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The Productivity & Sustainability of
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29. Soil Organic Matter and Soil Productivity: Searching for the Missing Link

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Soil-organic matter (SOM) is a complex array of components including soil fauna and flora at different stages of decomposition (Berg et al., 1982). Its concentration in soils can vary from 0.5% in mineral soils to almost 100% in peat soils (Brady, 1974). Organic matter (OM) in the surface mineral soil is considered a major determinant of forest ecosystem productivity because it affects water retention, soil structure, and nutrient cycling (Powers et al., 1990; Paul 199 1). Soil-organic matter is the major source of nitrogen available to plants and contains as much as 65% of the total soil phosphorus (Bauer and Black, 1994).

During decomposition, OM is broken down into various components including carbohydrates, amino acids, proteins, nucleic acids, lipids, tannins, lignin, and humus. Humus refers to the microbial resistant forms of SOM that remain after major portions of added plant and animal residues have decomposed. Its chemical nature has not been completely determined but it is believed to consist of various polymeric compounds, probably aromatic and aliphatic in composition (Schnitzer and Schulten, 1992). Humus has been found to affect the physical properties of soil (Elliot, 1986; Beare et al., 1994). The nonhumus components of SOM are crucial in nutrient cycling dynamics and are the primary source of food and energy for soil microorganisms (Cambardella and Elliot, 1992; Wander et al., 1994). As such, these components are the driving force for productivity.

The input into the OM pool in forest soils comes mainly from forest litter and fine root mortality, exudates, and sloughing (Vogt et al., 1986). Estimates of the net annual carbon (C) budget of a tree relegated to root growth and maintenance are disputed, but the range is from 20 to 65% (Persson, 1979). Global change could significantly alter the supplies of nutrients and water to the root systems, C-allocation patterns within and potentially between plants and, in this way, plants will be affected (Friend, 1988; Johnson, 1990; Wilson, 1988). Changes in the amount of carbon allocated to the root system will, in turn, affect the annual amount of fine root material entering the soil.

Nationally, efforts are underway to monitor forest ecosystem health and productivity. Soil parameters, including total SOM, account for many of the site quality indicators being collected. The recommended analytical procedure is to report SOM values in units of total elemental C (Nelson and Sommers, 1986). The feasibility of using total SOM as an indicator of soil productivity is problematic because of large seasonal fluctuations in its value. Haines and Cleveland (198 1) showed that the seasonal variability of SOM concentration for some Georgia soils could be more than 100%. Nutrient turnover rates are generally more relevant to forest productivity than is the total amount of SOM (Cole and Rapp, 1981) and this is consistently reflected in equations for predicting nitrogen (N) fertilization responses and N uptake. Variation in the factors regulating decomposition (C/N ratio, moisture, temperature) are often more closely related to standard measures of productivity than is the total amount of SOM (Edmonds and Hsiang, 1987; Binkley and Hart, 1987). Total SOM on a site is, at best, a key to long-term productivity potential or carrying capacity. What may be more important to short-term (i.e., annual) productivity is the dynamic relationship between the labile fraction of the SOM pool and plant growth. It is this labile fraction that is most sensitive to environmental change and variations in this fraction will have the most immediate impact on forest ecosystem productivity (Ruark and Blake, 1991; Wander et al., 1994; Eswaran et al., 1995).

Various models describing C and N dynamics have been reported in the literature. Some describe SOM as a dynamic system spanning a continuum of characteristics and qualities (Bosatta and Ågren, 1985; Ågren and Bosatta, 1987; Janssen, 1984). Others fractionate SOM into pools based on C accessibility to microorganisms (Jenkinson and Rayner, 1977; Parton et al., 1988). Forest productivity may be sensitive to climate variations that result in alteration of SOM decomposition rates, particularly those associated with the highly labile fractions that direct nutrient cycling and therefore, productivity (Ruark and Blake, 1991; Wander et al., 1994). To date, direct measurement and characterization of this labile SOM fraction have been elusive.

Soil-Organic Matter Characteristics

Relating forest productivity to levels of total SOM ignores the separate contributions that different SOM components have in the soil. For example, it has been shown that the carbohydrate fraction of SOM significantly increases soil aggregate stability and water infiltration (Cheshire, 1979; Oades, 1984; Roberson et al., 1991). Sometimes these changes can be subtle as in situations in which changes in land-management practices have induced improvements in soil structure without changing total organic C or total carbohydrate content (Hamblin and Davies, 1977; Baldock et al., 1987). In these situations, it has been shown that not all the carbohydrate fractions contributed to the improved soil structure. Instead it was shown that only soil carbohydrates originating from microbial activity have a positive correlation with the improved soil structure (Roberson et al., 1995).

The labile fraction comprises plant and animal residues at various stages of decomposition. The size of this fraction is regulated by such external factors as litter input, microbe population, and climate (Bosatta and Ågren, 1985; Ågren and Bosatta, 1987). Its high variability throughout the year accounts for most of the seasonal variability of total soil C at a particular site. The annual dynamics of this fraction are hypothesized to positively correlate with SOM decomposition rates and, consequently, nutrient-cycling rates (Ruark and Blake, 199 1; Wander et al., 1994). This fraction is believed to be directly affected by changes in C inputs and temperature fluxes induced by global change (Eswaran et al., 1995).

Past SOM Research

Past attempts to partition SOM into components that are biologically meaningful have been hindered by the various extraction methods used. The most prevalent method for separating SOM pools is with sodium hydroxide (NaOH) (Calderoni and Schnitzer, 1984). This procedure fractionates SOM into humic acids (HA), fulvic acids (FA), and humin. Humic acids are the SOM fractions that are only soluble in water at alkaline pH levels. Fulvic acids are soluble in water at both alkaline and acidic pHs but not at neutral pH. Humin is insoluble in water at all pH levels. This procedure, however, has come under much criticism in the literature. The primary concern is that NaOH can react with many organic compounds and may induce such sample modifications as polymerization, autoxidation, and hydrolysis (Stevenson, 1982). These chemical modifications create a series of compounds that are not in the soil and root environment and are not clear indicators of C-forms available in the soil. Another major concern is that the subdivision of SOM into HA, FA, and humin is arbitrary and bears no relationship to soil productivity. These criticisms have prompted development of other means of analyzing SOM that do not alter the chemical integrity in SOM; these results could then be related directly to relevant soil factors, particularly soil productivity.

Nondestructive methods have been used for the analysis of SOM. One such method is Fourier transform infrared spectroscopy (FTIR). This method has been used to obtain information on specific classes of compounds in the water soluble fraction (Sposito et al., 1976; Stevenson, 1982; Baes and Bloom, 1989). Unfortunately, the diversity of chemical functional groups present in SOM results in featureless spectra that provide little information on specific functional groups. However, some insight has been obtained by using the ratio of the absorption at two wavelengths, 465 nm and 665 nm, in the visible spectrum. This ratio, abbreviated as the ratio E_4/E_6, has been found to provide information on the chemical functional group character of SOM in solution, Chen et al., (1977) found that the E_4/E_6 ratio could be correlated to the molecular weight, the oxygen (0), C, and carboxylic acid (CO_2H) content, and the total acidity of the SOM. They found that small compounds with higher total acidity and higher CO_2H content had a larger E_4/E_6 ratio. Although the analysis is nondestructive and did not involve sample modification, this method only covers a small portion of the SOM pool (the water soluble fractions), and therefore, has apparent limited value in relating SOM and productivity.

One of the most promising techniques for SOM research has been nuclear magnetic resonance (NMR). Solid-state-cross-polarization-magic angle spinning ^{13}C NMR (CPMAS ^{13}C NMR) has been used to investigate decomposition processes. The CPMAS ^{13}C NMR spectra for decomposing litter showed that carbohydrates and proteins are rapidly degraded, lignin is slowly oxidized, and there is a relative increase of alkyl structures (Baldock et al., 1992; Baldock and Preston, 1995). Some oxidized lignin molecules are incorporated into humus, some are leached, and the rest are decomposed into stable subunits. The advantage of this technique is that the unsieved soil can be used in the analysis. Unfortunately, this procedure is limited by the SOM concentration in the soil and, hence, the abundance of the ^{13}C isotope. Naturally occurring ^{13}C represents only 1.1% of the total carbon concentration of a sample. This becomes particularly troublesome in the mineral soils of the southern United States where the carbon concentrations are usually low, typically ranging from 0.5% to 5%. Additionally, the presence of ferromagnetic species can degrade the homogeneity of the magnetic field and cause line broadening. In these situations, the soil must be treated to remove ferromagnetic species and concentrate the SOM. Even under “ideal” conditions (i.e., sufficient SOM concentration, no ferromagnetic species), substantial signal overlap in the spectrum occurs because of the complexity of the sample mixture. This makes it difficult to detect changes in organic functional groups resulting from microbial degradation or external factors (e.g., exposure to increased carbon dioxide (CO,), temperature fluxes, moisture fluxes, and so forth). This technique only provides qualitative information about changes in SOM. It does not provide insight into how the changes in SOM occur or how the different SOM components relate to soil productivity.

More recently, supercritical fluid extraction (SFE) has emerged as a promising means of investigating SOM dynamics. The advantage of SFE over conventional extraction techniques is that it is an efficient method that is chemically inert (Richards and Campbell, 1991). However, this technique has been limited by the fact that the commonly used SFE solvents (i.e., CO,, nitrous oxide (N_2O)) will only extract essentially nonpolar compounds. The range of the materials extracted can be extended by adding small amounts of a cosolvent that has specific capabilities (i.e., hydrogen bonding, dipole moment, and so forth) that the primary solvent does not. Binding of SOM in soils is primarily ionic, and thus limits the effectiveness of this technique for SOM research. Nevertheless, it has been successfully used to extract long-chain alkanes, alkenes, saturated and unsaturated fatty acids, alcohols, ketones, and alkyl esters from soils (Schulten and Schnitzer, 199 1). In addition to CO, and N_2O, researchers have used n-pentane, ethanol, and water as solvents (Schnitzer et al., 1986; Schnitzer and Preston, 1987; Schnitzer et al., 1992) to extract varying amounts of aliphatic and aromatic species. These extractions were done to characterize SOM chemical composition and no attempt was done to relate this information to soil productivity.

Current Research

To date, no consistent quantitative correlation has been made between total SOM and forest productivity. This has prompted researchers to shift from investigating the relationship between total SOM and productivity, to devising means to fractionate SOM into biologically meaningful pools. Presently, efforts are directed at isolating the labile from the recalcitrant SOM components. Labile SOM fractions are theorized to be correlated to nutrient-cycling dynamics (Ruark and Blake, 1991; Wander et al., 1994). Because prior linkages have been made between nutrient cycling and productivity (Cole and Rapp, 1981), a link between labile SOM and nutrient-cycling dynamics would be useful in predicting potential productivity changes. This, in turn, could guide the development and use of land-management practices.

Several methods have been devised for the extraction and characterization of labile SOM while maintaining the chemical integrity of the extracted SOM. Complementary methods have been developed based on SOM particle size and density fractionation. These methods physically divide SOM into pools differing in structure and biological function (Christensen, 1992). Size fractionation studies have shown that SOM in the sand-size fractions (> 53 μm) are more labile than the SOM in the clay- and silt-size fractions (Tiessen and Stewart, 1983; Gregorich et al., 1988). Density fractionation methods have also shown that during humification, SOM increases in density through its associations with soil minerals. Thus, SOM can be density fractionated into a light fraction, which consists of mineral-free organic matter, and a heavy fraction, which is composed of SOM adsorbed on aggregate surfaces and sequestered within organo-mineral aggregates (Strickland and Sollins, 1987). Various methods have been developed that combine these complementary particle size and density fractionation methods (Strickland and Sollins, 1987; Cambardella and Elliot, 1992; Meijboom et al., 1995). Although the degeneracy of the fractionated material has been verified (Buyanovsky et al., 1994; Cambardella and Elliot, 1994), no clear correlation between these fractions and soil productivity has been achieved.

Dissolved organic matter (DOM) is another measurement designed to investigate the labile SOM fraction. The basic tenet of this metric is that the nutrients that are immediately available to plants and microbes are contained in the soil solution (Ellert and Gregorich, 1995). In contrast, solid OM is viewed as less available to plants and microbes. However, information on the relationship between DOM and

C-mineralization is inconclusive. Although some researchers have shown a strong correlation between DOM and C mineralization (Seto and Yanagiya, 1983; Davidson et al., 1987), others have found a weak or nonexistent correlation between the two (Linn and Doran, 1984; Walters and Joergensen, 199 1; Cook and Allen, 1992). At present, no clear correlation between DOM and soil productivity has been made.

As described earlier, supercritical fluids (SCF) have been used for the extraction of organics from soils. In prior attempts to analyze SOM through SFE (Schnitzer et al., 1986; Schulten and Schnitzer, 1990; Capriel et al., 1990; Spiteller, 1985), only bulk extractions with no fractionation were achieved. Even so, Spiteller (1985) achieved four to five times better OM recoveries than with conventional NaOH extraction. Recent advances in instrumentation and the introduction of within-matrix derivatization techniques for the extraction of polar and ionic compounds (Miller et al., 199 1) allow for considerable improvements in extracting SOM. Sanchez and Ruark (1995) developed a SOM extraction method that used supercritical Freon-22™ ($CHClF_2$) as a solvent. At a prior date, this solvent was shown to be superior to CO, and N_2O for the extraction of organic materials from soils (Hawthorne et al., 1992). The extract obtained with this method was composed of low molecular weight materials ($<$ 900 Daltons) that had significant polar character (Sanchez and Ruark, 1995; Sanchez and Bursey, 1996, in review). Additionally, the high quality and degeneracy of the extract were shown by its low C/N ratio (18) as compared with the unextracted soil (35) Sanchez and Ruark (1995) correlated the annual dynamics of the labile SOM fraction and the annual biomass production of two soils. As it is relatively new, this method will require extensive testing before definitive statements can be made concerning linkages between the SFE extract and soil productivity.

Comparisons Between Methods

Identifying changes in the factors that drive productivity is important to understanding and predicting the impacts of global change on forested ecosystems. Global change induced variations in the labile SOM may provide indications of concurrent or future changes in forest productivity. The question then arises as to which labile SOM pool measurement should be used. Although all three general fractionation methods (i.e., particle and density fractionation, DOM, and SFE) attempt to fractionate labile and recalcitrant SOM fractions, there are significant differences between the methods.

Particle size and density fractionation results in the removal of recognizable plant fragments. These fragments decompose quickly but have wide C/N ratios and immobilized N (Sollins et al., 1984; Christensen, 1992). Also, the percentage of the total SOM concentration contained in these fractions can be highly variable (3 to 50%) (Ellert and Gregorich, 1995).

The DOM fraction is decomposed material, with a low molecular weight range and high level of polarity. Inorganic carbon is also contained in this fraction. Dissolved organic matter represents only a very small percentage (0.04 to 0.39%) of the total C (Ellert and Gregorich, 1995). Attempts to correlate DOM to productivity have been both variable and conflicting.

Similarly to DOM fractionation, supercritical Freon-22™ removes decomposed material. The molecular weight range of the extract is low, as compared with the whole soil, but is probably larger than the DOM molecular weight range. In addition to the polar and ionic compounds in the DOM fraction, the materials extracted by SFE contain components that are not water soluble. In our laboratory we found that the extract could represent up to 60% of the total soil C (Sanchez and Ruark, 1995). Because DOM represents a very small percentage of the total SOM, most of the extract obtained by SFE is not water soluble. The low C/N ratio of the SFE extract suggests that these components are susceptible to microbial degradation. Although this procedure shows promise in separating labile and recalcitrant SOM fractions, it is a new technique that has not been tested in other laboratories.

It is important to note that none of the methods have demonstrated a strong correlation to soil productivity. The missing link has yet to be discovered. Nevertheless, investigations concentrating on the labile SOM fraction presently appear to be our best effort at finding this missing link.

Carbon Sequestration

In addition to regulating forest ecosystem productivity, SOM dynamics are critical to carbon sequestering. The environmental constraints on sequestering in a given soil system are not well understood. Evidence exists suggesting that there may be a negative feedback between SOM levels and carbon allocation to plant root systems that limit carbon storage in the soil (Ruark and Blake, 1991). Significant increases in the recalcitrant SOM fractions may suggest the potential for carbon sequestration. Recalcitrant SOM fractions are highly protected because of their associations with soil minerals and because of their chemical stability (via their presumed high aromatic and aliphatic character); therefore, there is little annual variation in either their size or identity. Because this fraction has been linked to the physical properties of the soil (Elliot, 1986; Beare et al., 1994), fluxes in the size or chemical identity of this fraction may result in significant long-term changes in the soil.

Individual trees establish a long-lived network of primary, secondary, and tertiary roots. Transient crops of fine roots that turnover each year are attached to this main root system. As such, a concentration of labile SOM can be expected to build up adjacently to the large root system. A 38% increase in total soil C was found laterally within 30 mm of a permanent secondary root system; this increase was from a first rotation forty-year-old loblolly pine (*Pinus* ***taeda*** L.) stand grow-

Table 29.1. Soil-Carbon Level Within 3.0 cm Distances of Second-Order Laterals vs Levels in the 3.0 to 10.0 cm Distance Ranges

Distance (cm)	N	Meant (%C)	Standard Error (%C)
0-3.0	32	0.50	0.03
3.0-10.0	64	0.37	0.01

†Means differ statistically at $P < 0.0001$ level

ing on an abandoned farm site at the Department of Energy's Savannah River Site (DOE-SRS) in Aiken, South Carolina (Table 29.1). This increase was at a depth of 10 cm in the Ap horizon, where prior agricultural practices probably left a homogeneous plow horizon. Ruark and Blake (1991) termed this area of fine root turnover the "reoccurring rhizosphere" and considered the increased SOM content to be the result of fine root activity over the length of the rotation. The large spatial variability in total SOM and N that occurs in first generation pine stands within the priorly homogenized Ap layer of abandoned farm land suggests that the variability was heightened by plant activity (Ruark and Zamoch, 1992). Because OM input from the forest floor in these stands is predominantly in solution and from a single, dominant tree species, it should uniformly influence the mineral soil.

The SFE procedure developed by Sanchez and Ruark (1995) was used to investigate the carbon sequestration potential of soils in the southeastern United States. The study was conducted on three soil types that span an available moisture and texture gradient at the DOE-SRS. The soils were in the Lakeland (thermic, coated Typic quartzipsamment), Fuquay (loamy, siliceous, thermic Typic arenic plinthic paleudult), and Orangeburg (fine, loamy, siliceous, thermic Typic paleudult) series. A complete description of the analysis is presented elsewhere, but briefly, the existence of a reoccurring rhizosphere region for the Lakeland and Fuquay soils was confirmed. The increased SOM concentration in this area was greatest for first-order roots and declined going from secondary to tertiary roots. The carbon increase in the reoccurring rhizosphere region for the first order roots in the Lakeland soil was substantial (55% increase). Lakeland soils exhibited the largest detectable C buildup for each of the root orders. No reoccurring rhizosphere region was detected for the Orangeburg soil. It is possible that the finer texture and better water retention of the Orangeburg soil (sandy loam) discouraged fine root extension. If this is the case, it is possible that this soil has a more compact reoccurring rhizosphere region.

Supercritical fluid extraction of the soils from the reoccurring rhizosphere region for the three soil series showed that the additional carbon was soluble. This would suggest that there is not a significant amount of C sequestration in the recalcitrant SOM fractions occurring at these sites during the forty years that they have been established. However, spectral (^{13}C NMR) comparisons of the extracts obtained in and away from the reoccurring rhizosphere for the Lakeland and Fuquay soils showed subtle differences in the two regions. Extracts from the reoccurring rhizosphere region for each soil had a higher relative proportion of chemically stable compounds (e.g., aliphatics, aromatics) than did extracts away from this region. This may suggest that the potential exists for long-term carbon storage in these soils with continual carbon additions.

Potential Change Scenarios

Burning of fossil fuels and clearing of forests have resulted in an elevation of atmospheric CO_2 concentration by 25% since the industrial revolution began and it continues to rise at an approximate rate of 0.5% yr^{-1} (Houghton et al., 1990, 1992). The increased level of of CO_2 and other gases (i.e., methane, nitrous oxide, and others) may result in eventual surface warming because of the anticipated "greenhouse effect" (Rosenzweig, 1994). Several researchers have attempted to model the effects of increased CO_2 or surface temperature on forest ecosystems and have obtained significant variations in their results because of species differences, nutrient status, and air pollution inputs. However, there is a general trend for increasing litterfall, increasing decomposition rate, and decreasing SOM with increasing mean annual temperature (Johnson, 1995).

Most of the research on belowground responses has been conducted as experiments using container-grown seedlings (Norby et al., 1995). These research efforts have resulted in conflicting conclusions. For example, although several researchers have concluded that nutrient deficiency does not preclude growth responses to elevated CO_2 levels, other researchers have reached the opposite result (Norby et al., 1995). It is possible that the different conclusions obtained are the result of differences in tree species used. Despite the conclusions reached, it is a major leap to extrapolate any results obtained from container-grown seedlings to whole forest ecosystems.

There have been attempts, albeit on a small scale, at investigating whole ecosystem responses to elevated levels of CO_2. These experiments were conducted on the arctic tussock tundra (Oechel et al., 1991), the Chesapeake Bay salt marsh (Drake, 1992), and a tallgrass prairie (Owensby et al., 1993). Unfortunately, because of the economic, technical, and biological considerations, no attempt has been made to replicate these studies on intact forests. However, there are several ongoing studies looking at the aboveground and belowground responses of individual trees or small groups of trees to elevated CO_2 (Norby et al., 1995).

A very important observation obtained from the ongoing field studies has been an alteration of the C budget of trees. Norby et al., (1992, 1993) found that the fine root density of yellow poplar and white oak saplings was greater under elevated levels of CO_2. Because fine roots are major contributors to the SOM pool, this could signal an increase in C sequestration in the soil. The probability that this material is sequestered in the soil is lessened, however, by the observation that there is also an increase in microbial activity in response to increased levels of CO_2 and surface temperature (Johnson, 1995). Research on C sequestration in soils suggests that although the additional organic material entering the soil is labile, there is a shift in its chemistry that may allow for some stabilization in the soil.

Management Options

The challenge presently facing us is the management of our forests in order to minimize the effects of global change and perhaps even use it to our advantage. Considering that forests store 20 to 100 times more C per unit area than does cropland (Houghton et al., 1983), reforestation is an obvious avenue for C storage. Unfortunately, with the world's increasing demands for agriculture and wood products, implementing a reforestation strategy may be difficult to achieve on a global scale. We must be able to optimize the use of our forest ecosystems. Achieving maximum sustainable productivity from these forests may help in attenuating the rise in atmospheric CO, levels while lessening the need for deforestration.

Careful management of the forest soils is essential to achieving optimal sustainable productivity of forest ecosystems. Management systems comprising appropriate harvest, regeneration, and sivicultural options can be used to approach this goal. Extensive evidence exists that shows that extreme soil disturbance results in a loss of SOM, which subsequently contributes to the elevated atmospheric CO, concentration (Schlesinger, 1995). Stabilizing the SOM in forests can aid in obtaining optimum sustainable productivity without exacerbating the elevated atmospheric CO, problem. Although oxidation of SOM contributes to atmospheric CO,, increases in recalcitrant SOM could provide a negative feedback to global warming (Schlesinger, 1995).

A potential method of stabilizing OM in forest soils is through application of municipal biosolids. Municipal biosolids have been demonstrated to be effective in enhancing forest productivity (Beckett et al., 1977; McCaslin and O'Connor, 1982). Also important is the evidence that biosolids can sometimes promote C and nutrient stabilization in soils (Harrison et al., 1995).

Agroforestry is another alternative that is gaining popularity when there is limited available farm land. Agroforestry involves growing trees in conjunction or succession with crops to change the SOM and nutrient dynamics to increase annual crop production. Strategies include using deep-rooting trees to cycle nutrients from below the crop root zone and using N-fixing trees to minimize N loss. Compared to soils, the C pool in crops is more responsive to changes in atmospheric CO, levels (Schlesinger, 1995). Agroforestry systems are a potential means of achieving a balance between SOM turnover and stabilization.

References

Ågren GI, Bosatta E (1987) Theoretical analysis of the long-term dynamics of carbon and nitrogen in soils. Ecol 68: 118 l-l 189.

Baes AU, Bloom PR (1989) Diffuse reflectance and transmission Fourier transform infrared (DRIFT) spectroscopy of humic and fulvic acids. Soil Sci Soc Am J 53:695–700.

Baldock JA, Kay BD, Schnitzer M (1987) Influence of cropping treatments on the monosaccharide content of the hydrolysates of a soil and its aggregate fractions. Can J Soil Sci 67:489–499.

Baldock JA, Oades JM, Waters AG, Peng X, Vassallo AM, Wilson MA (1992) Aspects of the chemical structure of soil organic materials as revealed by solid-state ^{13}C NMR spectroscopy. Biogeochem 16:1–42.

Baldock JA, Preston CM (1995) Chemistry of carbon decomposition processes in forests as revealed by solid-state carbon- 13 nuclear magnetic resonance. In McFee WW, Kelly JM (Eds) *Carbon forms and functions in forest soils.* SSSA, Madison, WI.

Bauer A, Black AL (1994) Quantification of the effect of soil organic matter content on soil productivity. Soil Sci Soc Am J 58:185–193.

Beare MH, Hendrix PF, Coleman D (1994) Water stable aggregates and organic matter fractions in conventional and no-tillage soils. Soil Sci Soc Am J 58:777–786.

Beckett PHT, Davis RD, Milward AR, Brindley P (1977) A comparison of the effect of different sewage biosolids on young barley. Plant Soil 48:129–141.

Berg B, Hannus K, Popoff T, Theander 0 (1982) Changes in organic-chemical components during litter decomposition. Long-term decomposition in a Scots pine forest. I. Can J Bot 60:1310–1319.

Binkley D, Hart SC (1989) The components of nitrogen availability assessments in forest soils. Adv Soil Sci 10:57–1 12.

Bosatta E, Ågren GI (1985) Theoretical analysis of decomposition of heterogeneous substrates. Soil Biol Biochem 17:601–610.

Brady *NC* (1974) The *nature and properties of soils.* 8th Ed. MacMillan Publishing Co. Inc., New York.

Buyanovsky GA, Aslam M, Wagner GH (1994) Carbon turnover in soil physical fractions. Soil Sci Soc Am J 58:1167–1173.

Calderoni G, Schnitzer M (1984) Effects of age on the chemical structure of Paleosol humic acids and fulvic acids. Geochim et Cosmochim Acta, 48:2045–205 1.

Cambardella CA, Elliot ET (1992) Particulate soil organic matter changes across a grassland cultivation sequence. Soil Sci Soc Am J 56:777–783.

Cambardella CA, Elliot ET (1994) Carbon and nitrogen dynamics of soil organic matter fractions from cultivated grassland soils. Soil Sci Soc Am J 58:123–130.

Capriel P, Beck T, Borchert H, Harter P (1990) Relationship between soil aliphatic fraction extracted with supercritical hexane, soil microbial biomass and soil aggregate stability. Soil Sci Soc Am J 54:415–420.

Chen Y, Senesi N, Schnitzer M (1977) Information provided on humic substances by E_4/E_6 ratios. Soil Sci Soc Am J 41:352–358.

Chesire MV (1979) Origins and stability of soil polysaccharides. J Soil Sci 28: l-10.

Christensen BT (1992) Physical fractionation of soil and organic matter in primary size and density separates. Adv Soil Sci 20: l-90.

Cole DW, Rapp M (1981) Elemental Cycling. p 341–409. In Riechle DE (Ed) *Dynamic properties of forest ecosystems.* Cambridge University Press, Cambridge, England.

Cook BD. Allen DL (1992) Dissolved organic carbon in old field soils: Total amounts as a measure of available resources for soil mineralization. Soil Biol Biochem 24:585–594.

Davidson EA, Galloway LF, Strand MK (1987) Assessing available carbon: Comparison of techniques across selected forest soils. Commun Soil Sci Plant Anal 18:45–64.

Drake BG (1992) A field study of the effects of elevated CO, on ecosystem processes in Chesapeake Bay wetland. Aust J Bot 40:579–595.

Edmonds RL, Hsiang T (1987) Forest floor and soil influences on response of Douglas-fir to urea. Soil Sci. Soc. Am. 51:1332–1337.

Ellert BH, Gregorich EG (1995) Management-induced changes in the actively cycling fractions of soil organic matter. In McFee WW, Kelly JM (Eds) *Carbon forms and functions in forest soils.* SSSA, Madison, Wisconsin.

Elliot ET (1986) Aggregate structure and carbon, nitrogen and phosphorus in native and cultivated soils. Soil Sci Soc Am J 50:627–633.

Eswaran H, Van den Berg E, Reich P, Kimble J (1995) Global soil carbon resources. In Lal R, Kimble J, Levine E, Stewart BA (Eds) *Soils and global change.* CRC Press, Inc., Boca Raton, FL.

Friend AL (1988) Nitrogen stress and fine root growth of Douglas-fir. PhD dissertation, Univ WA-Seattle.

Gregorich EG, Kachanoski RG, Voroney RP (1988) Ultrasonic dispersion of aggregates: Distribution of organic matter in size fractions. Can J Soil Sci 68:395–403.

Haines SG, Cleveland G (1981) Seasonal variation in properties of five forest soils in southwest Georgia. Soil Sci Soc Am J 45:139–143.

Hamblin AP, Davies DB (1977) Influence of organic matter on the physical properties of some East Anglican soils of high silt content. J Soil Sci 28: 1 1–22.

Harrison RB, Henry CL, Cole DW, Xue D (1995) Long-term changes in organic matter in soils receiving applications of municipal biosolids. In McFee WW, Kelly JM (Eds) *Carbon forms and functions in forest soils.* SSSA, Madison, WI.

Hawthorne SB, Langenfeld JJ, Miller DJ, Burford MD (1992) Comparison of supercritical $CHClF_2$, N_2O, and CO, for the extraction of polychlorinated biphenyls and polycyclic aromatic hydrocarbons. Anal Chem 64: 1614-1622.

Houghton JT, Callander BA, Vamey SK (Eds) (1992) Climate change 1992: The supplementary report to the IPCC scientific assessment. World Meteorological Organization and United Nations Environment Programme. Cambridge University Press, Cambridge, England.

Houghton JT, Jenkins GJ, Ephraums JJ (Ed) (1990) Climate change: The IPCC scientific assessment. World Meteorological Organization and United Nations Environment Programme. Cambridge University Press, Cambridge, England.

Houghton R, Hobbie J, Melillo J (1983) Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO, to the atmosphere. Ecol Monogr 53:235–262.

Janssen BH (1984) A simple method for calculating decomposition and accumulation of “young” soil organic matter. Plant Soil 76:297–304.

Jenkinson DS, Rayner JH (1977) The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci 123:298–305.

Johnson JD (1990) Dry matter partitioning in loblolly and slash pine: Effects of fertilization and irrigation. For Ecol Manage 30: 147-157.

Johnson DW (1995) Role of carbon in the cycling of other nutrients in forested ecosystems. In McFee WW, Kelly JM (Eds) *Carbon forms and functions in forest soils.* SSSA, Madison, WI.

Linn DM, Doran JW (1984) Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci Soc Am J 48:1267–1272.

McCaslin BD, O’Connor GA (1982) Potential fertilizer value of gamma irradiated sewage biosolids on calcareous soils. NM Agric Exp Stat Bull 692.

Miller DJ, Hawthorne SB, Langenfeld JJ (1991) SFE with chemical derivatization for the recovery of polar and ionic analytes. In Proceedings of International Symposium on Supercritical Fluid Chromatography and Extraction, January 1991, Park City, Utah.

Meijboom FW, Hassink J, Van Noordwijk M (1995) Density fractionation of soil macroorganic matter using silica suspensions. Soil Biol Biochem 27: 1109-l 111.

Nelson DW, Sommers LE (1986) Total carbon, organic carbon, and organic matter. In Klute A (Ed) *Methods of soil analysis part* II. SSSA, Madison, WI.

Norby RJ, Gunderson CA, Wullschleger SD, O’Neill EG, McCracken MK (1992) Productivity and compensatory responses of yellow-poplar trees in elevated CO,. Nature (London) 357:322–324.

Norby RJ, O’Neill EG, Wullschleger SD, Gunderson CA, Nietch CT (1993) Growth enhancement of *Quercus alba* saplings by CO, enrichment under field conditions. Bull Ecol Soc Am 74(Suppl.):375.

Norby RJ, O'Neill EG, Wullschleger SD (1995) Belowground responses to atmospheric carbon dioxide in forests. In McFee WW Kelly JM (Eds) *Carbon forms and functions in forest soils.* SSSA, Madison, WI.

Oades JM (1984) Soil organic matter and structural stability: Mechanisms and implications for management. Plant Soil 76:3 19-337.

Oechel WC, Riechers G, Lawrence WT, Prudhome TT, Grulke N, Hastings SJ (1991) Longterm *in situ* manipulation and measurement of CO, and temperature. Func Ecol 6:86–100.

Owensby CE, Coyne PI, Auen LM (1993) Nitrogen and phosphorus dynamics of a tall-grass prairie ecosystem exposed to elevated carbon dioxide. Plant Cell Environ 16:843–850.

Paul EA (1991) Decompositon of OM. In J. Lederburg (Ed) *Encyclopedia of microbiology.* Academic Press, San Diego, CA.

Parton WJ, Stewart JWB, Cole CV (1988) Dynamics of C, N, P and S in grassland soil: A model. Biogeochem 5:109–131.

Persson H (1979) Fine root production, mortality, and decomposition in forest ecosystems. Vegetatio 41:101–109.

Powers RF, Alban DH, Miller RE, Tiarks AE, Wells CG, Avers PE, Cline RG, Fitzgerald RO, Loftis NS (1990) Sustaining site productivity in North American Forest: Problems and prospects. In Gessel SP, Lacate DS, Weetman GF, Powers *RF* (Eds) *Sustaining productivity of forest soils.* 7th North American Forest Soils Conference, July 24-28, 1988, Vancouver, BC, Fac For, UBC, Canada.

Richards M, Campbell RM (199 1) Comparison of supercritical fluid extraction, soxhlet, and sonication methods for the determination of priority pollutants in soil. LC·GC 9:358–364.

Roberson EB, Sarig S, Firestone MK (1991) Cover crop management of polysaccharide-mediated aggregation in an orchard soil. Soil Sci Soc Am J 55:734–739.

Roberson EB, Sarig S, Shennan C, Firestone MK (1995) Nutritional management of microbial polysaccharide production and aggregation in an agricultural soil. Soil Sci Soc Am J 59:1587–1594

Rosenzweig C (1994) Agriculture in a changing global environment. In *Soil and water science: key to understanding our global environment.* SSSA Special Publication 41. SSSA, Madison WI.

Ruark GA, Blake JI (1991) Conceptual stand model of plant carbon allocation with a feedback linkage to soil organic matter maintenance. In Dyck WJ, Mees CA (Eds) *Long-term field trails to assess environmental impacts harvesting.* Forest Research Institute, Rotorua, New Zealand, FRI Bull 161.

Ruark GA, Zamoch SJ (1992) Soil carbon, nitrogen, and fine root biomass sampling in a pine stand. Soil Sci Soc Amer J 56: 1945-1951.

Sanchez FG, Ruark GA (1995) Fractionation of soil organic matter with supercritical freon. In McFee WW, Kelly JM (Eds) *Carbon forms and functions in forest soils.* SSSA, Madison, WI.

Schlesinger WH (1995) An overview of the carbon cycle. In Lal R, Kimble J, Levine E, Stewart BA (Ed) *Soils and global change.* CRC Press, Inc., Boca Raton, FL.

Schnitzer M, Hindle CA, Meglic M (1986) Supercritical gas extraction of alkanes and alkanoic acids from soils and humic materials. Soil Sci Soc Am J 50:913–919.

Schnitzer M, Preston CM (1987) Supercritical gas extraction of soil with solvents of increasing polarities. Soil Sci Soc Am J 51:639–646.

Schnitzer M, Schulten HR (1992) The analysis of soil organic matter by pyrolysis-field ionization mass spectrometry. Soil Sci Soc Am J 56: 181 l-1817.

Schulten HR, Schnitzer M (1990) Aliphatics in soil organic matter in tine-clay fractions. Soil Sci Soc Am J 54:98–105.

Schulten HR, Schnitzer M (1991) Supercritical carbon dioxide extraction of long-chain aliphatics from two soils. Soil Sci Soc Am J 55:1603–1611.

Seto M, Yanagiya K (1983) Rate of CO, evolution from soil in relation to temperature and amount of dissolved organic carbon. Jpn J Ecol 33:199–205.

Sollins P, Spycher G, Glassman CA (1984) Net nitrogen mineralization from light- and heavy-fraction forest soil organic matter. Aust J Soil Res 30: 195–207.

Spiteller M (1985) Extraction of soil organic matter by supercritical fluids. Org Geochem 8:11 l-l 13.

Sposito G, Holtzclaw KM, Baham J (1976) Analytical properties of the soluble, metal complexing fractions in sludge-soil mixtures: II. Comparative structural chemistry of fulvic acid. Soil Sci Soc Am J 40:691–697.

Stevenson FJ *(1982) Humus chemistry: Genesis, compositiorz, reactions.* Wiley–Interscience, New York.

Strickland TC, Sollins P (1987) Improved method for separating light- and heavy-fraction forest soil organic matter. Soil Biol Biochem 16:3 l-37.

Tiessen H, Stewart JWB (1983) Particle size-fractions and their use in studies of soil organic matter. II. Cultivation effects on organic matter composition in size fractions. Soil Sci Soc Am J 47:509–514.

Vogt KA, Grier CC, Vogt DJ (1986) Production, turnover, and nutrient dynamics of above- and belowground detritus of world forests. In Macfadyen A, Ford ED (Eds) Advances *In ecological research.* Vol. 15. Academic Press, New York.

Walters V, Joergensen RG (1991) Microbial carbon turnover in Beech forest soils at different stages of acidification. Soil Biol Biochem 23:897–902.

Wander MM, Traina SJ, Stinner BR, Peters SE (1994) Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci Soc Am J 58:1130-l 139.

Wilson JB (1988) A review of evidence on the control of shoot:root ratio, in relation to models. Ann of Bot 6 1:433–449.