

CARBON STORAGE AND CARBON-TO-ORGANIC MATTER RELATIONSHIPS OF THREE FORESTED
ECOSYSTEMS OF THE ROCKY MOUNTAINS

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AUTHORIZATION TO SUBMIT
THESIS

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Abstract

Fluctuations in atmospheric carbon dioxide is influenced by carbon storage and cycling in terrestrial forest ecosystems. Currently, only gross estimates are available for carbon content of these ecosystems and reliable estimates are lacking for Rocky Mountain forests. To improve carbon storage estimates more information is needed on the relationship between carbon and organic matter, carbon concentrations of forest components, and how carbon storage varies among vegetation types. Therefore, this study used four different vegetation types (habitat types) to supply a portion of this information. In the Northern Rocky Mountains a subalpine fir and western hemlock were chosen, and two ponderosa pine habitat types in the Southern Rocky Mountains.

Forest soil carbon-to-organic matter (C/OM) relationships were developed for brown cubical rot, litter, humus, soil wood, and mineral soils at two depths. Currently a standard conversion factor (0.58) is used to convert organic matter (LOI) to carbon for Rocky Mountain soils. This study showed that C/OM ratios for mineral soils were much lower (0.17 to 0.44) than the traditional ratio for the four vegetation types. In addition, C/OM ratios were developed for brown cubical rot (0.51) and soil wood (0.51) which are both important soil components for sustaining western forest ecosystems.

In addition, this study also quantified carbon content and concentrations of various forest components in the four habitat types. Results indicated that most biomass occurred in the trees (> 50%). In the Southern Rocky Mountains greater than 50% of the carbon was located in tree boles and coarse roots. In contrast, for the Northern Rocky Mountain habitat types, a large portion of the carbon was located in organic soil components

and woody residue (40% to 48%). All the surface organic components in all the habitat types had carbon concentrations from 40% to 50% except for surface humus which had carbon concentrations between 20% and 40%. Mineral soil carbon concentrations were below 6% in all habitat types.

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Introduction

Forest management is changing. Future forest plans and prescriptions on public lands will likely emphasize diversity, scenic values, wildlife, water quality, sustainable ecosystems, or other attributes, rather than commodity production. Past forest practices consisted of managing individual stands of trees; today managers need to consider overall ecosystem processes and functions before developing management prescriptions (Graham 1990). To maintain those processes and functions, carbon is an essential element (Waring and Schlesinger 1985).

Organic carbon is the basic building block of all plant and animal life (Bolin and others 1979). Through photosynthesis, carbon dioxide in the atmosphere is converted to organic carbon which provides energy, nutrient storage, and plant structure. In forest ecosystems, organic carbon is stored in different locations including live and standing dead biomass, woody debris, litter, and soils. The manipulation of organic matter not only affects carbon storage but also other essential nutrients such as nitrogen, calcium, potassium, sulfur, and phosphorous (Binkley 1987; Jorgensen and Wells 1986). Recognizing the role of carbon and organic matter in the structure and function of forest ecosystems is essential for sustaining long- and short-term forest productivity.

Carbon storage and cycling in forest ecosystems also influences the global carbon cycle. Humans may increase both terrestrial carbon storage or atmospheric CO₂ amounts by manipulating forest and other terrestrial vegetation. Some actions that contribute to increasing atmospheric CO₂ include: converting forested areas to cities and towns which decreases the amount of vegetation; harvesting fuel wood (i.e., at least one-half of the Earth's population uses wood for heating and cooking); and harvesting timber with its associated activities (i.e., these activities can increase

decomposition thereby, decreasing the amount of organic carbon, and/or burning forest residues) (Aber and Melillo 1991; Graham and others 1990; Harmon and Hua 1991). In contrast, human activities can also increase carbon storage. For example, if accomplished over a wide area, fertilization of terrestrial ecosystems can increase photosynthesis thus potentially decreasing atmospheric CO₂ (Hampicke 1979). In addition, fire suppression has increased carbon storage in some forest ecosystems (Covington and Moore 1994). For instance, prior to active fire suppression, many forests burned at varying intervals with a range of intensities decreasing terrestrial carbon storage (Arno 1980; Habeck and Much 1973). But in recent history (i.e., last 70 years), fire suppression has decreased fire frequency encouraging carbon accumulation (Covington and Moore 1994). Because of these impacts on ecosystems and the subsequent affects on carbon storage and cycling, it is important that carbon storage and cycling be viewed on a global scale.

GLOBAL CARBON CYCLE

Carbon is stored and cycled in the atmosphere, ocean, and land. Oceans have the largest carbon reserves and the atmosphere has the least; the atmosphere is where carbon exchange between aquatic and terrestrial ecosystems occurs (Post and others 1990). Presently, among the three carbon storage sites, more information is available on atmospheric carbon.

Atmospheric Carbon Cycle

Originally, atmospheric carbon came from methane gas escaping from the Earth's crust. Additional carbon has entered the atmosphere by the burning of fossil fuels and human manipulation of terrestrial and oceanic ecosystems (Rotty and Marland 1986). When measurements began in 1958, total atmospheric

CO₂ content was 671 gigatons (billions of metric tons); since then, atmospheric CO₂ has increased exponentially and in 1988 content was 748 gigatons (Post and others 1990). This rapid increase in CO₂ content could potentially lead to the trapping of heat at the Earth's surface causing "global warming." This potential increase has initiated additional investigations on changes in atmospheric CO₂ concentrations.

Continuous atmospheric CO₂ measurements have indicated that concentrations are affected by biological changes occurring on land and in the oceans. It has been discovered that CO₂ concentrations in the lower atmosphere do not remain constant but change diurnally above terrestrial ecosystems (Freyer 1979). These fluctuations are caused by changes in the balance between photosynthesis, respiration, and decomposition. During daylight hours, photosynthesis is occurring. Once the sun sets, photosynthesis ceases, but respiration and decomposition continue. Consequently, higher concentrations of CO₂ exist during the night (Waring and Schlesinger 1985).

Atmospheric seasonal fluctuations are related to changes in photosynthesis during the growing season. Through the winter months, atmospheric CO₂ concentrations are stable since respiration, decomposition, and photosynthesis are low (Freyer 1979; Woodwell and others 1973). During the growing season, when plants are actively photosynthesizing, more CO₂ is used causing decreases in atmospheric CO₂. These changes in atmospheric CO₂ concentrations lag one and one-half months after changes in the growing season. As altitude increases, however, CO₂ concentrations caused by seasonal changes tend to be stabilized by air mixing (Freyer 1979; Woodwell and others 1973).

Ocean Carbon Cycling

The ocean is likely the largest carbon reservoir. Oceans contain three carbon forms: 1) dissolved inorganic carbon, bicarbonate (HCO_3), and carbonate (CO_3^{-2}) ions, 2) dissolved organic carbon, and 3) particulate organic carbon (live organisms or fragments of dead plants and animals) (Post and others 1990). Carbon dioxide exchange is controlled by the partial pressure of CO_2 both in the atmosphere and ocean. Because of these partial pressures, it has been theorized that CO_2 is released from the ocean at the middle and lower latitudes and is absorbed by the oceans at the north and south poles (Bolin and others 1979; Freyer 1979; Heimann and others 1986; Post and others 1990).

Cycling processes that influence the partial pressure of CO_2 between the atmosphere and ocean surface are: 1) physical processes which include the mixing and circulation of ocean water, 2) chemical processes which include the production and dissolution of calcium carbonate (CaCO_3) (Baes and Killough 1986; Bolin and others 1979; Wagener 1979), and 3) biological processes which includes the production and decomposition of organic matter (Bolin and others 1979; Mopper and Degens 1979; Post and others 1990).

These processes control carbon storage in the oceans. Initial estimates of total oceanic carbon content are: 37,000 gigatons of dissolved inorganic carbon, 1,000 gigatons of dissolved organic carbon, and 30 gigatons of particulate organic carbon. These are gross estimates, however, new sources of carbon are being continually located (Mopper and Degens 1979).

Terrestrial Carbon Cycle

Terrestrial ecosystems, in particular forest ecosystems, can store large amounts of carbon. The carbon cycle within terrestrial ecosystems begins with the conversion of CO_2 into live plant biomass by photosynthesis.

This is the link between the atmosphere and the biota (Ajtay and others 1979). Photosynthate and organic carbon are used for energy, plant structure, and water and nutrient storage. How plants allocate carbon depends on moisture, physiological characteristics, and nutrient availability. For example, if moisture is low, carbon is allocated to the roots for locating water reserves, or allocated to leaf structure for water interception (Kramer and Kozlowski 1979). Therefore, carbon content and allocation varies depending on factors such as vegetation, moisture, temperature, and light.

Portions of plant material are consumed and processed by animals. The remainder, after it dies, falls to the forest floor and is decomposed by microbes (invertebrates, bacteria, and fungi) within the soil. Therefore, carbon storage in terrestrial ecosystems also depends on the amount and decomposition state of the organic components. Plant decomposition depends on temperature, moisture, vegetation type, parent material, and fire activity (Aber and Melillo 1991; Bohn and others 1985; Harmon 1992; Harvey and others 1989). A portion of the carbon is returned to the atmosphere by root and microbial respiration (Aber and Melillo 1991). Not all substances are decomposed immediately. Some are stored on the Earth's surface and in soils as organic matter. In some cases, carbon from these substances are quickly released into the atmosphere by fire (Kilgore 1981).

Decomposing bacteria and microorganism populations are affected by temperature and moisture (Harmon and others 1986; Waring and Schlesinger 1985). Warm temperatures favor macro- and micro-organism populations, resulting in fast decomposition rates of organic materials. As temperature decreases, organism populations decline and species change, slowing decomposition. Microbial and decomposition response to moisture is parabolic; under extreme dry conditions lack of moisture can limit decomposition.

Similarly, when excess moisture exists, aeration is reduced, decreasing aerobic fungi that decompose organic matter (Griffin 1977; Waring and Schlesinger 1985). Of the two processes, temperature has the greatest affect on decay rate (Huntington and others 1988).

Substrate quality and subsequent decay rates depend on the type of carbon compounds present in organic biomass. Components that are high in proteins, cellulose, and hemicellulose are quickly consumed by organisms. The bonds in these simple carbon compounds take little energy to break, thus providing food at a low energy cost. Under these conditions, fungi and microorganism populations increase, immobilizing nutrients (Aber and Melillo 1991). After the simple carbon compounds are exhausted, the more complex carbon compounds such as lignin and humic substances remain. Specialized organisms need high amounts of energy to break the bonds within these compounds, therefore slowing decay rates. Mineralization (release of nutrients into the soil) occurs when microorganisms and fungi incapable of breaking these bonds die (Aber and Melillo 1991).

The size of the substrate also determines how quickly microorganisms consume carbon compounds. Piece size influences temperature and moisture. Large pieces usually contain higher moisture contents and are insulated against temperature changes. In addition, a large piece of material has more carbon and therefore takes more time to decompose than a small piece (Harmon and others 1986).

Where carbon is stored is also an important component of the terrestrial carbon cycle. For example, carbon is stored in live and standing dead plant tissue, woody debris, litter, and soil organic matter. Although a large portion of the carbon is in live biomass, a significant amount of carbon is also stored in woody residue, forest floor, and soils. The forest floor

and soils contain five organic components that contribute to carbon storage (Figure 1): 1) litter which encompasses the recognizable plant and animal materials such as conifer needles, insect frass, and deciduous leaves; 2) surface humus, which is unrecognizable, decomposed plant and animal material having a high content of complex hydrocarbons located above the mineral soil; 3) brown cubical rot which consists of woody in an advanced state of decay; 4) soil wood which consists of decaying wood incorporated within the mineral layers; and 5) mineral soil humus which is similar to surface humus except incorporated in the mineral soil (Aber and Melillo 1991; Harmon and others 1986; Harvey and others 1987; Waring and Schlesinger 1985).

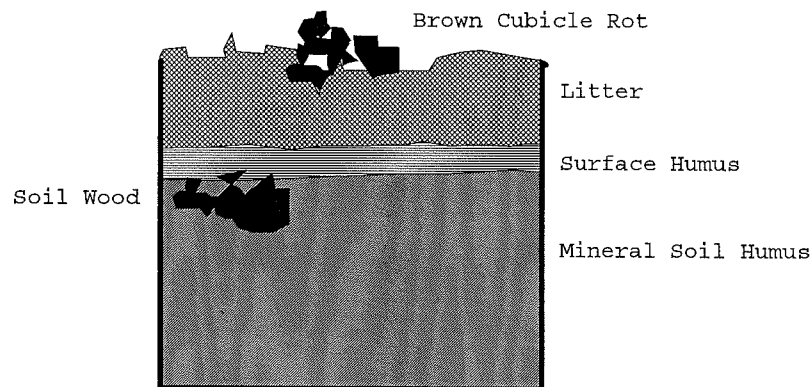


Figure 1. Five organic components located in forest soils.

The dead organic matter components of forests represent different substrate qualities, sizes, and decompositional states. On a global or local scale, the role of coarse woody debris (CWD), brown cubical rot, and soil wood in storing carbon is often overlooked because most estimates consider only living biomass, forest floor (litter and surface humus), and mineral soil carbon (Buringh 1984; Eswaran and others 1993; Franzmeier and others 1985; Huntington and others 1988; Schlesinger 1977; Post and others 1990). Forest type influences the kinds of carbon compounds present which subsequently affect decomposition rates. For example, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) decays more slowly than most conifers because the heartwood contains fungi-toxic compounds and high amounts of lignin (Scheffer and Cowling 1966). Therefore, if all other factors controlling decomposition were similar, a Douglas-fir forest may store more carbon in CWD, brown cubical rot, and soilwood than a true fir (*Abies* spp.) forest. In turn the amount of CWD affects soil wood, which is incorporated into soil mineral layers through freeze-thaw action and soil mixing (Harvey and others 1987).

Carbon is also stored in litter and surface humus in terrestrial ecosystems. The most common compounds and living organisms present in litter are cellulose, hemicellulose, lignin, macroorganisms (i.e., earthworms and ants) and microorganisms (i.e., fungi and bacteria) (Schlesinger 1977). These components, along with moisture and temperature influence litter decomposition and the accumulation of humus. Humic substances are high molecular weight compounds composed of aromatic units containing nitrogen, phenol and -COOH groups (Aber and Melillo 1991; Bohn and others 1985). Because of these complex compounds, surface humus decomposes slowly (Bohn and others 1985). For example, decomposition rates in southwestern ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws) litter are slow because of low moisture and/or

litter composition which decreases the amount of surface humus (Covington and Sackett 1984; Schlesinger 1977). In contrast, because of the higher moisture, decomposition rates of litter are faster in western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forests of the Northern Rocky Mountains resulting in greater humus accumulation (Vogt and others 1986).

Carbon concentrations in mineral soils decrease with depth (Woods 1989). Surface mineral layers have more macroorganisms and microbial activity which mixes and decomposes organic matter. The microbial biomass also contributes a substantial amount of mineral humus (approximately 10 percent) (Witkamp 1974). In addition, fine root turnover in the upper surface layers contributes a large amount of organic matter (Huntington and others 1989; Raich and Nadelhoffer 1989; Schlesinger 1977; Vogt and others 1986).

Parent material also affects carbon concentrations in mineral layers by influencing soil texture (clay content). This property contributes to the formation of organic-mineral complexes and soil aggregates (Oades 1988; Paul 1984). Soils high in clay content have the greatest amount of carbon since there are more exchange sites for organic-mineral complexes (Borchers and Perry 1992).

CARBON ESTIMATES

The global interest in estimating carbon reserves has shifted to northern forest ecosystems (Apps 1993). One reason for the sudden interest is that gross estimates of global carbon budgets have indicated that there is a missing carbon sink (Eswaran and others 1993; Post and others 1982; Post and others 1990). It has been theorized that the missing carbon sink may be located in northern forest ecosystems (Tans and others 1990). However, oceanographers feel the missing link is in the ocean (Bolin and others 1979).

The discrepancy in these two theories stems from the lack of knowledge of how much carbon is stored within these two reservoirs. Another reason northern forests are important in global cycling is the large quantities of carbon they contain. If "global warming" does occur, these forest may become carbon sources rather than carbon sinks. In addition, many of these forests are within industrialized nations where the economic and social pressures may potentially decrease the amount of forested area (Apps 1993).

Because forest ecosystems may be the carbon sink, several studies have investigated the role of forests in storing carbon. These studies have shown that there is wide variation in carbon storage among and within forest ecosystems. In forests of the Lake States, (Minnesota, Wisconsin, and Michigan) a study concluded that both stand age and forest type influence the amount of carbon stored in the forest floor (Grigal and Ohmann 1992). In Grigal and Ohmann's (1992) study, carbon continued to accumulate overtime since in these ecosystems, biomass was produced faster than it decomposed. Other research has also indicated that forest type may affect carbon storage but only if ecosystems were significantly different (Post and others 1982). In contrast, Grigal and Ohmann (1992) determined that wide variations in forest type were not necessary to notice subtle differences in carbon storage. The differences in carbon storage presented in these studies were probably related to effects forest type had on decomposition (i.e., moisture, temperature, radiation, and substrate quality).

Not only does vegetation type affect carbon storage, but its spatial arrangement may also affect carbon pools. Welch and Klemmedson (1973) compared a ponderosa pine stand to forest openings occupied by grass in the Southwest. In the ponderosa pine stand, total carbon was greater since a

large portion was in standing biomass. In contrast, carbon content in the mineral soil was higher in the grass ecosystem where most of the carbon was located below the soil surface.

Studies have also compared carbon storage in CWD between different forests (Harmon and Hua 1991; Keenan and others 1993). The results of these studies indicated that a large fraction of the terrestrial sink could be potentially located in woody debris. For example, Keenan and others (1993) reported that 60% of the forest floor in northern Vancouver Island was composed of woody material. In the Northern Rocky Mountains, up to 58% of the organic components can consist of CWD and soil wood (Harvey and others 1987).

Process models have also been used for predicting carbon pools and the movement of carbon and nutrients among pools. These estimates are usually based on processes such as photosynthesis, carbon allocation, and decomposition (Parton 1987; Sanford and others 1991; Rastetter and others 1991; Rastetter and others 1992). For example, the MBL-GEM Model (Rastetter and others 1991; Rastetter and others 1992) examines changes in fluxes and allocation of carbon and nitrogen among plant tissues and soils based on changes in atmospheric CO₂, temperature, soil moisture, irradiance, and inorganic nitrogen inputs. In order to use this type of model, the user must specify the amount of carbon and nitrogen in foliage, sapwood, heartwood, and fine roots and the total amount of carbon and nitrogen in soil humus.

Results and procedures from the types of studies described above have been used to estimate the terrestrial portion of the total global carbon pool. Post and others (1990) concluded that estimates of carbon in plants range from 420 to 830 gigatons and estimates of soil carbon range from 1,400 to 1,700 gigatons; however, they also stated that these are only gross estimates and are not very accurate. The reason for this inaccuracy is the wide variation

in vegetation type, decomposition rate, mineral soil, and how carbon is estimated in the multitude of studies reporting on carbon (Eswaran and others 1993; Hendrickson 1990; Pollard 1982; Post and others 1982; Post and others 1990; Rastetter and others 1991).

Carbon is usually estimated by converting biomass or soil organic matter weight to carbon via a conversion factor. For soils, a common method for determining organic matter is by loss-on-ignition (LOI). LOI is the ashing of mineral soil and other organic components at various temperatures and for different time periods (Ball 1964; Donkin 1991; Schnitzer 1982). Unfortunately, this method can remove bonded water from soils with high clay content, consequently overestimating organic matter concentrations. Although there are discrepancies in methodology, LOI has been documented as an effective method for determining organic matter if ashing occurs at a low temperature (375°) (Ball 1964; Donkin 1991). The standard value used to convert LOI to organic carbon is 0.58. This conversion factor was developed for agricultural soils. However, various studies have indicated that carbon-to-organic matter (LOI) ratios vary widely depending on vegetation type, parent material, and soil depth (Ball 1964; Donkin 1991; Lunt 1930; Nelson and Sommers 1982). Therefore, conversion ratios need to be developed for different vegetation and soil types. Unfortunately, in most cases, the traditional carbon-to-organic matter ratio is applied to mineral soil components. Currently, there is no conversion ratio for forest mineral soils in the Rocky Mountains. Likewise, there is no conversion ratio for the soil organic substrates (brown cubical rot, litter, surface humus, and soil wood) found in western forests.

For vegetation, plant biomass is estimated and than 50% of the biomass is assumed to be carbon (Grigal and Ohmann 1992; Hendrickson 1990; Linder and Axelsson 1982). Using this ratio assumes that all organic biomass has the same carbon concentration across different vegetation types and plant species. Although currently this is the best information available for estimating carbon, ratios would likely differ among and between vegetation types.

Since estimating carbon storage is a key element in predicting the effects of global warming and determining carbon sinks, it is important that valid conversion factors be used to minimize the amount of error these estimates may provide. **Therefore, providing these ratios and concentrations across vegetation types within the Rocky Mountains is the overall objective of this study.**

- 1) My first objective was to determine the conversion ratio between total carbon and organic matter concentrations in forest soils. The conversion ratios developed by this research will consider soil and vegetation types. The results will provide total carbon-to-organic matter ratios potentially applicable over wide areas of the Rocky Mountains.
- 2) My second objective was to determine carbon concentrations in live biomass, woody debris, litter, humus, and mineral soils and to determine where and what forest components are key in storing carbon in three forest types of the Rocky Mountains.

This information could potentially be applied to current data on biomass and organic matter for estimating carbon storage in Rocky Mountain forest ecosystems. In addition, this information could be used in process models to better describe and predict how forest ecosystems influence global carbon storage and atmospheric CO₂.

Methods

SITE SELECTION

The sites selected for the study included three climatic regimes: cool-wet, cold-dry, and warm-dry. The habitat types chosen to represent each of these regimes were selected after consultation with soil scientists, silviculturists, and forest managers. The selected habitat types are highly influenced by social and economical demands because of their relative productivity for timber production and other obtainable natural resources (Figure 2).

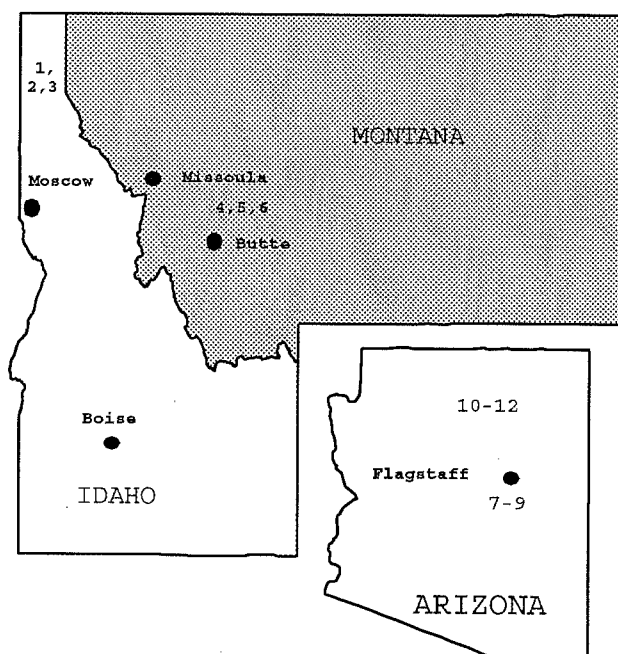


Figure 2. Map location of study sites.

The wettest and most productive site was a western hemlock/queencup beadlily (*Tsuga heterophylla*)/(Clintonia uniflora (Schult.) Kunth) (WH/CLUN) habitat type on Priest River Experimental Forest in northern Idaho. A cold-dry subalpine fir/dwarf huckleberry (*Abies lasiocarpa* (Hook.) Nutt.)/(*Vaccinium*

scoparium Leib.) (SAF/VASC) habitat type was located on the Deerlodge National Forest near Butte, Montana. Two warm-dry sites were selected in northern Arizona: a ponderosa pine/Arizona fescue (*Pinus ponderosa* Dougl. ex Laws.)/(*Festuca Arizona* Vasey) (PP/FEAR) habitat type on the Kaibab National Forest, and a ponderosa pine/gambel oak (*Quercus gambelli* Nutt.) (PP/QUGA) habitat type on the Coconino National Forest.

The WH/CLUN habitat type occurs at elevations from 760 to 1,580 m (2,500 to 5,200 ft). The site parent material is an ash cap over beltian metasedimentary rocks (Alt and Hydnmann 1989). Tree species include Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western larch (*Larix occidentalis* Nutt), western white pine (*Pinus monticola* Dougl. ex D. Don.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), grand fir (*Abies grandis* Dougl. ex D. Don) Lindl.), subalpine fir, Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), western redcedar (*Thuja plicata* Donn ex D. Don), and western hemlock. The overstory canopy of late seral stands is usually dense with a sparse herbaceous layer (Cooper and others 1991). WH/CLUN climate is characterized by dry summers with the majority of precipitation occurring during the fall and winter. Total precipitation averages between 710 to 1,520 mm (28 to 60 in), snowfall averages 262 cm (103 in). Average annual air temperature ranges from 4° to 10° C (40° to 50° F) (Graham 1990).

The SAF/VASC is one of the most abundant habitat types east of the Continental Divide in Montana. Elevations of the habitat type range from 2,130 to 2,590 m (7,000 to 8,500 ft). The parent material of the study site is volcanic (Hunt 1972). Lodgepole pine dominated the overstory with a minor component of Engelmann spruce, subalpine fir, and Douglas-fir. The understory is carpeted with dwarf huckleberry, scattered common juniper (*Juniperus communis* Pall.) and a minor component of pine grass (*Calamagrostis rubescens*

Buckl.). Precipitation ranges from 280 to 740 mm (11 to 29 in) with snowfall averaging 686 cm (270 in). Average annual air temperature ranges from -4° to 2° C (25° to 35° F) (Alexander and others 1990; Pfister and others 1977).

The PP/FEAR habitat type occurs at elevations from 2,300 to 2,500 m (7,540 to 8,200 ft) in northern Arizona. The parent material of the study site is limestone (Hunt 1972). The habitat type's overstory consists of ponderosa pine with a small amount of quaking aspen (*Populus tremuloides* Michx.). Understory vegetation includes Arizona fescue, Oregon grape (*Berberis repens* Lindl.), fendler ceanothus (*Ceanothus fendleri* A. Gray), wax gooseberry (*Ribes cereum* Lindl.), mountain muhly (*Muhlenbergia montana* Nutt.), and mutton grass (*Poa fenderliana* (Steud.) Vasey). Precipitation has a bimodal distribution with one wet season occurring July through October and another December through March. But, on the Kaibab plateau, however, greater than 50 percent of the precipitation falls between December and March. Total precipitation ranges from 520 to 600 mm (20 to 24 in) with snowfall averaging 1,120 mm (47 in). Mean annual air temperature ranges from 4° to 6° C (39° to 43° F) (Brewer and others 1991; Larson and Moir 1986).

The PP/QUGA habitat type occurs at elevations from 1,860 to 2,590 m (6,100 to 8,500 ft) with basalt parent material. The overstory consists of ponderosa pine with a minor component of gambel oak. Understory vegetation includes rose (*Rosa spp.*), skunk bush (*Rhus trilobata* Nutt.), New Mexico locust (*Robinia neomexicana* A. Gray), mutton grass, and mountain muhly. PP/QUGA climate is similar to the PP/FEAR but unlike the Kaibab Plateau, the majority of the precipitation falls during July through October (Brewer and others 1991; Larson and Moir 1986).

Prior to stand selection, forest silviculturists and soil scientists provided a list of stands within each vegetation and soil type that met the

following criteria: 1) managed and undisturbed stands in close proximity to each other with similar aspects and slopes; 2) undisturbed stands consisting of late-seral and old vegetation with no direct human activity; and 3) disturbed stands which were harvested within the last 5 to 10 years and had the remaining woody residue tractor-piled. From each list, three undisturbed and three disturbed stands were verified and selected (Table 1).

DATA COLLECTION

Forest components and data for biomass estimates were sampled using four plot types: 1) variable, 2) fixed, 3) microsite, 4) soil core and 5) line intersect (Table 2). Twelve points were systematically located on a random transect bisecting the stand. Soil component samples (Table 2) were combined to form four composites and other forest components were combined to form three composites.

A variable plot using probability proportional to size was used to sample large tree (> 12.7 cm (> 5.0 in) d.b.h.) total height and d.b.h. (diameter at 4.5 ft (1.4 m)). Sapwood, heartwood, coarse roots, and overstory crown samples were collected for carbon analysis from each tree species. Increment cores at d.b.h. were used to sample sapwood and heartwood. Coarse roots (> 1 cm diameter (> 0.5 in) were sampled 20 to 25 cm (7 to 10 in) below the soil surface on the down-hill side of the tree. A sub-sample of overstory crown (branches and needles) was collected from three trees per species. For consistency, crown samples were removed from the third highest whorl and from the north side of the tree.

Table 1. Description of selected stands.

Treatment	Habitat Type ¹	Cover Type	Age	Asp. Deg.	Slope %	Elev. M	Parent Mat. ²
Idaho Panhandle National Forest -- Priest Lake Ranger District (Priest River Experimental Forest)							
Undisturbed ³	WH/Clun	WH/DF/WL/WP	100	310	45	1280	Ash/Belt
Undisturbed	WH/Clun	WH/DF/WL/WP	100	340	45	1340	Ash/Belt
Undisturbed	WH/Clun	WH/DF/WL/WP	100	340	45	1340	Ash/Belt
Disturbed	WH/Clun	WH/DF/WL/WP	10	310	45	1300	Ash/Belt
Disturbed	WH/Clun	WH/DF/WL/WP	10	310	45	1320	Ash/Belt
Disturbed	WH/Clun	WH/DF/WL/WP	10	310	45	1320	Ash/Belt
Deerlodge National Forest -- Butte Ranger District							
Undisturbed	SAF/Vasc	LP	65	124	21	2073	Volcanic
Undisturbed	SAF/Vasc	LP	65	124	21	2073	Volcanic
Undisturbed	SAF/Vasc	LP	65	110	33	2073	Volcanic
Disturbed	SAF/Vasc	LP	8	124	21	2073	Volcanic
Disturbed	SAF/Vasc	LP	8	124	21	2073	Volcanic
Disturbed	SAF/Vasc	LP	8	110	33	2073	Volcanic
Kaibab National Forest -- North Kaibab Ranger District							
Undisturbed	PP/Fear	PP	127	0.00	0.00	2470	Limestone
Undisturbed	PP/Fear	PP	125	0.00	0.00	2470	Limestone
Undisturbed	PP/Fear	PP	123	0.00	0.00	2487	Limestone
Disturbed	PP/Fear	PP	10	0.00	0.00	2470	Limestone
Disturbed	PP/Fear	PP	10	0.00	0.00	2470	Limestone
Disturbed	PP/Fear	PP	10	0.00	0.00	2470	Limestone
Coconino National Forest -- Mormon Lake Ranger District							
Undisturbed	PP/Quga	PP	141	0.00	0.00	2134	Basalt
Undisturbed	PP/Quga	PP	150	0.00	0.00	2134	Basalt
Undisturbed	PP/Quga	PP	145	0.00	0.00	2134	Basalt
Disturbed	PP/Quga	PP	10	0.00	0.00	2134	Basalt
Disturbed	PP/Quga	PP	10	0.00	0.00	2134	Basalt
Disturbed	PP/Quga	PP	10	0.00	0.00	2134	Basalt

Table 1 continued.

¹Habitat types and species for cover types are:

In northern Idaho (Cooper and others 1991)

WH/Clun=Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)/queencup beadlelily
(*Clintonia uniflora* (Schult.) Kunth).

In western Montana (Pfister and others 1977)

SAF/Vasc=subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.)/dwarf huckleberry
(*vaccinium scoparium* Leib.).

In northern Arizona (Larson and Moir 1986)

PP/Fear=ponderosa pine (*pinus ponderosa* Dougl. ex Laws.)/Arizona fescue
(*Festuca Arizonica* Vasey).

PP/Quga=ponderosa pine/gambel oak (*Quercus gambellii* Nutt.).

²Parent materials (Alt and Hyndmann 1989; Hunt 1972).

Basalt: Black volcanic rock rich in iron, calcium, and magnesium and composed primarily of augite and plagioclase feldspar.

Volcanic (Rhyolite): Lava or shallow intrusion, fine grained, with composition equivalent to granite.

Limestone: Sedimentary rock or surface deposit of calcium carbonate.

Belt: Mildly metamorphosed, sedimentary rocks, including argillites, siltites, and quartzites, and dolomites.

Ash: Fine shreds of lava blown from Mount Mazama.

³ Undisturbed sites consisted of late seral vegetation with no direct human activity.

Disturbed sites were harvested and fuels were tractor piled within the last 5 to 10 years.

Table 2. Forest component and plot type where samples were collected.

Forest Component	Plot Type ¹				
	Variable	Fixed	Microsite	Transect	Soil Core
Trees					
Overstory Crown	X				
Sapwood (d.b.h.)	X				
Heartwood (d.b.h.)	X				
Coarse Roots > 1 cm diam.	X				
Fine Roots < 1 cm diam.					X
Understory Crown < 12.7 cm tall		X			
Understory Vegetation					
Medium Shrub 0.5-2.0 cm ²		X			
Small Shrub < 0.5 cm ²			X		
Forb and Grass			X		
Woody Residue					
Sticks < 7.5 cm diameter				X	
Solid Log > 7.5 cm diameter				X	
Rotten Log > 7.5 cm diameter				X	
Cones			X		
Organic Soil					
Brown Cubicle Rot			X		X
Litter			X		X
Humus			X		X
Soilwood			X		X
Mineral Soil					
Shallow Mineral 0-10 cm					X
Deep Mineral 10-20 cm					X

¹Plot Type.

Variable=Probability proportional to size (IPNF, Kaibab, Coconino 40 basal area factor (BAF); Deerlodge 20 BAF).

Fixed=0.0013 hectare.

Microsite= 30 cm hoop (Graham and others year).

Transect=50 feet (Brown 1974).

Soil core=10 cm by 30 cm.

²Shrub=basal diameter was used for size separation

The second plot type was a 13.5 m² (1/300 acre) circular plot. Foliage samples for carbon analysis were taken from the understory trees and, where present, from medium and tall shrubs. Number of trees, height, and d.b.h. were recorded for small trees (< 12.7 cm d.b.h. (< 5.0 in) taller than 1.4 m (4.5 ft) and basal diameter was measured on trees less than 1.4 m (4.5 ft) tall. Average basal diameter and number of stems were recorded for medium and tall shrubs.

The third plot type was a 30 cm (12 in) diameter hoop. Average basal diameter and number of stems for low shrubs were recorded. In addition, all cones and organic soil components were collected for carbon analysis (Table 2). Next to the microsite plot, a 10 cm by 30 cm (4 in by 12 in) soil core was extracted. Soil horizons were separated and depth recorded for each horizon; then the samples from each horizon were then placed in a cloth bag. Mineral soil bulk density was sampled at 0 to 10 cm (0 to 4 in) and 10 to 20 cm (4 to 8 in) depths using a 135.7 cm³ (8.4 in³) core sampler.

The fourth type of plot was a line intersect used to determine woody residue biomass (Brown 1974). Two 7.5 m (25 ft) transects were located in random directions from plot center. Woody residues were separated into stick (< 7.5 cm (< 3.0 in), solid log (> 7.5 cm (> 3.0 in), and rotten log. For carbon analysis, a sample was taken from each residue class. In disturbed stands, twelve random samples of brown cubical rot, litter, humus, soil wood, and mineral soils at two depths were collected for carbon analysis.

BIOMASS ESTIMATES

The Prognosis Model (Wykoff and others 1982) and field data were used to estimate tree biomass (Table 3 and 4). The Model provided a list which included total cubic foot volume, species, diameter, height, and number of

trees per unit area for each sample tree represented. Published regression equations in combination with this tree list provided estimates on crown, bole, bark, and coarse root weight (Baskerville 1965; Brown 1978; Feller 1992; Johnstone 1971; Kuiper and Coutts 1992; Whittaker and others 1974; Will 1966 cited in Santantonio 1977) (Table 3).

To estimate shrub biomass, Brown (1976) used basal stem diameter for different size shrubs (low, medium, and tall) and developed regression equations based on basal stem diameter. Therefore, in order to use these regression equations, I stratified shrubs into three height classes based on basal stem diameter: low (0 to 0.5 cm (0 to 0.2 in) basal stem diameter), medium (0.5 to 2.0 cm (0.2 to 0.75 in) basal stem diameter), and tall (2.0 to 5.0 cm (0.75 to 2 in) basal stem diameter) (Brown 1976) (Table 4). If grasses covered more than 10 percent of the site, their biomass was estimated using overstory basal area (Covington and Fox 1991) (Table 4). Weight estimates of sticks, solid, and rotten logs were determined using Brown's (1974) down woody debris transect methods. Cone and soil biomass were estimated directly from field sampling. Mineral soil biomass was estimated using core volume, percent coarse fragments, and bulk density. Oven-dry (60° C (140° F) for 12 hours) weight of cones, organic components, and fine roots were expanded to a per unit area basis.

Table 3. Regression equations used for estimating tree biomass. Tree components include: overstory crown weight, bole and bark weight, and coarse root weight.

Species ¹	Crown ²	Bole and Bark ³			Coarse Roots		
		Wt (lb) = Vol A + Vol B C			Log ₁₀ Wt (kg) = B Log ₁₀ DBH (cm) + Log ₁₀ A		
		A	B	C	B	Log ₁₀ A	References
PP	$\exp[0.2680+2.0740(\ln d)]$	25.0	0.24	21.8	2.445	-0.94	Will 1966 ⁴
ES	$\exp[1.0404+1.7096(\ln d)]$	21.8	0.19	30.6	2.151	-1.24	Whittaker et al. 1974
GF	$\exp[1.3094+1.6076(\ln d)]$	23.1	0.20	37.4	2.445	-1.71	Baskerville 1965 ⁴
SAF	$7.345+1.255(d^2)$	20.0	0.19	27.4	2.445	-1.71	Baskerville 1965
					Log ₁₀ Wt (lb) = B Log ₁₀ DBH ² (HT) (in ³ ft) + Log ₁₀ A		
WWP	$\exp[0.7276+1.5497(\ln d)]$	23.7	0.21	26.2	1.022	1.879	Johnstone 1971
WL	$\exp[0.4373+1.6786(\ln d)]$	32.4	0.24	24.3	1.022	1.879	
LP	$\exp[0.1224+1.8820(\ln d)]$	25.6	0.11	26.5	1.022	1.879	
					Wt (kg) = A (DBH) (cm)		
					B	A	Kuiper and Coutts 1992
DF < 17"	$\exp[1.368+1.5819(\ln d)]$	30.0	0.19	27.4	2.630	0.01	
DF > 17"	$1.0237(d^2) - 20.74$				ln Wt (kg) = B + A ln (DBH) (cm)		
WH	$\exp[0.7218+1.7502(\ln d)]$	28.1	0.19	31.2	-4.159	2.519	Feller 1990
WRC	$\exp[0.8815+1.6389(\ln d)]$	20.0	0.15	23.1	-4.159	2.519	

¹Tree species are WWP-western white pine (*Pinus monticola* Dougl. ex D. Don); WL-western larch (*Larix occidentalis* Nutt.); DF-Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco); GF-grand fir (*Abies grandis* Dougl. ex D. Don); WH-western hemlock (*Tsuga heterophylla* (Raf.) Sarg.); WRC-western red cedar (*Thuja plicata* Donn ex D. Don); ES-Engelmann spruce (*Picea engelmannii* Parry ex Engelm.); SAF-subalpine fir (*Abies grandis* Dougl. ex D. Don) Lindl.; LP-lodgepole pine (*Pinus contorta* Dougl. ex Loud.); PP-ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.).

²Brown 1978 - ln d=natural log diameter in inches.

³Vol=CuFt Volume; A=specific gravity of wood; B=% bark; C=specific gravity of bark.

⁴Cited in Santantonio and others 1977.

Table 4. Regression Equations used to estimate forb, grass, shrub, and tree crown weight for trees less than 5 cm (2 in).

Species ¹	Crown weight		Reference
DF	$\exp [-4.212 + 2.7168 (\ln h)]^2$		Brown 1978
LP	$\exp [0.0311 (h^2)]$		
WH	$\exp [-5.126 + 2.5639 (\ln h)]$		
GF	$0.0538 (h^2)$		
WRC	$0.0307 (h^2)$		
PP	$\exp [-2.7297 + 1.1707 (\ln h)]$		
Shrubs, Forbs and Grasses			
Species	$\ln Wt(g) = A + B \ln \text{ basal stem diameter (cm)}$		Brown 1976
	A	B	
Vaccinium Scoparium	3.113	2.148	
Juniperus communis	4.081	2.202	
Combined low shrub	3.565	3.565	
Forbs and Grasses	$\ln WT(kg/ha) = 2.517 - 0.294 \cdot (10^{-1}) \text{ Basal Area}(m^2/ha)$		Covington & Fox 1991

¹ Refer to Table 3 for species.

² $\ln h$ = natural log(total height in feet).

LABORATORY ANALYSIS

To estimate carbon-to-organic matter ratios, I conducted loss-on-ignition (LOI) (Ball 1964) and organic carbon analyses on soil components for the disturbed and undisturbed stands (Table 2). Carbon concentration was estimated for the tree, shrub, forb, grass, and woody residue samples (Table 2).

Field collections were returned to the laboratory located at the Intermountain Research Station, Moscow, Idaho, and prepared for carbon and organic matter analysis. Soils were oven-dried and sieved using screens with 2 mm openings. Roots were removed from the soils and coarse fragments greater than 2 mm diameter were weighed. The twelve samples from the litter, humus, brown cubical rot, soil wood, and mineral soils were each combined into four composites for each stand. The other forest components were oven-dried, ground, and combined into three samples per stand. Prior to conducting any laboratory analyses, mineral soils were tested for carbonates using 10% hydrochloric acid (Soil Survey Staff 1992).

The LECO Carbon, Hydrogen, Nitrogen (CHN-600) Autoanalyzer was used to determine organic carbon of soil and forest components. In this process a weighed and encapsulated sample is burned in a 950° C (1,742° F) resistance furnace. Combustion products are carbon dioxide, water vapor, elemental nitrogen, sulfur oxides, and nitrogen oxides. Carbon dioxide and water are constantly measured by infrared detectors. The measurements are weight compensated and displayed as percents.

Organic matter concentrations for soil components were determined using LOI methods. Each sample was weighed and placed into a muffle furnace at a temperature of 375° C (842° F) for 16 hours (Ball 1964). Samples were removed from the furnace and re-weighed, and organic matter concentrations were calculated from weight differences.

STATISTICAL ANALYSIS

Analysis of variance for a randomized complete block design was the primary analytical technique used in analyzing the data. Within each habitat type, a variety of data were collected from three individual randomly selected stands. These stands within each habitat type were used as replications in the analysis of variance (Steele and Torrie 1960). Mean values for each variable were computed for the stand prior to conducting the analysis. Therefore, the four habitat types served as the main affects in three replications (stands). For comparing characteristics between undisturbed and disturbed stands, a randomized complete block design was also used; the main affects were disturbance and the replications were the stands. Scheffe's multiple range test was used to separate main affect means when more than two means were compared. Carbon proportional data were transformed using the square root of the arcsin prior to performing the analysis of variance.

Regression analyses were used to describe the relationship between carbon and organic matter. First, a simple linear regression where the data determined the Y-intercept was used. To make the results of this study comparable to others that used simple ratios, a second regression analysis was conducted forcing the Y-intercept through zero, with full awareness that the statistics produced by this procedure would be biased.

Results

CARBON-TO-ORGANIC MATTER RELATIONSHIPS

Mineral soils tested using hydrochloric acid indicated no carbonates were present; therefore, all results are assumed to be organic carbon (Soil Survey Staff 1992). Carbon-to-organic matter (C/OM) ratios in both undisturbed and disturbed sites ranged from 0.43 to 0.56 in the organic soil components (brown cubical rot, litter, humus, and soil wood) while, the ratios in mineral soils on the same sites ranged from 0.13 in the SAF/VASC to 0.52 in the PP/FEAR habitat type (Table 5). These ratios were compared using an

Table 5. Carbon-to-organic matter ratios by soil components and habitat type for undisturbed and disturbed sites.

SOIL	Habitat Types ¹							
	PP/FEAR		PP/QUGA		WH/CLUN		SAF/VASC	
	Undist. ²	Dist.	Undist.	Dist.	Undist.	Dist.	Undist.	Dist.
Brown Cubicle Rot	x ³ 0.45	x 0.52	x 0.49	x 0.51	x 0.50	x 0.49	x 0.51	x 0.51
Litter	x 0.56	x 0.51	x 0.46	x 0.47	x 0.53	x 0.46	x 0.51	x 0.53
Humus	--	--	--	--	x 0.46	x 0.45	x 0.47	x 0.50
Soil Wood	x 0.51	x 0.51	x 0.43	x 0.49	x 0.52	x 0.49	x 0.51	x 0.52
Shallow Mineral 0-10 cm	x 0.52	x 0.42	x 0.26	x 0.26	x 0.25	x 0.23	x 0.20	x 0.21
Deep Mineral 10-20 cm	x 0.29	x 0.43	x 0.20	x 0.34	x 0.19	x 0.15	x 0.13	x 0.17

¹ Refer to Table 1 for habitat type designation.

² Undist.=undisturbed sites consisting of late-seral vegetation with no direct human activity.
Dist.=disturbed sites were harvested and fuels tractor piled within the last 10 years.

³ Comparisons between within habitat types are X, Y, and Z.

analysis of variance between undisturbed and disturbed sites for each soil component within each habitat type. The results from this analysis showed there were no significant ($p < .05$) differences in C/OM ratios within soil

components between the undisturbed and disturbed sites (Table 5). Because there were no significant differences, I combined the data for each soil component from both sites within each habitat type.

The ratios were then compared among habitat types within each soil component. No significant differences in C/OM ratios occurred in the litter, soil wood, and brown cubical rot among habitat types (Table 6). The C/OM ratios for surface humus and shallow mineral soil in the PP/FEAR were significantly higher (> 0.45) than the ratios in the other habitat types. Similarly, the C/OM ratio for deep mineral soil for the PP/FEAR was significantly greater (0.36) than the ratio for SAF/VASC (0.15) (Table 6).

Table 6. Carbon-to-organic matter ratios by soil component and habitat type.

Soil	Habitat Type ¹							
	PP/FEAR		PP/QUGA		WH/CLUN		SAF/VASC	
	Ratio	S.E. ²	Ratio	S.E.	Ratio	S.E.	Ratio	S.E.
Brown Cubicle Rot	x ³ 0.49	0.02	x 0.50	0.01	x 0.49	0.01	x 0.51	0.01
Litter	x 0.53	0.01	x 0.46	0.02	x 0.50	0.02	x 0.52	0.01
Humus	x 0.58	0.02	y 0.46	0.02	y 0.45	0.01	y 0.48	0.01
Soil Wood	x 0.51	0.01	x 0.46	0.04	x 0.50	0.01	x 0.51	0.01
Shallow Mineral 0-10 cm	x 0.47	0.03	y 0.26	0.02	y 0.24	0.01	y 0.20	0.02
Deep Mineral 10-20 cm	x 0.36	0.03	xy 0.23	0.04	xy 0.17	0.01	y 0.15	0.01

¹ Refer to Table 1 for habitat type designation.

³ Comparisons between within habitat types are X,Y, and Z.

² Standard error of the mean.

Using the above comparisons among habitat types, data having no significant differences were combined within each soil component. For example, brown cubical rot, litter, and soil wood data from all habitat types were combined by soil components. The surface humus, shallow and deep mineral

soil data for the SAF/VASC, WH/CLUN, and PP/QUGA habitat types were also combined. The PP/FEAR habitat type humus, shallow and deep mineral soil data were analyzed separately.

Equations for predicting carbon as a function of organic matter (determined by LOI) were developed using regression analysis (Table 7). This analysis showed a highly significant relationship ($p = 0.0001$) between carbon and organic matter for all soil components within the combined habitat types. The amount of variation in carbon explained by organic matter ranged from 46% for brown cubical rot to 78% for humus and soil wood (as indicated by the R-squares) (Table 7).

Table 7. Regression equations predicting carbon as a function of organic matter.

Combined Habitat Types ¹						
Soil	Sign.	R ²	A ⁴	S.E.	B	S.E.
Brown Cubicle Rot	0.0001	0.455	9.748	4.4	0.404534	0.05
Litter	0.0001	0.713	4.548	2.4	0.445316	0.03
Humus	0.0001	0.783	-1.002	2.0	0.484225	0.03
Soil Wood	0.0001	0.780	4.372	2.2	0.46301	0.03
Shallow Mineral	0.0001	0.633	0.111	0.3	0.238639	0.02
Deep Mineral	0.0001	0.638	0.277	0.2	0.156775	0.01
PP/FEAR ²						
Humus	0.0005	0.714	6.517	5.9	0.465882	0.09
Shallow Mineral	0.0001	0.755	-0.359	0.7	0.4751	0.06
Deep Mineral	0.0001	0.630	-0.340	0.5	0.406839	0.07

¹ Combined habitat types - Regressions were developed using pooled data from the WH/CLUN, SAF/VASC and PP/QUGA habitat types for humus and soils. Data were pooled from all habitat types for brown cubicle rot, soil wood, and litter regressions.

² PP/FEAR - Separate regression were conducted for the humus and mineral soils for the PP/FEAR habitat type.

⁴A and B are coefficients for regression equation (Carbon concentration = A+B(Organic matter concentration))

As noted earlier, the uniqueness of the PP/FEAR habitat type (Table 6), necessitated developing different regression equations for surface humus and mineral soil components. These relationships were also highly significant (p

< 0.0005); with the amount of variation in carbon explained by organic matter in mineral and surface humus soils exceeded 70% and deep mineral soils exceeded 60%.

Relationships between C/OM ratios when displayed fit the data well (Figures 3 and 4). Most soil components had data points dispersed along the regression lines, except soil wood and brown cubical rot where data points were clustered. Although the PP/FEAR habitat type had fewer data points available for the surface humus and mineral soils, the data showed a strong relationship between carbon and organic matter (Figures 4a, 4b, and 4c). The slopes for the regression equations for mineral soils produced in this study were lower than the traditional slope of 0.58 (Nelson and Sommers 1982) (Figures 3e, 3f, 4b, and 4c).

To compare the results of this study to other studies that used simple ratios, a second regression analysis was conducted forcing the Y-intercept through zero (Table 8). The results of this analysis improved the amount of variation in carbon explained by organic matter. For example, using this technique, the R-square for brown cubical rot increased from 0.455 to 0.997. This improvement in the R-square was because most of the data points were clustered (Figure 3a). Therefore, the analysis without the Y-intercept overestimated the amount of variation in carbon explained by organic matter.

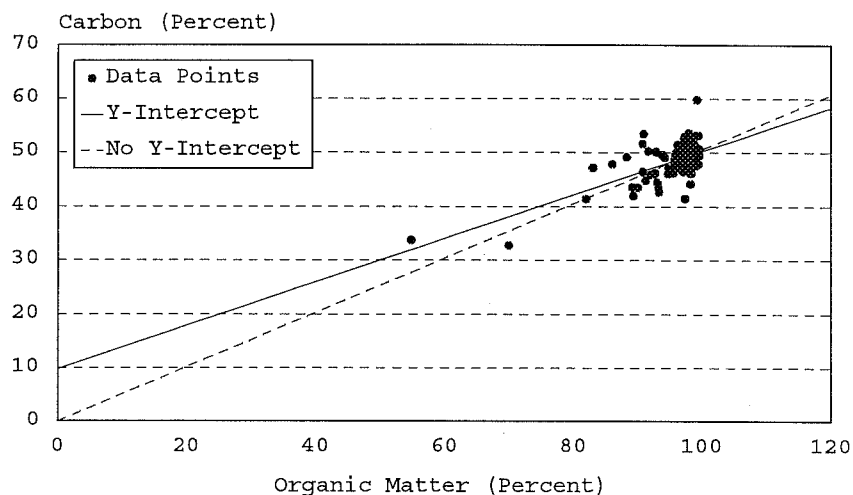


Figure 3a. Relationship between carbon and organic matter for combined habitat types for brown cubical rot showing regression with Y-intercept and regression without an intercept.

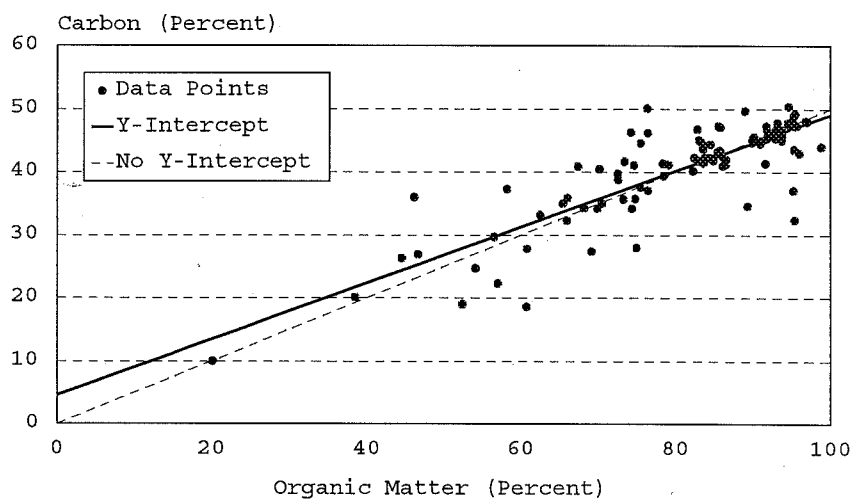


Figure 3b. Relationship between carbon and organic matter for combined habitat types for litter showing regression with Y-intercept and regression without an intercept.

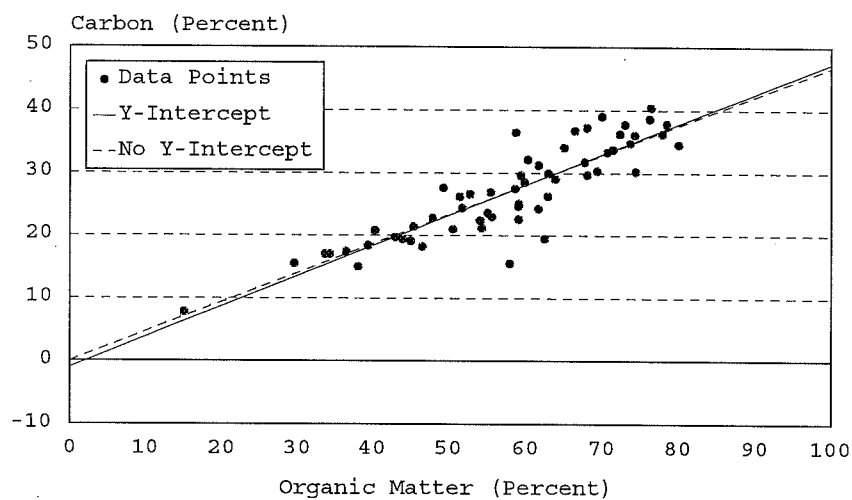


Figure 3c. Relationship between carbon and organic matter for combined habitat types for humus showing regression with Y-intercept and regression without an intercept.

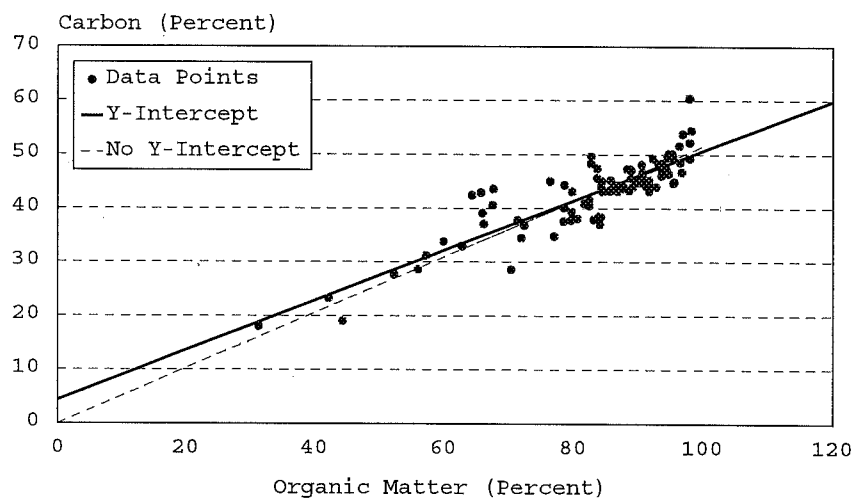


Figure 3d. Relationship between carbon and organic matter for combined habitat types for soil wood showing regression with Y-intercept and regression without an intercept.

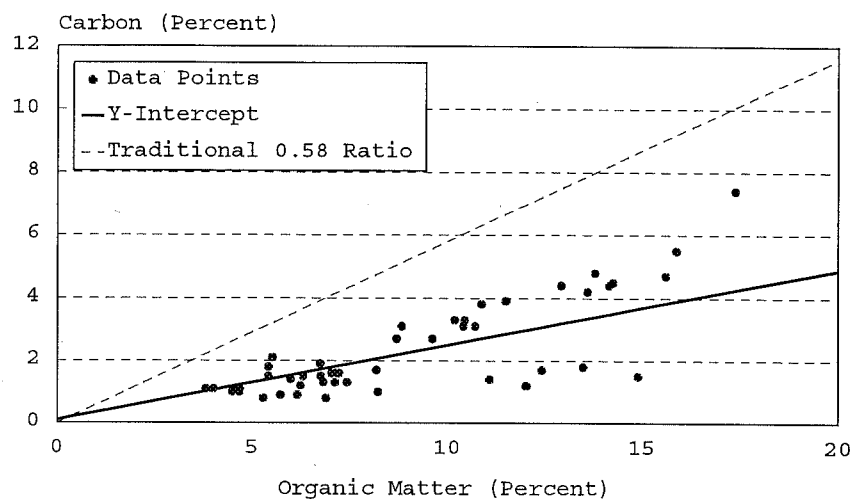


Figure 3e. Relationship between carbon and organic matter for combined habitat types for shallow mineral soil showing regression with Y-intercept and traditional 0.58 ratio (Nelson and Sommers 1982).

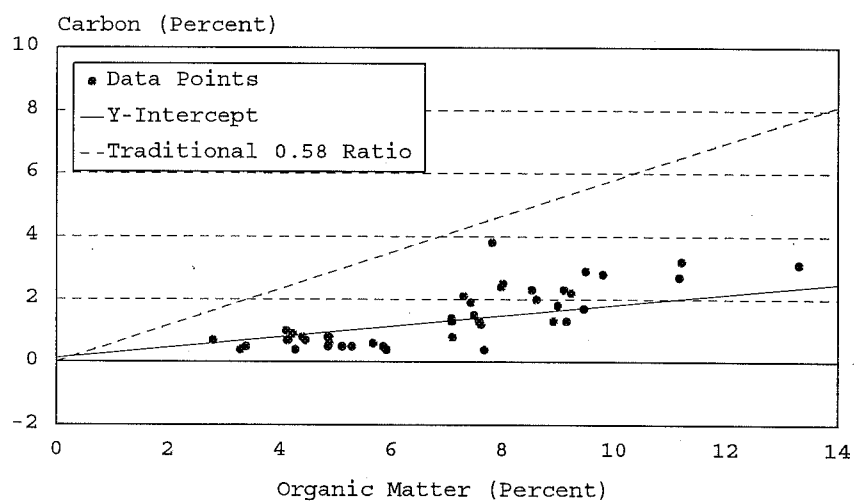


Figure 3f. Relationship between carbon and organic matter for combined habitat types for deep mineral soil showing regression with Y-intercept and traditional 0.58 ratio (Nelson and Sommers 1982).

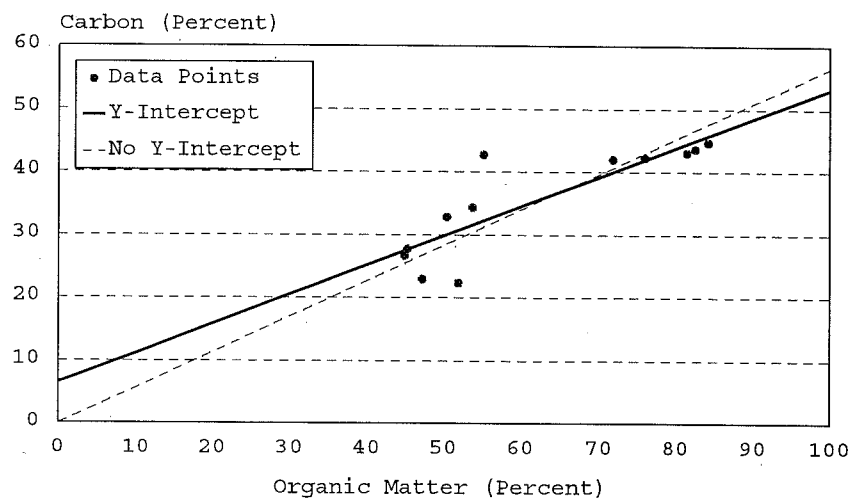


Figure 4a. Relationship between carbon and organic matter for PP/FEAR habitat type for humus showing regression with Y-intercept and regression without an intercept.

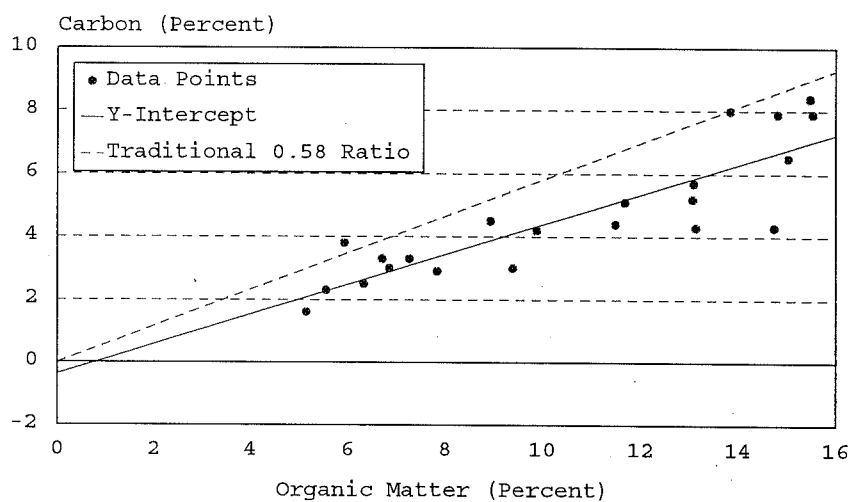


Figure 4b. Relationship between carbon and organic matter for PP/FEAR habitat type for shallow mineral soil showing regression with Y-intercept and traditional 0.58 ratio (Nelson and Sommers 1982).

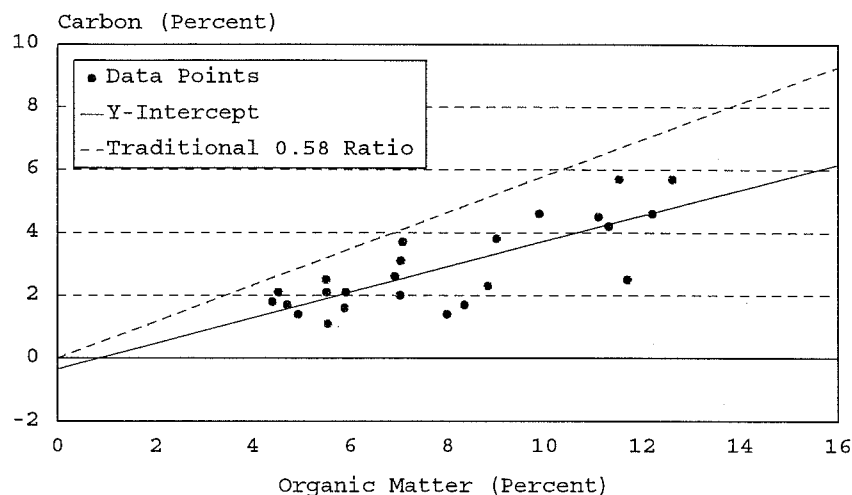


Figure 4c. Relationship between carbon and organic matter for PP/FEAR habitat type for deep mineral soil showing regression with Y-intercept and traditional 0.58 ratio (Nelson and Sommers 1982).

Table 8. Regression Coefficient predicting carbon as a function of organic matter using no Y-intercept.

Combined Habitat types ¹				
Soil	Significance	R ²	A ⁴	SE ³
Brown Cubicle Rot	0.0001	0.9967	0.506358	0.003
Litter	0.0001	0.9886	0.500214	0.006
Humus	0.0001	0.9842	0.467789	0.008
Soil Wood	0.0001	0.9938	0.514447	0.004
Shallow Mineral	0.0001	0.9066	0.246028	0.009
Deep Mineral	0.0001	0.8969	0.175837	0.007
PP/FEAR ²				
Humus	0.0001	0.9833	0.565066	0.022
Shallow Mineral	0.0001	0.9625	0.444486	0.019
Deep Mineral	0.0001	0.9311	0.368033	0.020

¹ Combined habitat types - Regressions were developed using pooled data from the WH/CLUN, SAF/VASC and PP/QUGA habitat types for humus and soils. Data were pooled from all habitat types for brown cubicle rot, soil wood, and litter regressions.

² PP/FEAR - Separate regression were conducted for the humus and mineral soils for the PP/FEAR habitat type.

³ Standard error of the mean.

⁴ Coefficient for regression equation (carbon concentration=A*organic matter concentration)

Most management activities manipulate a combination of forest components, not just individual parts such as litter or tree crowns. Therefore, I categorized individual forest components (Table 9). Tree components included overstory crown, bole, understory trees, coarse and fine woody roots. Understory vegetation included medium and low shrubs, forbs, and grasses. Woody residue included sticks (< 7.5 cm (2.9 in)), cones, and solid and rotten logs (> 7.5 cm (2.9 in)). Organic soils included brown cubical rot, litter, humus, and soil wood. Finally the last category included two mineral soils, shallow mineral (0 to 10 cm (0 to 4 in) below the forest floor), and deep mineral (10 to 30 cm (4 to 11 in) below the forest floor). In each category, I compared carbon concentrations and carbon content among and within habitat types.

Organic Biomass

Within habitat types there were significant ($p < 0.05$) differences among tree components (Table 9). The highest amount of biomass occurred in tree boles (> 400 Mg/ha (186 ton/ac)) and the least amount occurred in fine roots (< 0.5 Mg/ha (0.2 ton/ac)). Coarse roots contributed the second largest amount of biomass in all habitat types. Only in the ponderosa pine habitat types was the coarse root biomass significantly greater than the fine woody roots and overstory crown. In the western hemlock habitat type the overstory crown and coarse root biomass were significantly greater (> 50 Mg/ha (> 23 ton/ac)) than the understory trees and fine woody root biomass.

Table 9. Forest component biomass estimates (Mg/ha) by forest habitat type.

Forest Component	Habitat Type ¹							
	PP/FEAR		PP/QUGA		WH/CLUN		SAF/VASC	
	Mg/ha	SE ²	Mg/ha	SE	Mg/ha	SE	Mg/ha	SE
Trees								
Overstory Crown	x ³ 98.9c	7.0	x 113.4c	9.6	y 50.5bc	2.8	y 31.1b	3.8
Bole	x 414.9a	16.2	xy 387.7a	45.5	yz 267.9a	21.3	z 160.1a	30.8
Coarse Roots (> 1 cm diameter)	x 215.4b	10.4	x 251.7b	21.5	y 83.8b	10.6	y 68.1b	12.6
Fine Roots (< 1 cm diameter)	x 0.1d	0.1	x 0.3d	0.1	x 8.7c	1.9	x 4.8b	3.9
Understory Trees (< 12.7 tale)	x 1.1d	0.6	x 1.0d	0.5	x 0.3c	0.2	x 1.1b	0.2
Total	730.4	33.2	754.1	73.9	411.3	31.3	265.3	43.1
Understory Vegetation								
Medium Shrub (0.5-2.0 cm)	--	--	--	--	--	--	9.2b	3.5
Low Shrub (< 0.5 cm)	--	--	y 0.1a	0.1	--	--	x 31.5a	5.1
Herbage	x 0.1	0.01	x 0.3a	0.2	--	--	--	--
Total	0.1	0.01	0.4	0.2	--	--	40.7	4.7
Woody Residue								
Sticks (< 7.5 cm diam.)	z 2.3a	0.5	y 5.1b	0.7	x 11.1b	0.3	yz 2.9a	0.4
Solid Log (> 7.5 cm diam.)	y 4.0a	3.0	y 0.1b	0.1	x 42.2a	10.2	y 1.4a	0.9
Rotten log (> 7.5 cm diam.)	y 1.9a	1.0	y 4.0b	0.6	x 47.1a	6.2	y 8.4a	3.4
Cones	x 23.3a	7.8	x 26.6a	6.5	x 8.8b	1.7	x 7.1a	2.9
Total	31.4	8.8	35.9	7.1	109.0	14.4	19.9	3.0
Organic Soil								
Brown Cubicle Rot	x 0.4b	0.2	x 3.2b	1.3	x 3.4a	3.4	x 9.7b	5.0
Litter	x 32.5ab	5.5	x 62.9a	4.0	x 32.9a	16.4	x 39.9ab	11.4
Humus	x 65.3a	14.4	x 86.6a	8.4	x 127.4a	28.9	x 97.9a	21.5
Soilwood	x 0.7b	0.4	x 17.8b	8.2	x 103.2a	64.7	x 35.8ab	17.5
Total	98.9	19.9	170.5	12.9	266.8	58.1	183.4	43.9
Mineral Soil								
Shallow Mineral (0-10 cm)	x 1197.8b	15.5	x 1170.3b	51.6	z 511.8b	48.2	y 756.4b	41.2
Deep Mineral (10-20 cm)	x 2992.1a	17.5	x 2757.4a	45.2	y 1306.3a	120.8	y 1636.7a	19.9

¹Refer to Table 1 for habitat type designation.²Standard error of the mean.³Comparisons among habitat types are X,Y, and Z and among forest components within each forest category are a, b, and c.

Among habitat types, the biomass in the PP/FEAR tree boles was greater (> 350 Mg/ha (> 126 ton/ac) (Table 9). Coarse root biomass was significantly greater (> 215 Mg/ha (> 100 ton/ac) in the PP/FEAR and PP/QUGA habitat types than the coarse root biomass in the WH/CLUN and SAF/VASC habitat types (< 85 Mg/ha (< 40 ton/ac). A similar relationship occurred in the overstory crown among habitat types. The overstory biomass was greater (> 95 Mg/ha (> 44 ton/ac) in the PP/FEAR and PP/QUGA habitat types than in the overstory biomass of the WH/CLUN and SAF/VASC (< 50 Mg/ha (< 23 ton/ac) habitat types. Fine woody root biomass tended to be greater in the Northern Rocky Mountain habitat types than in the southwest ponderosa pine habitat types.

The tree components included several tree species (Table 9a). In the WH/CLUN habitat type, eight tree species contributed to total tree biomass. The majority consisted of western redcedar (134.5 Mg/ha (62 ton/ac) and western hemlock (129.1 Mg/ha (60 ton/ac) with a minor component of western white pine (17.5 Mg/ha (8 ton/ac) and subalpine fir (4.7 Mg/ha (2 ton/ac). In contrast, the biomass in the ponderosa pine habitat types (PP/FEAR and PP/QUGA) consisted exclusively of ponderosa pine and the biomass in the SAF/VASC habitat type consisted of lodgepole pine.

In three of the four habitat types understory vegetation did not contribute large amounts of biomass (Table 9). Only in the SAF/VASC were the shrubs a major component of the biomass (31.5 Mg/ha (15 ton/ac). The PP/QUGA only had 0.1 Mg/ha (0.05 ton/ac) of understory vegetation while the WH/CLUN had no understory vegetation.

Woody residue in solid and rotten logs contributed a large portion of the biomass in the WH/CLUN habitat type (Table 9). The biomass of these components was significantly greater (> 40 Mg/ha (< 19 ton/ac) than the biomass of the other woody residue components (< 12 Mg/ha (< 6 ton/ac).

Table 9a. Total biomass by tree species, forest components and habitat type.

Species ¹	Forest Components								
	Overstory Crown		Bole		Coarse Roots		Understory Tree		Total
	Mg/ha	SE ²	Mg/ha	SE	Mg/ha	SE	Mg/ha	SE	Mg/ha
WWP	1.0	0.6	12.6	6.3	3.9	2.0	0.0	0.0	17.5
WL	1.4	1.2	15.1	11.8	4.8	3.9	0.0	0.0	21.3
DF	6.2	2.4	39.5	14.3	10.6	3.4	0.0	0.0	56.3
GF	2.2	1.1	12.0	7.2	2.9	1.8	0.03	0.02	17.1
WH	16.2	3.5	91.0	30.4	21.8	6.6	0.1	0.1	129.1
WRC	18.7	3.3	81.0	20.6	34.6	10.2	0.2	0.1	134.5
ES	3.9	3.0	13.9	10.4	4.2	3.2	0.0	0.0	21.9
SAF	0.9	0.9	2.9	2.9	0.9	0.9	0.0	0.0	4.7
Total WH/CLUN	50.5	2.8	267.9	21.3	83.8	10.6	0.3	0.2	402.4
LP SAF/VASC	31.1	3.8	160.1	30.8	68.1	12.6	1.1	0.2	260.4
PP PP/FEAR	98.9	7.0	414.9	16.2	215.4	10.4	1.1	0.6	730.3
PP PP/QUGA	113.4	9.6	387.7	45.5	251.7	21.5	1.0	0.5	753.8

¹ Refer to Table 3 for tree species designation.

² Standard error of the mean.

Rotten logs were also an important component of woody residue in the SAF/VASC habitat type (8.4 Mg/ha (3.7 ton/ac)). Cones significantly contributed (7.1 Mg/ha (3.2 ton/ac)) to the biomass in this habitat type. Similarly, in the ponderosa pine habitat and PP/QUGA types, cone biomass tended to be greater than the other woody residue (26.6 Mg/ha (12 ton/ac)).

Among habitat types, there were significant differences in biomass among woody debris classes (Table 9). For example, solid and rotten logs contributed most of the woody residue biomass for the WH/CLUN habitat type, while cones played a major role in the woody residue biomass for the PP/QUGA habitat type. The greatest differences occurred in sticks. The WH/CLUN habitat type contained 11 Mg/ha (5 ton/ac), followed by the PP/QUGA habitat

type (5.1 Mg/ha (2.3 ton/ac), and SAF/VASC habitat type (2.9 Mg/ha (1.3 ton/ac). The PP/FEAR habitat type had the least woody residue in sticks (2.3 Mg/ha (1.0 ton/ac).

Of the organic soil components, surface humus tended to contribute more to the soil biomass than litter, soil wood, or brown cubical rot (Table 9). In the PP/FEAR habitat type, surface humus biomass was significantly greater than the biomass in the other organic soil components. Soil wood tended to contribute the highest amounts of organic material in the WH/CLUN habitat type and the lowest amounts in the PP/FEAR habitat type.

Trees contributed the highest total biomass among forest stratifications in all habitat types (Table 9b). Tree biomass in the ponderosa pine habitat types exceeded the biomass in the WH/CLUN and SAF/VASC habitat types. Understory vegetation tended to contribute the lowest biomass for all habitat types with the largest amount occurring in the SAF/VASC habitat type. Although there were no significant differences, organic soils tended to contribute the most biomass in the WH/CLUN and the least amount in the PP/FEAR habitat type. The greatest total biomass was in the ponderosa pine habitat types and WH/CLUN.

Table 9b. Total biomass (Mg/ha) by forest component and habitat types.

Forest Components	Habitat Types ¹							
	PP/FEAR		PP/QUGA		WH/CLUN		SAF/VASC	
	Mg/ha	SE ²	Mg/ha	SE	Mg/ha	SE	Mg/ha	SE
Trees	x ³ 730.4a	33.2	x 754.1a	73.9	y 411.3a	31.3	y 265.3a	43.1
Understory Vegetation	y 0.1b	0.01	y 0.4b	0.2	--	--	x 40.7b	4.7
Woody Residue	y 31.4b	8.8	y 35.9b	7.1	x 109.0b	14.4	y 19.9b	3.0
Organic Soils	x 98.9b	19.9	x 170.5b	12.9	x 266.8ab	58.1	x 183.4ab	43.9
Total ³	x 860.9	27.9	x 961.0	85.4	xy 787.0	36.6	y 509.3	3.1

¹Refer to Table 1 habitat type designation.²Standard error of the mean.³Comparisons among habitat types are x,y, and z and among forest components within each forest category are a,b, and c.

CARBON CONCENTRATIONS

Comparisons were conducted on carbon concentrations among forest groups (Table 10). In the tree strata, carbon concentrations ranged from 44% to 50% by weight. In all habitat types, carbon concentrations in fine and coarse roots were lower (44% to 47%) than the concentrations in overstory crown, bole, and understory trees (47% to 50%). Among habitat types, the only significant differences occurred in the understory trees, where WH/CLUN (47%) had a significantly lower carbon concentration than the understory trees in both the ponderosa pine (50%) and SAF/VASC (49%) habitat types.

Table 10. Forest component carbon concentrations by habitat type.

Forest Component	Habitat Type ¹							
	PP/FEAR		PP/QUGA		WH/CLUN		SAF/VASC	
	%	SE ²	%	SE	%	SE	%	SE
Trees								
Overstory Crown	x ³ 49.9a	0.2	x 49.9a	0.2	x 49.2a	0.2	x 49.4a	0.1
Bole	xy 49.0a	0.4	x 49.5a	0.2	yz 47.3a	0.2	z 47.2b	0.4
Coarse Roots (> 1 cm diam.)	x 47.2ab	0.7	x 48.6a	0.6	x 46.8a	0.3	x 47.1b	0.3
Fine Roots (< 1 cm diam.)	x 44.0b	1.2	x 46.2b	0.4	x 46.1a	0.4	x 44.9c	0.4
Understory Trees (< 12.7 cm dbh)	x 49.9a	0.03	x 49.8a	0.1	y 47.3a	0.2	x 49.1ab	0.2
Understory Vegetation								
Med. Shrub (0-2 cm basal diam.)	--	--	--	--	--	--	48.3a	0.2
Low Shrub (< 0.5 cm basal diam.)	x 47.1a	0.6	x 46.7a	0.5	x 45.8a	0.5	x 47.8a	0.2
Forb	x 42.7b	0.4	x 41.5b	0.6	x 41.6b	1.3	x 42.0b	0.4
Woody Residue								
Sticks (< 7.5 cm diam.)	x 49.1ab	0.3	x 49.0a	0.1	y 46.9a	0.3	y 47.6ab	0.2
Solid Log (> 7.5 cm diam.)	x 50.5a	1.5	x 49.5a	1.2	x 47.0a	0.2	x 46.0bc	0.1
Rotten Log (> 7.5 cm diam.)	x 46.3ab	0.9	x 50.8a	1.6	x 47.9a	0.7	x 48.9a	0.8
Cones	x 48.6ab	0.6	x 48.7a	0.4	y 46.0a	0.2	xy 46.5abc	0.3
Soil								
Brown Cubical Rot	x 48.2a	0.9	x 47.1a	1.5	x 48.1a	0.9	x 49.0a	0.7
Litter	x 41.3ab	1.5	x 32.7ab	3.4	x 34.0b	2.6	x 43.6ab	1.2
Humus	x 36.2b	3.6	xy 29.1b	4.4	y 21.9c	2.0	xy 26.8c	1.9
Soil Wood	x 47.2a	2.4	x 44.6ab	3.0	x 42.9ab	0.9	x 41.6b	1.0
Shallow Mineral (0-10 cm)	x 6.1c	0.5	x 4.5c	0.6	x 4.4d	0.6	y 1.4d	0.1
Deep Mineral (10-20 cm)	yz 1.9c	0.5	xy 2.5c	0.6	x 3.5d	0.3	z 0.7d	0.04

¹Refer to Table 1 for habitat type designation.²Standard error of the mean.³Comparisons of statistical significance among habitat types are X, Y, and Z and among forest components within each forest category are a, b, and c.

Ten different tree species contributed to the carbon concentrations for the tree components (Table 10). Therefore, I conducted comparisons on tree components to detect if any differences in carbon concentrations existed within and among tree species (Table 10a). For the overstory crowns, there were significant differences among species. For example, subalpine fir crowns had a higher carbon concentration (51%) than the other species while Engelmann spruce crowns had the lowest concentration (48%).

Table 10a. Carbon Concentrations by species and forest components.

Species ¹	Overstory Crown		Bole Wood				Coarse Roots		Understory Tree	
	%	SE ²	sap %	SE	Heart %	SE	%	SE	%	SE
WWP	x ³ 50.0ab	0.4	xy 48.5a	0.9	xy 48.9b	0.8	xy 48.4ab	0.1	Y 47.3ab	0.1
DF	Y 48.7bc	0.3	Z 47.1a	0.2	Z 47.4bc	0.3	X 49.8a	0.6	Z 47.5ab	0.4
GF	X 49.3ab	0.3	Y 47.7a	0.1	Y 47.7bc	0.1	Z 45.9cd	0.2	Y 47.8ab	0.3
WH	X 49.9ab	0.3	Y 46.4a	0.1	Y 47.1bc	0.2	Y 47.3bcd	0.2	Y 47.3ab	0.2
WRC	X 48.8bc	0.2	xy 47.1a	0.1	xy 48.0bc	0.3	Y 45.7cd	0.1	xy 46.6b	0.9
LP	X 49.5ab	0.1	Y 47.4a	0.03	Y 47.5bc	0.1	Y 47.1bcd	0.3	X 49.1ab	0.2
ES	xy 47.6c	0.1	Y 46.7a	0.2	Y 46.4c	0.2	Y 46.5bcd	0.3	X 48.0ab	0.1
SAF	X 50.5a	0.2	X 43.7a	3.5	X 47.4bc	0.2	X 45.7d	0.1	--	--
PP	xy 49.9ab	0.1	Y 47.5a	0.2	X 52.5a	0.8	Y 47.9abc	0.4	xy 49.9a	0.1

¹ Refer to Table 3 for tree species designation.

² Standard error of the mean.

³ Comparisons of statistical significance among habitat types are X, Y, and Z and among forest components within each forest category are a, b, and c.

The results revealed no significant differences among species in sapwood carbon concentrations (Table 10a); however, significant differences were noted in carbon concentrations for heartwood. These carbon concentrations ranged from 46% in Engelmann spruce to 53% in ponderosa pine.

Tree species also influenced carbon concentrations in coarse roots. For example, Douglas-fir contained 50% while subalpine fir contained only 46%. Carbon concentrations of the understory ranged from 48% to 49%; ponderosa pine understory was significantly greater than the understory carbon concentrations of the other species.

Within individual species, carbon concentrations between sapwood and heartwood showed no significant differences except in ponderosa pine where heartwood carbon concentration was 53% and sapwood was 48% (Table 10a). Although many significant differences occurred among components depending on species, the overstory crown and understory trees tended to have higher carbon concentrations than the other tree components.

Within the understory vegetation, shrubs showed no differences in carbon concentrations among habitat types (Table 10). However, carbon concentrations in the shrubs were significantly higher (45% to 48%) than in the forb or grass component (42%). In the SAF/VASC habitat type where both medium and low shrubs were growing, carbon concentrations did not differ significantly between the two size classes.

For woody residue, carbon concentrations, were significantly different only in the SAF/VASC habitat type (Table 10). Rotten logs had the highest carbon concentration (49%). Among habitat types, woody residue carbon concentrations showed greater differences. For example, sticks in the ponderosa pine habitat types had significantly more carbon (49%) than sticks in the WH/CLUN (47%) and SAF/VASC (48%) habitat types. A similar trend among habitat types also occurred in cones. Carbon concentrations in cones from

ponderosa pine and SAF/VASC habitat types were higher (> 48%) than in the mixed conifer habitat types (47%).

In the forest soil component, brown cubical rot tended to have higher carbon concentrations (ranging from 47% to 49%) than the other soil components (Table 10). Brown cubical rot in the PP/FEAR contained 48% and soil wood contained 47%. Within all habitat types, the mineral soils had the lowest carbon concentrations, ranging from 1% to 6%. There were no significant differences found as depth increased but the magnitude of the numbers did decrease. Within the organic components, surface humus had significantly lower carbon concentrations in the WH/CLUN and SAF/VASC habitat types than the other soil organic components. The similarities that did occur were in the ponderosa pine habitat types where surface humus carbon concentrations were similar to litter carbon concentrations.

Among habitat types, there were no differences in carbon concentrations in brown cubical rot, litter, and soil wood (Table 10). In the PP/FEAR habitat type, the surface humus carbon concentrations were significantly higher (36%) than in the WH/CLUN habitat type (22%). Carbon concentrations in surface humus were higher in habitat types having pine as a major component than in WH/CLUN. Shallow mineral soils tended to have the highest carbon concentrations in the ponderosa pine habitat types (> 4.5%). The lowest carbon concentrations occurred in the WH/CLUN (4%) and SAF/VASC (1%) habitat types. In the deep mineral soil, the lowest carbon concentrations occurred in the PP/FEAR (2%) and the SAF/VASC (1%) habitat types. The highest carbon concentrations in deep mineral soils were 2% in the PP/QUGA and 4% in the WH/CLUN habitat types.

CARBON CONTENT

Carbon content was calculated using organic biomass and carbon concentration (Table 11). The carbon content for tree boles was significantly higher in all habitat types. The ponderosa pine habitat types had the highest carbon content ranging from 192 Mg/ha to 203 Mg/ha (86 ton/ac to 95 ton/ac). Coarse roots tended to contribute the second largest portion of the carbon weight in the forest. Understory crown and fine roots had the lowest carbon weight in all habitat types.

Among habitat types the carbon content in the ponderosa pine overstory crowns, boles, and coarse roots was significantly higher than in the WH/CLUN and SAF/VASC habitat types (Table 11). Carbon content in the fine roots tended to be higher in the WH/CLUN (4.0 Mg/ha (1.8 ton/ac) and SAF/VASC (2.2 Mg/ha (0.9 ton/ac) habitat types when compared to the ponderosa pine types (0.1 Mg/ha to 0.2 Mg/ha (0.04 ton/ac to 0.09 ton/ac).

In the WH/CLUN habitat type, western hemlock (60.8 Mg/ha (27 ton/ac) and western redcedar (63.7 Mg/ha (29 ton/ac) contributed the largest amounts of carbon (Table 11a). The carbon weight contributed by western white pine (8.5 Mg/ha (4 ton/ac) and Douglas-fir (26.9 Mg/ha (12 ton/ac) was minor within this forest type. Ponderosa pine had the highest amounts of carbon in tree boles and coarse roots.

Within the understory vegetation, low and medium shrubs had the highest carbon content (15.0 Mg/ha (7 ton/ac) compared to the forbs and grasses in the SAF/VASC (Table 11). In contrast, grasses and forbs had higher carbon content in the PP/FEAR habitat type. Among habitat types, the SAF/VASC carbon content in shrubs was significantly higher than in the ponderosa pine types.

Table 11. Carbon content (Mg/ha) by forest component and habitat types.

Forest Component	Habitat Type ¹							
	PF/FEAR		PF/QUGA		WH/CLUN		SAF/VASC	
	Mg/ha	SE ²	Mg/ha	SE	Mg/ha	SE	Mg/ha	SE
Trees								
Overstory Crown	x ³ 49.3c	3.7	x 56.7c	5.1	y 24.8bc	1.2	y 15.4b	1.9
Bole	x 203.0a	6.6	x 191.8a	21.7	y 126.4a	10.3	y 75.8a	15.0
Coarse Roots (> 1 cm diam.)	x 101.7b	4.6	x 122.2b	9.0	y 39.3b	4.9	y 32.0b	5.7
Fine Roots (< 1 cm diam.)	x 0.1d	0.02	x 0.2d	0.05	x 4.0c	0.8	x 2.2b	1.7
Understory Trees (< 12.7 cm dbh)	x 0.5d	0.3	x 0.5d	0.2	x 0.1c	0.06	x 0.5b	0.1
Total	354.7	14.5	371.3	34.7	194.6	14.8	126.0	20.8
Understory Vegetation								
Medium Shrub (0.5-2 cm diam.)	--	--	--	--	--	--	x 4.5a	1.7
Low Shrub (< 0.5 cm diam.)	--	--	y 0.1a	0.04	--	--	x 15.0a	2.4
Herbage	x 0.1a	0.01	x 0.1a	0.01	--	--	--	--
Total	0.1	0.01	0.2	0.01	--	--	19.5	2.3
Woody Residue								
Sticks (< 7.5 cm diam.)	z 1.1ab	0.2	y 2.5b	0.3	x 5.1b	0.1	yz 1.4a	0.2
Solid Log (> 7.5 cm diam.)	y 1.9ab	1.4	y 0.1b	0.0	x 19.8a	4.8	y 0.6a	0.4
Rotten Log (> 7.5 cm diam.)	y 1.0b	0.5	y 2.0b	0.3	x 22.5a	2.8	y 4.2a	1.7
Cones	x 11.2a	3.6	x 13.0a	3.3	x 4.1b	0.7	x 3.3a	1.4
Total	15.2	4.3	17.6	3.6	51.5	6.5	9.5	1.5
Soil								
Brown Cubical Rot	x 0.4c	0.2	x 1.6b	0.6	x 1.5a	1.5	x 4.8a	2.4
Litter	x 12.6bc	1.3	x 20.4b	2.9	x 9.1a	4.5	x 17.0a	4.0
Humus	x 21.6b	5.0	x 22.7b	0.8	x 29.6a	11.4	x 25.6a	6.7
Soil Wood	x 0.3c	0.3	x 6.5b	2.3	x 44.3a	27.7	x 14.4a	6.5
Shallow Mineral (0-10 cm)	x 71.4a	3.9	x 55.2a	7.9	y 21.3a	2.9	y 11.0a	2.3
Deep Mineral (10-20 cm)	x 56.8a	6.4	x 66.0a	3.6	x 45.4a	3.2	y 10.9a	0.9
Total	163.2	14.5	172.4	9.3	151.2	28.0	83.7	16.9

¹Refer to Table 1 for habitat type designation. ²Standard error of the mean.³Comparisons of statistical significance among habitat types are X,Y, and Z and among forest components within each forest category are a, b, and c.

Table 11a. Carbon content by tree species, forest components and habitat type.

Species ¹	Forest Component								
	Overstory Crown		Bole		Coarse Roots		Understory Trees		Total
	Mg/ha	SE ²	Mg/ha	SE	Mg/ha	SE	Mg/ha	SE	Mg/ha
WWP	0.5	0.3	6.1	3.1	1.9	1.0	0.0	0.0	8.5
DF	3.0	1.2	18.7	6.7	5.2	1.6	0.0	0.0	26.9
GF	1.1	0.5	5.7	3.4	1.3	0.8	0.0	0.0	8.1
WH	8.1	1.7	42.4	14.4	10.3	3.1	0.0	0.0	60.8
WRC	9.1	1.6	38.7	9.7	15.8	4.7	0.1	0.06	63.7
ES	1.8	1.4	6.5	4.9	2.0	1.5	0.0	0.0	10.3
SAF	0.4	0.4	1.4	1.4	0.4	0.4	0.0	0.0	2.2
Total WH/CLUN	24.8	1.2	126.4	10.3	39.3	4.9	0.1	0.06	181.0
LP SAF/VASC	15.4	1.9	75.8	15.0	32.0	5.7	0.5	0.1	124.0
PP PP/Fear	49.3	3.7	203.0	6.6	101.7	4.6	0.5	0.3	355.0
PP PP/QUGA	56.7	5.1	191.8	21.7	122.2	9.0	0.5	0.2	371.0

¹ Refer to Table 3 for tree species designation.² Standard error of the mean.

In woody residues, the largest carbon content was in cones (11 to 13 Mg/ha (5 ton/ac to 6 ton/ac) in the ponderosa pine habitat types (Table 11). In the WH/CLUN habitat type rotten and solid logs contributed the most carbon (42 Mg/ha (19 ton/ac)). In the SAF/VASC, no significant differences occurred among woody residue components but the carbon content tended to be higher in cones and rotten logs.

Among habitat types, carbon content in rotten and solid logs tended to be higher in the WH/CLUN habitat type (Table 11). Although carbon content in cones contributed a large portion of the woody residue in the ponderosa pine habitat types, there were no significant differences compared to the cone carbon content in the WH/CLUN and SAF/VASC habitat types. Significant

differences in carbon content did occur among habitat types for sticks; the WH/CLUN and SAF/VASC habitat types had more carbon in this category than the ponderosa pine types.

The habitat types with highest carbon content located in the mineral soil (56 Mg/ha to 71 Mg/ha (25 ton/ac to 33 ton/ac) were the ponderosa pine habitat type (Table 11). Within the organic soil components, surface humus and litter in the PP/FEAR habitat type had significantly more carbon than the brown cubical rot and soil wood. In the PP/QUGA habitat type, carbon weight of all organic components were not significantly different. Significant differences only occurred in carbon content between the mineral and organic soil components. In the SAF/VASC and WH/CLUN habitat types, no significant differences in carbon content occurred among soil components.

Comparisons among habitat types showed no significant differences in carbon content across the soil components except in mineral soils (Table 11). Generally, the carbon content in shallow mineral soils for the ponderosa pine habitat types had higher amounts of carbon than that found in the WH/CLUN or SAF/VASC habitat types. In the deep mineral layers carbon content in the SAF/VASC (10.9 Mg/ha (5 ton/ac) was significantly less than the carbon content among the other habitat types.

I also compared total carbon content in each classification among and within habitat types (Table 11b). Within all habitat types, the highest carbon content was in the trees (126 Mg/ha to 371 Mg/ha (56 ton/ac to 165 ton/ac). Among habitat types, tree carbon content was higher in the ponderosa pine types when compared with the carbon content of the WH/CLUN and SAF/VASC habitat types. Woody residue in the WH/CLUN habitat type had the highest carbon content (51.5 Mg/ha (23 ton/ac). Carbon content in the soils was not significantly different among habitat types. The habitat types in this study having the highest carbon content were in the PP/FEAR and PP/QUGA Habitat

types (533 Mg/ha to 566 Mg/ha (238 ton/ac to 252 ton/ac). The lowest carbon content occurred in the SAF/VASC habitat types (239 Mg/ha (107 ton/ac) and the intermediate occurred in the WH/CLUN habitat type (394 Mg/ha (176 ton/ac).

Table 11b. Total carbon weight (Mg/Ha) by forest component and habitat type.

Forest Components	Habitat Types ¹							
	PP/FEAR		PP/QUGA		WH/CLUN		SAF/VASC	
	Mg/ha	SE ²	Mg/ha	SE	Mg/ha	SE	Mg/ha	SE
Trees	x ³ 354.7a	14.5	x 371.3a	34.7	y 194.6a	14.8	y 126.0a	20.8
Understory Vegetation	y 0.1c	0.01	y 0.2c	0.0	--	--	x 19.5b	2.3
Woody Residue	y 14.9c	4.3	y 17.6c	3.6	x 51.5b	6.5	y 9.5b	1.5
Soils	x 163.2b	14.5	x 172.4b	9.3	x 151.2ab	28.0	x 83.7ab	16.9
Total ³	x 532.9	9.3	x 561.5	40.4	y 397.3	17.9	z 238.8	6.8

¹ Refer to Table 1 for habitat type designation.

²Standard error of the mean.

³Comparisons among habitat types are X,Y, and Z and among forest components within each forest category are a, b,and c.

Discussion

Carbon is a critical element that plants accrue and use to support their structure and sustain physiological processes in temperate forest ecosystems (Waring and Schlesinger 1985). Not only is carbon a key element in forest ecosystems, but on a global scale, carbon is also essential for sustaining life (Bolin and others 1979). Estimating carbon reserves in all ecosystems is critical if we are to understand the role carbon plays in global warming (Post and others 1990; Schlesinger 1977). It is essential that we understand the potential human impacts on carbon storage in forest ecosystems and the resulting effects on the global carbon cycle. Although there are gross estimates available on global carbon storage, additional information on carbon concentrations in forest components could improve these estimates. This study provided carbon-to-organic matter ratios for forest soil components, carbon concentrations for soil and vegetative components, and estimates on total carbon content in three Rocky Mountain forest ecosystems.

CARBON-AND-ORGANIC MATTER RELATIONSHIPS

There is substantial information on organic matter in temperate forest ecosystems, usually provided by yield tables, standing biomass estimates, and other forest inventory information (Albrektson 1980). Estimating carbon content from these data requires using approximate conversion factors (Franzmeier and others 1985; Linder and Axelsson 1982). For soils, loss-on-ignition (LOI) (Ball 1964) is an easy cost-effective method for determining organic matter. To estimate soil carbon concentrations from these organic matter estimates, a traditional C/OM ratio of 0.58 is often applied. This traditional C/OM ratio is often inaccurate, however, because of variation among soil types.

Broadbent (1953) showed that conversion factors may differ quite significantly depending on soil type. He determined that some ratios may differ up to 50% from the traditional ratio. Nelson and Sommers (1982) agreed with Broadbent. They recommended developing C/OM conversion ratios for specific soil types. Until this study, there were no adequate ratios available that convert organic matter to carbon for forest soil components (litter, humus, brown cubical rot, soil wood, and mineral soils) of the Rocky Mountains.

This study used two regression techniques for predicting carbon as a function of organic matter (Figures 3 and 4). The techniques included a regression with a Y-intercept and another regression forcing the Y-intercept through 0. Most studies that predict carbon as a function of organic matter force the Y-intercept through 0 thus producing a simple ratio. This technique overestimates the amount of variation in carbon explained by organic matter, thereby over-estimating its reliability.

Upon plotting both regression equations, only small differences occurred between the two prediction techniques (Figures 3 and 4). When predicting carbon as a function of organic matter, the largest discrepancy appeared to occur when organic matter concentrations were low. For example, if organic matter concentrations for brown cubical rot were less than 80%, the regression equation without a Y-intercept would underestimate the carbon concentration. At higher organic matter concentrations, the simple ratio would give an adequate prediction of carbon. Using a curvilinear regression techniques may have provided a better prediction of carbon as a function of organic matter (Lunt 1930).

The simple C/OM ratios produced in this study were lower than C/OM ratios reported in other studies. For example, studies conducted in the northeastern and southeastern United States, reported C/OM ratios for

spodosols of 0.48 to 0.52 (Huntington and others 1989; Grigal and Ohmann 1992). Ratios from this study were much lower (< 0.36). One explanation for this discrepancy could be the differences in mineral soil carbon concentrations (Donkin 1991).

Studies reporting C/OM ratios greater than 0.40 for mineral soils, usually have soil carbon concentrations greater than 5%. For example, Huntington and others (1989) reported a C/OM ratio of 0.52 for spodosols in Pennsylvania. The Bh horizon they sampled had carbon concentrations greater than 8%. Similarly, Grigal and Ohmann (1992) determined a C/OM ratio of 0.52 for mineral soils in the north central lake states. According to Franzmeier and others (1985), carbon concentrations of mineral soils within this region were normally greater than 8%. Therefore, it appears if mineral soil carbon concentrations are greater than 5%, C/OM ratios tend to be greater than 0.40.

For the combined habitat types in this study, the carbon concentrations for mineral soils were less than 4.5% (Table 11). For similar soils, Donkin (1991) recommended a C/OM ratio of 0.28. Donkin (1991) determined carbon concentrations using the Walkley-Black Method (Nelson and Sommers 1982). Although I used a different method for determining carbon concentrations, this present study also had low C/OM ratios (0.17 to 0.36) in mineral soils when carbon concentrations were less than 5%.

The C/OM ratio in surface humus was the only ratio among organic soil components that varied among habitat types in this study. This was probably due to mineral soil mixing into the surface humus, thus influencing C/OM relationships. Particularly in the limestone parent material of the PP/FEAR habitat type.

The conversion ratios in this study for the organic soil components varied from 0.47 in the surface humus to 0.51 in litter, soil wood, and brown cubical rot. Lunt (1930) reported that deciduous forest litter in the north

central United States had a C/OM ratio of 0.52. Although in this study the litter was from coniferous forests, a similar C/OM ratio of 0.50 occurred.

Without specific C/OM ratios available for soil wood and brown cubical rot, the traditional 0.50 conversion ratio was applied to determine carbon as a function of organic matter in studies by Broadbent 1953 and Linder and Axelsson 1982). I determined that a ratio of 0.52 would produce better estimates of carbon in these organic substances.

The habitat types in this study were from divergent climate and moisture regimes located over a wide geographical area from the Northern to the Southern Rocky Mountains (Cooper and others 1991; Larson and Moir 1986; Pfister and others 1977). Although these areas were very diverse, there were no significant differences found in C/OM ratios among habitat types for litter, soil wood, and brown cubical rot. The different climatic conditions resulted in different decomposition rates and organic matter accumulation (Harmon and others 1986; Vogt and others 1986). Because of these conditions, one would assume that C/OM ratios would be different.

Even though decomposition rates varied among the habitat types used in this study, the composition of the litter, brown cubical rot, and soil wood were similar among sites. The reason for this similarity is because, the composition of these components at similar stages of decay is probably consistent across sites (Harmon and others 1986; Harmon and others 1992). Therefore, it was not unusual that the C/OM ratios for these materials were similar across the sites sampled.

There are some disadvantages in using C/OM ratios since they vary from site to site. But this method provides information on carbon at a low cost and does not require a large amount of technical expertise. The results from this study showed that using these C/OM ratios, carbon can be estimated across sites for the organic components such as litter, soil wood, and brown cubical

rot if organic matter concentrations are known. Although I would recommend developing C/OM ratios for mineral soils by soil type, using C/OM ratios from this study would provide better estimates of carbon than using the traditional ratio of 0.58 for most forest soils in the Rocky Mountains.

CARBON CONCENTRATIONS

To help improve the accuracy of estimates of carbon reserves in Rocky Mountain forests, this study determined carbon concentrations for forest components in three forest types. The results of this study are very comparable to the limited data available from other studies on carbon in the Rocky Mountains. Klemmedson's (1975) carbon concentrations for tree, understory, coarse woody debris, and other components in southwest ponderosa pine forests, ranged from 39% to 50%. The forest components from the ponderosa pine sites, in my study, had similar carbon concentrations (Table 12). In addition, carbon concentrations in all the forest types I sampled, were similar to those of Klemmedson's (1975).

Traditionally, a concentration of 50% was used for converting tree biomass to carbon content (Linder and Axelsson 1982). According to my results from this study, this estimate is reasonable, if the objective is to provide approximate estimates of total carbon. In this study significant differences in carbon concentrations of coarse roots and overstory crowns were detected among species; however, the maximum differences were only 1.7% for the overstory and 2.7% for coarse roots. These small differences would have an insignificant impact on carbon estimates when the variation in biomass estimates are included. For example, the amount of error introduced in root biomass estimations outweigh the small differences detected in carbon

Table 12. Carbon concentrations recommended for converting organic biomass to carbon content.

Forest Component	Carbon Concentration (%)
Trees	
Overstory Crown	49.5
Bole	47.6
Coarse Roots (> 1 cm diam.)	47.2
Fine Roots (< 1 cm diam.)	45.3
Understory Trees (< 12.7 cm tall)	48.4
Understory Vegetation	
Shrubs	47.2
Forbs and Grasses	41.4
Woody Residue	
Sticks (< 7.5 cm diameter) - PP/FEAR and PP/QUGA ¹	49.1
Sticks (< 7.5 cm diameter) - WH/CLUN and SAF/VASC ¹	47.2
Solid Log (> 7.5 cm diameter)	48.2
Rotten Log (> 7.5 cm diameter)	48.7
Cones - PP/FEAR and PP/QUGA	47.9
Cones - WH/CLUN and SAF/VASC	46.0
Soils	
Brown Cubicle Rot	48.0
Litter	37.9
Soil wood	44.2

¹ Significant differences occurred among habitat types, therefore, separate carbon concentrations were recommended. Refer to Table 1 for habitat type designation.

concentrations. On the other hand, to improve carbon content estimates for trees, an average carbon concentration for each tree component could be used. Based on this study, I recommend 49% for overstory crown, 48% for boles, 47% for coarse roots, and 48% for understory trees (Table 12). Similarly, better carbon content estimates for other forest components can be achieved by using more precise carbon concentrations (Table 12). This greater accuracy is dependent on good biomass estimates.

As noted earlier, several researchers have discussed the high variation among mineral soil carbon concentrations. I also found wide variations in carbon concentrations in deep mineral soils among habitat types. In the shallow mineral soils, the variations were not as extensive but as in the deep mineral soils, subtle differences were noted. Therefore, the results from this study suggest developing site specific carbon concentrations for predicting surface humus and mineral carbon content.

CARBON STORAGE

To estimate carbon content, organic biomass estimates used in this study came from several different sources. The most common method used for estimating above ground live biomass in trees in the Northern Rocky Mountains are regression equations developed by Brown (1978). These equations are considered adequate for predicting overstory crown biomass (Hanley 1976). In addition, the biomass estimates used in this study for coarse woody debris (Brown 1974) are also fairly accurate. In contrast, the cost of estimating coarse root biomass is expensive and time consuming. Consequently, few methods are available. Even though the root biomass regression equations used in this study came from an array of different sources, they appear to provide reasonable estimates when compared to the results of other studies (Table 4) (Hanley 1976; Klemmedson 1975).

In the ponderosa pine habitat types, carbon weight in trees were 20% higher than those reported by Klemmedson (1975) who conducted a similar study near Flagstaff, Arizona (Figure 5). This discrepancy is probably due to the difference in tree size between the two studies. Klemmedson sampled sapling and pole size trees, while trees sampled in this study were 50 cm to 100 cm (20 in to 40 in) in diameter. The amount of carbon stored in trees on the WH/CLUN was less than the amount stored on the ponderosa pine sites. Upon

looking at this information the ponderosa pine sites would appear to be more productive than the WH/CLUN sites. This can be misleading since the sites sampled on the WH/CLUN habitat type were not at their maximum growth potential, while the ponderosa pine sites were. When western hemlock habitat types are at their full growing capacity, the carbon storage potential could be much higher (Haig 1932).

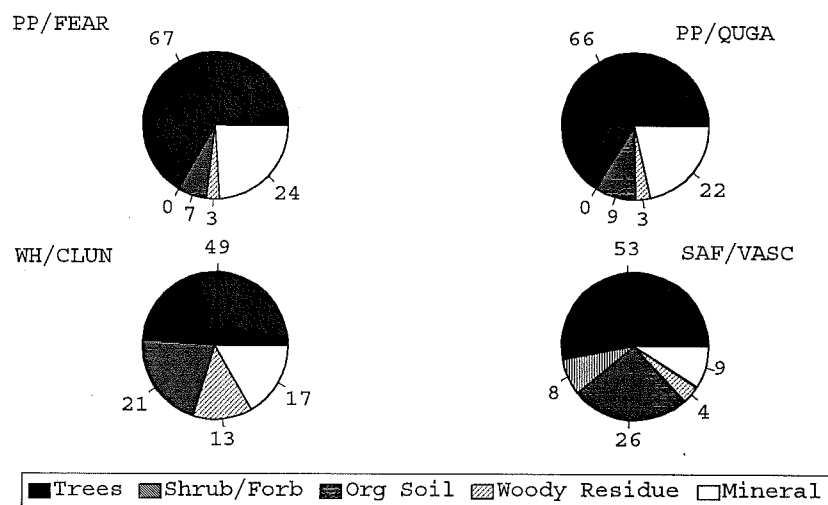


Figure 5. Carbon content proportions (PERCENT) for forest stratifications and habitat types.

Several studies have reported the importance of shrubs, forbs, and grasses for nutrient cycling (Chapin 1983; Jorgensen and Wells 1986) but rarely quantify the amount of carbon they can store. Dwarf huckleberry in the SAF/VASC, is a small shrub rarely considered for its ability to store carbon. In this study, 15 Mg/ha (6.7 ton/ac) of carbon were stored in this component. Forbs and grasses may also have the potential to be important carbon storage sites. In this study, however, they only stored a maximum of 0.1 Mg/ha (.04 ton/ac) across all habitat types. Prior to fire suppression, forbs and grasses were abundant in the ponderosa pine types but because of the lack of fire and over-grazing they are no longer an important component for storing

carbon (Covington and Moore 1994). Therefore, depending on forest type and forest history, small components within forest ecosystems should not be overlooked when estimating carbon pools.

Coarse roots have the potential to store large amounts of carbon (Figure 6). In the ponderosa pine habitat types, coarse roots stored more carbon than in the WH/CLUN and SAF/VASC habitat types. Carbon allocation to roots varies widely among sites depending on growing season, nutrient

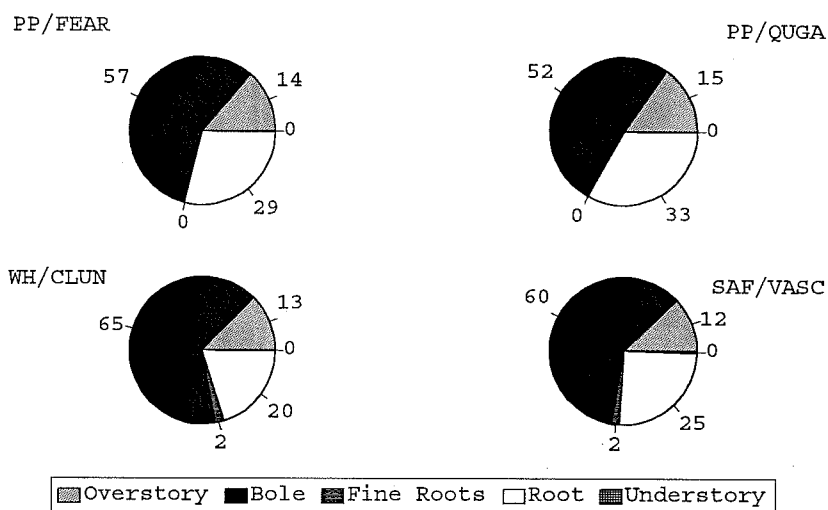


Figure 6. Carbon content proportions (PERCENT) for tree components and habitat types.

availability, climate, tree species, age, and genetic materials (Kramer and Kozlowski 1979). For example, the ponderosa pine forests sampled in this study were 25 to 50 years older than the WH/CLUN forest and 60 years older than the SAF/VASC forest. This difference in age possibly influenced the amount of carbon stored in roots. In contrast, the Northern Rocky Mountain habitat types had more fine woody roots than the ponderosa pine forests of the southwest. One potential reason for this is because moisture and nutrients

are located in the surface layers of Northern Rocky Mountain forests causing trees to allocate more carbon to fine root growth (Aber and Melillo 1991; Kramer and Kozlowski 1979; Page-Dumroese and others 1990).

Schlesinger (1977) discussed the importance detritus plays in ecosystem function and carbon cycling. He referred to root turnover, undecomposed litter, and soil humus but did not mention the contribution of woody residue. In contrast, Keenan and others (1993) recognized the importance of woody residue. They reported 161 Mg/ha (71.8 ton/ac) of carbon in woody material in western redcedar and western hemlock forests in northern Vancouver Island. Similarly, in the younger, inland hemlock forest I sampled, 51 Mg/ha (23.8 ton/ac) of carbon was found in woody materials (Table 11). Although woody material is beginning to be recognized as a carbon sink, it often only includes coarse woody debris (CWD), and does not consider other components which may be important for storing carbon. Therefore, I quantified where carbon is located within some of these other woody components (Figure 7).

This study showed that cones are a major component of the woody materials of these forest types. In the ponderosa pine habitat types, greater than 70% of the carbon in the woody residue was in cones. This component also stored 35% of the carbon in the SAF/VASC habitat type. The WH/CLUN habitat type had the least amount of carbon in cones (8%). In vegetation types such as ponderosa and lodgepole pine, where cones represent a large portion of the woody residue, it would be important to consider these components when estimating total carbon reserves.

Other types of woody residue also store large amounts of carbon. For example, in the WH/CLUN habitat type large and small woody residue contributed 13% of the total carbon on the site (Figure 5). Most of the carbon in woody residue in this habitat type was in the form of solid and rotten logs (> 79%) and smaller amounts of carbon were in sticks (Figure 7). CWD play a major

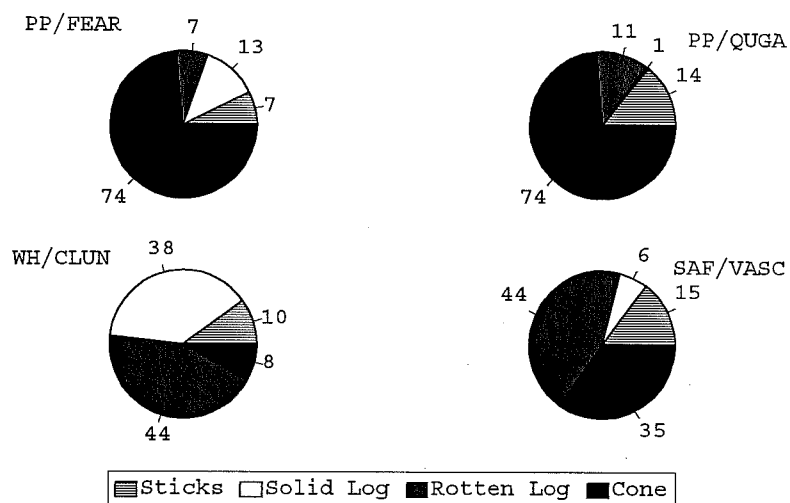


Figure 7. Carbon content proportions (PERCENT) for woody residue components and habitat types.

role in storing carbon in this habitat type while in the ponderosa pine habitat types, sticks were important carbon sinks. Likewise, Harmon and Hua (1991) recognized the importance of CWD for storing carbon in mature coastal Douglas-fir stands. Similarly, in this study, I showed the importance of CWD in storing carbon but also illustrated the importance of other woody materials (cones and sticks) as carbon sinks.

As snags, CWD, sticks, cones, and coarse roots decompose, they form soil wood and brown cubical rot, important soil components of Rocky Mountain forest ecosystems (Graham and others In press; Harvey and others 1987). Graham and others (1994) suggested that the forest floor may consist of 30% to 60% woody material which would have the potential to store large amounts of carbon. In this study, I showed that 25% to 30% of the soil carbon was in soil wood and brown cubical rot (Figure 8). Although I determined that less than 4% of the soil carbon in the ponderosa pine sites consisted of soil wood there is a large potential for soil wood recruitment. After the trees die the large amount of root biomass in these forest types will become soil wood.

Therefore, in Rocky Mountain forests, soil wood and brown cubical rot are important carbon sinks which are often overlooked.

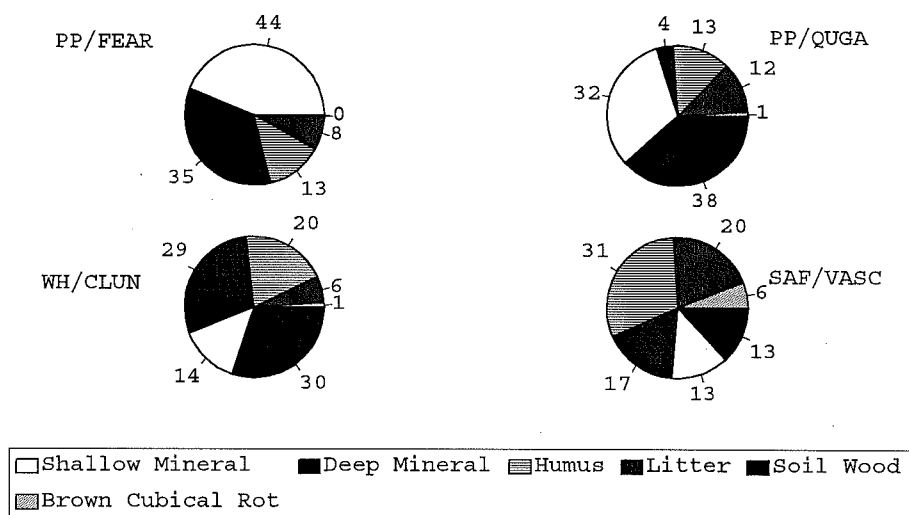


Figure 8. Carbon content proportions (PERCENT) for soil components and habitat types.

Litter and humus also store large amounts of carbon. The large amounts of litter in the ponderosa pine and the SAF/VASC habitat types are the result of the continuous shedding of needles (Kilgore 1981; Olson 1981). This attribute had a major effect on the amount of carbon stored in the litter and humus in these types. The proportion of carbon in the litter and humus located in the soils of the ponderosa pine habitat types ranged from 20% to 25%. These proportions were larger than the 10% reported by Klemmedson (1975). The difference in results is probably due to the differences in stand ages between the two studies. Klemmedson's (1975) stands were younger and did not produce as much litter and surface humus, while the stands I sampled in this study were over 200 years old and had higher amounts of carbon located in these components.

There were wide variations in carbon content in mineral soils among habitat types. The results from this study showed that in the ponderosa pine habitat types, greater than 70% of the forest soil carbon was stored in the mineral soils (Figure 8). In comparison, Klemmedson (1975) showed 89% of the total soil carbon content was in mineral soils. The amount of carbon in his soils were a result of the root turnover from the grass component on his site (Buol and others 1989). The WH/CLUN and SAF/VASC habitat types stored from 39 Mg/ha to 43 Mg/ha (17.4 ton/ac to 19.8 ton/ac) of the carbon in litter and surface humus (Table 11). These results did not differ greatly from the 50 Mg/ha to 60 Mg/ha (22.3 ton/ac to 26.8 ton/ac) of carbon in litter and humus reported by Keenan and others (1993) from sites in northern Vancouver Island. The ponderosa pine habitat types had a greater proportion and amount of carbon in mineral soils than the WH/CLUN and SAF/VASC habitat types (Table 11; Figure 8). The reason for this difference may be a greater clay content in soils of the ponderosa pine habitat types as compared to the soils in the WH/CLUN and SAF/VASC habitat types.

Carbon content across habitat types varied widely among the four forest categories (Figure 5). In the Northern Rocky Mountain habitat types carbon content was higher in the woody residue and forest floor compared to the ponderosa pine sites. One reason for this is the different fire regimes occurring between the Northern and Southern Rocky Mountain regions. The fire frequencies in the southwest have changed, since the early 1900's because of fire suppression. Without fire in these vegetation types, litter and humus accumulate, becoming important components for carbon storage (Covington and Moore 1994; Kilgore 1981). In contrast, the intermittent fire frequencies of the Northern Rocky Mountains allows these ecosystems to accumulate greater

amounts of woody residue, brown cubical rot, soil wood, litter, and surface humus in comparison to the Southern Rocky Mountains (Kilgore 1981; Olson 1981).

Other reasons for the variation in carbon storage among the forest types may be differences in climate and decomposition (Aber and Melillo 1991; Harmon and Hua 1991; Harvey and others 1987). For example, the warm temperatures in the southwest plus summer rains provide favorable conditions for microbes to decompose woody material, thus decreasing carbon storage (Clark 1957). The WH/CLUN and SAF/VASC habitat types have colder temperatures, thus slowing decomposition (Harmon and others 1986). Therefore, the basic environmental factors controlling decomposition contribute to the differences in carbon storage among the habitat types.

On a global scale, researchers have theorized that the major carbon sink is in mineral soils (Post and others 1982; Schlesinger 1986). But most global carbon estimates ignore many other forest components as potential carbon sinks. In this study, I showed that other forest components such as shrubs, cones, CWD, brown cubical rot, and soil wood can be major carbon sinks in Rocky Mountain forest ecosystems.

Conclusions

This study provided a key portion of the information needed for a better understanding of the contribution forest ecosystems make to the terrestrial carbon pool.

This information included:

- that C/OM ratios were consistent across three very diverse forest types for brown cubical rot, litter, and soil wood;
- that C/OM ratios for humus and mineral soils varied among forest types;
- that all the C/OM ratios were lower than the traditional ratio of 0.58;
- that C/OM ratios should be used with caution and that their reliability is often overstated;
- that carbon concentrations would be preferred over C/OM ratios for mineral soils because of the high variation in C/OM ratios;
- that carbon concentrations vary among tree components but are consistent among woody components independent of tree species and forest types;
- that biomass carbon concentrations were lower than the traditional 0.50;
- that the validity of carbon content is related to biomass estimates, which vary widely especially for coarse roots;
- that carbon estimates in forest ecosystems ignore many forest components which can contribute large proportions to the carbon pool;
- that carbon concentrations presented in this study can be used for converting biomass estimates and used in models for determining carbon content in a variety of forest types.

The accomplishments of this study can serve as the foundation for future research, with the ultimate goal of understanding how forests contribute to the global carbon cycle.

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