

CHAPTER 18:

SOIL CARBON IN ARID AND SEMIARID FOREST ECOSYSTEMS

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INTRODUCTION

Forests of the semiarid and arid zones of the interior western United States (US) are some of the most unique in North America. They occupy 11 to 34% of the landscape at mostly higher elevations (USDA Forest Service, 1981). These forests are characterized by a high diversity of flora, fauna, climates, elevations, soils, geology, hydrology, and productivity. Within the space of a few dozen kilometers, forests can change from desert shrublands to spruce and fir, the equivalent of going from northern Mexico to the Arctic. Because of the hydrologic cycle in the Interior West of the US, these forests are generally not known for their high productivity or contribution to the nation's wood supply. Some exceptions do exist in the ponderosa pine ecosystem. However, these forests have a high value due to other resources and amenities that they supply. In much of the western US, the primary source of municipal drinking water is runoff that emanates from the high elevation portions of these forests (Dissmeyer, 2000). These forests also provide habitat for wildlife, including many threatened and endangered species. Arid zone forests are now being utilized for recreation to such a degree by a rapidly expanding western US population that the value of the recreation amenities they supply exceed those of extractive resources (i.e., wood and minerals; Lyons, 1998).

Forests in the dry regions of the interior western US are characterized by an overriding system driver, water availability, which controls the type, amount, and productivity of vegetation. This driver controls key ecosystem processes and ultimately carbon (C) reserves. The arid region forests that are examined in this chapter are characteristically ones in which annual water losses through evapotranspiration exceed or are slightly less than annual precipitation. The presence of water, interacting with soil processes, soil properties, soil biota, and vegetation ultimately determines the amount, quality, and state of C.

The main objective of this paper is to describe the types of dry forests that occur in the Intermountain West of the US, the soils that they occupy, the interactions with current and future land management activities, and the potentials for additional C sequestration. High elevation forests that are part of the larger intermountain forest ecoregions are discussed in Chapter 17.

MAJOR FOREST ZONES OF THE INTERMOUNTAIN WEST

Bailey's (1995) ecoregion divisions of the United States categorizes the dry domain as one in which annual water losses through evapotranspiration exceed or are slightly less than annual precipitation. Perennial streams are rare in this domain. They either originate outside the dry domain, in mountaintop forests that are more characteristic of the humid domain, or from aquifers draining large arid basins. Since the amount of precipitation and evaporation, but not the ratio of the two climatic parameters, varies considerably across the arid Intermountain West, precipitation also cannot be used as a reliable parameter for defining these arid regions.

Our analysis of these dry forests includes all of Bailey's (1995) Dry Domain as well as portions of the Humid Domain (east side of the Cascades and Sierra ranges, and the California coastal chaparral and dry steppe provinces) that are semiarid. The major forest vegetation types found in the arid Intermountain West are listed in Table 18.1. Higher elevation or northerly forests featuring species such as Douglas-fir, spruces, true firs, aspen, and lodgepole pine are listed since they occupy the upper elevations of the forests in the Dry Domain (Bailey, 1995), but they are not considered further in this analysis.

These arid forests are an incredibly diverse mixture of trees, shrubs, herbs, and grasses. Only in some locations do these forests achieve the classical closed-canopy, dominant overstory condition. In most instances, however, the forests are more open woodlands in nature, hence the diversity of plant species and growth forms. The major forest types that warrant some additional discussion because of their areal extent include pinyon-juniper, ponderosa pine, chaparral, oak woodlands, and mesquite. Riparian forests occur throughout the Intermountain West but they occupy only 1 to 2 % of the landscape.

Forest Types

Pinyon-Juniper: These woodlands occupy over 191,400 km² in the interior of the western US (USDA Forest Service, 1981). This is the second largest forest type in the West by area, exceeded only by high-elevation and more northerly humid-zone spruce-fir forests. This forest type is primarily found in Arizona, Nevada, Utah, New Mexico, and Colorado, but smaller stands occur in California, Texas, Idaho, Oregon, Wyoming, and western Oklahoma (Eyre, 1980). Pinyon-juniper is found in the 313, M313, 321, 322, M331, 341, and M341 ecoregions (Table 18.1; Bailey, 1995). These woodlands are found on foothills, low mountains, mesas, and plateaus at elevations of 1,400 to 2,400 m. Annual rainfall can range from 250 to 500 mm. Pinyon-juniper woodlands are flanked by ponderosa pine forest at higher elevations and desert shrub, chaparral, or semiarid grasslands at lower elevations. Pinyon-juniper woodlands are frequently found in association with sagebrush communities. They occupy Aridisols (dry soils) with moderate to low organic matter content and Entisols (poorly developed soils). These forests rarely form closed canopies and their productivity is limited by moisture (Table 18.2)

Ponderosa Pine: This is the most widely distributed forest type in the North America. Ponderosa pine is really the only forest type in the arid western interior that is used for traditional, commercial timber forestry. It occupies over 136,500 km² from Canada to Mexico and coastal Oregon to central Nebraska (Eyre, 1980; USDA Forest Service, 1981). These forests occur across a broad environmental

gradient from 600 m in Oregon to 2,600 m in the southern Rocky Mountains. Rainfall varies from 250 to 710 mm across its range. Ponderosa pine is found in ecoregions 313, M313, M331, M332, M334, 341, M341, M242, and M261; Bailey, 1995). Ponderosa pine forests are located in a wide range of physiographic positions and rock types and, hence, also on a broad range of soil types, soil textures, and soil pH. Ponderosa pine forests are frequently bounded by pinyon-juniper woodlands or grasslands at lower elevations. Upper bounds are typically Douglas-fir or spruce-fir forests. Ponderosa stands tend to be more open in drier areas. Aboveground productivity is moderate to high for arid-zone ecosystems (Table 18.2), but is strongly dependent on tree density. Denser forests tend to have minimal understory communities.

Chaparral: The chaparral vegetation type is an association of dense evergreen shrubs and brushfields occupying over 62,600 km² in primarily ecoregions M313 and 261 in Arizona and California (Bailey, 1995). This vegetation type ranges in elevation from 300 to 3,000 m and is found in steep rugged terrain with rocky, infertile soils (Bolander, 1982; Tyrrel, 1982). Precipitation can vary from 300 to 635 mm with much of the annual rainfall occurring in a few high-intensity storms. Shrub plants in this association include species in the genera *Adenostoma*, *Arctostophylos*, *Ceanothus*, *Cercocarpus*, *Garrya*, *Quercus*, *Rhus*, and others. Arizona chaparral tends to have more understory grasses than the California types. Chaparral productivity can be exceptionally high for arid ecosystems, exceeding ponderosa pine productivity in some cases (Table 18.2). Productivity generally declines rapidly with age since disturbance (typically a stand-replacing fire). Severe wildfire is a key element in the lifecycle of chaparral. The various shrub species in chaparral have adapted to fire by allocating a substantial proportion of their net primary production to roots (Hibbert et al., 1974). Much of the ecosystem C pool is belowground, similar to the desert shrub vegetation type shown in Figure 18.1.

Oak Woodlands and Savannas: These dry forests are found predominantly from Texas to Arizona (ecoregion M331) and in California (ecoregions 261 and M262). The oak woodlands of the Southwest, sometimes called an encinal or Madrean evergreen formation, occupy about 80,300 km² and are mostly found at elevations of 1,200 to 1,800 m (Eyre, 1980). Rainfall in these areas ranges from 305 to 550 mm. Often this vegetation type does not have clear boundaries and may merge into pinyon-juniper or ponderosa pine at high elevations, and grasslands at lower ones. The oak woodlands are associated with a wide variety of arid zone shrubs, succulents, cacti, forbs, and grasses. In California, coastal oak woodlands range from sea level to 1,525 m with rainfalls of 260 to 1,280 mm. The oak woodlands are more savanna-like at lower elevations, but grade into continuous canopy and shrubby forests on steeper slopes. These stands contain over 40 species of evergreen shrubs. In some locations, oak woodlands include a variety of conifers and hardwoods in mixed stands. Aboveground net primary production in these oak woodlands is relatively moderate compared to other arid forests (Table 18.2).

Mesquite: This is a minor vegetation type that deserves some mention. It is more of a shrub-dominated rangeland that achieves the structure of a forest only on the best sites such as floodplains (Eyre, 1980). Mesquite ranges from central Texas to California and deep into Mexico. It occurs at elevations below 1,500 m and precipitation of <500 mm. Mesquite species are associated with a variety of shrubs, forbs, and grasses. They will readily invade abandoned farmland or recently disturbed soils. In some locations, mesquite plants will displace existing shrubs and grasses. Aboveground net primary production in these woodlands is similar to that of ponderosa pine, and like other woodlands and savannas, understory production increases dramatically with overstory (mesquite) removal (Heitschmidt et al., 1986).

Carbon Contents

Soil organic C contents in the upper 1 m of forest soils determined from the USDA Natural Resources Conservation Service soil characterization STATSGO database (Ramsey, 2002) shows an increasing organic C content moving from desert scrubland (2.5 kg m^{-2}) to warm conifer forests (13.6 kg m^{-2} , ponderosa pine and others) (Table 18.3; adapted from Kern, 1994). This reflects the same general trend in aboveground net primary production (Table 18.2). An interesting feature of these data is the high degree of site-to-site spatial variability within the ecosystem complex. The range between minimum and maximum can be as high as two orders of magnitude (warm conifer forests). This large degree of variation is probably indicative, in part, of differences among forest types (e.g., ponderosa pine, loblolly pine, slash pine, etc.) since the USDA Natural Resources Conservation Service ecosystem complex do not discriminate between true forest types (Eyre, 1980; Bailey, 1995).

FOREST SOILS OF THE INTERMOUNTAIN WEST

Landscape, Geologic, and Climatic Settings

The forest soils of the intermountain western United States are the most varied in the country because of their landscape settings, parent materials, climates, and biota. The interactions of these factors over time have produced the forest soils that characterize the region, and continue to influence the cycling of C and other elements.

The western US has the greatest landscape diversity in North America. Elevations range from sea level to over 4,400 m. Forests in this region occur because of the orographically induced climatic diversity controlled by the Rocky Mountains, the Basin and Range Province, the Sierra Nevada – Cascade, and the western coastal ranges. The forests are mostly contiguous along the main axis of the major mountain ranges but not between them. In the Southwest, the forests are often isolated on biogeographic “islands” since the ranges are often not contiguous (Warshall, 1995). Forests of the Intermountain West occur on rugged peaks and low ranges, over broad plateaus and isolated mesas, and along minor and major river systems.

Forest soils in the Intermountain West have formed in the complete range of geologic parent material (igneous, sedimentary, and metamorphic bedrock; erosional deposits; glacial residues; and volcanic eruption by-products). Climates that produced these soils have been highly variable due to a large range in elevation, latitude, mountain orientation to prevailing winds, and the time scale involved in soil formation. Soil moisture regimes vary from aquic to xeric because of the climatic variability produced by western US physiography (USDA Natural Resources Conservation Service, 1998). Because of the arid forest focus of this chapter, the only soils considered have aridic, ustic, or xeric soil moisture regimes. A similar range in soil temperature regimes are present, but the dry forest types occur mainly in mesic, thermic, and hyperthermic thermal regimes.

Soil Orders

The broadest category of groupings used in the US Soil Taxonomy used for making and interpreting soil surveys is Soil Order (USDA Natural Resources Conservation Service, 1998). The western US has the greatest variability in Soil Orders due to the landscape heterogeneity previously mentioned. (Figure 18.2).

There are 12 Soil Orders that are differentiated by the presence or absence of definitive diagnostic horizons or chemical and physical properties. The Soil Orders are: Alfisols, Andisols, Aridisols, Entisols, Gelisols, Histosols, Inceptisols, Mollisols, Oxisols, Spodosols, Ultisols, and Vertisols. The major Soil Orders in arid forests of the Interior West are Alfisols, Aridisols, Entisols, Inceptisols, and Mollisols. Andisols and Vertisols occur in a minority of locations. The remaining Soil Orders are unimportant in these dry forests.

Alfisols: These soils are found in semiarid and humid areas throughout the Intermountain West (Figure 18.2). They are common in many of the ponderosa pine and higher elevation forests. Alfisols have umbric or ochric epipedons, argillic (clay) horizons, and hold water at <-1.5 MPa for at least 90 days during the growing season (USDA Natural Resources Conservation Service, 1998). They are colder soils, having mean temperatures <8 °C at a mineral soil depth of 50 cm. They may also have base saturations of 35% or more. The total soil organic C content to a depth of 1 m is higher than Aridisols, but is not as high as Mollisols. It averages 7.0 kg m^{-2} and ranges from 4.4 to 8.7 kg m^{-2} (Chapter 4; Kern, 1994).

Aridisols: These soils are commonly found in the deserts of the western US (Figure 18.2). Aridisols occur from Mexico to the Canadian border and from east of the Pacific Coastal Ranges crest to the 98th meridian. They are too arid to support plant growth if the plants are not physiologically and structurally adapted to dry environments (USDA Natural Resources Conservation Service, 1998). Aridisols occupy many of the intermountain low-elevation basins. They commonly have clay-enriched sub-soils and/or cemented to slightly cemented horizons containing silt or carbonate deposits. These soils are dry for more than 50% of the days in a year when the mineral soil temperature at 50 cm depth is greater than 5 °C, and they are moist in some or all parts for less than 90 consecutive days when the soil temperature is greater than 8 °C. Aridisols normally occur in arid climates but some are found in semiarid ones. The total soil organic C to a depth of 1 m is low because of low net primary productivity. It averages 5.6 kg m^{-2} and ranges from 3.2 to 6.5 kg m^{-2} (Chapter 4; Kern, 1994).

Entisols: These soils are widely spread throughout the Intermountain West similarly to the Aridisols, but are more abundant in the northern portion since their classification is not limited by thermal regime (Figure 18.2). Soils that are described as Entisols have little or slight profile development because of their recent genesis. Their properties are more reflective of their parent material than any pedogenic processes. Entisols include soils formed on steep mountain slopes, floodplains, and sand dunes where geomorphic processes are actively removing or depositing parent material. They occur in many different environments, and may have no distinct diagnostic horizons within the upper 1 m. Because of their pedogenic youth, these soils are also low in C. Entisols average 6.9 kg m^{-2} organic C in the upper 1 m, but range from 2.8 to 28.8 kg m^{-2} (Chapter 4; Kern, 1994). Most Entisols have soil organic C contents that

are $< 10.0 \text{ kg m}^{-2}$. The high outlier is a moist soil Great Group (Hydraquents) that has relative large organic C pools because of wet conditions restricting decomposition processes (USDA Natural Resources Conservation Service, 1998).

Inceptisols: These soils occur over the same area as Aridisols and Entisols, but are more restricted to mountain regions, particularly in the southern half of the West (Figure 18.2). Inceptisols are soils that have one or more pedogenic horizons in which weatherable primary minerals other than carbonates or silica have been modified or leached out of the profile. In some circumstances, Inceptisols may have histic, mollic, ochric, or umbric epipedons (USDA Natural Resources Conservation Service, 1998). Unlike Aridisols, there is sufficient soil moisture for plants more than 50% of the year and for greater than 90 consecutive days during the growing season. Soil organic C content in the upper 1 m averages 11.7 kg m^{-2} , with a range of 6.2 to 34.9 kg m^{-2} (Chapter 4; Kern, 1994).

Mollisols: In the western US, these soils occur from Mexico to Canada, and from the Pacific Coast through the Great Plains (Figure 18.2). These are some of the most productive soils in the US because of their high organic matter content. Total organic C concentration of Mollisols is usually greater than 2.5%, but may be as low as 0.6% if certain other diagnostic criteria are met (USDA Natural Resources Conservation Service, 1998). Soils are classified as Mollisols if they have a mollic (high organic matter content) epipedon overlying mineral material with a base saturation greater than or equal to 50% at pH 7. Mollisols may have albic, argillic, calcic, cambic, gypsic, nitric, or petrocalcic diagnostic horizons, but not oxic or spodic ones. These soils typically form in grasslands or in forest and shrublands with significant understories of grasses or forbs. Soil organic C in the upper 1 m averages 12 kg m^{-2} and ranges from 6.9 to 20.4 kg m^{-2} (Chapter 4; Kern, 1994).

CARBON RESERVES OF ARID AND SEMIARID FOREST SOILS

The C reserves of forest soils in arid and semiarid regions are strongly soil based (Figure 18.1). Desert scrublands have 95% of their C banked in the soil while arid and semiarid woodland and scrubland ecosystems have only 65% ecosystem C in soils. Aboveground C fixation in arid zone forests is highest in ponderosa pine, but is still limited by soil and atmospheric moisture (Neary et al., 1999). Soil C reserves in the forest floor are subject to rapid oxidation by forest fires (DeBano et al., 1998), but mineral soil reserves are far more resistant to short- and long-term changes. Carbon reserves that are in the aboveground pool of arid forests are subject to sudden losses from fire (See Chapters 10 and 13). Belowground pools are much more stable (Neary et al., 1999).

Forest Floor

The forest floor (O horizon) is a critical component of ecosystem sustainability in that it provides a protective soil cover that mitigates erosion, aids in regulating soil temperature, provides habitat and substrates for soil biota, is a soil C pool, and can be the major source of readily mineralizable nutrients. However, in many arid and semiarid forests, organic matter inputs to soils are from primarily

belowground sources (Waring and Schlesinger, 1985; Neary et al., 1999). Organic matter input from above- and below-ground can significantly affect the nutrient pools and C storage in soils. It is also a major factor controlling total cation exchange capacity (organic and clay mineral).

Net primary productivity is moisture limited in arid and semiarid forests (Table 18.2), but decomposition rates in the absence of fire are even more moisture limited. Therefore, the forest floor develops from above-ground litterfall inputs at relatively moderate rates compared to other forests and, in the absence of fire, can accumulate to very high densities. For instance, Tiedemann (1987) contrasted above- and below-ground biomass, forest floor development, and nutrient pools on a shrub-grass-forb to sagebrush-grass to pinyon-juniper ecotone in the semiarid intermountain region of the western US. Across this gradient, the amount of forest floor increased from 3.0 to 100.0 Mg ha⁻¹.

On the Mogollon Rim of Arizona, ponderosa pine regenerates sporadically when high precipitation, high soil moisture, and a large seed crop coincide to produce above average germination and establishment of tree seedlings. The frequent fires in the pre-1870s forest reduced the thick seedling and sapling crops. After fire suppression, thick seedling crops in the early part of the 20th Century developed into overly dense forest stands with high fuel loads and ladder fuels. Stands which had tree densities of 12 - 20 stems ha⁻¹ evolved into dog-hair thickets of 1,000 - 1,200 stems ha⁻¹ (Covington, 1996).

Overstocked ponderosa pine ecosystems can reach a critical ecological point at which C built up in above-ground pools can be mobilized back into the atmosphere by high-severity, catastrophic wildfires (See also Chapters 10 and 13). Forest floor fuel loads that were 0.4 to 4.5 Mg ha⁻¹ prior to 1870 increased to as high as 112 Mg/ha, with an average of 49 Mg ha⁻¹ (Sackett et al., 1996). This ecosystem condition occurs in 2.8 million ha of ponderosa pine forest throughout the Intermountain West (Neary et al., 1999).

While total ecosystem C reserves have increased, they are clearly at very high fire risk to loss in high-severity fires. The forest floor and aboveground fuels situation that has developed in the past century in ponderosa pine forests and pinyon-juniper woodlands is clearly abnormal (Neary et al., 1999). Forest fuels treatments and the reintroduction of frequent low-severity prescribed fires will result in short-term losses from the forest floor C pool, but in the long run stabilize ecosystem-level pools as more C is allocated below-ground (Chapter 10). Nevertheless, there is considerable concern over the potential to quickly release large quantities of C to the atmosphere from forest floor and biomass burning (Eswaran et al., 2000).

Mineral Soil Organic Carbon

Most forest C is stored within the soil (see Chapters 3 and 4). The organic C content of forest soils in the arid and semiarid regions of the Interior West are on the low end of the soil organic C spectrum due to the inherently lower site productivity (Neary et al., 1999). In addition, soil organic C contents have a high degree of spatial variability due to high levels of microsite and landscape variability.

Landscape heterogeneity was mentioned above in terms of the wide range of landscapes that forests occupy in the Interior West. Landscape-level variability can be observed in data from the National Soil Survey laboratory characterization database (Table 18.4,

USDA Natural Resources Conservation Service, 1997). The mean soil organic C concentrations vary by an order of magnitude (0.04 to 4.91%) over the range of land resource areas. The ranges between maximum and minimum values are often two to three orders of magnitude. The high maximum values are due to aquic (wet) soils that were sampled.

Mineral Soil Inorganic Carbon

Carbonates are the main form of soil inorganic C (Eswaran et al., 2000). Compared to organic C, soil inorganic C in forest soils is less important. Only about 10% of the soil inorganic C is due to sequestration from atmospheric sources. Turnover rates of inorganic C are extremely long compared to organic C (85,000 y; Schlesinger, 1985). About 22% of the global soil inorganic C is in forest soils. Most C in the global soil inorganic C pool is in arid and semiarid lands without forest cover (Eswaran et al., 2000). Aridisols contain the largest pool of soil inorganic C, followed by Entisols and Mollisols.

MAJOR NATURAL FACTORS AFFECTING CARBON RESERVES

Changes in the C content of the soil pool are the net result of alterations in the input of C to the soil relative to soil C losses. Inputs include above- and below-ground plant litter, root exudates, and deposition (detention of C-rich sediments by physical processes and carbonate precipitation; Lal et al., 1998). Carbon losses occur via decomposition, volatilization, leaching, and wind and water erosional pathways (Bruce et al., 1999). The major factors that affect the balance between soil C inputs and losses are climate, net primary productivity, organic matter decomposition rates, erosion, and wildfire.

Climate

Climate determines the frequency and amount of precipitation inputs to ecosystems. Soil moisture is the key driver for both soil biological processes as well as aboveground productivity (Neary et al., 1999). The forests of the intermountain western US are characterized by frequent drought on both short- and long-term scales (Grissino-Mayer, 1996). There is tree ring evidence that the Southwest is currently in the wettest long-term moisture cycle in 2,200 years, and plant productivity and natural soil C inputs may be at a maximum. There is some corroborating evidence of this in pinyon-juniper expansion in the past 150 years (Gottfried and Pieper, 2000). Overlaid on these long-term trends are 5 to 10 year oscillations in precipitation amounts.

Net Primary Productivity

Net primary productivity provides the plant litter that comprises the major input to the soil C ecosystem pool. The more arid the forest conditions, the less C produced for incorporation into the mineral soil. The effects of this process are visible in the ambient levels of organic C in the Soil Orders (Kern, 1994).

Decomposition

Decomposition of plant litter at the soil surface and fine roots within the soil is a microbially mitigated process that is controlled, in part, by both soil temperature and moisture (Neary et al., 1999). Decomposition is the most important process on the loss side of the soil organic C equation. Decomposition rates in the Intermountain West are among the lowest in the continental United States, and diminish in the direction of the most arid ecosystems (Waring and Schlesinger, 1985; Hart et al., 1992).

Erosion

Erosion can be a major factor in soil C loss (see Chapter 11). It is an episodic process that is strongly linked to soil disturbances and land management practices (see Chapter 10). Erosional rates are presently not as high as they have been in the past due, in part, to reduced intensities of land management activities. For instance, virtually all forests in the Intermountain West are currently grazed or have been grazed by cattle. During the late 1800s, overgrazing in some locations led to erosional loss as high as 10 to 15 cm of organic C-rich A horizon material (mollic epipedon; Wildeman and Brock, 2000). Soil organic C losses via erosion can decrease site productivity and, depending on where it is deposited, be permanently lost from the system.

Wildfire

On the surface, it appears that wildfire adds to the loss side of the soil C balance equation. Certainly there are substantial changes in surface soil C immediately after a fire (DeBano et al., 1998). However, the meta-analysis by Johnson and Curtis (2001) clearly shows that, in the long-term (>10 y), wildfire increases soil C levels due to the sequestration of charcoal and recalcitrant, hydrophobic organic matter. Their analysis did not include any forest in the arid Interior West. Until this is confirmed for the arid forest soils discussed in this chapter, the generality of Johnson and Curtis's (2001) conclusions is uncertain.

Fire suppression in the southwestern US decreased fire frequency (Swetnam, 1990). Between 1910 and 1990, the area (5-year smoothed average) burned annually in Arizona and New Mexico by wildfires oscillated between 2,000 and 22,000 ha as woody biomass fuels increased. Fire in these forest and woodland ecosystems reached a critical level in 1991, with each subsequent year through 1996 resulted in a logarithmic increase in area burned. The 5-year running average reached nearly 75,000 ha in 1996, with the actual 1996 wildfire-burned area exceeding 100,000 ha (Neary et al., 1999).

Fire suppression contributed to the development of the overstocked ponderosa pine forests that we have in the Interior West, which have reduced considerably the productivity of understory species (Covington et al., 1997). Although forest floor C pools have

increased significantly over the past 100 years (Sackett et al., 1996), as well as tree fine-root biomass and production (Wright, 1996), inputs of herbaceous leaf and root litter to the soil have decreased dramatically (Hart et al., 1998).

MANAGEMENT ACTIVITIES AFFECTING CARBON RESERVES

Prescribed Fire

Prescribed fires and fuels treatments prior to prescribed fires can have significant impacts on aboveground C pools in arid forests. Usually these fires are of low enough severity that they do not affect the mineral soil C pool. Johnson and Curtis (2001) did note that their meta-analysis indicated short-term decreases in mineral soil C can occur after prescribed fires. As noted previously, their analysis did not include the dry forests of the Intermountain West, so this phenomenon is worth investigating further (see Chapters 10 and 13). Current forest management direction in the Intermountain West will result in far greater areas of the forests being treated with prescribed fire than was ever seen in the 20th Century. The net result will be decreases in forest floor, and aboveground biomass, and mineral soil C pools (Wright and Hart, 1997). However, over the long-term, some of these ecosystem losses will be offset by understory biomass and mineral soil C gains as grass and forb understories redevelop.

Grazing

Grazing is a major land management activity in most of the forests in the Interior West. In some regions, vegetation and fire management has resulted in unintended consequences. The extensive and prolonged overgrazing by sheep and cattle in the ponderosa pine forests and pinyon-juniper woodlands of the southwestern US resulted in a significant decline in the herbaceous biomass in interspace (inter-tree) areas (Kilgore, 1981). This overgrazing and subsequent reduction or removal of fine fuels, along with active fire suppression, have been implicated as causes for the decline in fire frequency. Natural, low-severity fires that occurred every 2 to 5 years in ponderosa pine forests (Dieterich, 1980) and every 10 to 30 years in pinyon-juniper woodlands (Wright et al., 1979) ceased. Subsequently, tree densities increased substantially, leading to the potential for low-frequency, high-intensity conflagrations (Covington et al., 1997).

Current levels of cattle grazing in forests are significantly lower than those of the 19th and early 20th Centuries (Ruyle et al., 2000). The impacts of grazing on rangeland ecosystem functions are directly related to grazing intensity. At low or moderate levels, Rice and Owensby (2001) suggested that grazing has no adverse impact on rangeland productivity or soil C. In fact, grazing at these intensities may increase soil C. Only high-intensity grazing has the potential for reductions in soil C. Part of the cattle grazing has been replaced by native and introduced wild ungulate use of the forested rangelands. These grazing impacts are reasonably well-regulated, so that overall impacts on forest soil C are expected to be minimal.

Harvesting

Harvesting impacts on the C pools of arid forests will not be discussed here as they are covered in more detail in other chapters (Chapters 11, 12, 14, and 15) in this book. Johnson and Curtis' (2001) literature review and meta-analysis showed that forest harvesting has little or no effect on soil C. Although their analysis did not include sites in the semiarid or arid West, the same conclusions would likely apply to these soils since the intensity and frequency of harvesting is lower in these forests.

CARBON SEQUESTRATION OPPORTUNITIES

It was previously mentioned that changes in the organic C content of the soil pool are the net result of alterations in the input of C to the soil and C loss via decomposition and erosion (Bruce et al., 1999). To realize a management-based net gain in soil C, ecosystem management must increase the amount of C entering the soil via an increase in net primary productivity (productivity increase) or decrease decomposition and erosion. Productivity in the arid forest ecosystems is already low due to moisture limitations (Table 18.2), and decomposition rates are the lowest in the continental US (Waring and Schlesinger, 1985; Hart et al., 1992).

Sequestration of C in forest soils of the Intermountain West via mechanical incorporation of organic material will be very site specific and greatly limited due to soil physical and institutional constraints. Many soils in the Interior West forests are lithic in nature, occupy steep slopes, and have developed on young mountain ranges and recent volcanic outflows. Much of the land base is in Federal ownership. Legal requirements associated with soil-based cultural heritage resources will most likely slow or prohibit extensive soil disturbances necessary to conduct a significant and successful organic matter sequestration program.

It is likely that many forest ecosystems of the Interior West have more C stored within them today than they did in pre-EuroAmerican times (circa prior to 1880; Hart et al., 1998). This is due to increases in stand-level tree productivity exceeding losses in herbaceous productivity over this period. Additionally, contemporary forests have more of their litter in recalcitrant (high lignin-to-nitrogen ratio) pine materials rather than more readily decomposed herbaceous litter (Kaye and Hart, 1998).

However, much of the gain in C storage in these ecosystems is in pools at high risk to loss from wildfire (aboveground biomass and forest floor). Conflagrations may result not only in rapid release of these C pools to the atmosphere, but might also be severe enough to cause reductions in net ecosystem C gain (i.e., net ecosystem production) for decades. Hence, perhaps the best C sequestration strategy in these inherently low productivity ecosystems is to return their structures to within their historical range of variability (Covington et al., 1997; Kaye and Hart, 1998). Although this will result in a net loss of C from these ecosystems, it will increase the amount of the total ecosystem C stored belowground, thus reducing the potential for its loss from wildfire (Neary et al., 1999). Additionally, returning these ecosystems to their historical structure will substantially decrease the risk of wildfire by reducing fuel loads and tree densities.

SUMMARY AND CONCLUSIONS

The forests in the dry regions of the interior western US are characteristically ones in which annual water losses through evapotranspiration exceed or are slightly less than annual precipitation. The presence of water, interacting with soil processes, soil properties, soil biota, and vegetation ultimately determines the amount, quality, and state of C in soil. The major forest types in the dry Interior West consist of ponderosa pine, pinyon-juniper, oak woodlands, chaparral, and mesquite. These forest types often occur with shrub and grass associations.

The soils of the forested intermountain western US are the most varied in the country because of their landscape settings, parent materials, climates, and biota. The interactions of these factors over time have produced forest soils that characterize the region and continue to influence the cycling of C and other elements. The major Soil Orders in these aridland forests are Alfisols, Aridisols, Entisols, Inceptisols, and Mollisols. These soils are generally characterized by having a large proportion of ecosystem C in the belowground pool, and low rates of both net primary productivity and decomposition.

Forest floor C pools have increased significantly in the past 100 years in aridland forests due to overgrazing and wildfire suppression. Forest floor fuel loads that were 0.4 - 4.5 Mg ha⁻¹ prior to 1870 have increased to as high as 112 Mg/ha, with an average of 49 Mg ha⁻¹ (Sackett et al., 1996). This situation is common throughout the Intermountain West, and a cause for concern. Severe wildfires have the potential to release large amounts of C back into the atmosphere.

Although these dry forests have larger amounts of inorganic C than more humid areas, organic C is still the most important fraction in the soil. Inorganic C, in the form of carbonates, accumulates at very slow rates and has long turnover times; hence, pedogenic carbonates are an unlikely pool for storing significant amounts of atmospheric C over the short-term.

There are essentially no opportunities for increasing C sequestration in these ecosystems. This is due to a variety of factors, including: water limitation of net primary production, the plethora of cultural resources that are affected by soil disturbance, and much greater C storage in these ecosystems currently than in the historical past. However, much of the current ecosystem C is at severe risk of loss due to wildfire. Hence, the best C sequestration strategy is to return their structures to within their historical range of variability, which included lower tree densities and greater herbaceous production. Although this will result in a net loss of C from these ecosystems, it will increase the amount of the total ecosystem C stored belowground, thus reducing the potential for its loss from wildfire. Additionally, returning these ecosystems to their historical structure will substantially decrease the risk of wildfire by reducing fuel loads and tree densities.

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Continued

Table 18.1 Vegetation zones and soils of the arid and semiarid interior western USA: Subtropical Steppe, Subtropical Desert, Temperate Steppe, Temperate Desert, East Side Marine, Mediterranean, California Dry Steppe, and Sierran East Side Steppe-Mixed Forest. (Adapted from Bailey 1995).

Bailey's Ecoregion	Area	Major Vegetation	Major Soils
300 DRY DOMAIN	10 ³ km ²		
310 Subtropical Steppe			
311 Great Plains Steppe & Shrub	45.6	Long-grass Prairie, Oak Savanna	Mollisols, Alfisols (minor)
313 Colorado Plateau Semi Desert	195.0	Arid Grasslands, Oak–Juniper Woodland, Pinyon-Juniper Woodland Ponderosa Pine, <i>Lodgepole Pine</i> – <i>Aspen</i> ¹ , <i>Subalpine Spruce-Fir</i> ¹	Aridisols, Entisols
315 Southwest Plateau & Plains Dry Steppe	416.7	Grasslands & Mesquite, Oak–Juniper, Needlegrass, Shrubs, Trees	Entisols, Mollisols, Alfisols, Vertisols
M313 AZ-NM Mountains Semidesert-Woodland- Conifer Forest –Alpine	130.0	Mixed Grasses, Chaparral, Oak-Juniper, Pinyon-Juniper Woodland Ponderosa Pine, <i>Douglas-fir</i> & <i>Aspen</i> ¹ , <i>Spruce-Fir</i> ¹	Varied, Entisols, Alfisols, Inceptisols, Mollisols (minor)
320 Subtropical Desert			
321 Chihuahuan Desert	220.7	Shrubs and short grasses, Cacti & Yuccas, Creosote Bush, Pinyon-Juniper Woodland, Oak–Juniper Woodland <i>Douglas-fir</i> & <i>White Fir</i> ¹	Aridisols, Entisols
322 American Semidesert& Desert	227.1	Cacti & Thorny Shrubs, Thorn-less Shrubs & Herbs, Creosote Bush, Paloverde, Bitterbrush, Joshua Tree, Pinyon-Juniper Woodland	Aridisols, Entisols
330 Temperate Steppe			
331 Great Plains-Palouse Dry Steppe	752.9	Shortgrass Prairie, Sagebrush & Rabbitbrush, Scattered Trees	Mollisols
332 Great Plains Steppe	347.1	Tallgrass Prairie to Shortgrass Steppe, Riparian Hardwoods	Mollisols, Entisols, Vertisols (minor)
M331 Southern Rocky Mountain Steppe-Open Woodland, Conifer Forest-Alpine Meadow	265.0	Grass and Sagebrush, Shrubs and Scrub Oak, Pinyon-Juniper Woodland, Ponderosa Pine, <i>Douglas-fir</i> ¹ , <i>Subalpine Spruce-Fir</i> ¹	Mollisols, Alfisols (minor), Aridisols, Inceptisols
M332 Middle Rocky Mountain Steppe- Conifer Forest-Alpine	211.9	Grass and Sagebrush, Ponderosa Pine, <i>Lodgepole Pine</i> / <i>Grasses</i> ¹ , <i>Douglas-fir</i> / <i>Grand Fir</i> ¹ , <i>Subalpine Spruce-Fir</i> ¹	Mollisols, Alfisols (minor), Inceptisols
M333 Northern Rocky Mountain Forest-Steppe- Conifer Forest– Alpine Meadow	98.7	<i>Douglas-fir</i> ¹ , <i>Cedar-Hemlock-Fir</i> ¹	Inceptisols

M334 Black Hills Conifer Forest	9.6	Sagebrush, Ponderosa Pine <i>White Spruce & Aspen</i> ¹ , <i>Paper Birch</i> ¹	Alfisols
340 Temperate Desert	277.4	Sagebrush Association, Pinyon-Juniper Woodland, Ponderosa Pine	Aridisols, Entisols
341 Intermountain Semi-desert and Desert		<i>Douglas-fir</i> ¹ , <i>Subalpine Spruce-Fir</i> ¹	
342 Intermountain Semidesert	412.1	Sagebrush & Grasses, Western Juniper	Aridisols/Entisols, Mollisols
M341 NV-UT Mountains Semidesert-Conifer Forest-Alpine Meadow	112.9	Sagebrush, Pinyon-Juniper Woodland, Ponderosa Pine <i>Douglas-fir</i> ¹ , <i>Subalpine Spruce-Fir</i> ¹	Aridisols, Mollisols
200 HUMID DOMAIN			
240 Marine			
M242 Cascade Mixed- Forest-Conifer Forest- Alpine Meadow ¹ EAST SIDE ONLY	138.3	Mixed Shrubs & Grass, Ponderosa Pine, <i>Douglas-fir</i> , <i>Cedar</i> , <i>Hemlock</i> ¹ , <i>Spruce</i> , <i>Fir</i> ¹	Aridisols
260 Mediterranean			
261 California Coastal Chaparral Forest and Shrub	26.7	Pine & Cypress, Sagebrush & Grasses, Live & White Oak, Chamise & Manzanita, Coyote Bush	Alfisols, Mollisols
M261 Sierran Steppe-Mixed Forest-Conifer Forest-Alpine Meadow ¹ EAST SIDE ONLY	176.9	Sagebrush-Pinyon Forest, Jeffrey /Ponderosa Pine <i>Fir</i> , <i>Cedar</i> , <i>Hemlock</i> , <i>Pine</i> ¹	Alfisols, Entisols
M262 California Coastal Open Woodland; Shrub-Conifer Forest-Meadow	63.5	Chaparral, Various oaks, Laurel, Madrone	Alfisols, Entisols, Mollisols

¹High elevation vegetation and soils covered in Chapter 17.

Table 18.2 Aboveground net primary production for selected ecosystems in the western US¹

Ecosystem	Aboveground Net Primary Production ²
	Mg C ha ⁻¹ y ⁻¹
Sagebrush	0.15
Desert Shrub	0.35 - 0.65
Shortgrass Steppe	0.58
Pinyon-Juniper Woodlands	0.60 - 1.4
Desert Grassland	0.70 - 1.2
Oak Woodlands	0.75
Ponderosa Pine	1.1 - 2.9
Mesquite	1.3 ³
Chaparral	2.1 - 4.3
Annual Grasslands	2.2
Tallgrass Prairie	2.2
Douglas-fir	3.1 - 5.8
Hemlock-Sitka Spruce	6.5 - 7.5

¹Data compiled from the following references: Whittaker and Niering, 1975; Caldwell et al., 1977; Schlesinger and Gill, 1980; Ehleringer and Mooney, 1982; Gholz, 1982; Jackson et al., 1985; Heitschmidt et al., 1986; Gower et al., 1992; Grier et al., 1992; Knapp and Smith, 2001; and S. Hart, unpublished data.

²Assumes dry mass is 50% C.

³Includes only herbaceous understory production.

Table 18.3 Mineral soil organic C content (to a 1-m depth) of selected forest ecosystem complexes (After Kern 1994)

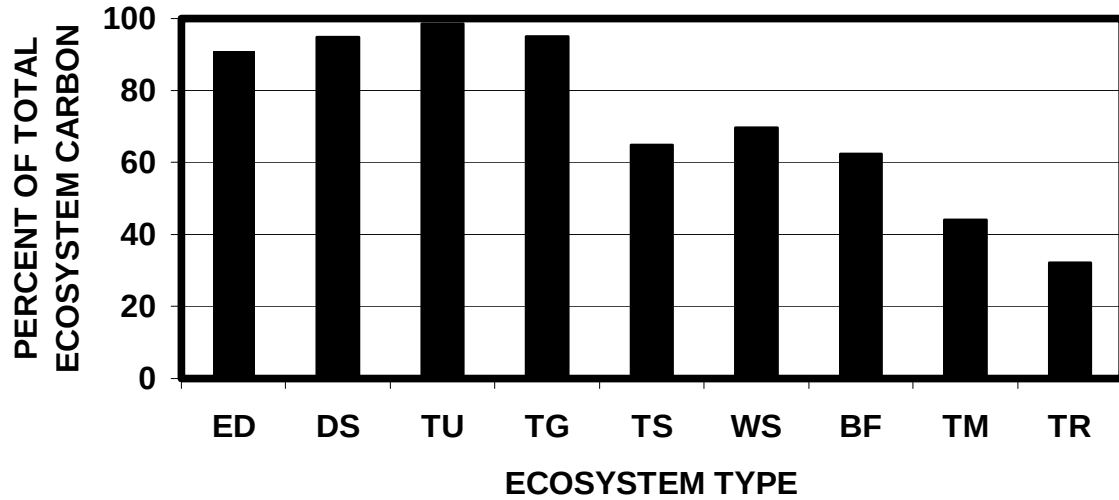
Ecosystem Complex	Mean	Min.	Max.
			kg organic C m ⁻²
Scrubland, hot desert/desert	2.5	0.3	5.8
Scrub/woodland/savanna, Mediterranean	7.5	0.6	50.0
Woodland or Scrubland, sparse	7.8	2.8	27.1
Woodlands, warm semiarid	10.2	8.9	11.3
Forest, warm conifer	13.6	0.3	45.1

Table 18.4 National Soil Survey characterization data for organic C by major selected land resource areas (MLRAs) containing dry forests (USDA Natural Resources Conservation Service 1997)

Land Resource Area Description	Number	Mean	Max.	Min.
		Organic C (%)		
Central Arizona Basin and Range	69	0.40	1.58	0.03
Sonoran Basin and Range	82	0.49	2.51	0.01
Southern California Mountains	48	0.73	3.94	0.04
New Mexico and Arizona Plateaus and Mesas	123	0.75	2.37	0.01
Central California Coast Range	140	1.14	24.36	0.02
Sierra Nevada Foothills	83	1.14	5.67	0.02
Semiarid Rocky Mountains	8	1.15	4.08	0.10
Central Nevada Basin and Range	114	1.20	14.82	0.02
Black Hills	73	1.37	10.50	0.04
Carson Basin and Mountains	154	1.37	26.10	0.01
Northern Rocky Mountain Foothills	124	1.43	10.00	0.04
Malheur Plateau	165	1.78	7.60	0.02
Wasatch and Uinta Mountains	253	2.38	42.57	0.03
Arizona and New Mexico Mountains	67	2.66	48.67	0.06
High Intermountain Valleys	49	2.66	33.40	0.05
Southern Rocky Mountain Foothills	21	3.24	41.18	0.29
Southern Rocky Mountains	454	4.01	62.27	0.02
Cascade Mountains Eastern Slope	225	4.91	56.74	0.01

Continued

Figure 18.1 Generalized percentages of ecosystem carbon in soils for extreme deserts (ED), desert scrub (DS), tundra (TU), temperate grasslands (TG), tropical savanna (TS), woodlands and shrublands (WS), boreal forest (BF), temperate forest (TM), and tropical forest (TR) (Adapted from Waring and Schlesinger 1985)



Continued

Figure 18.2 STATSGO derived Soil Orders of the western United States (Ramsey 2002)

