

Redwoods, restoration, and implications for carbon budgets

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ABSTRACT

The coast redwoods (*Sequoia sempervirens*) of California have several unique characteristics that influence interactions between vegetation and geomorphic processes. Case studies, using a combination of in-channel wood surveys and an air photo inventory of landslides, illustrate current conditions in a redwood-dominated watershed undergoing restoration work, and the influence of wood loading and landslides on the carbon budget. Redwood trees have extremely large biomass (trunk wood volumes of 700 to 1000 m³) and are very decay-resistant; consequently, they have a large and persistent influence on in-channel wood loading. Large wood surveys indicate high wood loading in streams in uncut forests (0.3–0.5 m³/m² of channel), but also show that high wood loading can persist in logged basin with unlogged riparian buffers because of the slow decay of fallen redwoods. Through a watershed restoration program, Redwood National Park increases in-channel wood loading in low-order streams, but the effectiveness of this technique has not yet been tested by a large flood. Another unique characteristic of redwood is its ability to resprout from basal burls after cutting, so that root strength may not decline as sharply following logging as in other types of forests. An air photo inventory of landslides following a large storm in 1997 indicated: 1) that in the Redwood Creek watershed the volume of material displaced by landslides in harvested areas was not related to the time elapsed since logging, suggesting that the loss of root strength was not a decisive factor in landslide initiation, 2) landslide production on decommissioned logging roads was half that of untreated roads, and 3) landslides removed an estimated 28 Mg of organic carbon/km² from hillslopes. The carbon budget of a redwood-dominated catchment is dominated by the vegetative component, but is also influenced by the extent of mass movement, erosion control work, and in-channel storage of wood.

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1. Introduction

Vegetative cover can change in response to human activities, climatic change, fire, pests, disease, and invasion by non-native species. Such changes in vegetation can influence geomorphic processes in many ways: through changes in sediment production, transport and deposition; hydrology (interception, infiltration, and runoff); hillslope erosion processes (rilling, gully, and mass movement); in-channel wood loading, sediment storage and roughness; and channel morphology (width, depth, and planform). In turn, geomorphic processes can influence the type and distribution of vegetation in a watershed through controls on disturbance regimes. For example, many conifer species in cool temperate forests occur in environments prone to disturbances from fire, wind, ice, floods, and mass movement events. Geomorphic processes can affect the spatial distribution of these disturbances through effects on topography, and the processes can be modified by anthropogenic disturbances, such as timber harvest. Disturbances can have important effects of the structure and function of old-growth forest stands, including nutrient cycling, modification of fuel loads, formation of cavity trees for

wildlife, and promotion of complex canopy architecture (Noss, 2000; Lorimer et al., 2009).

In the steep, forested terrain of the Pacific Northwest in the United States, channels are closely coupled with the vegetated hillslopes. In these upland settings, the geomorphic system is dominated by sediment production, transport and evacuation, whereas farther downstream channels become decoupled from hillslopes and sediment accumulates in floodplain valleys (Church, 2002). In uplands and upland valleys, vegetation strongly influences geomorphic processes and landforms through its influence on sediment production, storage and transport. Although interactions between vegetation and geomorphology have been studied in several regions (see Hupp et al., 1995), coast redwoods (*Sequoia sempervirens*) have several unique characteristics that influence such interactions. The purposes of this paper are to examine interactions between the coast redwood forest and geomorphic processes in steep, upland areas and to propose a conceptual base to link studies of geomorphology and carbon fluxes in the redwood region. First, I will present a general overview of redwood characteristics. Next I will present case studies involving in-channel wood loading and landslides and discuss how watershed restoration efforts influence these processes. Finally, I discuss the implications of these processes in formulating a carbon budget of a watershed.

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2. Regional setting

Coast redwoods (*S. sempervirens*) have been a dominant species in the California Coast Range for much of the Holocene (Sawyer et al., 2000a). The current distribution stretches from the southwestern tip of Oregon south to Monterey County, California (Fig. 1). The northern and central sub-regions are underlain primarily by Franciscan sandstones, mudstones and schists of the Mesozoic age, whereas bedrock in the southern sub-region is predominantly Cenozoic marine and non-marine sedimentary deposits. The area is tectonically active, with many faults and earthquakes. Most notable is the San Andreas Fault, which runs through much of the southern and central Coast Range and forms the boundary between the North American and

Pacific plates. In the northern Coast Range, a third plate is also present, delineating the Cascadian subduction zone.

At the northern end of the redwood range, redwoods blanket entire hillslopes. In the south, however, redwoods are commonly restricted to small pockets sheltered in narrow valleys, often surrounded by shrublands and grasslands. Consequently, redwood interactions with hillslopes are most strongly expressed in the northern part of the range. The redwood region has a Mediterranean climate, with mild, rainy winters and cool dry summers, but with frequent summer coastal fog. Annual precipitation varies between 640 and 3100 mm.

In redwood terrain, forested earthflows, debris torrents and shallow debris slides are common. For example, mass movement features (earthflows, rock slides, shallow debris slides, and debris

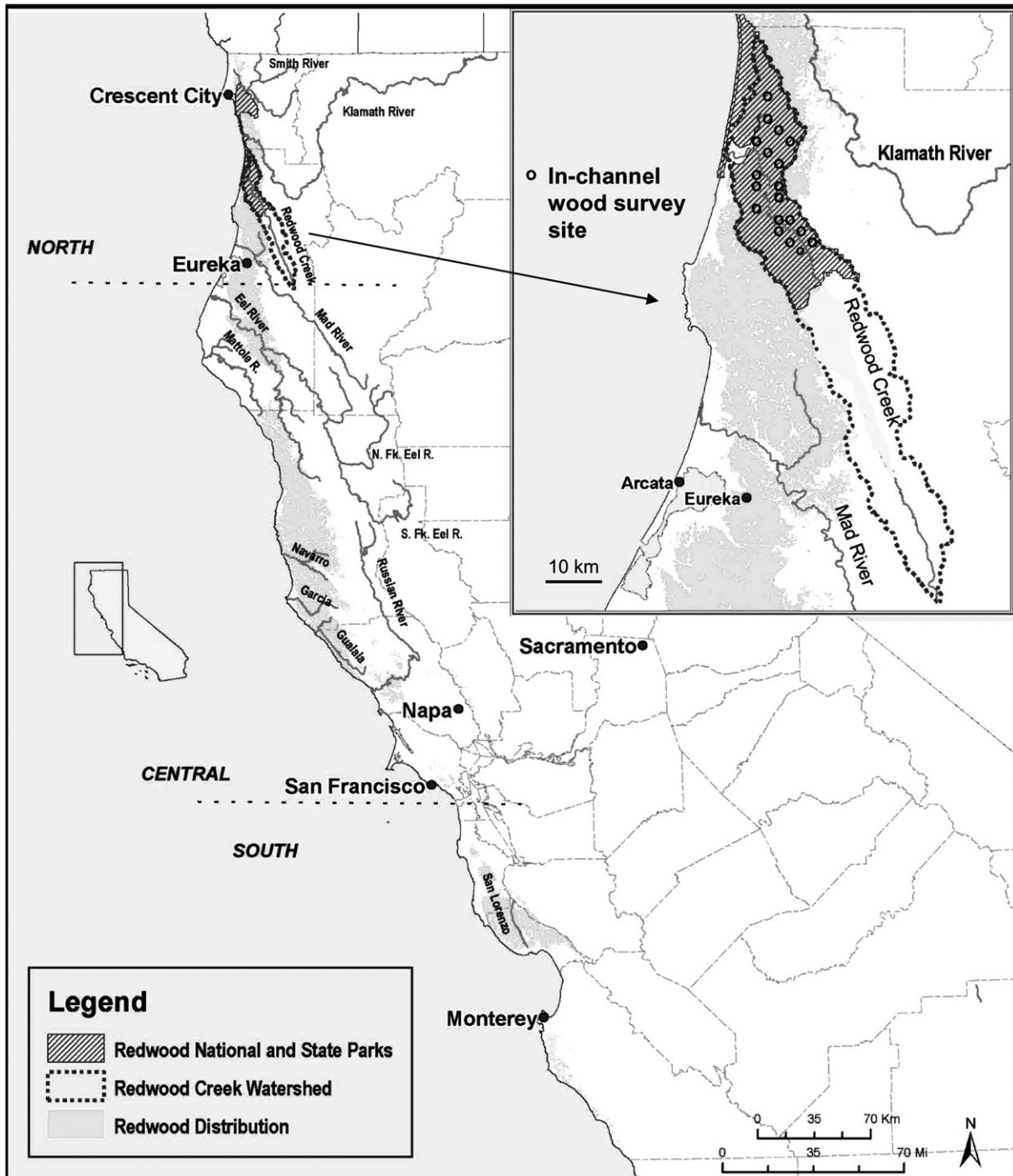


Fig. 1. Location map showing the range of coast redwood in California and the study site of the Redwood Creek basin.

torrents) encompass 27% of the Redwood Creek watershed in north coastal California, and an additional 19% of the basin exhibits disrupted ground and hummocky topography related to past mass movements (Falls et al., 2003). Trees influence mass movement processes through effects on root strength, the mass of wood itself, and its influence on interception and infiltration of rainfall (Swanston et al., 1995). The length of debris flow runout is moderated by the presence of wood (Lancaster et al., 2003), and in turn, wood loading in streams is influenced by the occurrence of debris flows.

Redwood is a shade-tolerant species with great longevity (up to 2200 years; Fritz, 1957), and old-growth stands are commonly highly uneven-aged (Veirs, 1982). The bark is thick (30 cm), fibrous, and fire resistant (Fig. 2a). The surface area of foliage in a redwood forest is large, and can store significant amounts of rainfall, resulting in low stemflow rates. For example, about 22% of incoming rainfall was intercepted by foliage in a second-growth redwood forest (Reid and Lewis, 2007). On undisturbed uplands in the redwood forest, overland flow is rare because of deep litter accumulation and high rates of infiltration of soils. Following logging, however, such processes as slopewash, rainsplash and rilling become common, erode soil, and lead to higher sediment yields (Marron et al., 1995).

The root system of redwoods is composed of widespread lateral roots with no taproot (Sawyer et al., 2000b). When a redwood topples through windthrow or streambank erosion, the rootwad, which is commonly 5 m or more in diameter, displaces a large mound of soil (Fig 2b). North coastal California is subject to regular windstorms, and

high winds are routine events in redwood forests, killing individual trees or even small clumps of trees (Noss, 2000). Fallen redwoods in streams form major obstructions to stream flow and are an important control on the dissipation of the energy of a stream (Fig. 2c). The volume of in-channel wood loading in redwood-dominated rivers is three times that of streams draining other conifer-dominated systems (Gurnell, 2003).

Scores of redwoods are greater than 100 m tall and individual old-growth trees have trunk wood volumes of 700 to 1000 m³ (Sawyer et al., 2000b). Old-growth redwood stands support some of the largest quantities of biomass in the world, up to 3500 Mg of stem biomass per hectare (Noss, 2000; Busing and Fujimori 2005). Redwood has the ability to vigorously resprout from basal burls after being damaged or harvested, and an ability to replace burned branches along the bole with new sprouts from epicormic buds, traits that are highly unusual for a conifer. Cut stumps are commonly encircled by many sprouts that sustain the stump–root system (Cole, 1983) (Fig. 2d). Although redwoods may be killed by extended soil saturation following floods, redwoods can form adventitious roots in flood deposits, which allow them to survive burial by meters of silt and sand. Redwood is very decay-resistant because of the presence of volatile essential oils and tannins (Sawyer et al., 2000b), and Franklin et al. (1981) suggest that redwoods may persist as long as logs as they do as living stems.

Because of decay resistance, redwoods are highly prized as lumber. As Europeans settled in California in the nineteenth century, they slowly began logging the massive redwoods. With the advent of new



Fig. 2. a) Fibrous, deeply furrowed bark of a redwood tree, b) Root wad of a fallen redwood showing lateral roots and lack of tap root (photo by Vicki Ozaki), c) In-channel wood. The tally for in-channel wood counted the log lying on the channel bed, but not the spanning log above the high water mark (photo by Sharon Kramer), d) Stump of a redwood that was harvested circa 1880. Four stump sprouts up to 0.4 m in diameter, sustained by the original root system, are growing at the base of the stump.

technology after World War II, large-scale tractor logging accelerated the harvest of old-growth redwoods, and the current extent of old-growth redwood stands is only about 10% of its pre-settlement distribution. When felled, redwoods tend to shatter upon impact with the ground. To protect the value of the harvested tree, bulldozers were used to construct layouts (swaths about 100 m long carved into the hillslopes and layered with loose soil and smaller trees) to soften the impact of a falling old-growth tree. This type of logging resulted in an extensive network of logging roads and vast expanses of mineral soil being exposed (Fig. 3).

Following logging operations, abandoned roads produce sediment in several ways. Forest roads, constructed across the steep slopes typical of this region, frequently result in landslides that contribute sediment directly into stream channels. During the period of 1954 to 1978, road-related landslides accounted for about 40% of total landslide volume, based on an inventory of landslides in 16 sub-basins of Redwood Creek, California (Pitlick, 1995). Unmaintained drainage structures, such as culverts, can become plugged with sediment or wood during storms, and divert runoff onto unchanneled hillslopes, resulting in extensive gullying. Road cuts can intercept groundwater and increase the amount of surface runoff (Wemple, 1998). Inboard ditches adjacent to road benches can reroute runoff to different basins. The compacted road surfaces, landslide scars, and gullied hillslopes represent a loss of soil and forest productivity. For example, the surface area of major forest roads in the Redwood Creek basin encompasses 50 km², about 7% of the total basin area. In addition, historically many stream channels were used as roads, where bulldozers cleared the streambeds of all merchantable wood.

As the environmental damage from harvest of redwoods was recognized, restoration efforts were initiated. The first large-scale watershed restoration program began in 1978 at Redwood National Park (RNP) in north coastal California, where 15,000 ha of previously logged land was transferred to the park. The program focuses on reducing erosion from abandoned logging roads. Typical treatments to reduce sediment delivery to streams from roads include decompacting and recontouring the road surface to restore natural drainage patterns, removing culverts and road fill from stream channels and reshaping the streambanks, and excavating unstable sidecast fill from the downslope side of road benches or landings. Since about 2000, RNP has implemented a policy of placing large volumes of wood in

newly excavated stream crossings to deter channel incision and bank erosion (Fig. 4). About 400 km of roads has been removed in the Redwood Creek basin since 1978. Although the long-term goal is to decrease erosion from roads, in the short-term, during road removal work, many young trees are cut down, large areas of ground are disturbed, and turbidity levels in adjacent streams rise (Klein, 2008). For example, in small headwater basins, road removal through heavy equipment work can bare one-fifth of the surface area (Fig. 5).

3. Case studies

3.1. In-channel wood loading

In-channel large wood provides critical structural elements in the redwood region. Redwood boles and root wads in stream channels influence channel morphology, sediment storage, and energy dissipation, as well as being an important component of aquatic habitat. Previous large wood surveys in the redwood region focused on low-gradient (primarily less than 2%) fish-bearing streams (Keller and Tally, 1979; Keller et al., 1995; Benda et al., 2002). Here I extend this type of work to steeper streams and restored stream channels.

The volume of in-channel wood in streams draining redwood forests was measured in tributaries of lower Redwood Creek and in excavated stream crossings in 2005 and 2006 (Fig. 1). The streams ranged from 14% in boulder cascades to less than 1% in gravel-bedded channels. The length of surveys extended 20 to 40 channel widths. Riparian forests adjacent to these streams ranged from old-growth redwood, a buffer of old-growth redwood between the stream and clearcut areas, and second-growth redwood forests. Surveys included all pieces of organic debris greater than 10 cm in diameter and 1.8 m long located within the bankfull channel, using the same criteria deployed in other surveys in this region to compare results (Keller et al., 1995). A piece suspended over the channel was only counted if it had an influence on the water during bankfull flow, and the portion of a piece of in-channel wood that extended beyond the bankfull width was not tallied. Defining bankfull stage in steep terrain can be challenging because of the scarcity of distinct floodplains. Several indicators were used to define bankfull stage: high flow marks, a change in vegetation, topographic breaks along the bank, a change in particle size in the bed and bank material, and the lower extent of lichens on

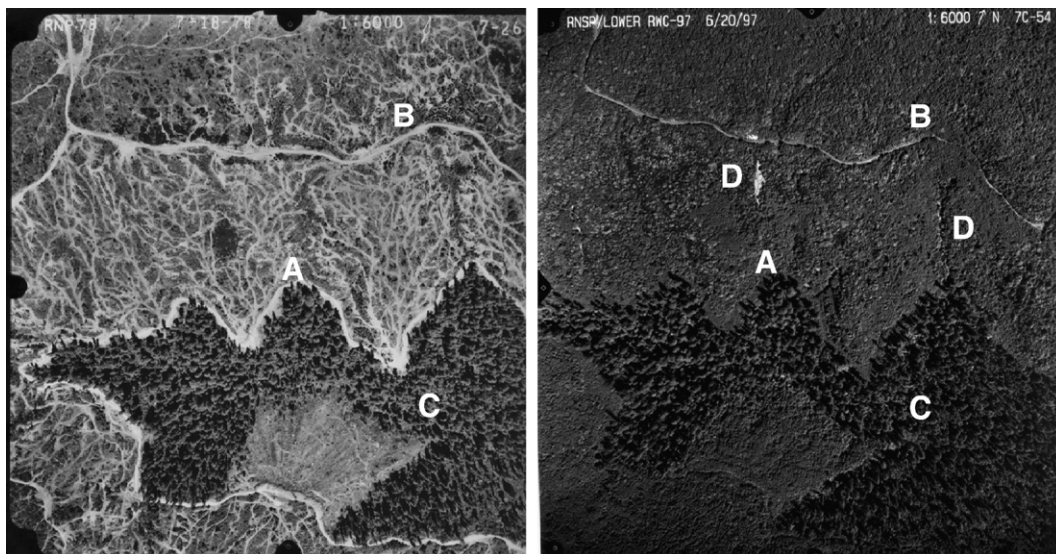


Fig. 3. a) 1978 aerial photograph (1:6000) showing main logging roads and networks of smaller skid trails in a tractor-yarded clearcut in Bond Creek, a tributary of Redwood Creek, where old-growth redwood recently had been harvested. b) The same location in 1997. A) A major haul road that existed in 1978 was decommissioned and became revegetated by 1997. B) A major haul road that has not yet been decommissioned. C) Bond Creek flows through a buffer of old-growth redwood trees at the base of a cable-yarded harvest unit. D) Debris flows triggered by a storm in 1997.



Fig. 4. Photograph of a newly excavated stream crossing following culvert removal from an abandoned logging road. View is looking upstream where the culvert and overlying road fill were removed and the streambanks pulled back to resemble natural topography. Stumps on the left side of the photo had been buried under road fill, but were exposed during the excavation. Following excavation, wood was placed on the banks and in the channel in order to control channel incision and streambank erosion.

boulders (Harrelson et al., 1994). The volume of wood in an individual piece was calculated as:

$$(\text{length} \times 3.14 \times (\text{radius at midpoint of bole})^2).$$

Individual logs in a log jam were measured, where possible. If a debris jam was too complex to count individual pieces, we measured the length, width, and height of the jam and estimated the void space of that volume to calculate the volume of wood contained in the jam.

Wood loading (reported as volume of wood per unit area of channel bed) varies widely (Table 1), but streams draining old-growth redwood forests have higher loadings than those draining second-growth forests (Fig. 6). The hillslopes adjacent to most of the steeper streams surveyed in this study had been heavily logged (Table 1). Nevertheless, streams with a riparian buffer strip of old-growth forest had higher wood loadings than those flowing through second-growth forests. Upper Miller Creek had the highest level of

Table 1

In-channel wood loading in tributaries of the Redwood Creek basin.

Sub-basin	Drainage area (km ²)	Channel gradient (%)	Percentage of basin in old-growth forest	Bankfull width (m)	Woody debris loading (m ³ /m ² of channel bed area)
Hayes	1.5	2.6	96	1.9	0.12
Little Lost	8.0	2.6	98	4.8	0.45
Man at gage					
Little Lost	10.7	0.9	89	4.5	0.01
Man at bridge					
Emerald	7.7	6.5	36	9.1	0.16
Cloquet	2.9	9.3	30	5.2	0.12
Elam	6.7	2.6	27	6.8	0.24
Larry Damm	4.8	0.7	21	8.7	0.02
Lost Man above Larry Damm	24.8	0.8	20	10.8	0.06
Lost Man below North Fork	16.0	–	20	13.1	0.02
Lower Miller	3.4	5.8	20	4.2	0.16
Bond	3.6	6.1	18	4.3	0.17
Tom McDonald	17.9	1.1	14	5.7	0.02
South Fork	10.2	3.3	12	6.5	0.15
Lost Man					
McArthur	9.8	1.0	12	4.7	0.03
North Fork Lost Man	5.8	2.3	9	4.7	0.04
Berry Glen	1.0	4.9	7	3.9	0.01
Fortyfour	8.0	8.0	6	6.7	0.03
Upper Miller	1.8	9.8	5	4.7	0.71
Middle Fork	5.9	4.3	2	10.4	0.10
Lost Man					
Excavated crossings	0.01–0.2	10–14	0	1–2	0.3–0.6

wood loading in the study, even though 95% of the basin had been logged, because many large old-growth redwoods had entered the stream through windfall. Windfall has been reported to be an important component of in-channel wood loading in other redwood-dominated basins as well (Reid and Hilton, 1998). Even one large tree can greatly influence wood loading. For example, in Upper Little Lost Man Creek 60% of total loading consisted of one redwood trunk (Keller and Tally, 1979) and in Prairie Creek nearly 25% of the total volume of in-channel redwood was contributed by just the extremely large pieces (greater than 2 m in diameter) (Kramer and Klein, 1999).

Currently, the National Park Service is experimenting with introducing large amounts of wood to stream crossings as abandoned roads are being decommissioned. Stream crossings that were excavated during road restoration work and armored with wood pieces

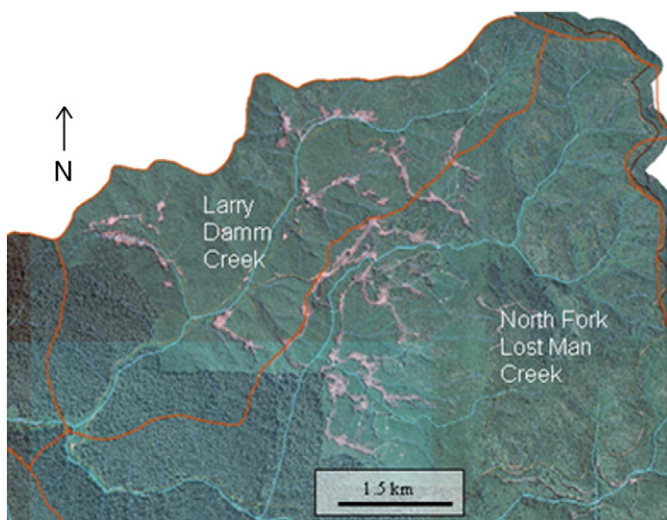


Fig. 5. Aerial photograph showing bare earth from forest clearing and ground reshaping that occurs during road removal activities in tributary basins of Redwood Creek, Redwood National Park, California. Overview of Lost Man Creek watershed within Redwood National Park. Bare land represents recent road restoration work that temporarily disturbs the ground surface and stream channels. Blue lines are perennial streams and the red line outlines sub-watersheds.

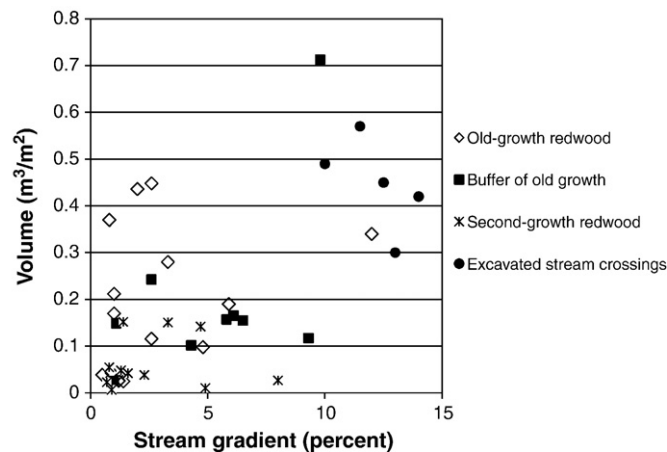


Fig. 6. Large wood loading in tributaries of Redwood Creek, CA. Data from other studies in this region are included for comparison: Old-growth (Keller et al. (1995) 9 sites; Benda et al. (2002) 1 site; Kramer and Klein (1999) 1 site); second-growth (Keller et al. (1995) 4 sites); and excavated stream crossings (Maurin (2008) 1 site).

placed in the channel by heavy equipment had higher wood loadings than most streams with a buffer of old-growth trees or streams draining second-growth forests (Fig. 6). Nevertheless, the architecture of this wood placement in excavated crossings differs from a natural step–pool structure, the size distribution of the wood is much smaller than in natural streams, and the species composition contains more hardwoods. This policy of wood placement has not yet been tested by a large (>10 year) storm. Future research is needed to assess the effectiveness of such wood placement in restoring structure and stability in small, steep channels, and its effect on aquatic biota.

Most of the channel length in a drainage network is represented by low-order streams. For example, in the Redwood Creek basin, fully 95% of the channel length of the drainage network is steeper than 1% grade (Falls et al., 2003) and about 460 km of perennial and intermittent stream channels has gradients between 1% and 20%. In these narrow channels, the majority of wood pieces are longer than the channel width; consequently, mobility of wood is probably low unless a debris flow reams out the channel. Data on wood loading for pristine, steep (>5%) streams are rare because such stream reaches are rare and difficult to access. More data on these steep tributaries are needed to calculate a total mass of in-channel wood, and this will be a focus of future research.

3.2. Landslides

Mass movement processes are a dominant means of supplying sediment and wood to coastal California rivers. Timber harvest and road construction commonly increase rates of landsliding in this region (Harden et al., 1995). Studies of landslides in other regions suggest that landslide frequency increases in forest stands that were clearcut one to 10 years earlier, because of decreases in root strength due to decay (O'Loughlin and Watson, 1979; Ziemer, 1981; Watson et al., 1999; Imaizumi et al., 2008). Loss of root strength in cutover redwood forests may not be as severe as in other forest types because of the ability of a redwood stump to sprout after harvest. Nevertheless, although redwood root strength may not decay rapidly, other hydrologic functions (interception, infiltration, etc.) are still affected by harvest (Reid and Lewis, 2007) and can lead to higher soil moisture and increased rates of landslides. Redwood root strength and the rate of root strength decay following harvest of redwood trees are not well studied, but have important implications for predicting potential hillslope instability and for prioritizing restoration efforts. An objective of the watershed restoration program at Redwood National Park is to decrease the number of landslides from roads through decommissioning work. I will use landslide inventories from the Redwood Creek basin to explore these topics.

Large storms in 1964, 1972, and 1975 (with return periods of 20 to 50 years) triggered hundreds of landslides in the Redwood Creek basin, and a storm in January, 1997, which generated a 10-year peak flow in Redwood Creek, activated an additional 261 landslides here. In 1980, about 1500 landslide scars from the earlier period were mapped along Redwood Creek and its major tributaries, and summary results were reported in Kelsey et al. (1995) and Pitlick (1995). The researchers measured the surface area of the landslide voids using a tape and rangefinder, and estimated depths by visually reconstructing the original hillslope shape prior to failure and estimating the average thickness of material lost. Volume was calculated as the product of area and depth. Based on field notes I located for 1170 of these landslides, I tabulated the area and volume of individual landslides. Following the methodology of Guzzetti et al. (2009), I fit the empirical data of area (A) and volume (V) to model the relationship between the two by the equation:

$$V = 0.452 \cdot A^{1.148} \quad (R^2 = 0.9433) \quad (1)$$

with A in m^2 and V in m^3 .

Shallow debris landslides and debris flows generated during the January, 1997 storm were mapped on 1:6000 air photos taken in the summer of 1997 (Fig. 3b) and this information was transferred to a GIS. In this region, vegetation commonly recolonizes landslide scars within a year or two, making it straightforward to differentiate landslides originating in 1997 from older landslides. Comparison of the mapped landslides with field-based road damage surveys conducted by Redwood National Park staff indicated that the minimum landslide scar detectable on the 1997 photos was 400 m^2 in area. The surface area of the mapped landslides was determined from the GIS, and for landslides greater than 400 m^2 pertinent data (underlying bedrock, hillslope gradient, association with roads or timber harvest units) were assembled (Curry, 2007; L. Reid, USFS, personal communication). The area–volume relationship defined by Eq. (1) was used to estimate volumes of material mobilized by these more recent landslides.

In 1997, shallow debris slides and debris torrents encompassed 45.4 ha of hillslope area (0.06% of the watershed area) and displaced 596,000 m^3 of material in the Redwood Creek basin, or 830 m^3/km^2 . This 1997 storm, the largest since the watershed rehabilitation program began, provided a test of the effectiveness of road decommissioning in reducing landslide frequency. Of the 261 landslides generated during this storm, 17 were associated with roads within Redwood National Park that had been decommissioned, mobilizing 115 m^3 of material/km of treated road. Untreated roads within the park had double the landslide production, with 235 m^3/km of untreated roads. The roads decommissioned early in the program, prior to 1997, had been identified by park staff as having the highest erosion risk, whereas most of the remaining roads are located in more stable areas. Consequently, the contrast in landslide mobilization from treated and untreated roads might be even greater if the relative erosion risks from the two types of road could be quantified. Association of a landslide with a road does not necessarily imply causation. Nevertheless, the data suggest that, although landslides were not eliminated on treated roads, decommissioning of abandoned logging roads seemed to reduce landslide production in comparison with untreated roads.

Timber harvest records are available from 1979 to 1997. Since 1979, 160.6 km^2 of the Redwood Creek basin has been logged, which is 22% of the total basin area, or almost 40% of non-park lands. Clearcutting was the dominant form of harvest. Of the 261 landslides triggered by the 1997 storm, 53 non-road-related slides occurred in areas harvested since 1979. These slides contributed 21% of the total volume of landslides generated during this storm.

The volume of material displaced by landslides on timber harvest units of a given age, normalized by the total area harvested during that year, varied widely, from no landslides to 2800 m^3/km^2 of area harvested (Fig. 7). The volume of material displaced by landslides in harvested terrain did not exhibit a clear pattern with the time since timber harvest, at least in the first 20 years following harvest. Other factors besides root strength, such as different parent materials, hillslope gradient, silvicultural and yarding methods, and degree of topographic convergence, are probably more important controls on landslide occurrence. For example, Curry (2007) demonstrated that the rate of landslides on a highly sheared, slightly metamorphosed mudstone unit that crops out along a fault zone was about 10 times higher than the basin average.

The results of this study contrast with two other landslide inventories. Pitlick (1995) showed that in the period of 1954 to 1978, non-road-related landslides on harvested areas in the Redwood Creek basin produced 2000 m^3/km^2 , somewhat higher than rates from more recently harvested units (Fig. 7), and these slides accounted for 41% of the total landslide volume during this period. On the other hand, Redwood Creek produced higher landslide volumes in recently harvested areas than those documented in a landslide inventory in redwood forests about 40 km south of Redwood Creek. There, in Freshwater Creek and North Fork and South Fork Elk River, harvest-associated

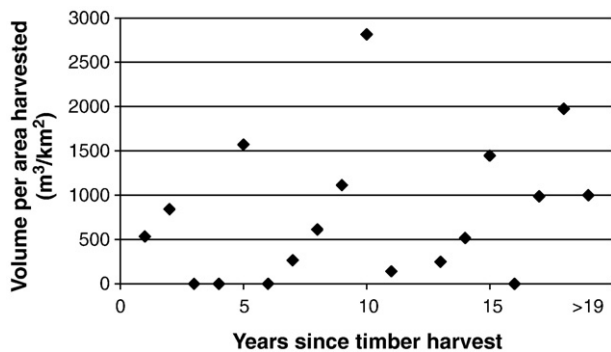


Fig. 7. Volume of material mobilized by harvest-unit landslides per unit area harvested compared to time since harvest.

landslides were grouped into only two categories, areas harvested more than and less than 15 years ago (California North Coast Regional Water Quality Control Board, 2005). The volumes of landslides in areas harvested less than 15 years ago ranged from 160 to 400 m³/km² of harvested area, and landslide volumes from forests harvested more than 15 years ago ranged from 45 to 135 m³/km². The reasons for the difference between the two study areas may be related to the factors stated above (differences in bedrock geology, slope steepness, silvicultural methods, stand composition, etc.). The role of root strength most likely changes with distance from the ocean, as redwood becomes less dominant with distance from the coastal fog belt. Clearly, more research is needed on the loss and recovery of root strength in a redwood forest following harvest. A larger sample size of harvest-related landslides coupled with on-the-ground investigation is needed for a more quantitative assessment of the role of root strength of redwoods in hillslope instability.

Another constraint on the present study is the problem of detecting roads, especially on older harvest units. Although harvest-associated landslides were not located on major haul roads, smaller skid trails that could alter hillslope hydrology may have been present. Rapid revegetation of the harvested hillslopes obscures roads (Fig. 3b), making it difficult to detect the full road network through air photo analysis. Field work is needed to supplement air photo inventories to accurately determine association of landslides with roads. Also, as association does not imply causation, geotechnical assessments are needed to discern the actual cause of failure.

In other tectonically active regions, earthquakes have triggered widespread landslide activity (Meunier et al., 2007). Tsunami and tree-ring evidence from North America and Japan point to a magnitude 8.7 to 9.2 earthquake occurring along the Cascadian subduction zone in January, 1700 (Atwater et al., 2005). The Redwood Creek basin would have been affected by this large earthquake, which occurred during what is usually one of the wettest winter months. Surprisingly, though, no even-aged 300-year old stands of trees, which would be indicative of landslide activity triggered by that earthquake, have been identified in the Redwood Creek basin (S. Veirs, retired NPS forest ecologist, personal communication). Extensive logging in the area may have obliterated evidence of earthquake-induced landslides. More recently, two magnitude 7.1 earthquakes occurred in 1980 and 1992, but no new landslides in the Redwood Creek basin were reported after these events.

4. Implications for the carbon budget

The interactions between vegetation and geomorphic processes have implications for carbon cycling. The development of carbon markets has raised the interest of society in carbon sequestration and emission, and much current research is now focused on changes in carbon storage through forest harvest and regeneration. Forests can absorb large amounts of atmospheric carbon dioxide (CO₂) through

photosynthesis, but can release CO₂ through decomposition or fire. In a forest, organic carbon accumulates in several pools: trees, understory, forest floor, coarse woody debris, and soil. Human alteration of erosion, sediment dispersal, and deposition may strongly affect the release and sequestration of carbon in the environment (Stallard, 1998).

Landslides provide a mechanism to strip vegetation and soil off a hillslope and deliver carbon directly to the drainage network (Hilton et al., 2008). Widespread landslide activity in the redwood region presumably affects carbon fluxes, but such fluxes have not yet been quantified. In some environments the carbon that is exported to the fluvial network from landslides is sequestered on floodplains as alluvial sediment accumulates. In the steep, forested terrain of northern California, however, channels and hillslopes are tightly linked. In this case, typical sites of sediment storage, such as in-channel or floodplain deposits, lakes or reservoirs, or colluvial deposits at the base of hillslopes, are very limited (Madej, 1995). For example, Pitlick (1995) showed that tributaries of Redwood Creek stored only 5% of the input from landslides. Although landslide deposits have the potential to bury and preserve soil carbon, the high sediment delivery ratio in this region implies that landslides are more effective in the export of carbon than in sequestration. Additionally, since 1968, lower Redwood Creek has been channelized within flood control levees, which has eliminated overbank and estuarine deposition near the mouth of Redwood Creek, and carbon is exported directly to the ocean.

Small rivers in steep terrain that were deforested in the 19th and 20th centuries have been recognized as a significant source of terrestrial sediment and carbon to the ocean (Gomez et al., 2004). Because of the small loss to floodplain storage, rivers in the redwood region are effective conduits of transporting particulate organic carbon to the ocean, similar to results found in New Zealand catchments (Gomez et al., 2003). For example, in 1995, the Eel River, 80 km to the south of Redwood Creek, discharged about 2.35×10^5 Mg (or 27 Mg/km²) of particulate organic carbon to the continental shelf during a single flood (Leithold and Hope, 1999).

To quantify carbon inputs, storage, and exports, a sediment budget approach can be adapted to include vegetative and soil carbon, as well as fossil carbon (derived from sedimentary bedrock). It is beyond the scope of this paper to investigate all aspects of the carbon budgets, which would include the examination of weathering, microbial activities in the soil, litter input, bioturbation, the role of colluvial hollows, a range of forest stand ages, etc. Other major erosional processes (surface erosion, rilling, gully, earthflows, and erosion from fires, floods, and windstorms) would need to be included in a full budget, but sufficient data are not available at this point to calculate these impacts on carbon budgets. The purpose here simply is to present a first-order estimate of carbon input from shallow debris slides and debris torrents to channels in the Redwood Creek basin. The organic carbon contents of various ecosystem components are listed in Table 2.

Carbon removal by landslides can be estimated using information on soils and vegetative biomass (Table 2). Landslides in this region commonly strip the soil and regolith down to bedrock, based on field mapping and examination of landslide scars. In the Redwood Creek basin, landslides typically occur on hillslopes >20°, and landslide deposits are rare on these steep slopes (Falls et al., 2003). The degree of soil development decreases downslope, which may reflect the stripping of weathered regolith and soil by landslides. On upper hillslopes, where slow-moving earthflows are present, prairie soils have a much higher carbon content, but an assessment of the annual contribution of earthflow material to streams was beyond the scope of this paper. In an old-growth forest, above-ground biomass accounts for the bulk of organic carbon, but in the present study no landslides were detected in old-growth forests. Biomass in a second-growth redwood forest, consisting of live standing trees, snags, and dead wood lying on the ground, is only one-fifth that of old-growth forests, and under these conditions soils represent a significant proportion of

Table 2
Organic carbon content of redwood ecosystem components.

Component	Organic carbon (Mg/ha)
Soils	
Lower hillslope forest	80–120 ^a
Upper hillslope prairie	200–300 ^a
In-channel wood	
Streams in old-growth forest	250–1700 ^b
Streams in second-growth forest	18–375 ^b
Second-growth redwood forest	
Live standing mass	290 ^c
Snags	24 ^c
Dead wood	17 ^c
Old-growth redwood forest	1750 ^d

^aUSDA Natural Resources Conservation Service (2008), ^bconverted wood loading from units of m³/m² of channel area to biomass by using a wood density of 0.5 Mg/m³ (Harmon et al., 1986), and then to carbon mass by using a factor of 50% (Smith et al., 2003), ^cChristensen et al. (2008), ^dNoss (2000) and converted biomass to carbon mass using a factor of 50% (Smith et al., 2003).

the organic carbon pool. Consequently, a landslide occurring on a lower hillslope in second-growth redwood forest would remove about 430 Mg/ha of vegetative and soil organic carbon. As a result, the storm in 1997 that initiated debris torrents and shallow debris slides covering 45.4 ha in area removed roughly 20,000 Mg of organic carbon from the hillslopes and delivered it to streams. This is equivalent to 28 Mg/km², similar to the particulate organic carbon yield of 27 Mg/km² in riverine sediment documented in a flood in the nearby Eel River (Leithold and Hope, 1999). In comparison, the total suspended sediment yield measured at the mouth of Redwood Creek in 1997 was 1,419,000 Mg (about 2000 Mg/km²). Larger storms in 1964, 1972, and 1975 resulted in more than 1800 streamside landslides encompassing 630 ha of forested terrain (Kelsey et al., 1995), and these landslides would have contributed roughly 280,000 Mg of carbon (almost 400 Mg/km²) to the river network.

Not all carbon delivered to streams gets transferred out of the watershed, because of in-channel storage of wood. The fate of trees that enter streams and rivers from mass movements depends on the size and steepness of the channels. Commonly first- and second-order streams lack sufficient stream power to mobilize large organic debris, and debris tends to remain in the channel until it decays or is transported by subsequent debris flows. In the Redwood Creek basin, streams >10% in gradient (typical of debris flow locations) represent two-thirds of the drainage network channel length (Falls et al., 2003), yet we have little information on wood loading in these streams. Farther down the channel network, large woody debris is mobilized more frequently and can form log jams. In the Redwood Creek basin these types of streams, typically 4% to 10% in slope, represent 19% of channel length, and wood loading ranges from 0.1 to 0.7 m³/m² of channel bed. In redwood-dominated streams of this type, in-channel wood traps about 75% of the volume of sediment stored in channels (Pitlick, 1995), so in-channel wood is important in moderating sediment transport as well as in storing carbon. In higher order streams where channel width is greater than the length of woody debris, log jams become infrequent and debris is found more commonly along channel margins or at the heads of bars. In Redwood Creek these channels (<4%) constitute only 15% of the channel network, and in these lower gradient reaches wood loading under old-growth forest conditions ranges from 0.1 to 0.5 m³/m². To complete a full budget for wood within a watershed, much more work is needed to quantify in-channel wood recruitment, storage, mobility, and persistence, especially in steep, low-order channels.

Anthropogenic changes, such as deforestation and road construction, result in changes in the cycling of carbon through accelerated upland erosion as well as loss of vegetation (Table 3). In the Redwood Creek basin, 80% of the old-growth forest has been harvested and unvegetated road surfaces account for 7% of the land area. In this

region, human activities clearly have accelerated the removal of terrestrial carbon. The influences of watershed restoration activities on carbon production and routing, however, are more complex. For example, as trees are cut during road removal work, they are converted from a carbon sink (absorbing CO₂) to a carbon source (upon decay). The cut logs placed in crossings are smaller in diameter than wood found in pristine streams, and have a higher percentage of hardwoods. Both of these factors will result in faster rates of decay of this in-channel wood than wood in pristine streams. In the short-term, some basins exceed 20% of ground disturbance through road removal and increases in sediment production and turbidity occur during the first few years. Although Table 3 lists possible impacts of land use activities on carbon flux, not enough data currently exist to quantify a net change in carbon flux in the Redwood Creek watershed. Certainly the effects of restoration on the carbon budget are multifaceted and more research on the interactions of restoration activities with carbon fluxes is needed.

Another unquantified factor in the carbon story is the effect of changes in vegetation across the landscape. Following intensive logging from the 1950s through the 1970s, some land that originally supported old-growth redwood stands became revegetated with Douglas fir as the dominant conifer. Land use, through timber harvest, conversion to vineyards or other forest types, or development, has greatly reduced the extent of the redwood forest during the last century. The long-term effects of the changes in forest composition on in-channel wood loading, root strength, nutrient cycling, etc. are not known. Although the redwood region is considered a temperate rainforest, it is not immune to fire. Studies of fire history report mean fire return intervals between 6 and 25 years for most study sites (Lorimer et al., 2009), although most of these fires are low intensity. To date, the role of fire in the redwood region in releasing carbon has not been well defined.

More recently, diseases such as Sudden Oak Death (SOD) and Port Orford cedar root rot are changing forest stand composition and structure in this region. Sudden Oak Death is caused by a funguslike pathogen *Phytophthora ramorum*, and is found throughout the range of redwoods. Since its appearance in 1995, Sudden Oak Death has killed hundreds of thousands of oaks, and the pathogen has also been found in the branches and needles of coast redwood. It is not yet clear how seriously the disease will impact redwoods. Port Orford cedar

Table 3
Impacts of anthropogenic activities and changes in forest structure on carbon cycle.

Activity	Carbon source	Carbon sink
Timber harvest		
Removes trees during road construction	X	
Cuts merchantable trees	X	
Produces logging residue (branches, needles, etc.)	X	
Increases ground fuel for fires	X	
Converts boles into lumber		X
Replants trees following harvest		X
Increases landslide rate	X	
Increases soil erosion	X	
Road decommissioning		
Removes trees along road alignment	X	
Increases revegetation through road decompaction		X
Replants trees		X
Reduces risk of landslides		X
Short-term increase in soil erosion	X	
Long-term reduction in soil erosion		X
Cuts trees and places wood in stream crossings	X	
Increases sediment storage upstream of wood		X
Possible increases in bank erosion from diversion by wood	X	
Changes in forest structure		
Tree mortality through windthrow, disease, pests, fire, drought, and flooding	X	

(*Chamaecyparis lawsoniana*) is found in the northern part of the redwood range and its roots are attacked by a fungus *Phytophthora lateralis*. The spores of this fungus move with surface water, so road ditches and streams are a vector for its spread. Exotic species can change the composition of terrestrial flora, but the long-term influence on geomorphic processes has not been quantified. For example, white sweet clover (*Melilotus albus*) is a 2-m high shrub that produces abundant amounts of seeds that are readily dispersed by water. This has allowed the plant to colonize many gravel bars and riparian areas in the redwood region, with unknown effects on sediment transport and channel stability. Finally, the spatial distribution of redwood forests is strongly related to the distribution of summer fog (Noss, 2000). Climate models predict changes in precipitation and fog patterns in California (Cayan et al., 2008), which may change the distribution of redwood forests, and thus biogenic carbon, through time.

5. Conclusions

Examples from the redwood region of north coastal California illustrate several interactions among vegetation, geomorphology, and watershed restoration activities. In-channel wood loading in streams draining old-growth redwood forests is high, but high wood loading also can persist in streams with an old-growth riparian buffer because of the slow decay of fallen redwoods. In the Redwood Creek basin, streams draining old-growth redwood forests had an estimated organic carbon loading of 250 to 1700 Mg/ha, higher than other conifer-dominated systems. As part of road removal work, cut logs are placed in stream crossings to increase wood loading in headwater streams, but the effectiveness of this technique in restoring stream function is still untested.

An inventory of landslides that were triggered during a 1997 storm showed that the volume of material mobilized by landslides associated with untreated abandoned logging roads on a per unit length basis was double that of landslides associated with decommissioned roads. The volume of material displaced by landslides within timber harvest units was not related to the time elapsed since logging, suggesting that loss of root strength was not a decisive factor in landslide initiation, but more research is needed. By stripping soil and trees from hillslopes, landslides are an important component in the export of carbon from steep, forested watersheds, and landslides removed an estimated 28 Mg of organic carbon/km² from hillslopes in the Redwood Creek basin during the 1997 storm.

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References

Atwater, B., Musumi-Rokkaku, S., Satake, K., Tsuji, Y., Ueda, K., Yamaguchi, D.K., 2005. The Orphan Tsunami of 1700. U.S.G.S. Professional Paper 1707. U.S. Geological Survey, Washington, D.C.

Benda, L.E., Bigelow, P., Worsley, T.M., 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A. *Canadian Journal of Forest Research* 32, 1460–1477.

Busing, R.T., Fujimori, T., 2005. Biomass production and woody detritus in an old coast redwood (*Sequoia sempervirens*) forest. *Plant Ecology* 177, 177–188.

California North Coast Regional Water Quality Control Board, 2005. Landslide Reduction Model for WWDRs in Elk River and Freshwater Creek. Attachment C. Santa Rosa, CA, 39 pp.

Cayan, D.R., Maurer, E.P., Dettinger, M.D., Tyree, M., Hayhoe, K., 2008. Climate change scenarios for the California region. *Climatic Change* 87 (Suppl 1), S21–S42.

Christensen, G.A., Campbell, S.J., Fried, J.S. (Eds.), 2008. California's forest resources, 2001–2005: five-year Forest Inventory and Analysis report. General Technical Report PNW-763. Pacific Northwest Research Station, USDA Forest Service, Portland, OR. 183 pp.

Church, M., 2002. Geomorphic thresholds in riverine landscapes. *Freshwater Biology* 47, 541–557.

Cole, D.W., 1983. Redwood sprout growth three decades after thinning. *Journal of Forestry* 81, 148–150.

Curry, T.L., 2007. A landslide study in the Redwood Creek basin, Northwestern California: Effects of the 1997 storm. M.S. thesis, Humboldt State University, Arcata, CA. 107 pp.

Falls, J.N., McGuire, D.J., Dell'Oso, D.R., 2003. Report on the geologic and fluvial geomorphic characteristics of the Redwood Creek watershed, California. California Geological Survey, Sacramento, CA. 261 pp.

Franklin, J.F., Cromack, K., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F., Juday, G., 1981. Ecological characteristics of old-growth Douglas-fir forests. General Technical Report PNW-118. Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, Portland, OR. 48 pp.

Fritz, E., 1957. The life and habits of redwood: the extraordinary are described by an authority. *Western Conservation Journal* 14, 4–7 38 pp.

Gomez, B., Trustrum, N.A., Hicks, D.M., Rogers, K.M., Page, M.J., Tate, K.R., 2003. Production, storage, and output of particulate organic carbon: Waipaoa River basin, New Zealand. *Water Resources Research* 39 (6), 1161. doi:10.1029/2002WR001619.

Gomez, B., Barkley, H.L., Hicks, D.M., Neff, H., Rogers, K.M., 2004. Organic carbon in floodplain alluvium: signature of historic variations in erosion processes associated with deforestation, Waipaoa River basin, New Zealand. *Journal of Geophysical Research* 109, F04011. doi:10.1029/2004JF000154.

Gurnell, A.M., 2003. Wood storage and mobility. In: Gregory, S.V., Boyer, K.L., Gurnell, A.M. (Eds.), *The Ecology and Management of Wood in World Rivers*. American Fisheries Society, Bethesda, MD, pp. 75–91.

Guzzetti, F., Ardizzone, F., Cardinali, M., Rossi, M., Valigi, D., 2009. Landslide volumes and landslide mobilization rates in Umbria, central Italy. *Earth and Planetary Science Letters* 279, 222–229.

Harden, D.R., Colman, S.M., Nolan, K.M., 1995. Mass movement in the Redwood Creek basin, northwestern California. Chapter G. In: Nolan, K.M., Kelsey, H.M., Marron, D. C. (Eds.), *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin*, Northwestern California. Professional Paper, vol. 1454. U.S. Geological Survey, Washington, D.C.

Harmon, M.E., Franklin, J.F., Swanson, F.J., 1986. Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* 15, 133–302.

Harrelson, C.C., Rawlins, C.L., Potyondy, J.P., 1994. Stream channel reference sites: an illustrated guide to field technique. General Technical Report RM-245. Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Ft. Collins, CO. 61 pp.

Hilton, R.G., Galy, A., Hovius, N., 2008. Riverine particulate organic carbon from an active mountain belt: importance of landslides. *Global Biogeochemical Cycles* 22, GB1017. doi:10.1029/2006GB002905.

Hupp, C.R., Osterkamp, W.R., Howard, A.D., 1995. *Biogeomorphology, Terrestrial and Freshwater Systems*. Elsevier, Amsterdam. 347 pp.

Imaizumi, F., Sidle, R.C., Kamei, R., 2008. Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan. *Earth Surface Processes and Landforms* 33, 827–840.

Keller, E.A., Tally, T., 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. In: Rhodes, D.D., Williams, G.P. (Eds.), *Adjustments of the Fluvial System*. Tenth Annual Geomorphology Symposium Series, Binghamton, New York. Kendall/Hunt Publishing Co., Dubuque, IA, pp. 169–197.

Keller, E.A., MacDonald, A., Tally, T., Merritt, N.J., 1995. Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek, Northwestern California. Chapter P. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin*, Northwestern California. Professional Paper, vol. 1454. U.S. Geological Survey, Washington, D.C.

Kelsey, H.K., Coghlan, M., Pitlick, J., Best, D., 1995. Geomorphic analysis of streamside landslides in the Redwood Creek basin, northwestern California. Chapter J. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin*, Northwestern California. Professional Paper, vol. 1454. U.S. Geological Survey, Washington, D.C.

Klein, R.D., 2008. Erosion and turbidity monitoring in Lost Man Creek, Redwood National and State Parks Water Years 2003–2008. Redwood National and State Parks, Arcata, CA. 35 pp.

Kramer, S., Klein, R.D., 1999. Dead wood dynamics in aquatic systems/dead wood demography in coastal forests. Abstract. Ecology and Management of Dead Wood in Western Forests, Western Section, Wildlife Society Conference. Nov. 1999. Reno, NV.

Lancaster, S.T., Hayes, S.K., Grant, G.E., 2003. Effects of wood on debris flow runoff in small mountain watersheds. *Water Resources Research* 39 (6), 1168. doi:10.1029/2001WR001227.

Leithold, E.L., Hope, R.S., 1999. Deposition and modification of a flood layer on the northern California shelf: lessons from and about the fate of terrestrial particulate organic carbon. *Marine Geology* 154, 183–195.

Lorimer, C., Porter, D.J., Madej, M.A., Stuart, J.D., Veirs Jr., S.D., Norman, S.P., O'Hara, K.L., Libby, W.J., 2009. Presettlement and modern disturbance regimes in coast redwood forests: implications for the conservation of old-growth stands. *Forest Ecology and Management* 258, 1038–1054. doi:10.1016/j.foreco.2009.07.008.

Madej, M.A., 1995. Changes in channel-stored sediment, Redwood Creek, Northwestern California, 1947–1980. Chapter O. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin*,

- Northwestern California. Professional Paper, vol. 1454. U.S. Geological Survey, Washington, D.C.
- Marron, D.C., Nolan, K.M., Janda, F.J., 1995. Surface erosion by overland flow in the Redwood Creek basin, Northwestern California — effects of logging and rock type, Northwestern California. Chapter H. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California*. Professional Paper, vol. 1454. U.S. Geological Survey, Washington, D.C.
- Maurin, L.P., 2008. First-year erosion responses following stream channel crossing fill removal in Redwood National and State Parks, Northwestern California. M.S. thesis, Humboldt State University, Arcata, CA. 85 pp.
- Meunier, P., Hovius, N., Haines, A.J., 2007. Regional patterns of earthquake-triggered landslides and their relation to ground motion. *Geophysical Research Letters* 34, L20408.
- Noss, R.F. (Ed.), 2000. *The Redwood Forest: History, Ecology, and Conservation of the Coast Redwoods*. Island Press, Washington, D.C. 339 pp.
- O'Loughlin, C.L., Watson, A.J., 1979. Root wood strength deterioration in radiata pine after clearfelling. *New Zealand Journal of Forestry Science* 9 (3), 284–293.
- Pitlick, J., 1995. Sediment routing in tributaries of the Redwood Creek basin, Northwestern California. Chapter N. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California*. Professional Paper, vol. 1454. U.S. Geological Survey, Washington, D.C.
- Reid, L.M., Hilton, S., 1998. Buffering the buffer. In: Ziemer, R.R. (Ed.), *Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story*. General Technical Report PSW-GTR-168, Pacific Southwest Research Station. USDA Forest Service, Albany, CA, pp. 71–80.
- Reid, L.M., Lewis, J., 2007. Rates and implications of rainfall interception in a coastal redwood forest. In: Standiford, R.B., Giusti, G.A., Valachovic, Y., Zielinski, W.J., Furniss, M.J. (Eds.), *Proceedings of "The Redwood Region Forest Science Symposium: What Does the Future Hold?"* General Technical Report PSW-GTR-194. Pacific Southwest Research Station. USDA Forest Service, Albany, CA, pp. 107–117.
- Sawyer, J.O., Gray, J., West, G.J., Thornburgh, D.A., Noss, R.F., Engbeck Jr., J.H., Marcot, B.G., Raymond, R., 2000a. History of redwood and redwood forests. In: Noss, R.F. (Ed.), *The Redwood Forest: History, Ecology, and Conservation of the Coast Redwoods*. Island Press, Washington, D.C., pp. 7–38.
- Sawyer, J.O., Sillett, S.C., Libby, W.J., Dawson, T.E., Popenoe, J.H., Largent, D.O., Van Pelt, R., Veirs Jr., S.D., Noss, R.F., Thornburgh, D.A., Del Tredici, P., 2000b. Redwood trees, communities and ecosystems: a closer look. In: Noss, R.F. (Ed.), *The Redwood Forest: History, Ecology, and Conservation of the Coast Redwoods*. Island Press, Washington, D.C., pp. 81–118.
- Smith, J.E., Heath, L.S., Jenkins, J.C., 2003. Forest volume-to-biomass models and estimates of mass for live and standing dead trees of U.S. Forests. General Technical Report NE-298. Northeastern Research Station. USDA Forest Service, Newtown Square, PA. 62 pp.
- Stallard, R.F., 1998. Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial. *Global Biogeochemical Cycles* 12 (2), 231–257.
- Swanston, D.N., Ziemer, R.R., Janda, R.J., 1995. Rate and mechanics of progressive hillslope failure in the Redwood Creek basin, Northwestern California. Chapter E. In: Nolan, K.M., Kelsey, H.M., Marron, D.C. (Eds.), *Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California*. Professional Paper, vol. 1454. U.S. Geological Survey, Washington, D.C.
- United States Department of Agriculture, Natural Resources Conservation Service, 2008. *Soil Survey of Redwood National and State Parks, California*. 916 pp. Accessible online at: http://soils.usda.gov/survey/printed_surveys/.
- Veirs, S.D., 1982. Coast redwood forest: stand dynamics, successional status, and the role of fire. In: Means, J.E. (Ed.), *Proceedings of "The Symposium on Forest Succession and Stand Development in the Pacific Northwest"*. Oregon State University, Corvallis, OR, pp. 119–141.
- Watson, A., Phillips, C., Marden, M., 1999. Root strength, growth, and rates of decay: root reinforcement changes of two tree species and their contribution to slope stability. *Plant and Soil* 217 (1–2), 39–47.
- Wemple, B.C., 1998. *Investigations of runoff production and sedimentation on forest roads*. Ph.D. Thesis. Oregon State University. Corvallis, OR. 118 pp.
- Ziemer, R.R., 1981. Roots and the stability of forested slopes. *Proceedings of an International Symposium on Erosion and Sediment Transport in Pacific Rim Steep-lands*, Christchurch, New Zealand, vol. 132. IAHS Publication, London, pp. 343–361.