

Soil carbon and nitrogen pools in mid- to late-successional forest stands of the northwestern United States: potential impact of fire

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Abstract: When sampling woody residue (WR) and organic matter (OM) present in forest floor, soil wood, and surface mineral soil (0–30 cm) in 14 mid- to late-successional stands across a wide variety of soil types and climatic regimes in the northwestern USA, we found that 44%–84% of carbon (C) was in WR and surface OM, whereas >80% of nitrogen (N) was in the mineral soil. In many northwestern forests fire suppression and natural changes in stand composition have increased the amounts of WR and soil OM susceptible to wildfire losses. Stands with high OM concentrations on the soil surface are at greater risk of losing large amounts of C and N after high-severity surface fires. Using the USDA Forest Service Regional Soil Quality Standards and Guidelines, we estimate that 6%–80% of the pooled C to a mineral-soil depth of 30 cm could be lost during a fire considered detrimental to soil productivity. These estimates will vary with local climatic regimes, fire severity across the burned area, the size and decay class of WR, and the distribution of OM in the surface organic and mineral soil. Estimated N losses due to fire were much lower (<1%–19%). Further studies on the amounts and distribution of OM in these stands are needed to assess wildfire risk, determine the impacts of different fire severities on WR and soil OM pools, and develop a link between C and N losses and stand productivity.

Résumé : Après avoir échantillonné les débris ligneux (DL) et la matière organique du sol (MO) présents dans la couverture morte, les billes au sol et le sol minéral de surface (0–30 cm) dans 14 peuplements entre les stades intermédiaire et final de succession, établis sur une variété de types de sol et soumis à différents régimes climatiques dans le nord-ouest des États-Unis, nous avons trouvé que 44 % à 84 % du carbone (C) se retrouvait dans les DL et la MO en surface tandis que plus de 80 % de l'azote (N) se retrouvait dans le sol minéral. Dans plusieurs forêts du nord-ouest, la lutte contre les incendies de forêt et les changements naturels dans la composition des peuplements ont eu pour effet d'augmenter la quantité de DL et de MO qui peut être perdue à cause des incendies de forêt. Les peuplements qui ont des concentrations élevées de MO à la surface du sol ont plus de chances de perdre de grandes quantités de C et de N après un feu de surface de forte sévérité. Selon le guide de la qualité des sols du Service forestier américain, nous estimons que 6 % à 80 % du réservoir de C jusqu'à 30 cm dans le sol minéral pourrait être perdu lors d'un incendie considéré comme néfaste pour la productivité du sol. Ces estimations devraient varier selon le régime climatique local, la sévérité du feu dans la zone brûlée, la dimension et la classe de décomposition des DL et la répartition de la MO dans les portions organique et minérale du sol de surface. Les pertes estimées de N dues au feu étaient beaucoup plus faibles (< 1 % à 19 %). D'autres études sur la quantité et la répartition de la MO dans ces peuplements sont nécessaires pour évaluer le risque d'incendie de forêt, déterminer les impacts de différentes sévérités du feu sur les DL et les réservoirs de MO du sol ainsi que pour établir un lien entre les pertes de C et de N et la productivité des peuplements.

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Introduction

Estimates of forest resources have historically focused on timber volume, growth, removals, or mortality. More recently, estimation of the value of forestland has included wildlife, water quality, or recreational opportunities. Although forests can be described in many ways, soil produc-

tivity — the ability of the soil to support plant growth — is a key factor for maintaining ecosystem function and value (Powers et al. 1998). Organic matter (OM) in woody residue (WR), forest-floor detritus, and the mineral soil is essential for maintaining ecosystem function by supporting soil carbon (C) cycling and sequestration, nitrogen (N) availability, gas exchange, water availability, and biological diversity (Jurgensen et al. 1997). Loss of OM resulting from stand disturbance (e.g., timber harvesting, fire) can drastically change long-term soil productivity (Henderson 1995; Grigal and Vance 2000).

Historically, many dry forests in the Pacific Northwest (Washington, Oregon, northern Idaho, and western Montana, USA, and southern British Columbia, Canada) have evolved with fire as a major disturbance factor (Stocks et al. 1998; Keane et al. 2002). Active fire suppression in these ecosystems and in other forest types with longer fire intervals has

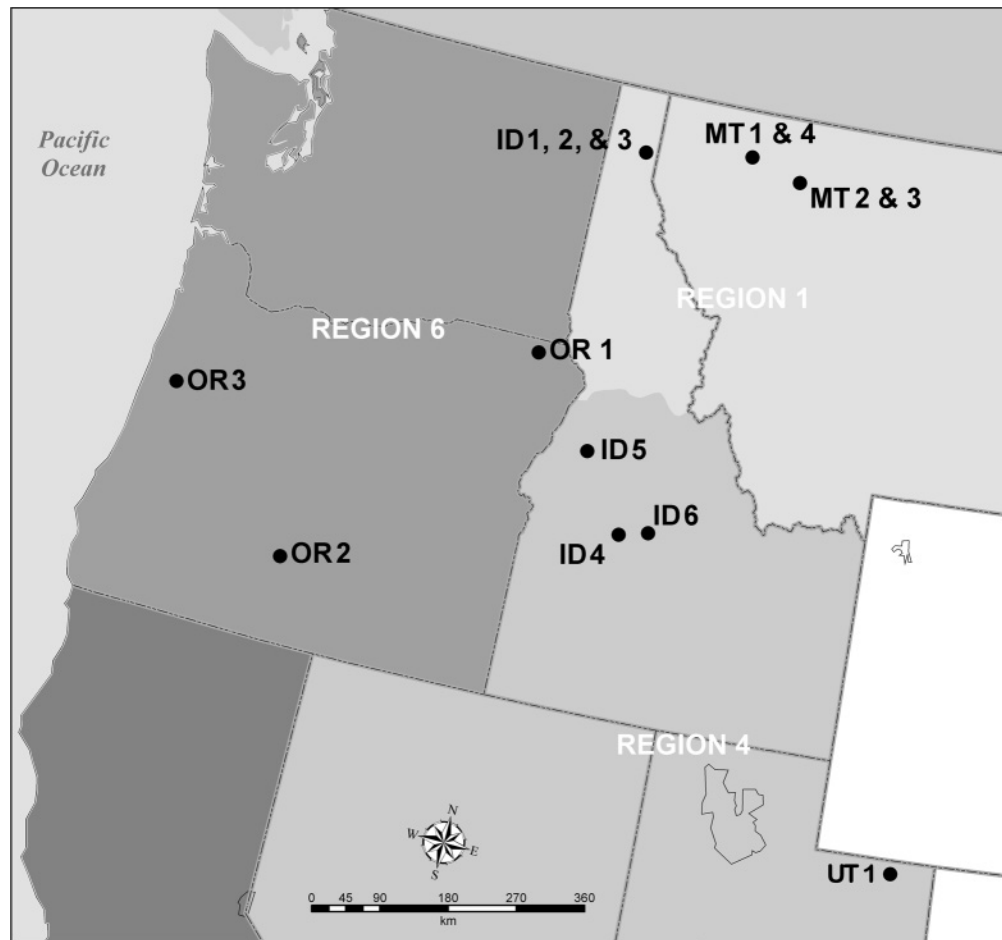
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Fig. 1. General locations of 14 stands in USDA Forest Service Regions 1, 4, and 6 sampled for this study.



greatly reduced the impact of wildfires and increased the amount of OM susceptible to loss during a high-severity fire in many stands (Page-Dumroese et al. 2003; Schoennagel et al. 2004). Currently, there is considerable interest in reestablishing fire as an integral part of ecosystem management on many forests in this region, especially those with short-interval, understory fire regimes (Brown et al. 1991; Keane et al. 2002; Stephens et al. 2004). Therefore, information on WR and soil OM in mid- to late-successional stages in many of these forest types is needed, since they often carry a high fire risk and are a focus of management practices to reduce fuel loads (Neary et al. 2000). Much is known about the distribution and amounts of OM, C, and N in WR, forest floor, and mineral soils in western North American ecosystems (e.g., Prescott et al. 1989; Arthur and Fahey 1992; Klopatek 2002). However, only a few studies have measured OM, C, or N in all WR and soil pools (Means et al. 1992; Busse 1994; Baird et al. 1999).

The US Forest Service (USFS) has been mandated to include soil protection as part of the National Forest Management Act (USDA Forest Service 1983). Consequently, the USFS has developed a series of standards and guidelines that use OM loss from the forest floor and mineral soil after prescribed burns as a surrogate of fire impacts on soil productivity (Powers et al. 1998). These guidelines have also been used as an index of soil C and N losses (Page-Dumroese et al. 2000). The British Columbia Ministry of

Forests uses professional assessment to evaluate the impacts of prescribed burning on OM loss (British Columbia Ministry of Forests Forest Practices Code 1997). Even though the long-term impact of fire on soil productivity is not well understood (Tiedemann et al. 2000; Carter and Foster 2004), these guidelines were developed using the best available scientific information and professional judgment.

The USFS Regional Soil Quality Standards and Guidelines can serve as an index or threshold to assess the potential effects of fire on C and N pools (Page-Dumroese et al. 2000). Forest types, soil properties, and climate vary widely among western USFS Regions and so the threshold for OM, C, and N losses considered detrimental to soil productivity in these guidelines also varies among Regions. Consequently, the objectives of our study were to (i) obtain baseline information on the amounts and distribution of WR and soil C, N, and OM in mid- to late-successional forests across a range of parent materials and climatic zones in the western USA; and (ii) estimate potential C and N losses due to detrimental fires, as defined by USFS Regional guidelines.

Methods

Field sampling

Forest floor, WR, and surface mineral soil were sampled from 14 mid- to late-successional forest stands in Idaho, Utah, Montana, and Oregon, and represent a wide range of

Table 1. Mid- to late-successional study sites sampled in three western USDA Forest Service (USFS) Regions.

USFS Region, State(s), dominant conifer/understory species, and stand ID	No. of samples*	Elevation (m)	Parent material	Stand age (years)	Forest-floor depth (cm)	Soil texture	Bulk density at 0–10 cm depth (Mg·m ⁻³)	Avg. precipitation (cm)	Avg. air temp. (°C)
USFS Region 1: northern Idaho/Montana									
<i>Abies lasiocarpa</i> / <i>Xerophyllum tenax</i> (MT 1)	48	1570	Limestone	250+	3	Loamy skeletal	1.02	75	6
<i>Tsuga heterophylla</i> / <i>Clintonia uniflora</i> (MT 2)	12	1130	Glacial outwash	200+	3	Loamy skeletal	0.96	79	5
<i>Abies lasiocarpa</i> / <i>Clintonia uniflora</i> (MT 3)	12	1143	Glacial till	200+	3	Loamy skeletal	1.14	79	5
<i>Abies lasiocarpa</i> / <i>Menziesia ferruginea</i> (MT 4)	48	1570	Limestone	250+	5	Loamy skeletal	1.00	83	6
<i>Tsuga heterophylla</i> / <i>Clintonia uniflora</i> (ID 1)	48	900	Basalt	120	3	Silty clay loam	0.68	85	7
<i>Abies lasiocarpa</i> / <i>Clintonia uniflora</i> (ID 2)	12	1780	Basalt	150	4	Sandy loam	0.92	88	6
<i>Abies lasiocarpa</i> / <i>Menziesia ferruginea</i> (ID 3)	12	1830	Gneiss	150	4	Coarse loamy	0.74	88	6
USFS Region 4: southern Idaho/Utah									
<i>Pinus ponderosa</i> / <i>Symphoricarpos albus</i> (ID 4)	48	1150	Granite	87	4	Sandy loam	1.32	60	11
<i>Abies grandis</i> / <i>Vaccinium globulare</i> (ID 5)	48	1580	Granite	92	3	Fine loamy	1.04	76	9
<i>Abies grandis</i> / <i>Linnaea borealis</i> (ID 6)	12	1600	Schist	120+	5	Loam	0.89	81	8
<i>Pinus contorta</i> / <i>Vaccinium scoparium</i> (UT 1)	12	3100	Colluvium	70	2	Loamy skeletal	1.69	191	5
USFS Region 6: Oregon									
<i>Abies grandis</i> / <i>Clintonia uniflora</i> (OR 1)	48	800	Basalt	130	4	Fine loamy	0.95	48	8
<i>Pseudotsuga menziesii</i> / <i>Berberis repens</i> (OR 2)	48	1146	Pumice	200	6	Coarse loamy	0.86	116	10
<i>Picea sitchensis</i> / <i>Alnus rubra</i> (OR 3)	15	50	Basalt	250+	10	Fine loamy	0.61	250	10

*Number of samples collected within each dominant conifer/understory species type.

climate and soil conditions across three USFS Regions (Fig. 1, Table 1). Trees in these stands ranged in age from 70 to >250 years and showed no evidence of intermediate harvest activities (thinning) or fire within the sampling area. In six stands, three replicate 2-ha plots on the same slope, aspect, and habitat type were established in each stand approximately 1 km apart. In each stand, 4 cores were collected 100 m apart for a total of 12 cores/stand (Table 1). Fifteen soil cores were collected as described above from the *Picea sitchensis* (Bong.) Carr. stand (5 cores/replicate). In the seven other stands soil samples were taken at 20-m grid points within the three replicate 2-ha plots for a total of 48 cores/site. All soil samples were collected with a 10 cm diameter core sampler to a mineral soil depth of 30 cm. The large size and mass of the corer allowed us to obtain representative samples from soils with large coarse-fragment components (Jurgensen et al. 1977). All cores were separated in the field by forest floor (O_i , O_e , and O_a horizons combined), soil wood, and mineral soil at two depths (0–10 and 10–30 cm). Soil wood is highly decomposed WR of decay class 5 (Triska and Cromack 1979) that is covered by forest-floor material and not measured in WR transects (Jurgensen et al. 1997). Three bulk-density cores were taken from the 0–10, 10–20, and 20–30 cm depths in each 2-ha plot. Ten 15.2-m linear transects were established in each 2-ha plot to estimate biomass of sound and rotten wood. We used the wood-classification categories and specific-gravity values outlined in Brown (1974). Woody debris <0.6 cm in diameter (1-h fuel) was sampled as part of the forest floor.

Laboratory analysis

All live roots were hand-separated from the forest-floor, soil-wood, and mineral-soil samples. Soil and root samples were dried at 80 °C and the mineral soil was passed through a 2 mm mesh sieve to remove coarse fragments. All forest-floor, soil-wood, and mineral-soil subsamples were ground to pass a 0.04-mm mesh and analyzed for total C and N contents with a LECO-600 analyzer (LECO Corp., St. Joseph, Mich.). Soil OM content was estimated by mass loss after 16 h combustion at 375 °C (Ball 1964). Bulk-density cores were dried to a constant mass at 105 °C and weighed. Mineral soil C, N, and OM contents were corrected for coarse-fragment content and extrapolated to a hectare basis using the fine-fraction bulk density (Cromack et al. 1999). We did not analyze the coarse-fragment component (>2 mm), which has been found to contain appreciable amounts of C and N in some soils (Harrison et al. 2003; Whitney and Zabowski 2004). C and N contents in WR of different tree species were calculated using C and N concentrations from Keenan et al. (1993), Laiho and Prescott (1999), and D.S. Page-Dumroese (unpublished data).

Estimation of C and N losses

All three USFS Regions have defined a detrimental fire as one that has severely affected soil over 15% of the burned area (forest stand for prescribed fire or fire perimeter for a wildfire). As defined by each of the USFS Regions, severely burned soils have altered physical and biological properties resulting from high-intensity fire. These two definitions are consistent among these USFS Regions, although different criteria are used to determine the impacts of detrimental fire

on the mineral soil and acceptable forest-floor losses due to fire. Consequently, C and N losses from a similar high-severity fire could be considered detrimental to soil productivity in one USFS Region but not in another. The USFS Regional guidelines for detrimental fire and the assumptions we used when estimating possible C and N losses are as follows: USFS Region 1 (Montana and northern Idaho) — *the forest floor is destroyed and the A horizon has had intensive heating*. Since we sampled the mineral soil in 10 cm depth increments, we obtained the A-horizon thickness at each site and assumed that 50% of the C and N from this soil depth was volatilized. USFS Region 4 (southern Idaho and northern Utah) — *loss of either 5 cm depth or one-half of the forest floor (whichever is less)*. We calculated loss of nutrients in the forest floor based on forest-floor depth and assumed no C and N losses from the surface mineral soil. USFS Region 6 (Washington and Oregon) — *the surface of the mineral soil is oxidized to a red color and the next 1.5 cm is blackened because of charring of OM*. We assumed that all the forest floor was destroyed and that 50% of the C and N in the surface 1.5 cm of mineral soil was volatilized.

Our methods for calculating C and N losses due to a detrimental fire are outlined in Page-Dumroese et al. (2000). We assumed that a high-severity fire was likely to occur in each of our stands, even though some stands may rarely experience such an event because of their climatic regime (e.g., the coastal *P. sitchensis* stand). We also assumed that fire destroyed all roots in the forest floor and soil wood and 50% of the roots in the affected mineral soil depth (Swezy and Agee 1991). The effect of fire on WR is not a specific part of these guidelines, but WR is mentioned as being necessary to maintain long-term soil productivity. Based on our evaluation of the literature, we assumed that all small-diameter WR (<7.5 cm) was burned (Little and Ohmann 1988; Beese 1992), and that 50% of the large (>7.5 cm), sound WR and 80% of the “rotten” WR would be lost according to the detrimental-fire guidelines in each USFS Region. These assumptions for fire loss of large WR are discussed below. We calculated possible C and N losses under two different fire scenarios: (1) a high-severity fire on 15% of the burned area (15% of a forest stand), which is defined as the threshold for detrimental-fire effects on soil productivity in the USFS fire guidelines, and (2) a high-severity fire on 100% of the burned area, which would be a fire having the most detrimental impact on soil productivity.

Results and discussion

Amounts and distribution of OM, C, and N pools

Woody residues

WR (>0.6 cm diameter) biomass in our mid- to late-successional stands ranged from 33 Mg·ha⁻¹ on the two driest sites (*Pinus ponderosa* Laws. (ID4) and *Pinus contorta* Dougl. ex Loud. (UT1)) to 228 Mg·ha⁻¹ in the *P. sitchensis* stand (OR3) on the Oregon coast (Table 2). The amount of WR present is a function of forest type, time since last disturbance, type of disturbance (e.g., blowdown, fire), and wood decay conditions on the site (Harmon and Hua 1991; Tinker and Knight 2000). C and N pools in WR closely followed biomass distribution, being lowest on dry, fire-prone sites in Region 4 and highest in Region 6 along the Oregon

Table 2. Biomass, carbon (C), and nitrogen (N) contents of woody residue in mid- to late-successional stands of the northwestern USA.

Dominant conifer/understory species	Mass (Mg·ha ⁻¹)	C (%)	N (%)	C (Mg·ha ⁻¹)	N (kg·ha ⁻¹)
USFS Region 1					
<i>A. lasiocarpa</i> / <i>X. tenex</i> (MT1)					
0.6–7.5 cm	11 (23)	46.1	0.49	5	54
>7.5 cm sound	20 (6)	46.2	0.12	9	24
>7.5 cm rotten	19 (9)	47.7	0.51	9	98
Total	50			23	176
<i>T. heterophylla</i> / <i>C. uniflora</i> (MT2)					
0.6–7.5 cm	6 (8)	58.0*	0.41	3	23
>7.5 cm sound	18 (16)	52.9	0.16	10	29
>7.5 cm rotten	52 (32)	57.6	0.16	30	84
Total	76			43	136
<i>A. lasiocarpa</i> / <i>C. uniflora</i> (MT3)					
0.6–7.5 cm	8 (7)	52.8*	0.66	4	55
>7.5 cm sound	21 (13)	49.8	0.08	11	17
>7.5 cm rotten	30 (31)	48.4	0.23	15	69
Total	59			30	141
<i>A. lasiocarpa</i> / <i>M. ferruginea</i> (MT4)					
0.6–7.5 cm	14 (9)	52.8*	0.66	7	92
>7.5 cm sound	48 (23)	48.2	0.17	23	81
>7.5 cm rotten	35 (18)	47.5	0.24	17	84
Total	97			47	257
<i>T. heterophylla</i> / <i>C. uniflora</i> (ID1)					
0.6–7.5 cm	6 (3)	52.8*	0.66	3	37
>7.5 cm sound	50 (15)	49.3	0.1	25	50
>7.5 cm rotten	58 (21)	48.1	0.15	28	87
Total	114			56	174
<i>A. lasiocarpa</i> / <i>C. uniflora</i> (ID2)					
0.6–7.5 cm	7 (15)	52.8*	0.66	4	49
>7.5 cm sound	35 (25)	52.4 [†]	0.07	19	25
>7.5 cm rotten	15 (13)	57.1 [†]	0.18	9	27
Total	57			32	101
<i>A. lasiocarpa</i> / <i>M. ferruginea</i> (ID3)					
0.6–7.5 cm	25 (14)	43.7	0.57	11	143
>7.5 cm sound	41 (19)	48.2	0.15	20	62
>7.5 cm rotten	31 (14)	47.3	0.27	14	82
Total	97			45	287
USFS Region 4					
<i>P. ponderosa</i> / <i>S. albus</i> (ID4)					
0.6–7.5 cm	7 (5)	50.9*	0.25	3	17
>7.5 cm sound	19 (10)	47.8*	0.06	9	11
>7.5 cm rotten	7 (9)	46.5	0.21	3	15
Total	33			15	43
<i>A. grandis</i> / <i>V. globulare</i> (ID5)					
0.6–7.5 cm	13 (4)	51.6	0.76	7	102
>7.5 cm sound	14 (6)	48.5	0.17	7	24
>7.5 cm rotten	77 (31)	47.9	0.14	37	107
Total	104			51	233
<i>A. grandis</i> / <i>L. borealis</i> (ID6)					
0.6–7.5 cm	5 (6)	52.8*	0.66	3	34
>7.5 cm sound	26 (11)	52.4 [†]	0.07	13	18
>7.5 cm rotten	6 (4)	57.1 [†]	0.18	3	11
Total	37			19	63
<i>P. contorta</i> / <i>V. scoparium</i> (UT1)					
0.6–7.5 cm	10 (4)	50.9*	0.25	5	25
>7.5 cm sound	14 (6)	47.8*	0.06	7	9
>7.5 cm rotten	9 (4)	47.7	0.16	4	14
Total	33			16	48

Table 2 (concluded).

Dominant conifer/understory species	Mass (Mg·ha ⁻¹)	C (%)	N (%)	C (Mg·ha ⁻¹)	N (kg·ha ⁻¹)
USFS Region 6					
<i>A. grandis</i> / <i>C. uniflora</i> (OR1)					
0.6–7.5 cm	9 (6)	52.8*	0.66	5	56
>7.5 cm sound	22 (9)	56.8 [†]	0.09	13	20
>7.5 cm rotten	11 (8)	57.1 [†]	0.18	7	21
Total	42			25	97
<i>P. menziesii</i> / <i>B. repens</i> (OR2)					
0.6–7.5 cm	11 (9)	50.8	0.81	5	86
>7.5 cm sound	29 (13)	47.2	0.08	14	23
>7.5 cm rotten	38 (27)	45.6	0.15	17	57
Total	78			36	166
<i>P. sitchensis</i> / <i>A. rubra</i> (OR3)					
0.6–7.5 cm	9 (16)	52.8*	0.66	5	59
>7.5 cm sound	158 (14)	56.8 [†]	0.09	90	142
>7.5 cm rotten	61 (26)	57.5 [†]	0.08	35	48
Total	228			130	249

Note: Values are given as the mean with the standard error of the mean in parentheses. Values not accompanied by a footnote are unpublished data (D.S. Page-Dumroese).

*From Laiho and Prescott (1999).

[†]From Keenan et al. (1993).

coast (OR3). Large WR (>7.5 cm diameter) predominated on all sites, with advanced (“rotten”) brown-rot decay stages — decay classes 4 and 5 (Triska and Cromack 1979) — constituting 19%–85% of this OM pool. Highly decomposed WR contained less C and more N than sound wood, which reflects the immobilization of N during wood decay, microbial dinitrogen fixation in the wood, or N inputs from the mineral soil by fungal hyphae during the decay process (Jurgensen et al. 1989; Means et al. 1992). Small WR (<7.5 cm diameter) contained ~16% of the total C in WR, but varied from 4% in the *P. sitchensis* stand (OR3) to 31% in the *P. contorta* stand (UT1). The contribution of small-diameter wood to total WR N pools was much larger (~41%), ranging from 17% in old-growth *Tsuga heterophylla* (Raf.) Sarg. (MT2) to 58% in an eastern Oregon *Abies grandis* (Dougl.) Lindl. stand (OR1).

Roots

Estimates of live-root biomass obtained from soil cores ranged from <1 Mg·ha⁻¹ in a dry, mixed *A. grandis* stand in eastern Oregon (OR1) to >3 Mg·ha⁻¹ in a *Pseudotsuga menziesii* (Mirb.) Franco stand in the Oregon Cascades (OR2) (Fig. 2). Surface OM (forest floor and soil wood) contained the highest root biomass in 10 of the 14 stands. Three of the four stands in Region 4 had higher root mass in the surface mineral soil than in surface OM and this was likely a function of forest-floor thickness. In the Rocky Mountains, root biomass has been shown to be positively correlated with depth of the surface OM horizons (Harvey et al. 1980). In addition, surface OM is critical for maintaining root biomass, and loss of this layer (inclusive of WR) can also cause significant declines in ectomycorrhizal fungi (Harvey et al. 1981). Root C and N concentrations did not differ among the various soils, so average values of 41% C and 1.2% N were used in our calculations (D.S. Page-Dumroese, unpublished data). Correlations between root biomass and horizon depth were insignificant (data not shown) and likely due to sample variability. Compared with

other soil components, root C and N pools were very small, so they were included in the totals for surface OM and mineral soil (Table 3).

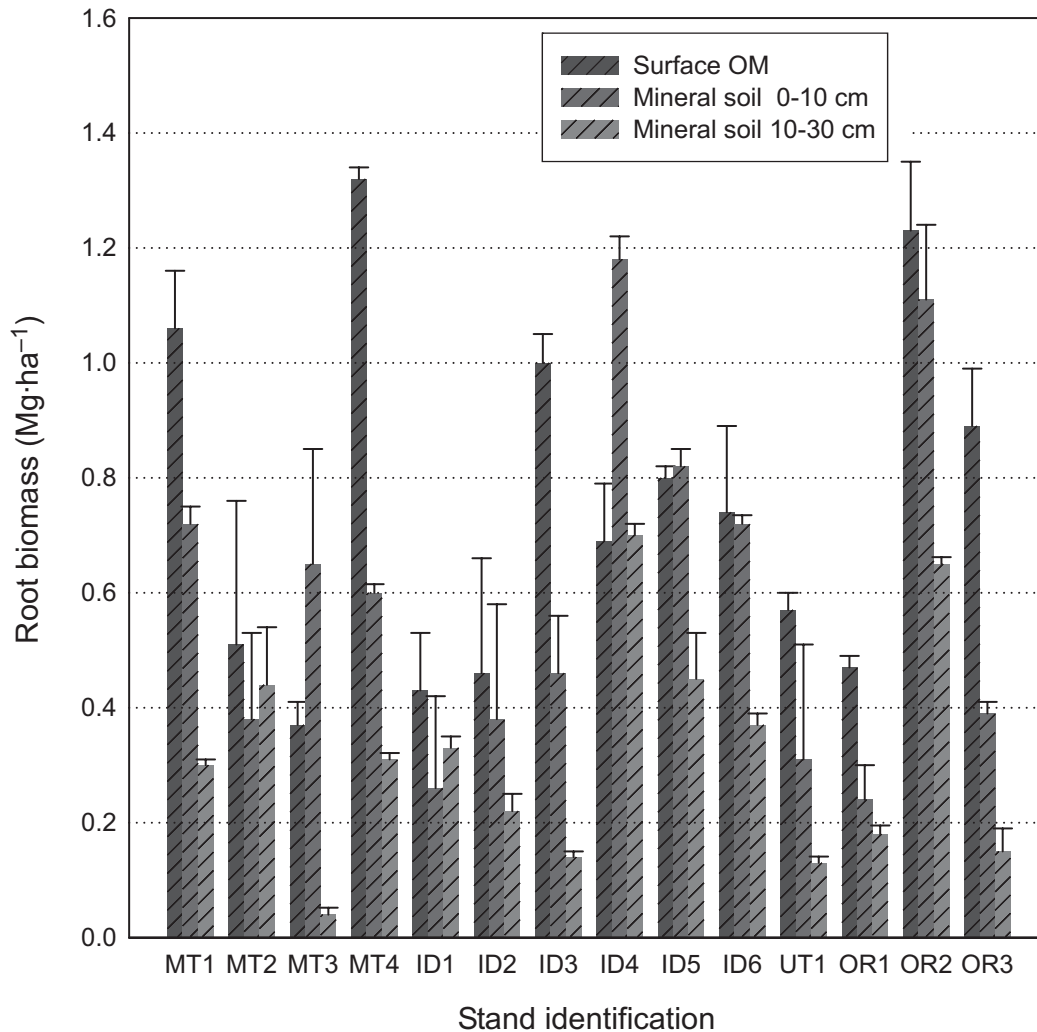
Large, structural roots can contain substantial amounts of OM, C, and N, especially in late-successional or old-growth stands (Van Lear et al. 2000). Biomass of large roots is often estimated as a function of tree diameter or a percentage of aboveground biomass (Pregitzer 2003). However, we did not have tree or stand data for our sites, so large roots were not included in our C- and N-pool calculations. Excavations of the root systems of older trees have shown that they can contain 15%–30% of total tree biomass (Van Lear and Kapeluck 1995) and a C/N ratio of 15–20 (Pregitzer et al. 1997).

Total amounts

The distribution and amounts of OM, C, and N in WR and soil components varied considerably among forest types and locations (Table 3). The sizes and distribution of these pools reflect differences in forest type, historical management practices, and fire-exclusion policies (Jurgensen et al. 1997; Page-Dumroese et al. 2003). Overall, soils in Region 4 had relatively low OM pools, which reflects the dry, rocky soils and frequent fires that are characteristic of intermountain forests. The highest totals were found in the high-rainfall areas of western Oregon (Region 6). WR (both sound and rotten) was a significant source of OM in our stands, containing 8%–26% of total OM pools. Combined WR and surface-soil OM (forest floor and soil wood) accounted for over 60% of total OM pools in high-elevation *Abies lasiocarpa* (Hook.) Nutt. stands in Montana (MT1 and MT4), but only 37% in a coastal Oregon *P. sitchensis* (OR3) forest.

C contents of WR and surface OM (forest floor and soil wood) ranged from a high of 258 Mg·ha⁻¹ in a coastal Oregon *P. sitchensis* stand (OR3) to a low of 61 Mg·ha⁻¹ in a *P. contorta* stand in eastern Utah (UT1). C content was usually much lower in soil wood than in forest floor, but accounted for 5%–24% of the total pools. Combined, WR,

Fig. 2. Distribution of roots in soil sample cores. Surface organic matter (OM) includes roots within the forest floor and soil wood. Error bars represent the standard error of the mean.



forest floor, and soil wood contained >50% of the soil C to a mineral-soil depth of 30 cm in 13 of the 14 stands, while the 0–10 cm soil depth contained more C than the 10–30 cm depth in nearly half the stands.

In contrast to C, N pools were much larger in the mineral soil than in the surface organic layers (Table 3). This reflects higher C:N ratios in the forest floor (average C:N ratio = 41) and soil wood (average C:N ratio = 72) than in the mineral soil (average C:N ratio = 16). Total N contents were highest in the volcanic-ash-influenced soils of northern Idaho (ID1, ID2, ID3). The surface mineral soil (0–10 cm) is an especially important source of N, containing from 29% to 56% of the total N pools, compared with only 8%–19% from the WR and surface OM combined.

Extensive information is available on both C and N in WR, forest floor, and mineral soil of North American forests (Oliver and Larson 1990), but it is difficult to develop large-scale assessments of these pools from the published literature (Henderson 1995; Heath et al. 2003; Johnson and Kern 2003). For example, Prichard et al. (2000) and Sanscrainte et al. (2003) determined C and N pools in the forest floor and surface mineral soil, while Covington and Sackett (1984),

Prescott et al. (1989), Keenan et al. (1993), and Laiho and Prescott (1999) sampled WR and the forest floor. Arthur and Fahey (1992) measured N in WR, forest floor, and mineral soil, but not C. In some studies, only the mineral soil was sampled (Homann et al. 1995; Piątek et al. 2003). We could find only three western USA studies that measured C and N pools in WR, surface OM, and mineral soil in mid- to late-successional forests (Table 3).

The use of different WR-sampling protocols also makes it difficult to compare estimates of C and N pools among studies. We measured both large (>7.5 cm) and small (<7.5 cm) diameter WR (Table 2), but other studies only measured “coarse” WR, which was defined as downed wood >3 cm in diameter (Baird et al. 1999), >7.5 cm in diameter (Busse 1994), or >10 cm in diameter (Means et al. 1992). Tinker and Knight (2000) included all stumps, woody lateral roots, and snags >7.5 cm in diameter in their estimates of coarse woody residue in burned and unburned stands in Yellowstone National Park. If we had sampled only downed wood >7.5 cm in diameter in our stands, we would have underestimated C and N pools in WR by an average of 15% and 40%, respectively. However, the impact of small-diameter WR on

Table 3. Distribution of woody residue and soil organic matter, C, and N in mid- to late-successional stands in the northwestern USA, including fine roots in the forest floor, soil wood, and mineral-soil pools.

Dominant conifer/understory species	Organic matter		Carbon		Nitrogen	
	Soil (Mg·ha ⁻¹)	Distribution (%)	Soil (Mg·ha ⁻¹)	Distribution (%)	Soil (kg·ha ⁻¹)	Distribution (%)
USFS Region 1						
<i>A. lasiocarpa</i> / <i>X. tenax</i> (MT1)						
Woody residue	50 (6)	23	23 (6)	21	176 (12)	7
Forest floor	114 (10)	52	62 (20)	57	175 (18)	87
Soil wood	7 (4)	3	5 (3)	5	10 (6)	<1
Mineral soil (0–10 cm)	35 (5)	16	13 (5)	12	1328 (19)	56
Mineral soil (10–30 cm)	15 (2)	7	5 (1)	5	696 (5)	29
Total	221		108		2385	
<i>T. heterophylla</i> / <i>C. uniflora</i> (MT2)						
Woody residue	76 (11)	18	43 (4)	21	136 (6)	5
Forest floor	151 (20)	35	75 (9)	36	198 (10)	8
Soil wood	29 (8)	7	20 (4)	10	32 (7)	<1
Mineral soil (0–10 cm)	100 (3)	23	39 (3)	19	1343 (11)	52
Mineral soil (10–30 cm)	75 (11)	17	28 (3)	14	886 (18)	34
Total	431		205		2595	
<i>A. lasiocarpa</i> / <i>C. uniflora</i> (MT3)						
Woody residue	59 (16)	13	30 (8)	15	141 (11)	4
Forest floor	120 (60)	27	59 (29)	29	174 (12)	5
Soil wood	42 (7)	9	20 (4)	10	43 (6)	<1
Mineral soil (0–10 cm)	129 (13)	29	51 (15)	25	1852 (53)	54
Mineral soil (10–30 cm)	100 (11)	22	43 (5)	21	1228 (21)	36
Total	450		203		3438	
<i>A. lasiocarpa</i> / <i>M. ferruginea</i> (MT4)						
Woody residue	97 (12)	26	47 (5)	30	257 (12)	8
Forest floor	143 (10)	39	75 (11)	47	228 (22)	7
Soil wood	17 (8)	5	9 (4)	6	24 (10)	<1
Mineral soil (0–10 cm)	64 (5)	17	17 (2)	11	1427 (13)	47
Mineral soil (10–30 cm)	48 (4)	13	10 (4)	6	1117 (21)	37
Total	369		158		3053	
<i>T. heterophylla</i> / <i>C. uniflora</i> (ID1)						
Woody residue	114 (21)	20	56 (7)	21	174 (9)	3
Forest floor	102 (37)	18	56 (21)	21	148 (14)	3
Soil wood	75 (30)	13	43 (12)	16	79 (10)	2
Mineral soil (0–10 cm)	122 (5)	21	49 (6)	18	1896 (25)	36
Mineral soil (10–30 cm)	165 (19)	28	66 (6)	24	2946 (43)	56
Total	578		270		5243	
<i>A. lasiocarpa</i> / <i>C. uniflora</i> (ID2)						
Woody residue	57 (6)	10	32 (5)	13	101 (7)	3
Forest floor	103 (28)	17	55 (10)	22	173 (9)	5
Soil wood	105 (5)	18	60 (10)	24	98 (12)	2
Mineral soil (0–10 cm)	100 (14)	17	33 (5)	13	1095 (42)	29
Mineral soil (10–30 cm)	228 (12)	38	69 (8)	28	2325 (35)	61
Total	593		249		3792	
<i>A. lasiocarpa</i> / <i>M. ferruginea</i> (ID3)						
Woody residue	97 (5)	19	45 (6)	18	287 (10)	7
Forest floor	136 (14)	27	88 (5)	35	152 (25)	3
Soil wood	80 (5)	16	23 (7)	10	68 (32)	2
Mineral soil (0–10 cm)	99 (21)	19	64 (5)	26	1180 (20)	29
Mineral soil (10–30 cm)	96 (36)	19	28 (13)	11	2416 (41)	59
Total	508		248		4103	
USFS Region 4						
<i>P. ponderosa</i> / <i>S. albus</i> (ID4)						
Woody residue	33 (4)	8	15 (5)	8	43 (11)	1

Table 3 (continued).

Dominant conifer/understory species	Organic matter		Carbon		Nitrogen	
	Soil (Mg·ha ⁻¹)	Distribution (%)	Soil (Mg·ha ⁻¹)	Distribution (%)	Soil (kg·ha ⁻¹)	Distribution (%)
Forest floor	128 (16)	32	92 (15)	46	207 (27)	7
Soil wood	26 (14)	6	18 (12)	9	64 (14)	2
Mineral soil (0–10 cm)	101 (10)	25	45 (10)	23	1020 (21)	33
Mineral soil (10–30 cm)	116 (7)	29	29 (6)	14	1764 (28)	57
Total	404		199		3098	
<i>A. grandis</i> / <i>V. globulare</i> (ID5)						
Woody residue	104 (7)	23	51 (6)	26	233 (15)	9
Forest floor	86 (2)	19	59 (5)	31	203 (25)	8
Soil wood	44 (3)	10	38 (1)	20	54 (21)	2
Mineral soil (0–10 cm)	64 (5)	15	20 (2)	10	1041 (15)	40
Mineral soil (10–30 cm)	145 (9)	33	24 (3)	13	1095 (41)	41
Total	443		192		2626	
<i>A. grandis</i> / <i>L. borealis</i> (ID6)						
Woody residue	37 (4)	10	19 (5)	14	63 (12)	2
Forest floor	122 (18)	33	55 (8)	40	127 (20)	5
Soil wood	40 (4)	11	17 (2)	13	79 (17)	3
Mineral soil (0–10 cm)	82 (7)	22	18 (2)	13	1159 (29)	47
Mineral soil (10–30 cm)	85 (30)	24	27 (4)	20	1061 (43)	43
Total	366		136		2489	
<i>P. contorta</i> / <i>V. scoparium</i> (UT1)						
Woody residue	33 (10)	17	16 (4)	16	48 (11)	2
Forest floor	65 (12)	33	33 (10)	31	78 (16)	5
Soil wood	21 (16)	11	12 (8)	11	28 (12)	1
Mineral soil (0–10 cm)	34 (4)	17	15 (3)	14	784 (31)	39
Mineral soil (10–30 cm)	42 (21)	22	30 (5)	28	1070 (26)	53
Total	195		106		2008	
USFS Region 6						
<i>A. grandis</i> / <i>C. uniflora</i> (OR1)						
Woody residue	42 (6)	12	25 (3)	14	97 (14)	6
Forest floor	139 (9)	38	100 (43)	57	71 (12)	4
Soil wood	81 (8)	22	22 (12)	13	87 (32)	6
Mineral soil (0–10 cm)	60 (11)	17	12 (2)	7	622 (20)	38
Mineral soil (10–30 cm)	39 (8)	11	15 (4)	9	742 (18)	46
Total	361		174		1619	
<i>P. menziesii</i> / <i>B. repens</i> (OR2)						
Woody residue	78 (10)	17	36 (9)	12	166 (14)	5
Forest floor	127 (12)	27	72 (46)	23	201 (30)	7
Soil wood	50 (9)	11	27 (2)	9	95 (37)	3
Mineral soil (0–10 cm)	105 (7)	22	83 (22)	26	1112 (49)	37
Mineral soil (10–30 cm)	108 (15)	23	94 (13)	30	1432 (52)	48
Total	468		312		3006	
<i>P. sitchensis</i> / <i>A. rubra</i> (OR3)						
Woody residue	228 (12)	22	130 (8)	30	249 (17)	6
Forest floor	157 (14)	15	77 (38)	18	183 (32)	5
Soil wood	111 (26)	11	51 (6)	12	84 (6)	2
Mineral soil (0–10 cm)	307 (11)	29	117 (12)	27	1405 (35)	36
Mineral soil (10–30 cm)	244 (15)	23	55 (13)	13	1999 (42)	51
Total	1047		430		3920	
Other western studies						
<i>P. menziesii</i> (Oregon)*						
Woody residue	222	49	100	43	183	4
Forest floor	55	12	31	13	662	13
Mineral soil (0–30 cm)	173	39	102	44	4155	83
Total	450		233		5000	

Table 3 (concluded).

Dominant conifer/understory species	Organic matter		Carbon		Nitrogen	
	Soil (Mg·ha ⁻¹)	Distribution (%)	Soil (Mg·ha ⁻¹)	Distribution (%)	Soil (kg·ha ⁻¹)	Distribution (%)
<i>P. contorta</i> (Oregon) [†]						
Woody residue	37.7		19	23	40	2
Forest floor	na		9	11	174	7
Mineral soil (0–60 cm)	na		54	66	2217	91
Total			82		2431	
<i>P. contorta</i> (Washington) [‡]						
Woody residue	22	3	11	13	13	<1
Forest floor	2	<1	9	11	210	6
Mineral soil (0–60 cm)	760	97	64	76	3200	93
Total	784		84		3423	
<i>P. ponderosa</i> (Washington) [‡]						
Woody residue	6	<1	3	3	23	<1
Forest floor	2	<1	7	8	160	2
Mineral soil (0–60 cm)	767	99	77	89	6300	97
Total	775		87		6483	

Note: Values are given as the mean with the standard error of the mean in parentheses.

*From Means et al. (1992). Forest floor includes any soil wood present.

†From Busse (1994). Forest floor includes any soil wood present

‡From Baird et al. (1999). Forest floor includes any soil wood present.

estimates of total C and N pools would have been small (<5%).

We measured mineral-soil C and N at two depths (0–10 and 10–30 cm). In contrast, Means et al. (1992) sampled four mineral-soil layers to a depth of 1 m, while Busse (1994) and Baird et al. (1999) gave one C and N value for the entire 0–60 cm soil depth. The greater the depth of mineral soil sampled, the lower the contribution of surface OM to total soil C and N pools (Henderson 1995; Harrison et al. 2003; Homann et al. 2004; Whitney and Zabowski 2004). For example, WR and forest floor in an old-growth western Oregon *P. menziesii* stand composed 56% of the total C pool when C content was calculated to a mineral-soil depth of 30 cm (Table 3), but dropped to 38% when all soil C down to 100 cm was included (Means et al. 1992). Large amounts of N were also present in deeper mineral-soil layers, which lowered the total N contribution of the WR and surface OM from 17% to 8%.

Total amounts of C and N found in these stands reflect their disturbance history, especially fire (Jurgensen et al. 1997; Johnson and Curtis 2001). However, climatic conditions, especially above- and below-ground temperature and moisture regimes, also play major roles in soil C and N accumulation by controlling both tree-growth and OM-decomposition rates (Tilman et al. 2000). Temperature and water relationships impact C and N cycling on a broad, regional scale (Borchers and Perry 1992), but soil factors (e.g., texture, parent material, pH) determine the size and distribution of C and N pools in individual stands (Edmonds and Chappell 1994).

Impact of fire on C and N pools

Woody residues

Since the amount of WR lost is a function of fire severity, the actual amount of WR consumed by fire is a function of

fuel loading, fuel moisture level, and weather conditions during the burn. The resulting variability in fire severity is reflected in the large differences in WR remaining after both prescribed fires and wildfires reported in the literature. For example, Baird et al. (1999) reported that 33% of coarse WR (>3 cm) in a low-elevation *P. ponderosa* stand in eastern Washington was lost after a wildfire. In contrast, a prescribed burn after a high-elevation *P. contorta* forest in eastern Washington was logged reduced WR (>7.5 cm) by over 80% (Lopushinsky et al. 1992). Nearly 50% of WR (>12.5 cm) was burned during the Biscuit fire in western Oregon (Azuma et al. 2004). Brown et al. (1985) reported that 80%–100% of WR (>7.5 cm) was lost during prescribed fires when fuel moisture levels were near 10%, but only 25%–40% was burned when the WR moisture content averaged 30%.

The WR decay class also affects the amount of WR remaining after a fire. Covington and Sackett (1984) found that coarse WR (>7.5 cm) was reduced by 63% after underburning an Arizona *P. ponderosa* stand, but only 14% of sound wood was burned compared with 99% of the decayed wood. In Montana, on average, 36% sound and 85% decayed wood (>7.5 cm) was removed with prescribed fire after post-harvest residue treatments (Steele 1980). Using a conservative estimate of WR loss, Tinker and Knight (2000) reported that 16% of downed wood was consumed by a wildfire in Yellowstone Park fire, and 85% of this was in decay classes 3, 4, and 5. Since the C:N ratio of WR decreases as decay progresses (Means et al. 1992), the burning of decayed wood would result in higher N and lower C losses than from a comparable mass of sound wood. Decay class 4 and 5 logs usually have a higher moisture content than sound logs, but when these decayed logs dry out, which often occurs under high fire danger conditions, they are more susceptible to loss during a fire (Amaranthus et al. 1989).

As shown above, the amounts of WR left after a wildfire

or prescribed fire can vary greatly depending on stand and fire conditions. We realize that our assumption that losses of 50% of large (>7.5 cm), sound WR and 80% of rotten WR would occur under the detrimental fire guidelines of each USFS Region is arbitrary. However, “standard” WR values are needed to compare the risk of C and N loss from fire across a wide range of forest and climatic conditions. Based on a review of the literature, we think our values are reasonable and reflect the disproportional loss of decayed wood from both wildfires and prescribed fires.

Total OM, C, and N losses

The amount of OM lost during a fire depends on fire severity. As described in Methods, the fire guidelines for Regions 1 and 6 define a detrimental fire as destroying all the forest floor and affecting the surface mineral soil, and would be the same as for a high-severity fire (Ryan 2002). In our “low-impact” fire scenario, which assumes that fire removes 50% of sound and 80% of rotten WR, destroys all forest floor and soil wood, and chars the surface mineral soil on only 15% of the burned area, total WR and soil C losses for forests in Regions 1 and 6 would be low (1%–11%). If 100% of the burned area had a high-severity fire (a “maximum-impact” fire), C losses would be much higher, ranging from 57% to 60% in Region 1 and from 42% to 80% in Region 6 (Table 4). As expected, a stand with a high percentage of total OM at or near the soil surface (*A. grandis*, OR1) would be more affected by high-severity fire than a stand with lower amounts of surface OM, such as the *P. sitchensis* stand on the Oregon coast (OR3).

In contrast, a fire considered detrimental to soil productivity in the USFS Region 4 guidelines only removes 5 cm or one-half the thickness of the forest floor, which can occur in fires of low to moderate severity (Ryan 2002). Forests in USFS Region 4 often have low soil nutrient levels (Binkley 1991), and the guidelines assume that soil productivity is affected at a lower fire-severity threshold. Using Region 4 guidelines, C losses would range from 6% in our low fire-severity scenario to 53% when a detrimental fire occurs over 100% of the area (Table 4). If a high-severity fire occurred in these forests (i.e., all the forest floor is lost), the respective C losses would increase to 9% and 78%. The potential impact of light- to moderate-severity fires on soil productivity in these forests illustrates a problem in using only high fire severity as an index of detrimental-fire effects.

In addition to reducing soil C pools, fire often produces large amounts of charcoal. Charcoal is highly resistant to decomposition and may be a significant source of recalcitrant C in burned soils (Schmidt and Noack 2000). C from surface OM can also accumulate in the upper mineral soil if fire conditions allow a hydrophobic layer to form (Neary et al. 1999). However, we could not find any information on how much C is deposited in the mineral soil by this OM vaporization/condensation process.

In contrast, a high-severity fire would have much less effect on soil N pools than on C pools, as the majority of N is in the mineral soil. For stands sampled in the three USFS Regions, N losses would range from 1% in “low-impact” fires (15% of the area) to 19% when the entire soil surface is severely burned (Table 4). Since the fire guideline for Region 4 is more conservative than the guidelines for Regions

1 and 6, smaller N losses (<1%–12%) are considered detrimental to soil productivity.

Many studies have reported large C and N losses from WR and the forest floor after prescribed fires and wildfires (e.g., Grier 1975; Feller 1988; Little and Ohmann 1988). In contrast, levels of available N (NH_4 and NO_3) in the surface mineral soil usually increase immediately after fire, and can result in short-term gains in soil productivity (DeLuca and Zouhar 2000; Johnson and Curtis 2001). However, repeated N losses due to subsequent fires may impact long-term soil productivity unless N-fixing plants, such as *Ceanothus* sp., become established (Newland and DeLuca 2000). We could only find one study from western forests that measured the effect of fire on all C and N pools (WR, surface OM, and mineral soil) in a stand. Baird et al. (1999) estimated that C and N losses from WR and the forest floor were >90% in a *P. ponderosa* stand and a *P. contorta* stand after a wildfire in eastern Washington (Table 5). Large amounts of N were lost from the mineral soil (0–60 cm depth), and total N losses were much larger than any calculated for our soils. Both of their stands had much lower prefire surface organic and mineral soil C and N pools than stands used in our study, which likely reflects previous fire history in these dry forests.

Conclusion

We have shown that it is possible to use the USFS soil-quality guidelines to estimate potentially detrimental losses of C and N due to prescribed or wildland fires if baseline data from undisturbed stands are available. The distribution of soil C and N pools is a function of local climatic regimes, past management practices, and fire-suppression activities. A stand with a high percentage of OM at or near the soil surface (WR, forest floor, soil wood) would experience more C and N losses than a stand with lower amounts of surface OM. However, the impact of fire on total soil N pools would be much less than for C, as most N is in the mineral soil. The amount of WR left after both prescribed and wildland fires varies greatly, depending on fuel load, fire conditions, and WR decay class.

Management implications

Postburn assessments of surface OM content are a common practice on both public and private lands to determine the effect of wildfires and prescribed fires on soil properties, and to estimate potential changes in productivity (Page-Dumroese et al. 2000). As discussed earlier, very little baseline information is available on total amounts of OM, C, and N in WR and mineral soil in western forests; this is needed to gauge the impact of fire on below-ground ecosystems. Our study has shown large differences in the sizes and distribution of C and N pools in 14 mid- to late-successional stands across a wide variety of soil types and climatic regimes. Not surprisingly, stands that have high OM concentrations on the soil surface are at greater risk if a high-severity fire were to occur. However, the likelihood of such a fire would be much less in stands with high-severity, stand-replacing fire regimes (e.g., *A. lasiocarpa*, MT1; *P. sitchensis*, OR3) than in stands with low-severity, surface fire regimes such as the *P. ponderosa* stand (ID4) (Schoennagel et al. 2004). C and N losses due to these fires could greatly impact soil processes and subsequent stand

Table 4. Average estimates of C and N losses from fire using USFS Regional Soil Quality Standards and Guidelines from USFS Regions 1, 4, and 6.

	C losses			N losses		
	15% of burned area [†] (Mg·ha ⁻¹)	100% of burned area [‡] (Mg·ha ⁻¹)	Profile (%)	15% of burned area [†] (kg·ha ⁻¹)	100% of burned area [‡] (kg·ha ⁻¹)	Profile (%)
USFS Region 1						
<i>A. lasiocarpa</i> (5)						
Woody residue	4	25	2–13	24	158	<1–5
Surface OM	12	78	6–40	34	227	1–7
Mineral soil	1	10	<1–4	13	84	<1–3
Total	17	113	9–57	71	469	1–15
<i>T. heterophylla</i> (2)						
Woody residue	5	35	2–15	18	118	<1–3
Surface OM	26	97	6–41	34	229	1–7
Mineral soil	1	9	<1–4	22	148	<1–4
Total	32	141	8–60	74	595	1–14
USFS Region 4						
<i>P. ponderosa</i> (1)						
Woody residue	1	9	<1–5	5	35	<1–1
Surface OM	9	62	5–31	23	157	<1–5
Mineral soil	0	0	0	0	0	0
Total	10	71	5–36	28	192	<1–6
<i>A. grandis</i> (2)						
Woody residue	4	26	2–16	19	127	<1–5
Surface OM	9	60	5–37	29	190	1–7
Mineral soil	0	0	0	0	0	0
Total	13	86	7–53	48	317	1–12
<i>P. contorta</i> (1)						
Woody residue	2	11	2–10	6	40	<1–2
Surface OM	5	31	5–29	12	77	<1–4
Mineral soil	0	0	0	0	0	0
Total	7	42	7–39	18	117	<1–6
USFS Region 6						
<i>A. grandis</i> (1)						
Woody residue	2	16	1–9	12	82	<1–5
Surface OM	18	122	10–70	23	158	1–10
Mineral soil	1	2	<1–1	5	35	<1–2
Total	31	140	11–80	40	275	1–17
<i>P. menziesii</i> (1)						
Woody residue	4	26	1–8	15	103	<1–3
Surface OM	15	99	5–32	44	296	1–10
Mineral soil	1	7	<1–2	29	190	<1–6
Total	20	132	6–42	88	589	1–19
<i>P. sitchensis</i> (1)						
Woody residue	12	78	3–18	25	169	<1–4
Surface OM	19	128	4–30	40	267	1–7
Mineral soil	1	9	<1–2	12	85	<1–2
Total	42	215	7–50	77	511	1–13

Note: Surface organic matter (OM) includes forest floor, soil wood, and fine roots. Mineral soil was to a depth of 30 cm.

*Numbers in parentheses show the number of stands.

[†]Fifteen percent of the area is above detrimental threshold values.

[‡]One hundred percent of the impacted area is above detrimental threshold values.

restoration (Henderson 1995; Grigal and Vance 2000). The total amounts of C and N lost will depend on fire severity over the burned area, the size and decay class of large-diameter WR, and the distribution of OM in the surface organic and mineral soil.

It is often assumed that prescribed fires are of lower severity and have less impact on both forest floor and mineral soil OM than wildfires (Robichaud and Hungerford 2000). However, prescribed fires range widely in severity, depending on fuel load, fuel moisture content, slope position, and

Table 5. C and N losses due to a wildfire in eastern Washington (Baird et al. 1999).

Stand type	C		N	
	Preburn total pool (Mg·ha ⁻¹)	Loss from fire (%)	Preburn total pool (kg·ha ⁻¹)	Loss from fire (%)
<i>P. ponderosa</i>				
Surface OM	10	90	183	95
Mineral soil (60 cm depth)	77	30	630	23
Total	87	37	813	39
<i>P. contorta</i>				
Surface OM	20	90	220	95
Mineral soil (60 cm depth)	64	10	300	13
Total	84	29	520	48

Note: Surface organic matter (OM) includes woody debris.

slope aspect (Little and Ohmann 1988; Brown et al. 1991; Oswald et al. 1999; Vose et al. 1999; Huffman et al. 2001). Wildfires also exhibit large spatial variability in severity, ranging from light charring of surface litter to destruction of all surface OM (Robichaud and Hungerford 2000; Wang 2002). While the fire guidelines for Regions 1 and 6 assume that removal of all the forest floor by a high-severity fire would be detrimental to soil productivity, smaller OM losses from light- to moderate-severity fires in Region 4 could also negatively impact productivity.

Unfortunately, little information is available on how much OM can be lost as a result of fire without affecting soil productivity, but it is usually assumed that the greater the OM loss, the greater the impact (Jurgensen et al. 1997). It must be remembered that these USFS fire guidelines were developed using the professional judgment of field personnel and the relatively limited scientific information available. They were designed to give forest managers a threshold when developing postfire site-restoration practices, not for use in estimating the extent of soil productivity lost as a result of fire. As discussed earlier, detrimental fires, as defined in the USFS guidelines, had relatively little impact on OM content in the surface mineral soil. However, as was shown by Baird et al. (1999), a severe wildfire can cause much greater C and N losses from the mineral soil than we calculated using these guidelines. This would be especially important for N, which is more concentrated in the surface mineral soil. For example, the 0–10 cm mineral-soil layer in our stands contained 29%–56% of the total N pool. N is usually the most limiting nutrient in western forests (Tiedemann et al. 2000), so a fire hot enough to remove large amounts of N from the mineral soil would have a much greater impact on soil productivity than a fire that destroyed only the forest floor. In addition to the immediate loss of mineral-soil N, long-term changes in N availability or microbial activity may result from the loss of surface OM (Klemmedson and Tiedemann 1995)

Studies are needed to determine the impact of fires that differ in severity on OM pools in WR and surface soil horizons, and to develop a link between C and N losses and stand productivity. The North American Long-Term Soil Productivity study was established in the USA and Canada to investigate the effect of OM removal on soil productivity (Powers et al. 2005), but fire was not included as a disturbance variable in that study. However, the physical removal

of surface OM in this study generally resulted in lower mineral-soil C pools and reduced N availability 10 years after treatment, and tree growth was reduced on low-productivity sites (Powers et al. 2005). Recently, the Fire and Fire Surrogate study was started by the USDA and US Department of the Interior to evaluate the effects of mechanical fuel-reduction treatments and prescribed-fire severity on above- and below-ground productivity in a variety of forest ecosystems across the USA (Weatherspoon 2000). Such information as that collected in our study is needed when developing harvest and site-preparation techniques that reduce wildfire risk, as required by the recently enacted Health Forest Resource Act of 2003 in the USA or the criteria and indicators for sustainable forest management in Canada (Canadian Council of Forest Ministers 2003), but also for maintaining adequate amounts of OM for continued soil productivity and C sequestration.

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