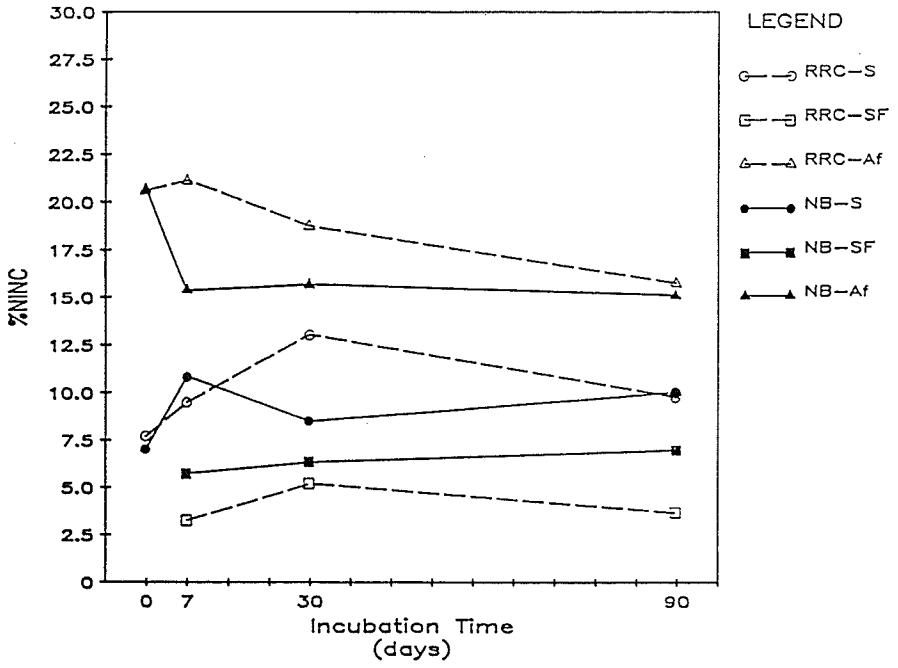

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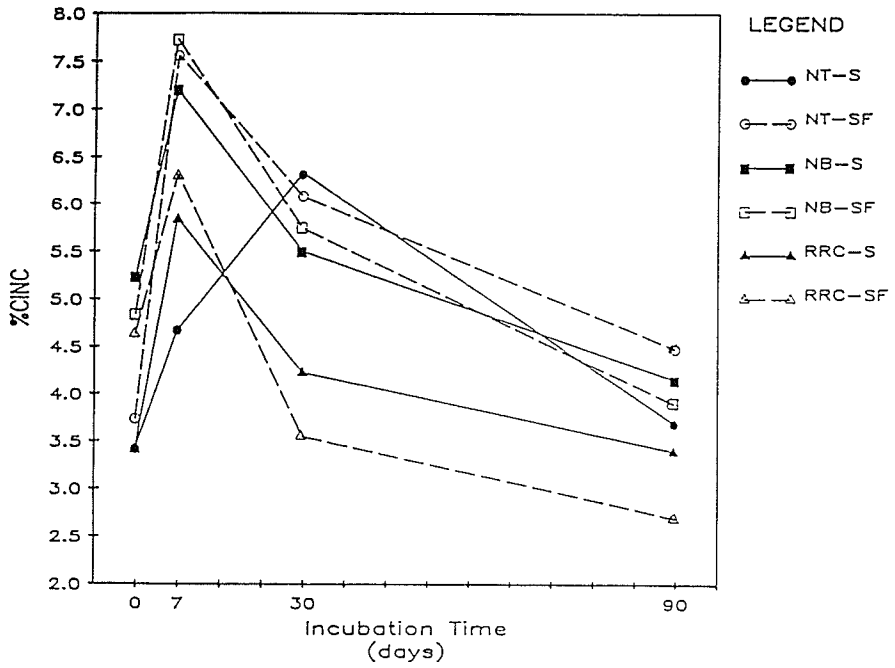
Figure 3.6. The incorporation of ^{15}N from different amendment treatments into (a) Fraction A and (b) Fraction B of soils containing different amounts of clay. Soils NB and RRC are as explained in Fig. 3.2. Treatments S, SF, and Af are as explained in Fig. 3.3.

the Kjeldahl analysis of the HA extracts. Also, as well as having the highest clay content, the RRC soil had the highest proportion of vermiculitic clays (determined by X-ray diffraction analysis; data not shown). The lower levels of N incorporation in the SF treatment may therefore result from increased susceptibility of fertilizer N to losses by denitrification and/or NH_4^+ fixation.

3.3.3. Effect of C/N Ratio of Amendment

The C:N ratio has been identified as a factor strongly influencing the decomposition of materials in the soil (cf. Alexander 1977 cited in Jawson and Elliott 1986). Knapp et al. (1983b) assert that the rate of residue decomposition increases with decreasing C:N ratio. Work by these investigators (Knapp et al. 1983a) with wheat straw amended with various levels of N fertilizer supports this generally accepted claim. These studies, however, did not relate decomposition rates to incorporation dynamics. Thus, although a more rapid rate of CO_2 evolution might be expected from the SF than from the S treatment, the implication of this for incorporation of C and N into active SOM is not clear.

C incorporation dynamics generally appeared to be slower in treatments which had higher residue C:N ratios (See Appendix 4. for a table including levels of significance). At 7 days Fr-A of the S treatment in the NT soil had a lower ($P<0.05$) $\%C_{INC}$ than that of the SF treatment (Fig 3.7.a). Thus, in the soil with lower organic matter content, the higher C/N ratio in the S treatment resulted in slower C incorporation into Fr-A. This same trend was apparent in Fr-A of the



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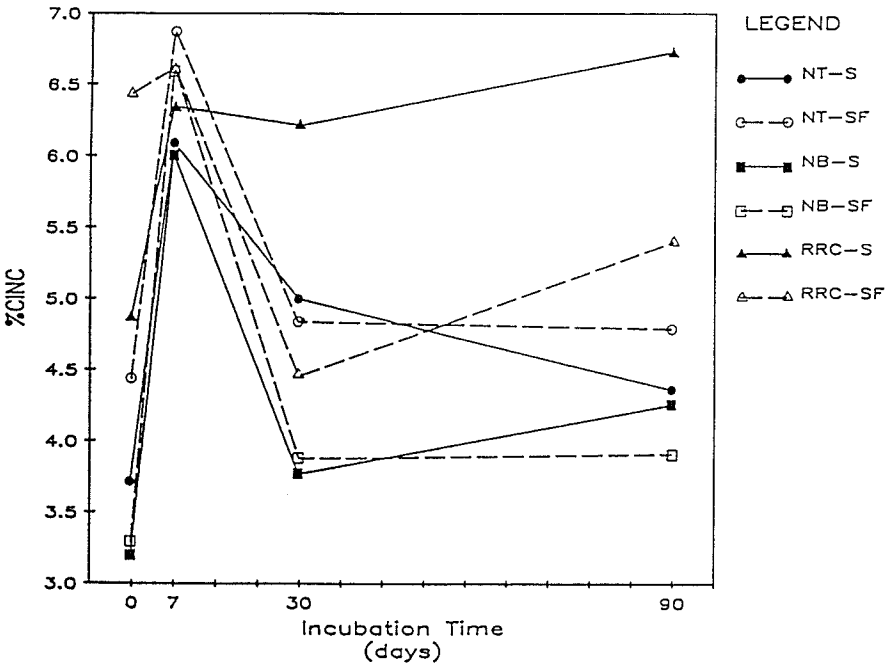
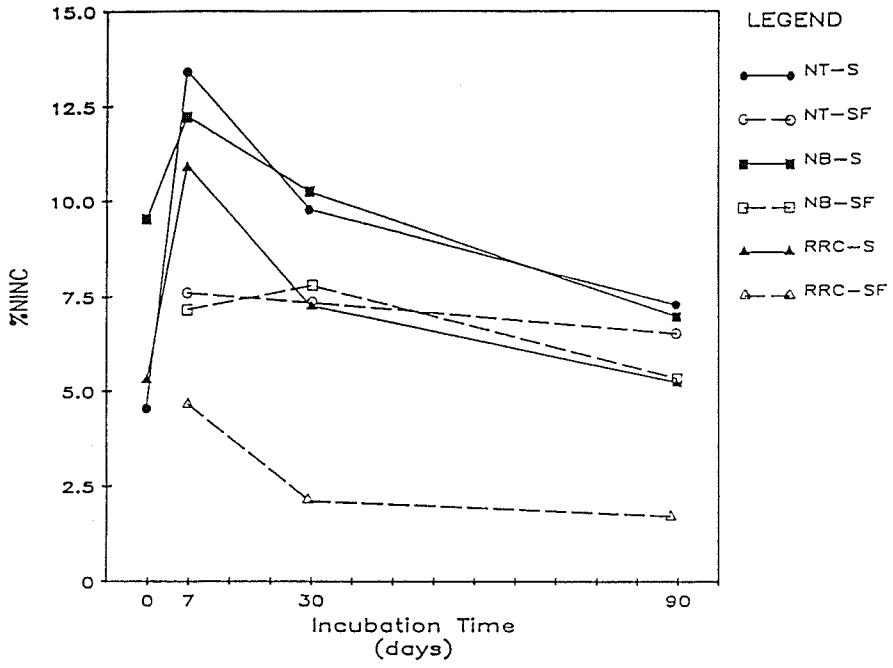


(b).

Figure 3.7. The incorporation of ^{14}C into (a) Fraction A and (b) Fraction B of the NB, NT, and RRC soils from treatments with different C:N ratios. Soils NB, NT, and RRC are as explained in Fig. 3.2. Treatments S and SF are as explained in Fig. 3.3.

RRC soil. In Fr-B (Fig. 3.7.b.) there were no significant differences in $\%C_{INC}$ values attributed to differences in C:N ratios of the residue in the Newdale soils. In the RRC soil, however, differences ($P<0.05$) between levels of incorporated C in the S and SF treatments were measured at 0 and 30 days. At 0 days the SF treatment had higher ($P<0.05$) $\%C_{INC}$ while that in the S treatment was higher ($P<0.05$) at 30 days. Therefore, the C from the amendment with a higher C/N ratio was apparently incorporated more slowly in Fr-B of the RRC soil. Furthermore, a higher level of $\%C_{INC}$ was maintained by the end of the 90 days for the residue amendment with a higher C/N ratio.

The N incorporation results were opposite to those observed for C incorporation (See Appendix 4. for a table including levels of significance). That is, the $\%N_{INC}$ values tended to be lower throughout the incubation period in the SF treatment which was expected to decompose more rapidly. In Fr-A (Fig. 3.8.a.) the values of $\%N_{INC}$ in the SF treatments were lower ($P<0.05$) than those in the S treatments of the same soil at 7 days, but, because the $\%N_{INC}$ in the S treatment declined during the course of the incubation while those in the SF treatment did not, these differences disappeared as the incubation proceeded. The levels of incorporated N in Fr-B (Fig. 3.8.b.) were quite constant over the course of the incubation, with only the S treatments in the NT and RRC soils having $\%N_{INC}$ values at 30 days higher ($P<0.05$) than those at 7 or 90 days. In Fr-B the values of $\%N_{INC}$ in the SF treatments of the NB and RRC soils were usually significantly lower ($P<0.05$) than those in the S treatments in the same soil. On the whole, then, a smaller proportion of the N added in the SF treatment was



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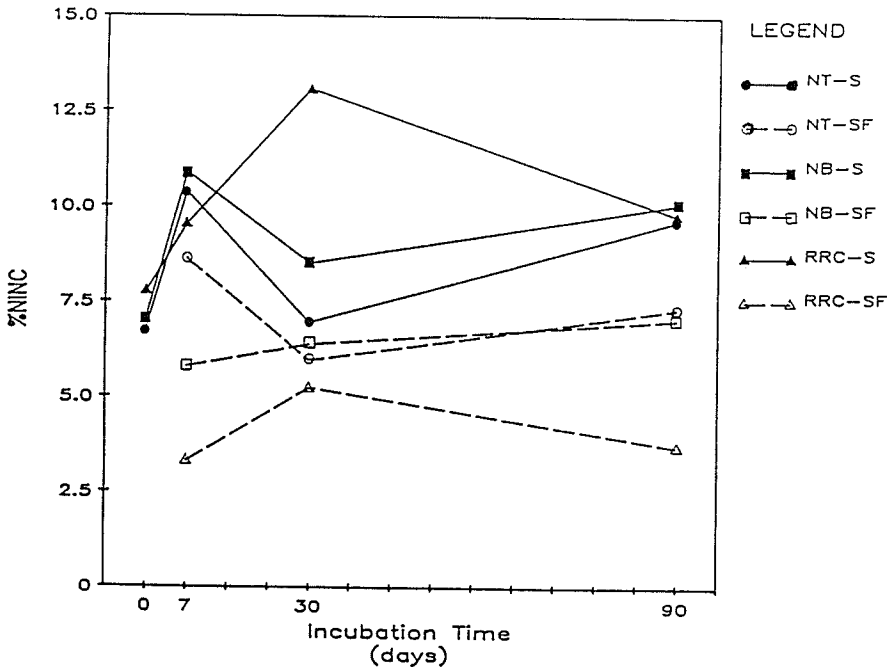


(b).

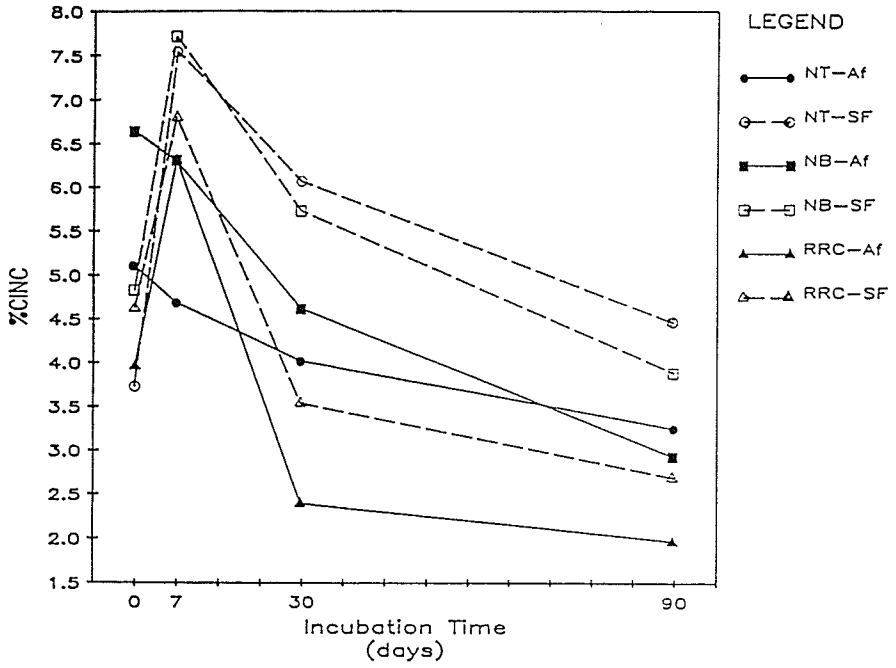
Figure 3.8. The incorporation of ^{15}N into (a) Fraction A and (b) Fraction B of the NB, NT, and RRC soils from treatments with different C:N ratios. Soils NB, NT, and RRC are as explained in Fig. 3.2. Treatments S and SF are as explained in Fig. 3.3.

incorporated into the extracted humic acid fractions when compared to the N in the S treatment where no fertilizer was used. The source of this anomaly may again be related to the behavior of the fertilizer N in the soil.

3.3.4. Effect of Form of Carbon and Nitrogen in Amendment

The chemical availability, as well as the amount, of nutrients in residues has been found to be important to the residue decomposition and nutrient recycling process (Till et al. 1982) since the chemical form of C and N in added substrates influence microbial dynamics. Jawson and Elliott (1986) concluded that the rate of decomposition is proportional to the amount of soluble nutrients in the residues. Herman et al. (1977) stressed that the % lignin and % carbohydrate are as important as the C:N ratio in controlling the rate of residue decomposition. Reinertsen et al. (1984) concluded that the rate of decomposition depends more upon the availability of C than upon that of N (cf. Knapp et al. 1983a). Azam et al. (1985) showed that more $(NH_4)_2SO_4$-N was incorporated into microbial biomass when it was added to the soil with a legume residue than when added alone. Treatments Af and SF thus represent contrasting residue decomposition/nutrient recycling situations.

Incorporation of C followed patterns which appeared to be related to the type of soil (See Appendix 5. for a table including levels of significance). In the RRC soil in both fractions $\%C_{INC}$ values were similar in the Af and SF treatments with a slight trend toward higher values in the SF treatment (Fig. 3.9.). The results from the Newdale



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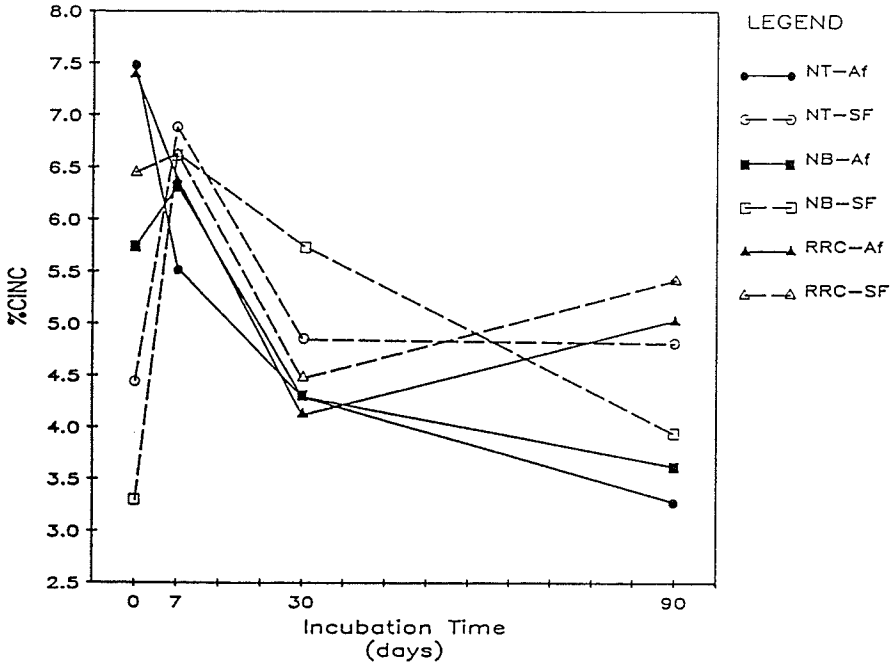


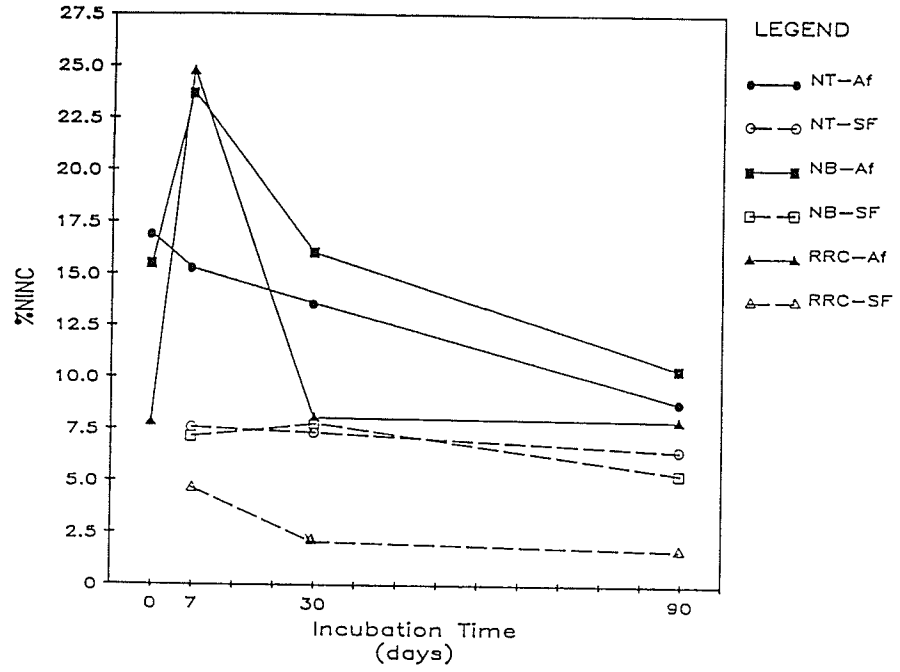
(b).

Figure 3.9. The incorporation of ^{14}C into (a) Fraction A and (b) Fraction B of the NB, NT, and RRC soils from treatments with different form of C and N. Soils NB, NT, and RRC are as explained in Fig. 3.2. Treatments SF and Af are as explained in Fig. 3.3.

soils were not quite as consistent. At 0 days in both Fraction A and Fraction B the $\%C_{INC}$ in the Af treatments appeared to be higher (usually significantly -- $P<0.05$), but this trend reversed (sometimes significantly -- $P<0.05$) after even a short period of incubation (Fig. 3.9.). The significantly higher ($P<0.05$) values of $\%C_{INC}$ from the SF treatment were observed at 7 and 30 days (i.e. in the middle of the incubation period) and the most dramatic increases relative to the Af treatment were noted in the NT soil (Fig. 3.9.). In the RRC soil, then, there was the least difference in the level of C incorporation between the SF and Af treatments.

The incorporation of C thus appeared to be higher in the SF treatment than in the Af treatment. This is not entirely unexpected, because treatments Af and SF represent contrasting residue decomposition/nutrient recycling situations. Both treatments contained similar amounts of C and N -- C:N ratio approximately 12. The young alfalfa material, however, is expected to contain high levels of soluble C and N and a low level of lignin. On the other hand, the straw was probably more highly lignified and relatively deficient in soluble C and N. Further, although fairly soluble, much of the N in the SF treatment was added in a form (i.e. KNO_3) which was perhaps not readily utilized by microorganisms (Paul and Juma 1981). According to the literature, then, more rapid decomposition could be expected in the Af than in the SF treatment.

The dynamics of N incorporation in all soils were similar for the two fractions, but trends apparent in Fr-A were more clearly discernible in Fr-B (Fig. 3.10.). The levels of $\%N_{INC}$ in Fr-A of the Af treatments



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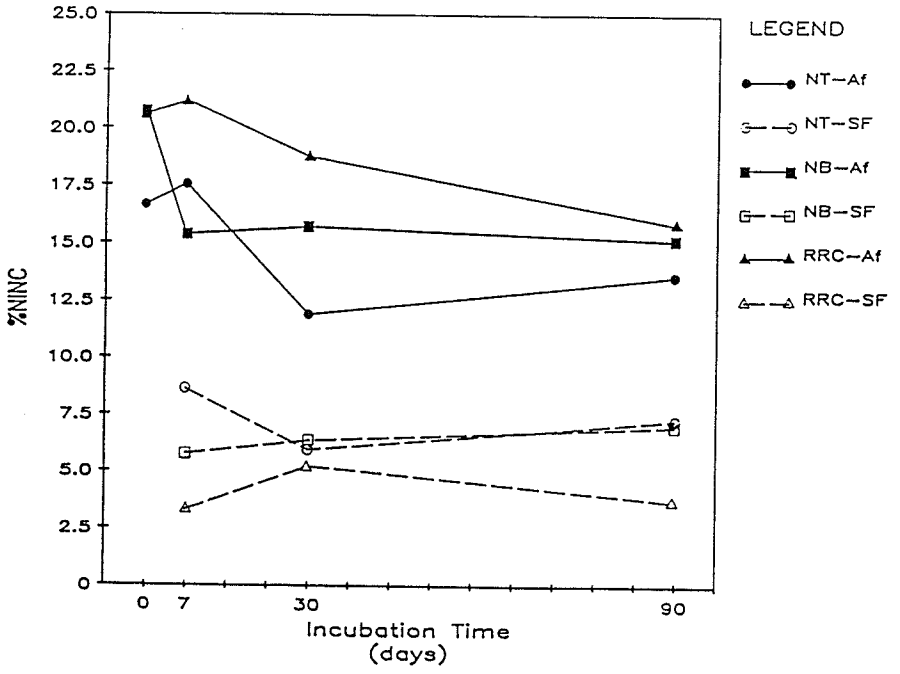

(b).

Figure 3.10. The incorporation of ^{15}N into (a) Fraction A and (b) Fraction B of the NB, NT, and RRC soils from treatments with different C:N ratios. Soils NB, NT, and RRC are as explained in Fig. 3.2. Treatments SF and Af are as explained in Fig. 3.3.

were higher ($P<0.05$) than those in the SF treatment in the same soil. In Fr-B the levels of incorporated N were again higher ($P<0.05$) in the Af treatments, but there also appeared to be a trend (especially in the middle of the incubation period) toward higher values of $\%N_{INC}$ in the Af treatment of the RRC soil than in that treatment in the Newdale soils. Thus, although C tended to be incorporated to a greater extent in the SF than in the Af treatment, N incorporation was significantly higher ($P<0.05$) in the Af treatment.

McGill et al. (1975) found that microbial N transformations were highly dependent upon C transformations. In the present investigation, however, patterns of N incorporation were frequently observed to be different from those of C. This could indicate that incorporation dynamics are subject to other influences in addition to microbial transformations; namely, factors characteristic to the type of soil.

In studying the decomposition of three grass species, Herman et al. (1977) found no appreciable differences in the nature of the SOM formed from the different substrate. The present study found that, although the chemical form of the labelled materials incorporated in S, SF, and Af was not determined, different amounts of C and N were incorporated from the respective treatments. The levels of $\%N_{INC}$ seemed to be more influenced by residue composition than were those of $\%C_{INC}$. By the end of the 90-day incubation period significant differences ($P<0.05$) in $\%C_{INC}$ values among treatments within soils were the exception; significant differences ($P<0.05$) in $\%N_{INC}$ levels after 90 days, however, were the rule (eg. Fig 3.10.b.). Thus, under the conditions studied, C

and N incorporation dynamics appear to have been influenced to differing degrees by residue composition.

The incubation procedure used by Herman et al. (1977) -- 20:200 suspension of grass root material in continuously bubble-aerated distilled water -- resulted in decomposition rates considerably slower than would be expected in a soil system. This finding led them to state that soils contribute substantially to SOM dynamics by providing nutrients and stable extracellular enzymes, buffering pH, adsorbing toxic metabolites, and maintaining proper moisture and aeration conditions. The results of the present study indicate that different soils may contribute differently to decomposition and incorporation processes. Incorporation dynamics in the RRC soil were different from those in the Newdale soils (Fig. 3.5., 3.6.). These differences usually were most evident in the middle of the incubation period. Incorporation of C was usually higher in the Newdale soils than in the RRC soil in Fr-A, but lower than that in RRC in Fr-B. The same tendencies were apparent in Fr-A and Fr-B for N incorporation except that $\%N_{INC}$ levels in the SF treatments were always lowest in the RRC soil. Thus, if different soils do result in distinct incorporation levels, these influences would be expected to be primarily important for short-term SOM dynamics.

4. EFFECT OF VARIOUS AMENDMENTS ON THE STABILITY OF SOILS AGAINST DISPERSION BY WATER AND BY PERIODATE-TETRABORATE

4.1. Introduction

Soil management practices have been shown to affect short term soil aggregate stability by influencing the dynamics of active soil organic matter (SOM) (Lynch 1984; Oades 1984). Polysaccharides are active SOM materials which contribute significantly to the stabilization of soil aggregates (Tisdall and Oades 1982; Emerson et al. 1986). The level of polysaccharide in the soil is related to the amount and type of materials added to the soil (Dormaar et al. 1979; Dormaar 1983; Knapp et al. 1983b).

The contribution of polysaccharide materials to aggregate stabilization has frequently been evaluated by means of sodium periodate oxidation (Oades 1984; Emerson et al. 1986). An appreciable portion (15-20 percent) of soil carbohydrate is resistant to periodate oxidation (Cheshire et al. 1984). However, because microbial polysaccharides appear to be preferentially oxidized (Cheshire et al. 1983; Cheshire et al. 1984), the periodate treatment may be most useful for evaluating the short term stability effects related to different management practices.

The polyanionic nature of many soil minerals and polysaccharides requires that adsorptive interactions between them be mediated by polyvalent cations (Theng 1979; Goh et al. 1987). The amount and influence of polyvalent cations in the soil is a function of soil type, whereas the level of polysaccharide is influenced by the nature of materials added to the soil. Soil aggregate stability is thus dependent

both upon soil type and soil management practices.

The objectives of this study were: (i) to determine the effect of various residue additions on the aggregate stability of soils, and (ii) to evaluate the influence of these residue amendments on the contribution of periodate/tetraborate sensitive materials to aggregate stability.

4.2. **Materials and Methods**

4.2.1. Soils, Plant Materials, and Treatments

The soils, plant materials, and treatments used were described in detail in Section 3.2. Only the samples collected after 90 days of incubation were used for aggregate stability studies.

4.2.2. Determination of Log Geometric Mean Diameter of Amended Soils

The effect of the amendments on the aggregate stability of the 90-day samples was studied by wet sieving (Yoder 1936). Air-dry subsamples (50.0 g) were placed on the top of a nest of six sieves with mesh sizes of 4.00, 1.99, 0.99, 0.85, 0.50, and 0.25 mm. The sieves were lowered into water and oscillated at a constant rate (4.0 cm stroke length; 29 strokes per min) for 10 min. The soil remaining on each of the sieves was dried at 110°C and weighed. A correction was made for the original (i.e. air dry) water content so that the oven dry soil weight on each sieve could be expressed as a fraction of the original weight of the sample. Wet sieving data was obtained for samples from each of the 24 incubation pots, giving duplicate data for each of the soil-amendment

combinations.

The log geometric mean diameters (LGMD) of the amended soils were calculated. The method developed by Gardner (1956) for the determination of this parameter was based on the finding that soil aggregate size distribution is log-normally distributed. The procedure consisted of plotting the logarithm of sieve mesh size against the percent oversize (i.e. the percent of soil weight accumulated in size fractions as large or larger than the sieve mesh size) on a log-probability scale. The LGMD was read from the intersection of the curves with the 50 percent oversize line.

In the present work a SAS program was utilized to determine the LGMD (see Appendix 6.). The obtained percent oversize values (i.e. the proportion of soil aggregates of a given size and larger) were transformed to Z-values by the PROBIT function. A Z-value quantifies the magnitude of deviation from the mean; that is, a variable with a Z-value of -1.0 is 1 standard deviation below the mean. The natural logarithm of the sieve mesh sizes was plotted against the Z-values (from the two duplicates) from each soil-amendment combination. The program performed linear regression on the plotted data, developed a linear equation, and calculated aggregate size for the zero Z-value, i.e. LGMD. The LGMD and line slope values calculated for the soil-amendment pairs were then compared by t-test using the following equations:

$$S = ((S_{T1}^2 + S_{T2}^2) / 2)^{1/2} \quad \text{and}$$

$$t = ((\text{LGMD or Slope})_{T1} - (\text{LGMD or Slope})_{T2}) / S,$$

where S^2_{T1} and S^2_{T2} represent the respective error variances of the two treatments, T_1 and T_2, being compared and S is the standard error of the comparison. The treatments whose comparison resulted in a t value greater than 2.228 (i.e. $t_{0.05}$, 10 df) had LGMD or slope values which were significantly different. Statistical analyses were performed on LGMD values. To facilitate discussion, LGMD values were converted to geometric mean diameter (GMD) which are expressed in mm.

4.2.3. Measurement of Dispersion Due to Periodate/Tetraborate Treatment

The amount of clay disaggregation in a water and in a periodate/tetraborate system was compared by turbidimetric measurement of the obtained clay suspension. The procedure used is a modification of that presented by Cheshire et al. (1983).

4.2.3.1. Water Treatment: One g of air dry soil and 25 mL of H_2O were shaken (3.2 cm horizontal displacement; 140 displacements per min) for one hour in a 50 mL centrifuge tube. The suspension was centrifuged at 8500 *g* for 20 min and the clear supernatant was discarded. The residue was resuspended in 25 mL of H_2O, centrifuged at 8500 *g* for 20 min, and the supernatant discarded. Using a Vortex Mixer, the residue was again resuspended in 25 mL of H_2O. The whole suspension was transferred to a graduated cylinder and the volume brought to exactly 100 mL. The graduated cylinder was tipped end over end five times and allowed to stand undisturbed on a flat bench. After 3 h 50 min the top 5 cm of the suspension, which was 10 mL in volume, was siphoned off and stored in capped bottles.

4.2.3.2. Periodate/Tetraborate Treatment: In this treatment the

initial suspension of the one g of soil was achieved in 25 mL of a 0.02 $mol \cdot L^{-1}$ $NaIO_4$ and 0.08 $mol \cdot L^{-1}$ NaCl solution (Solution A). After centrifugation the residue was resuspended in 25 mL a 0.01 $mol \cdot L^{-1}$ $Na_2B_4O_7$ solution (Solution B). The remainder of the procedure was carried out exactly as in the water treatment. Each soil was subjected to the periodate/tetraborate treatment in the same glassware that was used for the water treatment.

4.2.3.3. Turbidimetric Measurements: The absorbance of the suspension siphoned from the graduated cylinders was used to calculate the amount of clay dispersed in the amended soils due to the water and periodate/tetraborate treatments. A standard curve was obtained by measuring the absorption at 615 nm of suspensions containing known amounts of clay. The clay used to develop a standard curve for a given soil was fractionated from that soil. The standard curves in Solution A, Solution B, and H_2O were measured and were found to be the same. Thus, one standard curve could be used for all suspensions of the same soil.

The same volume of siphoned suspension was used for the turbidimetric analysis of all samples. The stored suspensions were shaken, allowed to stand for two min, and three mL transferred to a cuvette. The cuvette was inverted three times, inserted into the spectrophotometer (Hewlett Packard model 8452A Diode Array spectrophotometer), and left for one min. The absorbance of the suspension was then measured for 10 min in order to obtain the clay concentration (Clay Conc) according to the equation:

$$\text{Clay Conc (mg mL}^{-1}) = \frac{\text{Absorbance - 0.243}}{1.727},$$

which was obtained by solving the calibration (or standard) curve for Clay Conc. The clay concentration was converted to per cent clay (% Clay) in the suspension:

$$\% \text{ Clay} = \text{Clay Conc (mg mL}^{-1}) \times (10 \text{ mL} / 10000 \text{ mg}) \times 100.$$

4.2.3.4. Calculation of Dispersion Due to Periodate/Tetraborate Treatment: The per cent dispersible clay (% DC) was calculated as follows:

$$\% \text{ DC} = \% \text{ Clay} / \frac{\text{Initial sample wt.}}{1.00 + \text{Fraction moisture of airdry soil}}.$$

After calculating % DC it was possible to determine the relative dispersibility index (RDI -- Goh et al. 1987) of the soil samples:

$$\text{RDI} = \frac{\% \text{ DC}}{\text{Clay content of soil (\%)}}.$$

The amount of clay dispersed in the H_2O treatment was subtracted from that achieved by the periodate/tetraborate treatment in order to calculate the degree of dispersion due to the oxidation and dissolution

by periodate/tetraborate. The difference in RDI values of the water- and periodate/tetraborate-treated soils (dRDI) was considered a qualitative measure of the aggregation due to materials susceptible to destruction by the periodate/tetraborate solutions.

4.2.4. Chemical Analysis

The aluminum (Al) and iron (Fe) contents of the supernatant obtained by centrifugation of the sonicated residue of Na-pyrophosphate extracted soil (Spt-2) were measured (details of extraction procedure described in Section 3.2.5. -- see Fig 3.1.). Aliquots of 1.00 mL, representing $1/170^{th}$ of Spt-2, were diluted tenfold and their Al content (in $\mu g/g$ of sample) measured (Perkin-Elmer Model 560 atomic absorption spectrophotometer). A further fivefold dilution was required to measure the Fe content of Spt-2. The Al and Fe contents of the extracts, expressed as $\mu g\ g^{-1}$ organic matter fraction (ppmF), could thus be calculated as follows:

$$\text{ppmF } (\mu g\ g^{-1}) = \frac{\text{Sample Reading } (\mu g\ g^{-1}) \times \text{Dilution Factor} \times \text{Total Extract Volume } (mL \times g\ mL^{-1}))}{\text{Fraction wt } (g)}.$$

4.3. Results and Discussion

4.3.1. Water Stable Aggregates

Significant differences ($P<0.05$) in GMD attributed to treatment effects were observed in all soils (Table 4.1.). Differences in the size of the GMD reflected differences in the abilities of the

decomposition products of the various treatments to stabilize soil aggregates.

The GMD values of the aggregates collected by wet sieving of the soils that had received the S treatments were either the highest or statistically similar to the highest GMD ($P<0.05$) values in all three soils. This is believed to have occurred by the binding action of polysaccharides and is consistent with the work of Knapp et al. (1983b) who found that when N is limiting, excess available C is apparently

Table 4.1. Geometric mean diameter of the amended NB, NT, and RRC soils. Soils: NB = Newdale clay loam bottom of knoll; NT = Newdale clay loam top of knoll; and RRC = Red River Clay. Treatments: C = control; S = wheat straw; SF = straw + N fertilizer; and Af = alfalfa

Treatment	Geometric Mean Diameter (mm)		
	NB	NT	RRC
C	0.2580 abc‡	0.2642 b	0.9647 bc
S	0.3122 a	0.3273 a	1.5677 a
SF	0.2616 b	0.3302 a	0.7619 c
Af	0.2227 c	0.2425 b	1.0770 b

‡ numbers in the same column followed by the same letter are not significantly different ($P<0.05$) by t-Test

immobilized as polysaccharide. Elliott and Lynch (1984) also showed that the numbers of bacteria, the production of "extracellular slimy materials", and the degree of aggregation increased as N content of decomposing straw decreased. The S treatment had the highest C:N ratio (26.35) of the amendments studied; therefore, the highest level of polysaccharide production and subsequent aggregate stabilization could

be expected in this treatment.

The effect of the SF treatment on GMD values may be interpreted in terms of the chemical characteristics of the given soil. It was found that the lower the cation exchange capacity (CEC) of the soil the larger were the GMD values in the SF treatment compared with those in the other treatments in that soil (Table 4.1.). Thus, in the NT soil (CEC = 18.32 cmol (+) kg^{-1}) the GMD of the SF treatment was similar to that of the S treatment and greater ($P<0.05$) than that of the control. The GMD of the NB soil (CEC = 30.32 cmol (+) kg^{-1}) was lower ($P<0.05$) than that of the S treatment but similar to that of the control. In the RRC soil (CEC = 38.78 cmol (+) kg^{-1}) the GMD of the SF treatment was lower ($P<0.05$) than that of the other treatments. Also, the slope of the regression line of the log-probability plot of the SF treatment wet sieving data was significantly lower ($P<0.05$) than that of the control in the RRC soil (Table 4.2.). This indicates a wider aggregate size distribution in the

Table 4.2. Aggregate size distribution of the amended soils expressed as the slope of the linear regression of the log-probability plot of the wet sieving data. Soils NB, NT, and RRC and treatments C, S, SF, and Af as explained in Table 4.1.

Treatment	Slope		
	NB	NT	RRC
C	-1.0688 bc‡	-1.0415 ab	-1.6111 a
S	-1.2419 a	-1.1860 a	-1.5062 a
SF	-0.9868 c	-0.9686 b	-0.9750 c
Af	-1.0923 b	-1.1467 a	-1.2919 b

‡ numbers in the same column followed by the same letter are not significantly different ($P<0.05$) by t-Test

SF treatment and suggests that the addition of KNO_3 caused the dispersion of aggregates in the RRC soil. It thus appears that the the higher the CEC of the soil the greater the negative effect of KNO_3 fertilizer addition on GMD values.

Within the same soil type the GMD values in the Af treatment were statistically similar to those of the control (Table 4.1.). This observation can also be explained on the basis of the findings of Elliott and Lynch (1984) and Knapp et al. (1983b). The alfalfa was harvested at a stage (i.e. budding/preblooming) at which the level of N was high and that of lignin was low. Thus, microbial degradation of the alfalfa would be expected to be rapid and relatively complete with little immobilization of C as polysaccharides. This is consistent with the data described in Section 3.3. which showed that significantly less ($P<0.05$) C was incorporated into the active SOM from treatment Af than from treatments S and SF.

The wet sieving data (i.e. slope of linear regression and GMD values) indicated apparent similarity of the aggregate size distributions of the two Newdale soils (Table 4.1. and Table 4.2.). Given the similarity of the clay content of these soils, it might be expected that higher GMD values would be obtained in the NB soil because of its much higher SOM content. It has been proposed, however, that cultivation and/or erosion may alter the chemical character of SOM (Schimel et al. 1985). Oades (1984) found that the SOM of degraded soils (i.e. frequently cultivated with low input of organic material) contained more acidic functional groups per unit weight (i.e. higher FA:HA ratio in degraded soil) than that of a related soil with higher

SOM content. Thus, differences in the composition of the SOM in the NB and NT soils might result in different stabilization interactions in the two soils.

4.3.2. Iron and Aluminum Contents

Polyvalent cations are present in greater amounts per weight of extracted humic substance in the NT soil than in the NB soil. The Al and Fe contents of humic material (i.e. Supernatant 2 -- see Fig. 3.1.), which was resistant to initial extraction by $Na_4P_2O_7$ (pH 10) but which was extractable following sonication, of the amended soils are reported in Table 4.3. Significantly higher ($P<0.05$) levels of Al were found complexed with the humic material of the NT soil. Oades (1984) found increased clay dispersibility and decreased levels of water-stable aggregates when the acidity of the SOM increased in a soil system where Fe was the dominant cation. In the Newdale soils considerably more Al than Fe was associated with the extracted humic material. The difference in Al content in the NB and NT may thus reflect different stabilization interactions in the two soils; that is, polyvalent cations may contribute more extensively to aggregate stability in the NT soil than in the NB soil.

4.3.3. Dispersion Due to Water and Periodate/Tetraborate Treatment

The wet sieving data indicate that the GMD and the aggregate distribution of the NB and NT soils are similar (Table 4.1. and Table 4.2.). In contrast, the dispersibility of the NT soil aggregates in water is significantly higher ($P<0.05$) than that of the NB soil

Table 4.3. Concentration of Al and Fe in Supernatant 2 (see Fig. 3.1.) extracted following sonication of the $Na_4P_2O_7$-extracted residue. Soils and treatments as explained in Table 4.1.

Amended Soil	Al		Fe	
	ppm	mmol kg^{-1}	ppm	mmol kg^{-1}
NB-C	1764 e	65.4	1070 abc	19.2
NB-S	1712 e	63.4	1247 ab	22.3
NB-SF	1675 e	62.1	1358 a	24.3
NB-Af	1694 e	62.8	1118 abc	20.0
NT-C	2225 cd	82.5	884 cd	15.8
NT-S	2273 bc	84.2	581 d	10.4
NT-SF	2122 d	78.7	1020 bc	18.3
NT-Af	2191 cd	81.2	827 cd	14.8
RRC-C	2350 b	87.1	868 cd	15.5
RRC-S	2514 a	93.2	813 cd	14.6
RRC-SF	2545 a	94.3	825 cd	14.8
RRC-Af	2364 b	87.6	830 cd	14.9

‡ numbers in the same column followed by the same letter are not significantly different ($P<0.05$) by the Duncan's Multiple Range Test.

aggregates (Table 4.4.). The dispersibility determination subjected the soils to much more drastic treatments (e.g. shaking for one hour, resuspension with a Vortex mixer, and several end-over-end manipulations of graduated cylinders and cuvettes) than the wet sieving analysis. The turbidimetrically measured dispersion data thus show that the NB soil aggregates are "stronger" than those of the NT soil despite the fact that the NT soil contained more free $CaCO_3$ which could act as a cementing agent. This is a further indication that different stabilization interactions are dominant in the two Newdale soils.

Differences between the stabilization interactions in the two

Table 4.4. The stability of NB, NT, and RRC aggregates to dispersion in water prior to and after $NaIO_4/Na_2B_4O_7$ treatment, expressed in terms of water dispersible clay (WDC) and relative dispersibility index (RDI). Soils and treatments as described in Table 4.1.

Amended Soil	Water		$NaIO_4/Na_2B_4O_7$		
	WDC(%)	RDI	WDC(%)	RDI	dRDI
NB-C	7.45	0.220 b‡	14.52	0.430 d	0.210 b
NB-S	7.40	0.219 b	14.79	0.438 cd	0.219 b
NB-SF	8.48	0.251 b	15.36	0.454 c	0.203 b
NB-Af	8.05	0.238 b	14.68	0.434 cd	0.196 b
NT-C	12.57	0.411 a	18.00	0.588 b	0.177 b
NT-S	11.44	0.374 a	17.47	0.571 b	0.197 b
NT-SF	13.52	0.442 a	17.60	0.575 b	0.133 b
NT-Af	12.56	0.410 a	17.82	0.582 b	0.172 b
RRC-C	19.36	0.262 b	48.87	0.661 a	0.399 a
RRC-S	18.21	0.246 b	48.90	0.662 a	0.416 a
RRC-SF	21.64	0.292 b	47.95	0.649 a	0.357 a
RRC-Af	19.59	0.265 b	48.72	0.659 a	0.394 a

‡ numbers in the same column followed by the same letter are not significantly different ($P<0.05$) by the Duncan's Multiple Range Test.

Newdale soils which result in the "weaker" aggregates in the NT soil are threefold. First, because the NT soil has slightly lower clay and appreciably lower SOM content than the NB soil, there are fewer organo-mineral interactions in the NT soil. Second, since the dRDI values are higher in the NB soil than in the NT soil, it appears that the lower level of water dispersible clay (WDC) in the NB soil after 90 days of incubation is due to larger amounts of newly synthesized carbohydrate material than in the NT soil. Third, the lower dRDI values in the NT soil indicate that Al and Fe cations, which are present in greater amounts in the NT soil (Table 4.3.) which and are impervious to the

$NaIO_4/Na_2B_4O_7$ treatment, contribute more extensively to aggregate stability in the NT than in the NB soil.

The RDI values of the periodate/tetraborate treated soils were appreciably higher than those of the water treated soils (Table 4.4.). Cheshire et al. (1984) showed that some of the disruption of aggregates obtained by treatment with $NaIO_4/Na_2B_4O_7$ is attributed to the dispersive effects of the added Na. Oades (1984) pointed out that materials other than polysaccharides are oxidized by the periodate/tetraborate treatment. However, these and other investigators (Emerson et al. 1986) agree that the periodate/tetraborate treatment does provide a qualitative indication of the contribution of polysaccharide materials to aggregate stability.

It has further been asserted that the periodate/tetraborate treatment preferentially destroys microbial polysaccharides (Cheshire et al. 1984). Periodate more easily oxidizes hydroxyl groups which are vicinal and *cis* than those which are vicinally *trans* (Bobbitt 1956). Microbial polysaccharides contain larger proportions of sugars with vicinally *cis* hydroxyl groups than do plant polysaccharides (Cheshire et al. 1984). The loss of aggregate strength following treatment with periodate/tetraborate is therefore attributed to the destruction of microbial polysaccharides.

The calculated dRDI values (i.e. periodate/tetraborate RDI - water RDI) thus reflect the contribution of microbial polysaccharides to aggregate stabilization (Table 4.4.). The larger the dRDI the greater the importance of microbial polysaccharides to aggregate strength. The RRC soil had the highest ($P<0.05$) dRDI values and those of the Newdale

soils were similar ($P<0.05$) to each other. This could be related to the higher clay content of the RRC soil; that is, since the RRC soil has a higher clay content, more niches for polysaccharide occlusion and more surface area for clay-polysaccharide interaction are available. There appeared to be differences in the dRDI values between amendment treatments within soils, but these were not statistically significant ($P<0.05$). Generally, the dRDI values in the SF and Af treatments tended to be lower than those in the S treatments.

5. SUMMARY AND CONCLUSIONS

The present study has demonstrated that in the short term the properties of the soil and the composition of the amendments added to that soil influence the dynamics of active SOM and the parameters of soil structural stability.

The results of the present study concur with the findings of other investigators and thus add impetus to the advancement of a comprehensive understanding of soil management. Herman et al. (1977) concluded that soil properties and substrate characteristics contribute equally to the decomposition dynamics observed in a given situation. The present study showed that the clay and SOM content of the soils, the C:N ratio plus form of C and N of the materials added to the soils influence the incorporation of C and N into the active SOM pool and affect the stability as well as the size distribution of soil aggregates. It is thus quite clear that effective management of the soil resource requires attention to the characteristics both of the soil and of the materials to be added to the soil.

The present investigation has served to reiterate, and perhaps to clarify, some of the findings of longer term studies. Previous work has stressed the importance of active SOM to the sustained chemical and physical fertility of the soil (Oades 1984; Paul 1984) and have emphasized the effect of long term management practices on active SOM dynamics (Dormaar et al. 1979; Janssen 1984; McGill et al. 1986) and on aggregate stability (Tisdall and Oades 1982; Dormaar 1983; Lynch 1984; Goh et al. 1987). The present study found that, while the number of

significant ($P<0.05$) differences in C and N incorporation among soils and treatments frequently declined toward the end of the incubation period (e.g. Fig. 3.9.a, 3.10.a., and Appendix 3.), significant ($P<0.05$) differences in GMD values among treatments in the same soil were measured after 90 days of incubation (Table 4.1.). This indicates that not only do soil and amendment characteristics influence short term active SOM dynamics, but that these influences are also manifested in more persistent effects on soil structure. The crucial role of active SOM to sustained soil productivity is thus confirmed and furthered by the findings of the present study.

The major contribution of the present investigation to an improved understanding of soil management has perhaps been to raise questions regarding active SOM dynamics and aggregate stabilization interactions.

In this study the levels of incorporated C and N in all soils at the end of the incubation period were usually higher (significantly higher -- $P<0.05$ -- in the RRC soil) in Fr-B than in Fr-A (Fig. 3.2. and Appendix 1.). It thus appears that the Fr-A material has a slightly faster turnover rate than does that of Fr-B. The relevance of this apparent difference in turnover rate to the ability of the respective fractions to contribute to effective nutrient cycling, however, is unclear. The importance of Fr-B as a short to medium term storehouse for nutrients is frequently stated in the literature (Paul and McGill 1977; Anderson and Paul 1984; Christensen and Sorensen 1985). Further investigation is required to establish the role of Fr-A in the nutrient cycling process.

Another aspect of the present investigation which prompts further study is the aggregate stabilization dynamics observed in the Newdale soils. The wet sieving determination indicated similarity in LGMD values and in aggregate size distribution between the NB and NT soils (Table 4.1., 4.2.). However, the turbidimetrically measured dispersibility in water and in periodate/tetraborate of the NT soil was higher ($P<0.05$) than that of the NB soil (Table 4.4.). The binding mechanisms operative in the NT soil were thus more susceptible than those of the NB soil to the turbidimetric analysis, which was mechanically more disruptive than was the wet sieving determination. In the present work, then, the aggregates in the soil with the higher SOM content were "stronger" than those in the soil with the higher ($P<0.05$) level of Al in Fr-B (Table 4.3.). Additional study of the Newdale soils might establish if qualitative differences do indeed exist between the binding mechanisms characteristic of the NB and NT soils.

It was also found that the C and N incorporation dynamics and the aggregate stability and size distribution parameters in the SF treatment were different from those in the S and Af treatments . The $\%N_{INC}$ values were usually lowest ($P<0.05$) in the SF treatment (Fig. 3.10.). The aggregate size distributions were more dispersed ($P<0.05$) in the SF than in the other treatments; that is, the slope of the regression line of the log-probability plot of the SF treatment wet sieving data tended to be lower (significantly ($P<0.05$) in the RRC soil) in the SF treatments (Table 4.2.). It is possible to propose both biological and physico-chemical reasons for these differences.

The incorporation and stabilization dynamics observed in the SF

treatment may be related to the effect of the added KNO_3 on microbial dynamics. Investigators have found that fertilizer N stimulates microbial activity less than do other amendments (Biederbeck et al. 1984; McGill et al. 1986). Other researchers have observed that the addition of legume residues with fertilizer N (Azam et al. 1985) and the use of no-till systems (Coleman et al. 1983) increase the incorporation of N into the SOM. Still other studies have indicated differential utilization by soil microorganisms of different types of N fertilizers (Aleynikova and Utrobina 1973). It is thus apparent that the N added in the SF treatment may have modified microbial activity in comparison to that in the S and Af treatments, but further study is required to conclusively attribute reduced N incorporation and dispersed aggregate size distribution to this effect.

The influence of the fertilizer on the chemical status of the soil may also have contributed to the incorporation and stabilization dynamics observed in the SF treatment. The addition of K^+ and the possible production of NH_4^+ by the reduction of NO_3^- in anaerobic microsites could have increased aggregate dispersion by displacing divalent cations from the exchange complex (Grant 1986; Goh et al. 1987). However, fertilizer N which remained in the NO_3^- form may also have contributed to dispersion by adsorption to cations on the exchange complex. This would increase the net negative charge of the colloids and increase repulsive forces between particles. Because the degree of dispersion appeared to increase with increasing CEC of the soil (Table 4.2.), this anion adsorption effect seems plausible. However, the exact mechanism is not known and further study is required.

In conclusion, this investigation has been useful in reiterating the importance of active SOM to the chemical and physical fertility of the soil in focusing some of the questions which remain to be addressed. That is, neither the mechanisms of active SOM dynamics nor those of aggregate stabilization interactions have been fully explained, but the impact of management practices and soil type on these processes has been underscored. Indeed, the results of this short term study may provide clues to an understanding of the long-term effects of management practices observed by Dormaar (1983), McGill et al. (1986), Goh et al. (1987), and other investigators.

The potential benefits of incorporating an understanding of active SOM dynamics into soil resource management strategy are significant (Paul 1984). It is therefore hoped that this thesis will help to maintain the present momentum in soil science research toward more sophisticated investigations of the nature of biological soil processes in recognition of their importance to sustained soil productivity.

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APPENDIX 1. Incorporation of labelled C and N into Fraction A and Fraction B of the NB, NT, and RRC soils. Soils: NB = Newdale clay loam bottom of knoll; NT = Newdale clay loam top of knoll; and RRC = Red River Clay. Treatments: S = wheat straw; SF = straw + N fertilizer; and Af = alfalfa.

	%C_{INC}							
Soil	0 d		7 d		30 d		90 d	
	Fr-A	Fr-B	Fr-A	Fr-B	Fr-A	Fr-B	Fr-A	Fr-B
NB-S	5.240 def‡	3.208 ij	7.214 ab	6.018 cd	5.517 cde	3.776 ghij	4.166 fghi	4.267 fghi
NB-SF	4.856 efg	3.292 ij	7.740 a	6.620 bc	5.751 cde	3.880 ghij	3.899 ghij	3.918 ghij
NB-Af	6.633 bc	5.740 cde	6.313 bcd	4.755 efgh	4.642 efgh	4.168 fghi	2.948 j	3.610 hij
NT-S	3.431 gh‡	3.730 fgh	4.686 efgh	6.102 bcd	6.346 abc	5.005 cdef	3.699 fgh	4.370 efgh
NT-SF	3.750 fgh	4.442 efgh	7.565 a	6.883 ab	6.090 bcd	4.840 defg	4.493 efgh	4.802 defg
NT-Af	5.130 cdef	7.476 a	4.706 efg	5.527 cde	4.039 fgh	4.285 efgh	3.269 h	4.074 fgh
RRC-S	3.436 hijk‡	4.870 cdefgh	5.864 abcdef	6.354 abcde	4.240 fghij	6.219 abcde	3.406 hijk	6.737 abc
RRC-SF	4.652 defgh	6.446 abcd	6.826 ab	6.625 abc	3.560 ghijk	4.464 efghi	2.710 ijk	5.411 bcdefg
RRC-Af	3.981 fghij	7.390 a	6.332 abcde	6.376 abcd	2.410 jk	4.109 fghij	1.982 k	5.030 bcdefgh
	%N_{INC}							
NB-S	9.567 efg‡	7.069 ghi	12.284 d	10.924 de	10.277 def	8.550 efgh	7.024 ghi	10.120 def
NB-SF	NA	NA	7.213 ghi	5.811 i	7.843 fghi	6.400 hi	5.373 i	7.058 ghi
NB-Af	15.583 c	20.775 b	23.821 a	15.431 c	16.122 c	15.768 c	10.453 def	15.196 c
NT-S	4.599 g‡	6.758 efg	13.470 abcd	10.413 cdef	9.820 defg	6.961 efg	7.330 efg	9.686 defg
NT-SF	NA	NA	7.640 efg	8.653 defg	7.385 efg	5.975 fg	6.540 fg	7.350 efg
NT-Af	16.999 ab	16.719 ab	15.347 abc	17.629 a	13.673 abcd	11.961 bcde	8.828 defg	13.676 abcd
RRC-S	5.332 ghijk‡	7.781 fghi	10.985 ef	9.560 efg	7.302 fghij	13.105 de	5.284 ghijk	9.808 ef
RRC-SF	NA	NA	4.699 hijk	3.333 jk	2.124 k	5.259 ghijk	1.733 k	3.700 ijk
RRC-Af	7.870 fghi	20.687 b	24.903 a	21.233 ab	8.099 fgh	18.814 bc	7.987 fghi	15.875 cd

‡ %C_{INC} and %N_{INC} values followed by the same letter are not significantly different ($P<0.05$). (statistical comparisons of %C_{INC} and %N_{INC} grouped by soil type)

APPENDIX 2. Comparison of the incorporation dynamics of C and N from the various amendments into Fr-A and Fr-B of soils differing in organic matter content. Soils NB and NT and treatments S, SF, and Af are as explained in Appendix 1.

Soil	%C_{INC}							
	Fr-A				Fr-B			
	0 d	7 d	30 d	90 d	0 d	7 d	30 d	90 d
NT-S	3.431 lmn‡	4.687 ghijkl	6.346 bcde	3.699 klmn	3.730 hijk‡	6.102 bcd	5.005 defg	4.369 ghijk
NT-SF	3.750 jklmn	7.565 ab	6.090 cdef	4.493 ghijklm	4.442 fghij	6.883 ab	4.840 efgh	4.802 efghi
NT-Af	5.130 efghij	4.706 ghijkl	4.039 ijklmn	3.268 mn	7.476 a	5.527 cdef	4.285 ghijk	4.074 ghijk
NB-S	5.241 efghi	7.213 abc	5.517 defgh	4.166 hijklmn	3.208 k	6.018 bcd	3.776 hijk	4.267 ghijk
NB-SF	4.856 fghijk	7.740 a	5.751 defg	3.899 ijklmn	3.292 jk	6.620 abc	3.880 ghijk	3.918 ghijk
NB-Af	6.633 abcd	6.313 bcde	4.641 ghijkl	2.948 n	5.740 cde	4.755 efghi	4.169 ghijk	3.610 ijk
	%N_{INC}							
NT-S	4.599 h‡	13.471 bcd	9.821 def	7.330 fgh	6.708 hijk‡	10.413 efgh	6.977 hijk	9.686 fghij
NT-SF	NA	7.640 fgh	7.386 fgh	6.540 fgh	NA	8.653 fghijk	5.976 jk	7.350 ghijk
NT-Af	16.999 b	15.347 bc	13.637 bcd	8.828 efgh	16.719 bc	17.629 ab	11.961 def	13.676 cde
NB-S	9.567 defg	12.284 cde	10.278 def	7.024 fgh	7.069 hijk	10.924 efg	8.550 fghijk	10.121 efghi
NB-SF	NA	7.213 fgh	7.843 fgh	5.373 gh	NA	5.811 k	6.401 ijk	7.059 hijk
NB-Af	15.583 bc	23.882 a	16.122 bc	10.453 def	20.775 a	15.431 bcd	15.768 bc	15.196 bcd

‡ %C_{INC} and %N_{INC} values followed by the same letter are not significantly different ($P<0.05$). (statistical comparisons on data for %C_{INC} and %N_{INC} and for each fraction were run separately)

APPENDIX 3. Comparison of the incorporation dynamics of C and N from the various amendments into Fr-A and Fr-B of soils differing in organic matter content. Soils NB and RRC and treatments S, SF, and Af are as explained in Appendix 1.

Soil	%C_{INC}							
	Fr-A				Fr-B			
	0 d	7 d	30 d	90 d	0 d	7 d	30 d	90 d
RRC-S	3.436 ijkl‡	5.864 bcde	4.240 fghi	3.406 ijkl	4.870defghij‡	6.354 abcde	6.219 abcde	6.737 ab
RRC-SF	4.651 efgh	6.826 abc	3.560 ijkl	2.710 klm	6.446 abcd	6.625 abc	4.464 fghij	5.411 bcdefgh
RRC-Af	3.979 ghijk	6.332 abcd	2.410 lm	1.982 m	7.389 a	6.346 abcde	4.109 ghij	5.030 cdefghi
NB-S	5.241 defg	7.213 ab	5.517 cdef	4.166 ghij	3.208 j	6.018 abcdef	3.776 hij	4.267 ghij
NB-SF	4.856 efgh	7.740 a	5.751 cde	3.899 hijk	3.292 j	6.620 abc	3.880 hij	3.918 hij
NB-Af	6.633 abcd	6.313 bcde	4.641 ghijkl	2.948 n	5.740 cde	4.755 efghi	4.169 ghijk	3.610 ijk
	%N_{INC}							
RRC-S	5.332 fg‡	10.981 de	7.303 ef	5.285 fg	7.781 efgh‡	9.561 def	13.105 bc	9.809 def
RRC-SF	NA	4.699 fg	2.125 g	1.734 g	NA	3.334 j	5.259 hij	3.700 ij
RRC-Af	7.870 ef	24.904 a	8.100 ef	7.987 ef	20.687 a	21.233 a	18.815 a	15.875 b
NB-S	9.567 de	12.284 cd	10.278 de	7.024 ef	7.069 fgh	10.924 cd	8.550 defg	10.121 de
NB-SF	NA	7.213 ef	7.843 ef	5.373 fg	NA	5.811 ghij	6.401 ghi	7.059 fgh
NB-Af	15.583 bc	23.882 a	16.122 b	10.453 de	20.775 a	15.431 b	15.768 b	15.196 b

‡ %C_{INC} and %N_{INC} values followed by the same letter are not significantly different ($P<0.05$). (statistical comparisons on data for %C_{INC} and %N_{INC} and for each fraction were run separately)

APPENDIX 4. Comparison of the incorporation dynamics of C and N from amendments differing in C:N ratio into Fr-A and Fr-B of different soils. Soils NB, NT, and RRC and treatments S and AF are as explained in Appendix 1.

Soil	%C_{INC}							
	Fr-A				Fr-B			
	0 d	7 d	30 d	90 d	0 d	7 d	30 d	90 d
NT-S	3.431 jk‡	4.687 fghij	6.346 bcde	3.699 jk	3.730 efg‡	6.102 abc	5.005 bcde	4.369 defg
NT-SF	3.750 jk	7.565 ab	6.090 cdef	4.493 ghij	4.442 defg	6.883 a	4.840 cdef	4.802 cdef
NB-S	5.241 efghi	7.213 abc	5.517 defgh	4.166 hij	3.208 g	6.018 abc	3.776 efg	4.267 defg
NB-SF	4.856 fghij	7.740 a	5.751 defg	3.899 ijk	3.292 fg	6.620 a	3.880 defg	3.918 defg
RRC-S	3.436 jk	5.864 cdefg	4.240 hij	3.406 jk	4.870 cdef	6.354 abc	6.219 abc	6.737 a
RRC-SF	4.651 fghij	6.332 abcd	3.560 jk	2.710 k	6.446 ab	6.625 a	4.464 defg	5.411 abcd
	%N_{INC}							
NT-S	4.599 de‡	13.471 a	9.821 abc	7.330 bcd	6.708 gh‡	10.413 bc	6.977 fgh	9.686 bcde
NT-SF	NA	7.640 bcd	7.386 bcd	6.540 cd	NA	8.653 bcdefg	5.976 ghi	7.350 defgh
NB-S	9.567 abc	12.284 a	10.278 abc	7.024 bcd	7.069 efgh	10.924 ab	8.550 bcdefg	10.121 bc
NB-SF	NA	7.213 bcd	7.843 bcd	5.373 de	NA	5.811 hij	6.401 gh	7.059 efgh
RRC-S	5.332 de	10.981 ab	7.303 bcd	5.285 de	7.781 cdefgh	9.561 bcdef	13.105 a	9.809 bcd
RRC-SF	NA	4.699 de	2.125 e	1.734 e	NA	3.334 j	5.259 hij	3.700 ij

‡ %C_{INC} and %N_{INC} values followed by the same letter are not significantly different ($P<0.05$). (statistical comparisons on data for %C_{INC} and %N_{INC} and for each fraction were run separately)

APPENDIX 5. Comparison of the incorporation dynamics of C and N from amendments differing in form of C and N into Fr-A and Fr-B of different soils. Soils NB, NT, and RRC and treatments SF and Af are as explained in Appendix 1.

Soil	%C_{INC}							
	Fr-A				Fr-B			
	0 d	7 d	30 d	90 d	0 d	7 d	30 d	90 d
NT-SF	3.750 ghijk‡	7.565 ab	6.090 bcde	4.493 fghi	4.442 efghi‡	6.883 ab	4.840 defgh	4.802 defgh
NT-Af	5.130 defg	4.706 efghi	4.039 ghij	3.268 ijkl	7.476 a	5.527 cde	4.285 efghi	3.268 ghi
NB-SF	4.856 defgh	7.740 a	5.751 cdef	3.899 ghijk	3.292 i	6.620 abc	3.880 ghi	3.918 ghi
NB-Af	6.663 abc	6.313 abcd	4.641 efghi	2.948 jkl	5.740 bcd	4.755 defgh	4.285 efghi	3.610 hi
RRC-SF	4.651 efghi	6.332 abc	3.560 hijk	2.710 jkl	6.446 abc	6.625 abc	4.464 efghi	5.411 cdef
RRC-Af	3.979 ghij	6.332 abcd	2.410 kl	1.982 l	7.389 a	6.376 abc	4.109 ghi	5.030 defg
	%N_{INC}							
NT-SF	NA	7.640 de	7.386 de	6.540 de	NA	8.653 g	5.976 ghi	7.350 g
NT-Af	16.999 b‡	15.347 b	13.673 bc	8.828 de	16.719 cde‡	17.630 bcd	11.961 f	13.676 ef
NB-SF	NA	7.213 de	7.843 de	5.373 ef	NA	5.811 ghi	6.401 ghi	7.059 gh
NB-Af	15.583 b	23.822 a	16.122 b	10.453 cd	20.775 ab	15.431 cde	15.768 cde	15.196 def
RRC-SF	NA	4.699 ef	2.125 f	1.734 f	NA	3.334 i	5.259 ghi	3.700 hi
RRC-Af	7.870 de	24.904 a	8.100 de	7.987 de	20.687 ab	21.233 a	18.815 abc	15.875 cde

‡ %C_{INC} and %N_{INC} values followed by the same letter are not significantly different ($P<0.05$). (statistical comparisons on data for %C_{INC} and %N_{INC} and for each fraction were run separately)

APPENDIX 6. SAS program used to determine Log Geometric Mean Diameter LGMD) of NB, NT, and RRC soils after 90 days of incubation. Sample data taken from straw (S) treatment in NB soil.

```
TITLE 'AGGREGATE SIZE DISTRIBUTION EQUATION';
TITLE2 'LINEAR REGRESSION ANALYSIS';
TITLE3 'NB-S';
DATA AGGREG;
ACCWT = 0;
DO SIEVE = 4.00, 1.99, 0.99, 0.85, 0.50, 0.25;
     INPUT SOIL $ TREAT REP SAMPWT SOILWT;
     LNSIEVE = LOG(SIEVE);
     ACCWT = ACCWT + SOILWT;
     RATIO = ACCWT / SAMPWT;
     PROB = PROBIT(RATIO);
     OUTPUT;
END;
CARDS;

NB S 1 48.24 1.30        NB S 2 47.59 0.86
NB S 1 48.24 2.15        NB S 2 47.59 2.89
NB S 1 48.24 3.79        NB S 2 47.59 4.67
NB S 1 48.24 1.19        NB S 2 47.59 2.24
NB S 1 48.24 6.33        NB S 2 47.59 6.53
NB S 1 48.24 16.11       NB S 2 47.59 8.49

PROC PRINT;
PROC PLOT;
     PLOT LNSIEVE * PROB=TREAT / HREF=0;
PROC REG DATA=AGGREG;
     MODEL LNSIEVE = PROB;
```

** Definitions **

SOIL -- soil type (i.e. NB, NT, or RRC)
TREAT -- residue amendment treatment (i.e. C, S, SF, or Af)
REP -- pot number (i.e. first or second duplicate)
SAMPWT -- weight of soil which was wet sieved (oven dry basis)
SOILWT -- weight of soil collected from a given sieve (oven dry basis)
LNSIEVE -- natural logarithm of sieve mesh size
ACCWT -- weight of soil accumulated on sieves (oven dry basis)
RATIO -- proportion by weight of soil aggregates of a given size and larger (i.e. fraction of original soil sample collected on sieves)
PROB -- computed probability of the sieve mesh size being larger (negative Z-value) or smaller (positive Z-value) than the mean aggregate diameter (i.e. the mean aggregate diameter represented by PROB = 0)

****

APPENDIX 6 (continued). Sample output of SAS program -- NB-S data.

OBS	ACCWT	SIEVE	SOIL	TREAT	REP	SAMPWT	SOILWT	LNSIEVE	RATIO	PROB
1	1.30	4.00	N	S	1	48.24	1.30	1.3863	0.026949	-1.9277
2	3.45	1.99	N	S	1	48.24	2.15	0.6881	0.071517	-1.4646
3	7.24	0.99	N	S	1	48.24	3.79	-0.0101	0.150083	-1.0361
4	8.43	0.85	N	S	1	48.24	1.19	-0.1625	0.174751	-0.9356
5	14.76	0.50	N	S	1	48.24	6.33	-0.6931	0.305970	-0.5073
6	30.87	0.25	N	S	1	48.24	16.11	-1.3863	0.639925	0.3583
7	0.86	4.00	N	S	2	47.59	0.86	1.3863	0.018071	-2.0953
8	3.75	1.99	N	S	2	47.59	2.89	0.6881	0.078798	-1.4132
9	8.42	0.99	N	S	2	47.59	4.67	-0.0101	0.176928	-0.9271
10	10.66	0.85	N	S	2	47.59	2.24	-0.1625	0.223997	-0.7588
11	17.19	0.50	N	S	2	47.59	6.53	-0.6931	0.361210	-0.3552
12	25.68	0.25	N	S	2	47.59	8.49	-1.3863	0.539609	0.0994

DEP VARIABLE: LNSIEVE

ANALYSIS OF VARIANCE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PROB>F
MODEL	1	9.46767098	9.46767098	556.736	0.0001
ERROR	10	0.17005689	0.01700569		
C TOTAL	11	9.63772787			

ROOT MSE	0.1304059	R-SQUARE	0.9824
DEP MEAN	-0.029597	ADJ R-SQ	0.9806
C.V.	-440.605		

PARAMETER ESTIMATES

VARIABLE	DF	PARAMETER ESTIMATE	STANDARD ERROR	T FOR HO: PARAMETER=0	PROB > |T|
INTERCEP	1	-1.16421113	0.06106929	-19.064	0.0001
PROB	1	-1.24192368	0.05263449	-23.595	0.0001

APPENDIX 6 (continued). Sample output of SAS program -- NB-S data.