# Carbon Concentrations and Carbon Pool Distributions in Dry, Moist, and Cold Mid-Aged Forests of the Rocky Mountains

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**Abstract**—Although "carbon" management may not be a primary objective in forest management, influencing the distribution, composition, growth, and development of biomass to fulfill multiple objectives is; therefore, given a changing climate, managing carbon could influence future management decisions. Also, typically, the conversion from total biomass to total carbon is 50 percent; however, we believe this value is not consistent across all forest components. Therefore, the objectives of this study are to: acknowledge the appropriate carbon concentrations and distribution of carbon pools and provide improved estimates of carbon content in four habitat types with different climatic regimes—(dry (Arizona), cold (Montana), and moist (Idaho)—of the Rocky Mountains, USA. We quantified biomass, carbon concentrations, and carbon amounts for trees, soils, woody debris, and coarse and fine roots. We found that in most cases our carbon concentrations were less than the typical conversion of 50 percent. Thus we recommend the following conversions from biomass to carbon: trees should be 49 percent for overstory crown, 48 percent for boles, 48 percent for understory trees, and 47 percent for coarse roots; for understory plants concentrations should be 47 percent for shrubs and 41 percent for forbs and grasses; woody residue should be 48 percent for solid logs, 49 percent for rotten logs, 48 percent for brown cubical rotten wood, and 44 percent for buried wood; cones should be 48 percent in ponderosa pine forests and 46 percent in cold and moist forests; sticks in ponderosa pine forests should be 49 percent and in the moist and cold climate regimes sticks should be 47 percent. Unique carbon pools often overlooked include cones, woody debris, and buried wood. Given these results, additional research questions could be pursued, such as the effect of successional stage on carbon pool distributions, or as forests grow and develop, if carbon concentrations change or if only biomass distribution changes over time.

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## Introduction

Forest plans and prescriptions on public lands emphasize a variety of values, such as biological diversity, scenery, wildlife, water quality, sustainable ecosystems, and other values, in addition to commodity production. Past forest practices consisted of managing individual stands of trees (Graham 1990) as separate entities; today managers need to consider overall ecosystem processes and functions before developing management prescriptions of large landscapes (Jain and Graham 2005), particularly with the uncertainty associated with climate change (Joyce and others 2008). In addition, because management actions have the potential to manipulate carbon, acknowledging changes in carbon pools may be a critical element that will need documentation in the future (Waring and Schlesinger 1985).

In forest ecosystems, organic carbon is stored in different locations, including live and dead standing biomass, down woody debris, litter, and soils. Thus

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the manipulation of these organic substances not only affects carbon storage but also other essential nutrients such as nitrogen, calcium, potassium, sulfur, and phosphorous (Binkley and Richter 1987; Jorgensen and Wells 1986). Therefore, 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.

Although a large portion of carbon is in live biomass, a significant amount of carbon is also stored in coarse woody debris (CWD), the forest floor, and soils. The forest floor and soils contain five organic components that contribute to carbon storage (fig. 1): 1) litter, which encompasses recognizable plant and animal materials such as conifer needles, insect frass, and deciduous leaves; 2) humus, which is unrecognizable, decomposed plant and animal material having a high content of complex hydrocarbons located above the mineral soil; 3) brown cubical rotten wood (BCR), which consists of woody debris in an advanced state of decay located on the surface; 4) soil wood, which is decaying wood incorporated within the mineral layers; and 5) mineral soil organic matter, which is organic matter incorporated in the mineral soil (Aber and Melillo 1991; Harmon and others 1986; Harvey and others 1987; Waring and Schlesinger 1985). The dead organic matter components of forests represent different substrate qualities, including sizes and state of decomposition; thus each has its own unique carbon pools.

Because the type of vegetation influences the kinds of carbon compounds present, carbon pools vary depending on forest type. This, combined with the

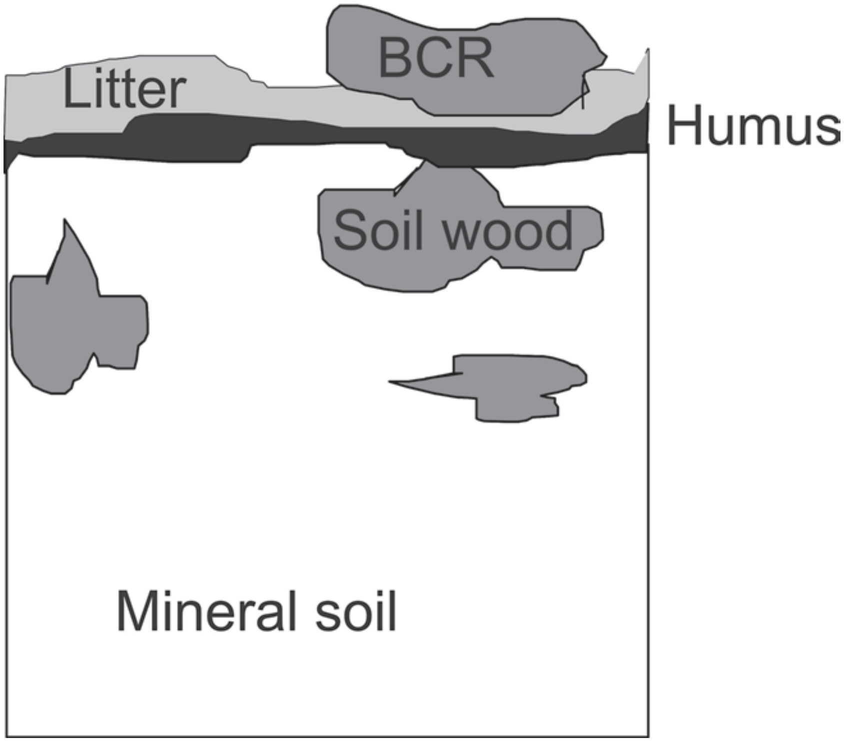

**Figure 1**—The forest floor and mineral soils contain five organic elements: litter, humus, brown cubical rotten wood (BCR), soil wood, and organic matter in the mineral soil. All these elements contribute to storing carbon. The difference between BCR and soil wood is the location of the material; soil wood is buried, often below the humus and litter, while BCR is on the surface. Soil organic matter typically decreases with depth (Woods 1989).

local climate, subsequently affects 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, BCR, and soil wood than a true fir (*Abies* spp.) forest. In turn, the amount of CWD created within a forest type also affects soil wood amounts, which is incorporated into soil mineral layers through freeze-thaw action, soil mixing, and erosion (Harvey and others 1987). For example, on moist forests the accumulation of CWD and soils wood is much greater than dry forests in the southwestern United States (Graham and others 1994).

## Carbon Estimates

There is wide variation in carbon storage among and within forest ecosystems. In forests of the Lake States, (Minnesota, Wisconsin, and Michigan), Grigal and Ohmann (1992) concluded that both stand age or successional stage and forest type influence the amount of carbon stored in the forest floor. They found that carbon continued to accumulate over time because in these ecosystems biomass was produced more rapidly 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). However, Grigal and Ohmann (1992) determined that wide variations in forest type were not necessary to notice subtle differences in carbon storage.

The role of CWD, BCR, 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 (Buringh 1984; Eswaran and others 1993; Franzmeier and others 1985; Huntington and others 1988; Post and others 1990; Schlesinger 1977). Studies have compared carbon storage in CWD between different forests (Harmon and Hua 1991; Keenan and others 1993). The results of these studies indicate that a large fraction of the terrestrial sink could potentially be located in woody debris. For example, Keenan and others (1993) reported that 60 percent of the forest floor in northern Vancouver Island was composed of woody material. In the Northern Rocky Mountains, up to 58 percent of the organic components can consist of CWD and soil wood (Harvey and others 1987).

To estimate carbon storage in vegetation, the amount of carbon is estimated to be 50 percent of the biomass (Grigal and Ohmann 1992; Hendrickson 1990; Lamlom and Savidge 2003; Linder and Axelsson 1982). Using this ratio assumes that all organic biomass has the same carbon concentration across different vegetation types and species. Although this is the best and most popular information currently available for estimating carbon, we hypothesize that ratios should differ among and between vegetation types.

Because estimating carbon storage is a key element in predicting the effects of climate change and determining carbon pools, it is important that valid conversion factors be used to minimize the amount of error these estimates may provide. Moreover, knowing where carbon is stored is important across vegetation types within the Rocky Mountains. Therefore, the objectives of this study are to acknowledge the appropriate carbon concentrations and distribution of carbon pools and provide improved estimates of carbon content in three forests types with different climatic regimes (dry, cold, and moist) of the Rocky Mountains. Although carbon management may not be a primary objective in forest management, knowing the changes and distribution of carbon pools may potentially influence management decisions in a future with climate change.

# Methods

## *Site Selection*

The sites selected for the study (fig. 2) include 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 wettest and most productive site was a western hemlock/queen cup beadlily (*Tsuga heterophylla* (Raf.) Sarg.)/ (*Clintonia uniflora* (Schult.) Kunth) (WH/CLUN) habitat type (Cooper and others 1991) on the Priest River Experimental Forest in northern Idaho (sites 1-3). A cold-dry subalpine fir/dwarf huckleberry (*Abies lasiocarpa* (Hook.)Nutt.)/(*Vaccinium scoparium* Leib.) (SAF/VASC) habitat type (Pfister and others 1977) was located on the Deerlodge National Forest near Butte, Montana (sites 4-6). Two warm-dry sites were selected in northern Arizona: a ponderosa pine (*Pinus ponderosa* C. Lawson)/gambel

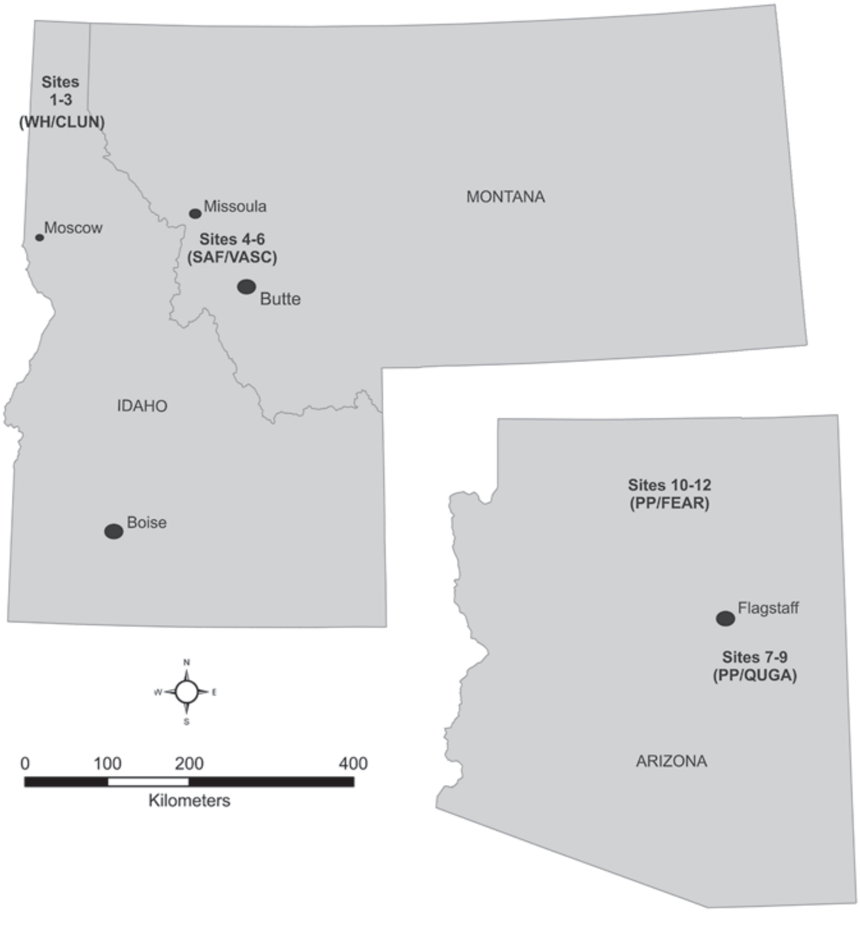

**Figure 2**—The general locations of study areas. Study sites 1-3 are located in northern Idaho within the western hemlock (*Tsuga heterophylla* (Raf.) Sarg./queencup beadlily (*Clintonia uniflora* (Schult.) Kunth) (WH/CLUN) habitat type (Cooper and others 1991). Study sites 4-6 are located in western Montana within the subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.)/dwarf huckleberry (*Vaccinium scoparium* Leib.) (SAF/VASC) habitat type (Pfister and others 1977). Study sites 7-12 are located in northern Arizona: 7-9 are located within the ponderosa pine (*Pinus ponderosa* C. Larson)/gambel oak (*Quercus gambelii* Nutt.) (PP/QUGA) (Larson and Moir 1986) and 10-12 are located within the ponderosa pine (*Pinus ponderosa* Dougi. ex Lawsi/Arizona fescue (*Festuca arizonica* Vasey) (PP/FEAR). Please refer to table 1 for specific characteristics of each site.

oak (*Quercus gambelii* Nutt.) (PP/QUGA) habitat type on the Coconino National Forest (Larson and Moir 1986) (sites 7-9) and a ponderosa pine/Arizona fescue (*Festuca arizonica* Vasey) (PP/FEAR) habitat type on the Kaibab National Forest (sites 10-12).

The WH/CLUN habitat type (Cooper and others 1991) occurs at elevations from 760 to 1,580 m (2,500 to 5,200 ft). Parent material is an ash cap over belt metasedimentary rocks (Alt and Hyndman 1989). Tree species include Douglas-fir, western larch (*Larix occidentalis* Nutt), western white pine (*Pinus monticola* Dougl. ex D. Don.), lodgepole pine (*Pinus contorta* Dougl. ax 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. 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 inches); snowfall averages 262 cm (103 inches). Average annual air temperature ranges from 4 to 10 °C (40 to 50 °F) (Graham 1990).

SAF/VASC is one of the most abundant habitat types east of the Continental Divide in Montana. Elevations 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). The overstory in the sites for this study are dominated by lodgepole pine, 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 inches), with snowfall averaging 686 cm (270 inches). Average annual air temperature ranges from –4 to 2 °C (25 to 35 °F) (Alexander and others 1990; Pfister and others 1977).

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), muttongrass (*Pea fendleriana* (Steud.) Vasey), and mountain muhly (*Muhlenbergia montana* Nutt.). PP/QUGA climate is similar to PP/FEAR (described below) but unlike the Kaibab Plateau, the majority of the precipitation falls during July through October (Brewer and others 1991; Larson and Moir 1986). Sites 7 through 9 were located on the Coconino National Forest in Arizona (table 1, fig. 2).

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 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's ceanothus (*Ceanothus fendleri* A. Gray), wax gooseberry (*Ribes cereum* Lindl.), mountain muhly, and muttongrass. Precipitation has a bimodal distribution with one wet season occurring July through October and another December through March. However, on the Kaibab plateau, greater than 50 percent of the precipitation falls between December and March. Total precipitation ranges from 520 to 600 mm (20 to 24 inches), with snowfall averaging 1,120 mm (47 inches). Mean annual air temperature ranges from 4 to 6 °C (39 to 43 °F) (Brewer and others 1991; Larson and Moir 1986).

Although we recognize that successional stage and/or stand age may influence the amount and distribution of carbon pools, our objective was to determine if the ratios and carbon pool location varied across different habitat types. To accomplish this we acquired a list, within each habitat and soil type, from forest

**Table 1**—Description of selected stands within each habitat type. Refer to figure 2 for study site locations.

| Cover type-study site | Age | Aspect (°) | Slope (%) | Elevation (m) | Parent material[b] |
|---|---|---|---|---|---|
| **The WH/CLUN[a] on the Idaho Panhandle National Forest—Priest Lake Ranger District (Priest River Experimental Forest)** | | | | | |
| WH/DF/WL/WP-1[c] | 100 | 310 | 45 | 1280 | Ash/Belt |
| WH/DF/WL/WP-2 | 100 | 340 | 45 | 1340 | Ash/Belt |
| WH/DF/WL/WP-3 | 100 | 340 | 45 | 1340 | Ash/Belt |
| **The SAF/VASC[a] on the Deerlodge National Forest—Butte Ranger District** | | | | | |
| LP-4[c] | 65 | 124 | 21 | 2073 | Volcanic |
| LP-5 | 65 | 124 | 21 | 2073 | Volcanic |
| LP-6 | 65 | 110 | 33 | 2073 | Volcanic |
| **The PP/QUGA[a] on the Coconino National Forest—Mormon Lake Ranger District** | | | | | |
| PP-7[c] | 141 | 0 | 0 | 2134 | Basalt |
| PP-8 | 150 | 0 | 0 | 2134 | Basalt |
| PP-9 | 145 | 0 | 0 | 2134 | Basalt |
| **The PP/FEAR[a] on the Kaibab National Forest—North Kaibab Ranger District** | | | | | |
| PP-10[c] | 127 | 0 | 0 | 2470 | Limestone |
| PP-11 | 125 | 0 | 0 | 2470 | Limestone |
| PP-12 | 123 | 0 | 0 | 2487 | Limestone |

[a] Habitat types and species for cover types: In northern Idaho (Cooper and others 1991) WH/CLUN = western hemlock (*Tsuga heterophylla* (Raf.) Sarg./queencup beadlily (*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* C. Larson/Arizona fescue (*Festuca arizonica* (Vasey) and PP/QUGA = ponderosa pine/gambel oak (*Quercus gambelii* Nutt.).

[b] Parent materials are (Alt and Hyndman 1989; Hunt 1972) **Ash**, fine shreds of lava blown from Mount Mazama; **Belt**, mildly metamorphosed sedimentary rocks, including argillites, siltites, quartzites, and dolomites; **Volcanic (Rhyolite)**, lava or shallow intrusion, fine grained, with composition equivalent to granite. **Basalt**: Black volcanic rock rich in iron, calcium, and magnesium, composed primarily of plagioclase; and **Limestone**, sedimentary rock or surface deposit of calcium carbonate.

[c] Species are WH = western hemlock, DF = Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), WL = western larch (*Larix occidentalis* Nutt), WP = western white pine (*Pinus monticola* Dougl. ex D. Don.), LP = lodgepole pine (*Pinus contorta* Dougl. ax Loud.), and PP = ponderosa pine. The number following species cover type refers to the site number located on figure 2.

silviculturists and soil scientists of undisturbed stands consisting of mid-to late seral vegetation. From each list, three sites were randomly selected and then verified (table 1).

## *Data Collection*

Twelve points were systematically located on a random transect bisecting the site. From these points, forest components and data for biomass estimates were sampled using five plot types: 1) variable, 2) fixed, 3) microsite, 4) soil core, and 5) line intersect (table 2). A variable plot using probability proportional to size was used to sample total height and d.b.h. (diameter at 4.5 ft; 1.4 m) for trees ≥12.7 cm (5 inches) d.b.h. 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; 0.5 inches diameter) were sampled 20 to 25 cm (7 to 10 inches) 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.

The second plot type was a 13.5 $m^2$ (1/300 acre) fixed-area circular plot (table 2). Trees <12.7 cm (5 inches) d.b.h. occurring on this plot were tallied and their heights were measured; for trees ≥1.4 m (4.5 ft) tall, d.b.h was measured, while basal diameter was measured on trees <1.4 m (4.5 ft) tall. In addition, foliage samples for carbon analysis were taken from the understory trees. Average basal diameter and number of stems occurring on the plot were also recorded for the following shrub

**Table 2—**Forest components and plot types where measurements and samples were obtained.

| | Plot type[a] | | | | |
|---|---|---|---|---|---|
| **Forest component** | **Variable** | **Fixed** | **Microsite** | **Line intersect** | **Soil core** |
| Trees | | | | | |
| Overstory crown | X | | | | |
| Sapwood[b] | X | | | | |
| Heartwood[b] | X | | | | |
| Coarse roots (≥1 cm diameter) | X | | | | |
| Fine roots (<1 cm diameter) | | | | | X |
| Understory crown (<12.7 cm tall) | | X | | | |
| Understory vegetation[c] | | | | | |
| Small shrubs (<0.5 cm) | | | X | | |
| Medium shrubs (0.5 to 2.0 cm) | | X | | | |
| Forbs and grasses | | | X | | |
| Woody residue[d] | | | | | |
| Sticks (<7.5 cm diameter) | | | | X | |
| Solid logs (≥7.5 cm diameter) | | | | X | |
| Rotten logs (≥7.5 cm diameter) | | | | X | |
| Cones | | | X | | |
| Organic soil | | | | | |
| Brown cubical rotten wood | | | X | | X |
| Litter | | | X | | X |
| Humus | | | X | | X |
| Soil wood | | | X | | X |
| Mineral soil[e] | | | | | |
| Shallow mineral (0-10 cm) | | | | | X |
| Deep mineral (>10, up to 30 cm) | | | | | X |

[a] Plot types: 1) variable, based on probability, proportional to tree diameter. On the Idaho Panhandle, Kaibab, and Coconino National Forests, we used a 40 basal area factor (BAF); on the Deerlodge we used a 20 BAF; 2) fixed, a 0.0013 ha (24th acre) circular plot; 3) microsite, a 30 cm (12 inches) circular plot; 4) transect, 15.2 m (50 ft) in length (Brown 1974); and 5) soil core, l0 by 30 cm (4 by 12 inches).

[b] Sampled using increment cores at 1.4 m (4.5 ft).

[c] Shrub size classes are from Brown (1976).

[d] Size classes are from Brown (1974).

[e] Soil depths are from Jurgensen and others (1977).

size-classes from Brown (1976): low (0 to 0.5 cm; 0 to 0.2 inches) and medium (0.51 to 2.0 cm; 0.2 to 0.75 inches); tall shrubs (2.01 to 5.0 cm; 0.76 to 2 inches) were not present in any of the plots. When present, foliage samples for carbon analysis were taken for medium shrubs. The third plot type (microsite) was a 30 cm (12 inches) diameter hoop (table 2). All cones and organic soil components were collected for carbon analysis on this plot. Next to the microsite plot, a fourth type of plot consisted of extracting a 10 by 30 cm (4 by 12 inches) soil core. Litter, humus, soilwood (rotten wood buried in established humus or mineral soil horizon), and BCR were separated. Mineral soil was separated into two depths: shallow mineral (0 to 10 cm depth) and deep mineral (10-30 cm depth). Depth of each horizon was recorded and the entire sample was taken from the core from each horizon and placed in a cloth bag. Mineral soil bulk density was sampled at 0 to 10 cm (0 to 4 inches) and 10 to 20 cm (4 to 8 inches) depths using a 135.7 cm$^3$ (8.4 in$^3$) core sampler. Samples of BCR, litter, humus, soil wood, and mineral soils at two depths were collected for carbon analysis.

The fifth type of plot was a line intersect to determine woody residue biomass (Brown 1974) (table 2). 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 inches), and solid and rotten logs ≥7.5 cm (3 inches). For carbon analysis, a sample was taken from each residue class.

## Biomass Estimates

The Forest Vegetation Simulator (FVS) (Dixon 2002; Wykoff and others 1982) and field data were used to estimate tree biomass (tables 3 and 4). FVS provided a list that included total cubic foot volume, species, diameter, height, and number of trees per unit area for each sample tree represented. Published regression equations (tables 3 and 4) 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).

To estimate shrub biomass, we used regression equations (table 4) for the basal stem diameter-based size-classes (Brown 1976) described above. 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 and logs (solid and rotten) 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) weights of cones, organic components, and fine roots were expanded to a per unit area basis.

## Laboratory Analysis

Field collections were taken to the Forestry Sciences Laboratory in Moscow, Idaho, and prepared for carbon and organic matter analysis. Soils were oven-dried and sieved using screens with 2 mm (0.08 inches) openings. Roots were removed

**Table 3**—Regression equations used for estimating biomass for components of trees ≥5 cm (2 inches). Columns A, B, and C show coefficient values for specific species.

| | | **Bole and bark**[c] | | | **Coarse roots** | | |
|---|---|---|---|---|---|---|---|
| | | **Wt (lb) =VolA +VolBC** | | | **Log$_{10}$WT (kg) =B(log$_{10}$DBH(cm) +Log$_{10}$A** | | |
| **Species**[a] | **Crown**[b] | **A** | **B** | **C** | **B** | **Log$_{10}$A** | **Reference** |
| PP | exp[0.2680+2.0740(Ind)] | 25.0 | 0.24 | 21.8 | 2.445 | –0.94 | Will 1966[d] |
| ES | exp[l.0404+l.7096(Ind)] | 21.8 | 0.19 | 30.6 | 2.151 | –1.24 | Whittaker and others 1974 |
| GF | exp[l.3094+l.6076(Ind)] | 23.1 | 0.20 | 37.4 | 2.445 | –1.71 | Baskerville 1965 |
| SAF | 7.345+1.255(diameter$^2$) | 20.0 | 0.19 | 27.4 | 2.445 | –1.71 | Baskerville 1965 |
| | | | | | **Log$_{10}$Wt (lb) =Blog$_{10}$DBH$^2$(in) Ht(ft) +log$_{10}$A** | | |
| WWP | exp(0.7276+l.5497(Ind)] | 23.7 | 0.21 | 26.2 | 1.022 | 1.879 | Johnstone 1971 |
| WL | exp[0.4373+l.6786) (Ind)] | 32.4 | 0.24 | 24.3 | 1.022 | 1.879 | Johnstone 1971 |
| LP | exp[0.1224+l.8820(Ind)] | 25.6 | 0.11 | 26.5 | 1.022 | 1.879 | Johnstone 1971 |
| | | | | | **Wt(kg)=A(DBH) (cm)** | | |
| | | | | | **A** | **B** | |
| DF <43 cm | exp[l.368+l.5819(Ind)] | 30.0 | 0.19 | 27.4 | 0.01 | 2.630 | Kuiper and Coutts 1992 |
| DF ≥43 cm | 1.0237(diameter$^2$) - 20.74 | | | | | | |
| | | | | | **lnWt(kg)=B+Aln(DBH) (cm)** | | |
| WH | exp[0.72l8+l.7502(Ind)] | 28.1 | 0.19 | 31.2 | –4.159 | 2.519 | Feller 1992 |
| WRC | exp(0.88l5+1.6389(Ind)] | 20.0 | 0.15 | 23.1 | –4.159 | 2.519 | Feller 1992 |

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

[b] Ind = natural log diameter in inches (Brown 1978); $d^2$ = diameter$^2$.

[c] Wt = Weight; Vol = ft$^3$ ; A = specific gravity of wood; B = percentage of bark; C = specific gravity of bark.

[d] Cited 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 inches). Columns A and B show coefficient values for specific species.

| Species[a] | Crown weight[b] | | Reference |
|---|---|---|---|
| Douglas-fir | exp[–4.212 + 2.7168 (lnht] | | Brown 1978 |
| Lodgepole pine | exp[0.0311(height$^2$) | | Brown 1978 |
| Western larch | exp(–5.126 + 2.5639(lnht)] | | Brown 1978 |
| Grand fir | 0.0538 (height$^2$) | | Brown 1978 |
| Western redcedar | 0.0307 (height$^2$) | | Brown 1978 |
| Ponderosa pine | exp[–2.7297 + 1.1707 (lnht)] | | Brown 1978 |
| | **Shrubs, forbs, and grasses** | | |
| | lnWt(g)= A+ Bln basal stem diameter (cm) | | Brown 1976 |
| | A | B | |
| *Vaccinium scoparium* | 2.113 | 2.148 | |
| *Juniperus communis* | 4.081 | 2.202 | |
| Combined low shrub | 3.565 | 3.565 | |
| Forbs and grasses[c] | 1nWt(kg/ha)=2.517 – 0.294 (10$^{-1}$)BA[c] | | Covington & Fox 1991 |

[a] Refer to table 3 for scientific names of species.

[b] lnht=natural log of height (ft)

[c] BA is basal area in m$^2$/ha

from the soils and coarse fragments greater than 2 mm (0.08 inches) diameter were weighed. The twelve samples from the litter, humus, BCR, soil wood, and mineral soils were each combined into four composites for each stand. Each composite was composed of three adjacent samples that were collected along the transect line. Similar to the soils, 12 samples were collected from the other forest components, were oven-dried and ground, and then placed into three composites. Before conducting any laboratory analyses, mineral soils were tested for carbonates using 10 percent hydrochloric acid (Soil Survey Staff 1992). The LECO Carbon, Hydrogen, Nitrogen (CHN-600) Autoanalyzer was used to determine the organic carbon concentration of soil and forest components.

### *Statistical Analysis*

Analysis of variance for a randomized complete block design was used to analyze 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 (Steel and Torrie 1960). Mean values for each variable were computed for the stand prior to analysis. Therefore, the four habitat types described above served as the main effects in three replications (stands). Scheffé's (1953) S test was used to separate main effect means when more than two means were compared. Carbon proportional data (percent) were transformed using the square root of the arcsine prior to performing the analysis of variance. The analyses were conducted at P-level of $\leq$0.05.

## Results

### *Organic Biomass*

In all habitat types, outside the mineral soil, the highest amount of biomass occurred in tree boles and the least amount occurred in fine roots (table 5), while coarse roots contributed the second largest amount. Among habitat types, PP/FEAR and PP/QUGA tree bole biomass was greater than other habitat types

**Table 5**—Forest component biomass (Mg/ha) estimates (mean) and standard error ($S_{\bar{x}}$) by forest habitat type. The different letters (x, y, or z) indicate significant differences; if letters are the same there were no significant difference among the habitat types. Refer to table 1 for habitat type designation.

| | Habitat type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | PP/FEAR | | PP/QUGA | | WH/CLUN | | SAF/VASC | |
| Forest component | Mg/ha | $S_{\bar{x}}$ | Mg/ha | $S_{\bar{x}}$ | Mg/ha | $S_{\bar{x}}$ | Mg/ha | $S_{\bar{x}}$ |
| **Trees** | | | | | | | | |
| Overstory crown | 99 | 7 | 113 | 10 | 51 | 3 | 31 | 4 |
| Bole | 415 | 16 | 388 | 46 | 268 | 21 | 160 | 31 |
| Coarse roots (≥1 cm diameter) | 215 | 10 | 252 | 22 | 84 | 11 | 68 | 13 |
| Fine roots (<1 cm diameter) | 0.l | 0.1 | 0.3 | 0.1 | 9 | 2 | 5 | 4 |
| Understory trees (<12.7 cm tall) | 1 | 0.6 | 1 | 0.5 | 0.3 | 0.2 | 1 | 0.2 |
| | x | | x | | y | | y | |
| Total | 730.1 | 33.7 | 754.3 | 78.6 | 412.3 | 37.2 | 265.3 | 52.2 |
| **Understory vegetation** | | | | | | | | |
| Medium shrub (0.5-2.0 cm) | — | — | — | — | — | — | 9 | 4 |
| Low shrub (<0.5 cm) | — | — | 0.l | 0.1 | — | — | 32 | 5 |
| Forbs and grasses | 0.1 | 0.01 | 0.3 | 0.2 | — | — | — | — |
| | y | | y | | | | x | |
| Total | 0.1 | 0.01 | 0.4 | 0.2 | — | — | 41 | 9 |
| **Woody residue** | | | | | | | | |
| Sticks (<7.5 cm diameter) | 2 | 1 | 5 | 1 | 11 | 0.3 | 3 | 0.4 |
| Solid Log (≥7.5 cm diameter) | 4 | 3 | 0.l | 0.1 | 42 | 10 | 1 | 1 |
| Rotten log (≥7.5 cm diameter) | 2 | 1 | 4 | 1 | 47 | 6 | 8 | 3 |
| Cones | 23 | 8 | 27 | 7 | 9 | 2 | 7 | 3 |
| | y | | y | | x | | y | |
| Total | 31.4 | 13 | 36.1 | 9.1 | 109 | 18.3 | 19 | 7.4 |
| **Organic soil** | | | | | | | | |
| Brown cubicle rot | 0.4 | 0.2 | 3 | 1 | 3 | 3 | 10 | 5 |
| Litter | 33 | 6 | 63 | 4 | 33 | 16 | 40 | 11 |
| Humus | 65 | 14 | 87 | 8 | 127 | 29 | 98 | 22 |
| Soil wood | 1 | 0.4 | 18 | 8 | 103 | 65 | 36 | 18 |
| | x | | x | | x | | x | |
| Total | 99.4 | 20.6 | 171 | 21 | 266 | 113 | 184 | 56 |
| **Mineral soil** | | | | | | | | |
| | x | | x | | z | | y | |
| Shallow mineral (0-10 cm) | 1198 | 16 | 1170 | 52 | 512 | 48 | 756 | 41 |
| | X | | x | | Y | | y | |
| Deep mineral (>10, up to cm) | 2992 | 18 | 2757 | 45 | 1306 | 121 | 1637 | 20 |

(table 5) and coarse root biomass was significantly greater (>215 Mg/ha; 100 tons/acre) than the other habitat types (<85 Mg/ha; 40 tons/acre). However, fine root biomass was greater in the WH/CLUN and SAF/VASC habitat types.

In addition to tree components, table 5 shows biomass estimates for understory vegetation, woody residue, organic soil, and mineral soil. With the exception of SAF/VASC, where shrubs were a significant component (>40 Mg/ha; 18 tons/acre), understory vegetation did not contribute large amounts of biomass. PP/QUGA had only 0.1 Mg/ha (0.05 tons/acre), while WH/CLUN did not have any. Among habitat types, there were significant differences in biomass across woody debris classes. For example, solid and rotten logs contributed most of the woody residue biomass for WH/CLUN, while cones contributed significantly in the ponderosa pine habitat types. Mineral soil had the greatest total weight, with deep mineral having more mass than shallow mineral.

Several tree species contributed to total tree biomass (no table shown). Eight species occurred in the WH/CLUN habitat type, with the majority consisting of western redcedar (134.5 Mg/ha; 62 tons/acre) and western hemlock (129.1 Mg/ha; 60 tons/acre), along with a minor component of western white pine (17.5 Mg/ha; 8 tons/acre) and subalpine fir (4.7 Mg/ha; 2 tons/acre). Tree biomass in the ponderosa pine habitat types consisted of only ponderosa pine and for SAF/VASC, only lodgepole pine.

## *Carbon Concentrations*

Carbon concentrations were compared among forest components and habitat types (table 6). In all habitat types, carbon concentrations in fine and coarse roots were lower (44 percent to 47 percent) than the concentrations in overstory crown, bole, and understory trees (47 percent to 50 percent). Some of the lowest carbon concentrations (32 percent to 42 percent) occurred in the forbs and grasses component of understory vegetation. Among habitat types, the only significant differences occurred in the understory trees, where WH/CLUN had a significantly lower carbon concentration (47 percent) than the understory trees in both the ponderosa pine (50 percent) and SAF/VASC (49 percent) habitat types.

For woody residue, among the habitat types, solid log carbon concentrations were significantly lower in the SAF/VASC habitat type than the other habitat types; however, this was not statistically significant (table 7). We also had non-statistically significant results concerning rotten logs. However, those created from ponderosa pine had some of the lowest carbon concentrations (46 percent) compared to the other habitat types. Sticks in the ponderosa pine habitat types had significantly more carbon (49 percent) than sticks in the WH/CLUN (47 percent) and SAF/VASC (48 percent) habitat types. A similar trend occurred with cones, with 49 percent for ponderosa pine habitat types, 46 percent for WH/CLUN, and 47 percent for SAF/VASC.

**Table 6**—Carbon concentrations (%) are for vegetation by habitat type with the mean and standard error ($S_{\bar{x}}$). Significant differences among the means across habitat types are presented as x, y, and z located above the value. Significant differences among the means across different forest components within a habitat type are presented as "a" and "b" located next to the value. If the letter is the same no significant differences were identified. For habitat type designation, refer to table 1.

| | PP/FEAR | | PP/QUGA | | WH/CLUN | | SAF/VASC | |
|---|---|---|---|---|---|---|---|---|
| **Forest component** | **%** | **$S_{\bar{x}}$** | **%** | **$S_{\bar{x}}$** | **%** | **$S_{\bar{x}}$** | **%** | **$S_{\bar{x}}$** |
| | | | | **Trees** | | | | |
| Overstory crown | x<br>49.9 a | 0.2 | x<br>49.9 a | 0.2 | x<br>49.2 a | 0.2 | x<br>49.4 a | 0.1 |
| Bole | xy<br>49.0 a | 0.4 | x<br>49.5 a | 0.2 | yz<br>47.3 a | 0.2 | z<br>47.2 b | 0.4 |
| Coarse roots (≥1 cm diameter) | x<br>47.2 ab | 0.7 | x<br>48.6 a | 0.6 | x<br>46.8 a | 0.3 | x<br>47.l b | 0.3 |
| Fine roots (<1 cm diameter) | x<br>44.0 b | 1.2 | x<br>46.2 b | 0.4 | x<br>46.1 a | 0.4 | x<br>44.9 c | 0.4 |
| Understory trees (<12.7 cm dbh) | X<br>49.9 a | 0.03 | x<br>49.8 a | 0.1 | y<br>47.3 a | 0.2 | x<br>49.l ab | 0.2 |
| | | | | **Understory vegetation**[a] | | | | |
| Medium shrub (0.5-2.0 cm basal diameter) | — | — | — | — | — | — | 48.3 a | 0.2 |
| Low shrub (<0.5 cm basal diameter) | x<br>47.l a | 0.6 | x<br>46.7 a | 0.5 | x<br>45.5 a | 0.5 | x<br>47.8 a | 0.2 |
| Forbs and grasses | x<br>42.7 b | 0.4 | x<br>41.5 b | 0.6 | x<br>41.6 b | 1.3 | x<br>42.0 b | 0.4 |

[a] Shrub size classes are from Brown (1976).

**Table 7**—Carbon concentrations (%) for vegetation by habitat type with the mean and standard error ($S_{\bar{x}}$). Refer to table 1 for habitat type designation. Significant differences among the means across habitat types are presented as x, y, and z located above the value. Significant differences among the means across different forest components within a habitat type are presented as "a" and "b" located next to the value. If the letter is the same no significant differences were identified.

| | PP/FEAR | | PP/QUGA | | WH/CLUN | | SAF/VASC | |
|---|---|---|---|---|---|---|---|---|
| **Forest component** | **%** | **$S_{\bar{x}}$** | **%** | **$S_{\bar{x}}$** | **%** | **$S_{\bar{x}}$** | **%** | **$S_{\bar{x}}$** |
| **Woody Residue** | | | | | | | | |
| Sticks (<7.5 cm diam.) | x<br>49.l ab | 0.3 | x<br>49.0 a | 0.1 | y<br>46.9 a | 0.3 | y<br>47.6 ab | 0.2 |
| Solid log (≥7.5 cm diam.) | x<br>50.5 a | 1.5 | x<br>49.5 a | 1.2 | x<br>47.0 a | 0.2 | x<br>46.0 bc | 0.1 |
| Rotten log (≥7.5 cm diam.) | x<br>46.3 ab | 0.9 | x<br>50.8 a | 1.6 | x<br>47.9 a | 0.7 | x<br>48.9 a | 0.6 |
| Cones | x<br>48.6 ab | 0.6 | x<br>48.7 a | 0.4 | y<br>46.0 a | 0.2 | xy<br>46.5 abc | 0.3 |
| **Soil** | | | | | | | | |
| Brown cubical rot | x<br>48.2 a | 0.9 | x<br>47.l a | 1.5 | x<br>48.l a | 0.9 | x<br>49.0 a | 0.7 |
| Litter | x<br>41.3 ab | 1.5 | x<br>32.7 ab | 3.4 | x<br>34.0 b | 2.6 | x<br>43.6 ab | 1.2 |
| Humus | x<br>36.2b | 3.6 | xy<br>29.l b | 4.4 | y<br>21.9 c | 2.0 | xy<br>26.8 c | 1.9 |
| Soil wood | x<br>47.2 a | 2.4 | x<br>44.6 ab | 3.0 | x<br>42.9 ab | 0.9 | x<br>41.6 b | 1.0 |
| Shallow mineral (0-10 cm) | x<br>6.l c | 0.5 | x<br>4.5 c | 0.6 | x<br>4.4 d | 0.6 | y<br>1.4 d | 0.1 |
| Deep mineral (>10, up to 30 cm) | yz<br>1.9c | 0.5 | xy<br>2.5c | 0.6 | x<br>3.5d | 0.3 | z<br>0.7d | 0.04 |

In the forest soil component, BCR tended to have statistically significant higher carbon concentrations (ranging from 47 percent to 49 percent) than the other soil components within each habitat type (table 7). More importantly, in all habitat types, the mineral soils had the lowest carbon concentrations, ranging from 1 percent to 6 percent. Within habitat types, concentrations for deep mineral soil were lower than those for shallow mineral soil, except WH/CLUN, which had 4 percent for both. The similarities that did occur were in the ponderosa pine habitat types where concentrations for humus were similar to those for litter.

Nine different tree species contributed to carbon concentrations for the tree components (table 8). For the overstory crowns, there were significant differences among species. For example, subalpine fir crowns had the highest (51 percent), while Engelmann spruce crowns had the lowest (48 percent). The results revealed no significant differences among species in sapwood carbon concentrations; however, significant differences were noted for heartwood, ranging from 46 percent for Engelmann spruce to 53 percent for ponderosa pine. For example, subalpine fir contained 46 percent while Douglas-fir contained 50 percent. Understory concentrations did not range as much (48 percent to 50 percent), with ponderosa pine having the highest (50 percent). For coarse root concentrations among species, Douglas fir had the highest (50 percent), while western redcedar and subalpine fir had the lowest concentrations (each had 46 percent).

**Table 8**—Carbon concentrations (%) for individual species with the mean and standard error ($S_{\bar{x}}$). Significant differences among the means across habitat types are presented as x, y, and z located above the value. Significant differences among the means across different forest components within a habitat type are presented as "a" and "b" located next to the value. If the letter is the same no significant differences were identified. Refer to table 1 for habitat type designation.

| | Overstory crown | | Bole wood | | | | Coarse roots | | Understory crown | |
|---|---|---|---|---|---|---|---|---|---|---|
| Species[a] | % | $S_{\bar{x}}$ | Sap wood % | $S_{\bar{x}}$ | Heart wood % | $S_{\bar{x}}$ | % | $S_{\bar{x}}$ | % | $S_{\bar{x}}$ |
| WWP | x<br>50.0 ab | 0.4 | xy<br>48.5a | 0.9 | xy<br>48.9 b | 0.8 | xy<br>48.4 ab | 0.1 | y<br>47.3 ab | 0.1 |
| DF | y<br>48.7 bc | 0.3 | z<br>47.l a | 0.2 | z<br>47.4 bc | 0.3 | x<br>49.8 a | 0.6 | z<br>47.5 ab | 0.4 |
| GF | x<br>49.3 ab | 0.3 | y<br>47.7 a | 0.1 | y<br>47.7 bc | 0.1 | z<br>45.9 cd | 0.2 | y<br>47.8 ab | 0.3 |
| WH | x<br>49.9 ab | 0.3 | y<br>46.4 a | 0.1 | y<br>47.l bc | 0.2 | y<br>47.3 bcd | 0.2 | y<br>47.3 ab | 0.2 |
| WRC | x<br>48.8 bc | 0.2 | xy<br>47.l a | 0.1 | xy<br>48.0 bc | 0.3 | y<br>45.7 cd | 0.1 | xy<br>46.6 b | 0.9 |
| LP | x<br>49.5 ab | 0.1 | y<br>47.4 a | 0.03 | y<br>47.S bc | 0.1 | y<br>47.l bcd | 0.3 | x<br>49.l ab | 0.2 |
| ES | xy<br>47.6 c | 0.1 | y<br>46.7 a | 0.2 | y<br>46.4 c | 0.2 | y<br>46.5 bcd | 0.3 | x<br>48.0 ab | 0.1 |
| SAF | x<br>50.5 a | 0.2 | x<br>43.7 a | 3.5 | x<br>47.4 bc | 0.2 | x<br>45.7 d | 0.1 | — | — |
| PP | xy<br>49.9 ab | 0.1 | y<br>47.5 a | 0.2 | x<br>52.5 a | 0.8 | y<br>47.9 abc | 0.4 | xy<br>49.9 a | 0.1 |

[a] Tree species are WWP-western white pine (*Pinus monticola* Dougl. ex D. Don); DF-Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco); GF-grand fir (*Abies grandis* Dougl. cx D. Don); WH-western hemlock (*Tsuga heterophylla* (Raf.) Sarg.); WRC-western red cedar (*Thuja plicata* Dorm cx D.Don>; LP-lodgepole pine (*Pinus contorta* oougl. cx Loud.); ES-Engelmann spruce (*Picea Engelmannii* Parry cx Engelm.); SAF-subalpine fir (*Abies lasiocarpa* (Dougl. cx D. Don) Lindl; PP-ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.)

## Carbon Content

We compared total carbon content in each classification among and within habitat types (fig. 3). The ponderosa pine types were considerably higher than others, with 562 Mg/ha (251 tons/acre) for PP/QUGA and 533 Mg/ha (238 tons/acre) for PP/FEAR; WH/CLUN had 394 Mg/ha (176 tons/acre) and SAF/VASC had 239 Mg/ha (107 tons/acre).

Within all habitat types, the highest proportion of carbon content was in trees; PP/FEAR had 62 percent, PP/QUGA 61 percent, SAF/VASC 42 percent, and WH/CLUN 40 percent. The component with the lowest proportion of the total carbon content for all four habitat types was woody residue, with WH/CLUN having the highest proportion (11 percent) compared to the others. Carbon content in the soils was not significantly different among habitat types.

In all habitat types (no figure shown), carbon content in trees was dominated by the boles, followed by coarse roots and understory crowns; fine roots had the least amount of carbon (fig. 3). Interestingly, carbon content in fine roots tended to be higher in the WH/CLUN (4.0 Mg/ha; 1.8 tons/acre) and SAF/VASC (2.2 Mg/ha; 0.9 tons/acre) habitat types compared to the ponderosa pine types (0.1 to 0.2 Mg/ha; 0.04 to 0.09 tons/acre). In SAF/VASC, shrubs had higher carbon content (15.0 Mg/ha; 7 tons/acre) compared to the forbs and grasses. In contrast, grasses and forbs had higher carbon content in PP/FEAR.

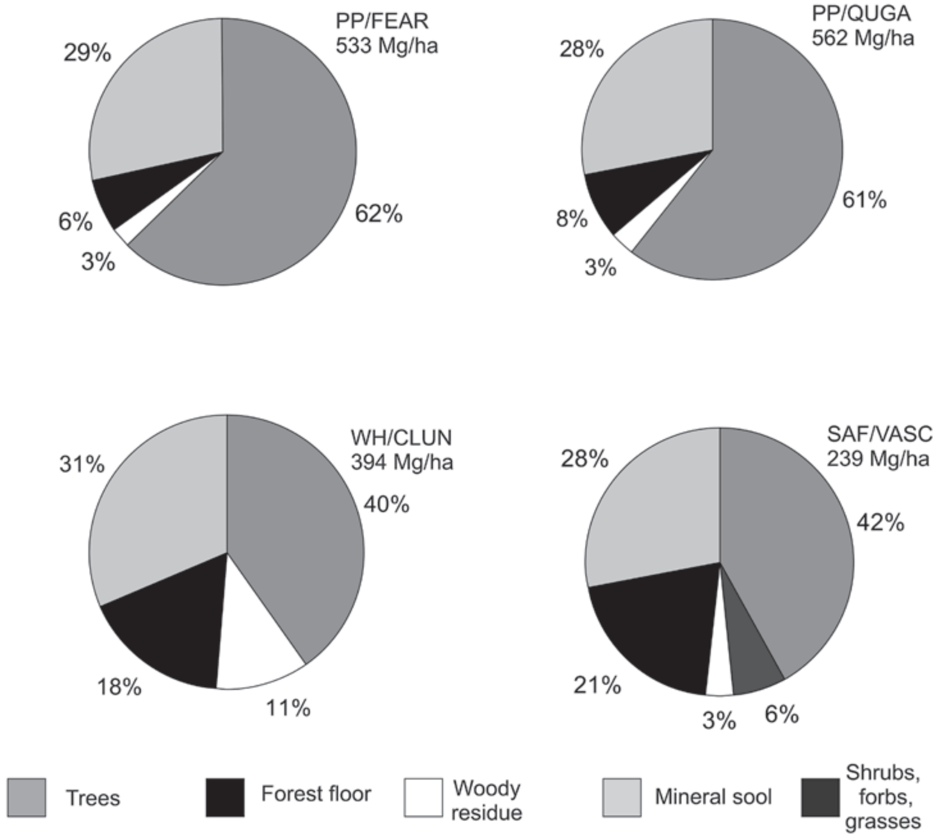

**Figure 3**—The distribution of carbon for trees, forest floor, woody residue, mineral soils, and understory vegetation (shrubs, forbs, and grasses) in the four habitat types (see figure 2 for habitat type definitions). The ponderosa pine sites (PP/FEAR and PP/QUGA) had significantly more carbon in the trees than the WH/CLUN or SAF/VASC sites. Woody residue, although a minor component, was significantly more abundant in WH/CLUN than the other sites. Shrubs and grasses tended to contribute more towards total carbon content in WH/CLUN and SAF/VASC compared to the ponderosa pine sites.

For woody residue components, cones comprised a rather large proportion of total carbon content in the ponderosa pine habitat types; PP/FEAR had 73 percent of the 15 Mg/ha in cones and PP/QUGA had 74 percent of the 18 Mg/ha in cones (fig. 4). In the WH/CLUN habitat type rotten (44 percent) and solid logs (38 percent) contributed the most carbon. In SAF/VASC, no significant differences occurred among woody residue components but the proportion of carbon content tended to be higher in cones (35 percent) and rotten logs (44 percent). Significant differences did occur among habitat types for sticks; SAF/VASC (15 percent) and PP/QUGA (14 percent) had more than WH/CLUN (10 percent) and PP/FEAR (7 percent).

Carbon content within the forest floor was dominated by mineral soil in the PP/FEAR habitat type (fig. 5). Within the organic soil components, humus and litter in PP/FEAR had significantly more than BCR and soil wood, while in PP/QUGA organic components (litter, humus, soil wood, and BCR) were not a significant contribution. In the SAF/VASC and WH/CLUN habitat types, no significant differences occurred among any of the soil components, indicating that carbon was well distributed among the different soil components. Comparisons among habitat types showed no significant differences in carbon content across the soil components, except in mineral soils. Generally, the content in shallow mineral soils for the ponderosa pine habitat types was higher than WH/CLUN or SAF/VASC.

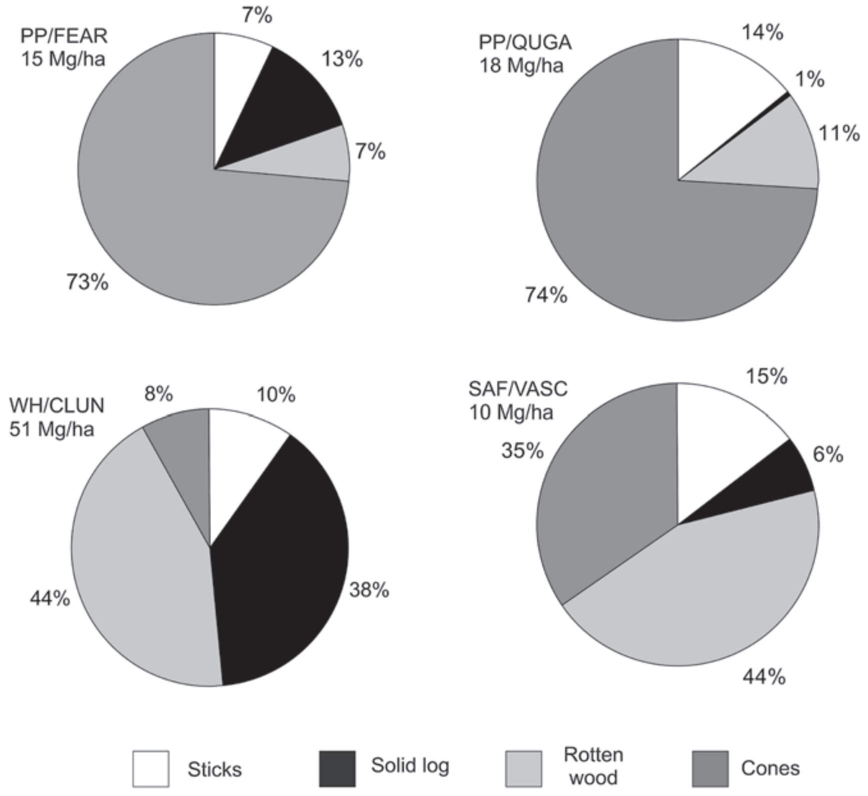

**Figure 4**—The distribution of woody residue in each of the habitat types. For the PP/FEAR and PP/QUGA, most of the woody residue was in cones, with 73% and 74% respectively. WH/CLUN had the highest amount of carbon in woody residue, with 51 Mg/ha; the greatest proportions of this occurred in solid and rotten logs. SAF/VASC had the lowest amount of carbon in woody residue; a large percentage of this was in cones (35%) and rotten wood (44%).

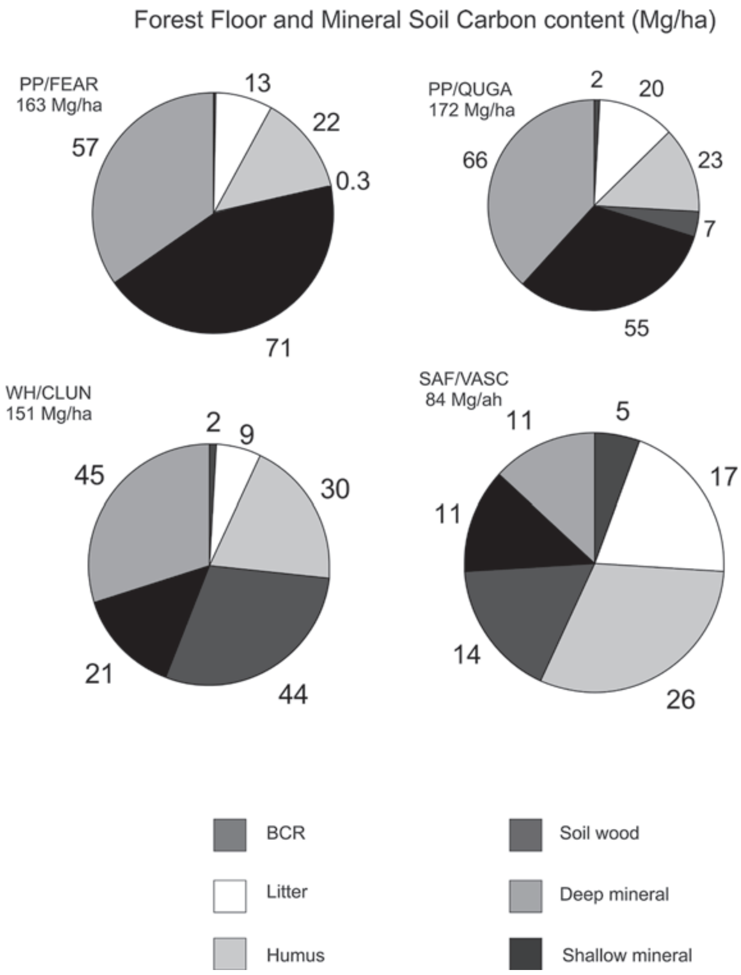

**Figure 5**—The distribution of carbon content varied widely among the different habitat types. In the ponderosa pine habitat types (PP/FEAR and PP/QUGA), mineral soil (shallow and deep) dominated. In contrast, for WH/CLUN and SAF/VASC, carbon was located in many more places besides litter (for example, humus, BCR, and soil wood). In addition, shallow mineral soil contained more carbon in WH/CLUN than in SAF/VASC.

In the deep mineral layers, carbon content (10.9 Mg/ha; 5 tons/acre) in SAF/VASC was significantly less than the carbon content among the other habitat types.

# 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). Besides being a key element in forest ecosystems, carbon is also essential for sustaining life on a global scale (Bolin and others 1979). Estimating carbon reserves in all ecosystems is critical if we are to understand the role carbon plays in climate change (Post and others 1990; Schlesinger 1977). It is also 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, additional information on carbon concentrations in forest components could improve those estimates.

## *Carbon Concentrations*

To help improve the accuracy of estimates of carbon reserves in Rocky Mountain forests, this study quantified carbon concentrations for forest components in four habitat types (table 1). These results are comparable to other studies on carbon in the Rocky Mountains. For example, Klemmedson's (1975) carbon concentrations for tree, understory, coarse woody debris, and other components in southwest ponderosa pine forests ranged from 39 percent to 50 percent. The forest components from the ponderosa pine sites in our study had similar concentrations (table 9). In addition, concentrations in all forest types sampled were similar to those of Klemmedson's (1975) and Lamlom and Savidge (2003).

Traditionally, a concentration of 50 percent was used for calculating carbon content from tree biomass, as evaluated by Lamlom and Savidge (2003). This estimate is reasonable if the objective is to provide approximate estimates of total carbon. In this study, we found there to be significant differences in carbon concentrations of coarse roots and overstory crowns among species; however, the maximum differences were only 1.7 percent for the overstory and 2.7 percent for coarse roots. These small differences would have an insignificant impact on carbon estimates when the variations in biomass estimates are included. For example, the amount of error introduced in root biomass estimations outweighs the small differences detected in carbon 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, we recommend 49.5 percent for overstory crown, 47.6 percent for boles, 47.2 percent for coarse roots, and 48.4 percent for understory trees (table 9). Similarly, better carbon content estimates for other forest components can be achieved by using more precise carbon concentrations.

## *Carbon Storage*

In the ponderosa pine habitat types, carbon weights in trees were 20 percent higher than those reported by Klemmedson (1975), who conducted a similar study near Flagstaff, Arizona. This discrepancy is probably due to the difference in tree size between the two studies and our successional stage. Klemmedson sampled sapling and pole-sized trees, while trees sampled in this study were mature and ranged from 50 to 100 cm (20 to 40 inches) d.b.h. The amount of carbon storage in WH/CLUN trees was less than the amount stored on the ponderosa pine sites. This appears to suggest that the ponderosa pine sites are more productive than the WM/CLUN sites. However, this can be misleading because the sites sampled

**Table 9**—Carbon concentrations recommended for converting organic biomass to carbon content for habitat types evaluated in this study. Because significant differences occurred among habitat types, separate carbon concentrations are recommended. Refer to table 1 for habitat type designation.

| Forest component | Carbon concentration (%) |
|---|---|
| **Trees** | |
| Overstory crown | 49.5 |
| Bole | 47.6 |
| Coarse roots (>1 cm diameter.) | 47.2 |
| Fine roots (≤1 cm diameter) | 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 | 49.1 |
| Sticks (<7.5 cm diameter)—WR/CLUN and SAF/VASC | 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—WR/CLUN and SAF/VASC | 46.0 |
| **Soils** | |
| Brown cubicle rotten wood | 48.0 |
| Litter | 37.9 |
| Soil wood | 44.2 |

on the WH/CLUN habitat type were not at their maximum growth potential and relatively young, while the ponderosa pine sites were older and maximum growth potential may have been reached (Pearson 1950). When western hemlock habitat types are at their full growing capacity, the carbon storage potential could be much higher (Haig 1932).

Several studies have reported the importance of shrubs, forbs, and grasses for nutrient cycling (Chapin 1983; Jorgensen and Wells 1986), yet 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 tons/acre) of carbon were stored in this component. Forbs and grasses may also have the potential to be important for carbon storage. This study, however, found a maximum of only 0.1 Mg/ha (.04 tons/acre) across all habitat types. Before fire suppression, forbs and grasses were abundant in the ponderosa pine types. However, due to lack of fire as well as over-grazing, in this study, they were an insignificant element for carbon storage (Covington and Moore 1994). However, with the advent of more wild and prescribed fire, these pools could shift and thus grass and forbs could play a greater role in storing carbon both above and below (rapid root turnover may increase carbon concentration in mineral soil) the soils surface. 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. In the ponderosa pine habitat types, we found that 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 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 most likely influenced the amount of carbon stored in roots and other carbon pools. The Northern Rocky Mountain habitat types had more fine woody roots than the ponderosa pine forests of the southwest. This may be 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, referring to root turnover, undecomposed litter, and soil humus, but did not mention the contribution of woody residue. Keenan and others (1993) recognized the importance of woody residue, reporting 161 Mg/ha (71.8 tons/acre) of carbon in woody material in western redcedar and western hemlock forests in northern Vancouver Island. Similarly, in the younger inland western hemlock forest we sampled, 51 Mg/ha (23.8 tons/acre) was found in woody materials. Although woody material is beginning to be recognized as a carbon sink, usually only coarse woody debris is considered, while other components that may be important for storing carbon are ignored. For this reason, we quantified where carbon is located within some of these other woody components (fig. 4).

This study found that cones are a major component of the woody materials of three (PP/FEAR, PP/QUGA, and SAF/VASC) of the four habitat types (fig. 4). In the ponderosa pine habitat types, greater than 70 percent of the carbon in the woody residue was in cones. In the SAF/VASC habitat type, cones also stored a significant proportion (35 percent); WH/CLUN had the least amount (8 percent). In vegetation types such as ponderosa and lodgepole pine, where cones represent a large portion of the woody residue, it is 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 11 percent of the total carbon on the site (fig. 3), with more than 80 percent in solid and rotten logs (fig. 4). These results show that CWD plays a major role in storing carbon in WH/CLUN habitat types while sticks are important in ponderosa pine habitat types.

As snags, CWD, sticks, cones, and coarse roots decompose, they form soil wood and BCR, important soil components of Rocky Mountain forest ecosystems (Graham and others 1994; Harvey and others 1987). Graham and others (1994) suggested that forest floors may consist of 30 to 60 percent woody material. In this study, we found that 25 to 30 percent of the soil carbon was in soil wood and BCR (fig. 5). Although in the ponderosa pine sites less than 7 Mg/ha (3.1 tons/acre) of the soil carbon consisted of soil wood, there is a large potential for soil wood recruitment after trees die and root biomass becomes soil wood. In Rocky Mountain forests, soil wood and BCR are important carbon sinks that are often overlooked.

Litter and humus also store large amounts of carbon. The large amounts of litter in the ponderosa pine and SAF/VASC habitat types are the result of the continuous shedding of needles (Kilgore 1981; Olson 1981). The proportion of carbon in the litter and humus located in the soils of the ponderosa pine habitat types in this study ranged from 20 percent to 25 percent. These proportions were larger than the 10 percent reported by Klemmedson (1975). This is probably due again to the differences in stand ages or successional stage between the two studies. Klemmedson's (1975) stands were younger and did not produce as much litter and surface humus, while this study's stands were over 200 years old.

Carbon content in mineral soils varied among habitat types. The results from this study show that in the ponderosa pine habitat types, greater than 70 percent of the forest soil carbon was stored in the mineral soils (fig. 5). In comparison, Klemmedson (1975) found that 89 percent of the total soil carbon content was in mineral soils. This amount was the result of root turnover from the grass component (Buol and others 1989). In the WH/CLUN and SAF/VASC habitat types, litter and humus contained 39 to 43 Mg/ha (17.4 to 19.8 tons/acre) of carbon (fig. 5). These results did not differ greatly from the 50 to 60 Mg/ha (22.3 to 26.8 tons/acre) in litter and humus reported by Keenan and others (1993) from sites in northern Vancouver Island. The ponderosa pine habitat types had more carbon in mineral soils than WH/CLUN and SAF/VASC (fig. 5), which may be due to higher clay content in soils of the ponderosa pine habitat types.

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, warm temperatures in the southwest coupled with summer rains provide favorable conditions for microbes to decompose woody material (Clark 1957), while WH/CLUN and SAF/VASC have colder temperatures, thus slowing decomposition rates (Harmon and others 1986). These 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). However, most global carbon estimates ignore many other forest components. In this study, we found that other forest components such as shrubs, cones, CWD, BCR, and soil wood can be major carbon sinks in Rocky Mountain forest ecosystems.

# Conclusions

Typically, the conversion of 0.50 is used to provide estimates of carbon pools; however, this study provided a suite of values that vary depending on the species, substrate, and location. Moreover, these values tended to be less than the conventional value, leading one to overestimate total carbon amounts in these forest types if the typical conversion is used. In addition to carbon concentrations, we showed the variability in carbon content as a function of forest type and that minor elements such as cones, shrubs, and brown cubical rotten wood can contribute to the total carbon pool. Given these results, a series of additional research questions could be pursued such as the effect of successional stage on carbon pool distributions. For example, young forests may not contain the brown cubical rotten wood mid- to late-seral moist forests contain. Also, as forests grow and develop, do carbon concentrations change or does only biomass distribution change over time? Thus, determining if carbon concentrations vary as a function of successional change could provide invaluable information concerning variation of carbon over time and space.

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