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Effects of Road Decommissioning on Carbon Stocks, Losses, and Emissions in North Coastal California

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Abstract

During the last 3 decades, many road removal projects have been implemented on public and private lands in the United States to reduce erosion and other impacts from abandoned or unmaintained forest roads. Although effective in decreasing sediment production from roads, such activities have a carbon (C) cost as well as representing a carbon savings for an ecosystem. We assessed the carbon budget implications of 30 years of road decommissioning in Redwood National Park in north coastal California. Road restoration techniques, which evolved during the program, were associated with various carbon costs and savings. Treatment of 425 km of logging roads from 1979 to 2009 saved 72,000 megagrams (Mg) C through on-site soil erosion prevention, revegetation, and soil development on formerly compacted roads. Carbon sequestration will increase in time as forests and soils develop more fully on the restored sites. The carbon cost for this road decommissioning work, based on heavy equipment and vehicle fuel emissions, short-term soil loss, and clearing of vegetation, was 23,000 Mg C, resulting in a net carbon savings of 49,000 Mg C to date. Nevertheless, the degree to which soil loss is a carbon sink or source in steep mountainous watersheds needs to be further examined. The ratio of carbon costs to savings will differ by ecosystem and road removal methodology, but the procedure outlined here to assess carbon budgets on restoration sites should be transferable to other systems.

Key words: **redwood, reforestation, road removal, soil organic carbon.**

Introduction

Roads traversing forested public lands provide access for timber harvest, recreation, fire protection, fuels reduction, thinning, and other land management activities. More than 880,000 km of roads have been built on federal lands to produce this transportation network (Havlick 2002). Nevertheless, abandoned or poorly maintained roads represent a threat to forest and aquatic ecosystems through soil compaction, reduced soil infiltration, concentration of runoff through road drainage structures, disruption of natural drainage networks, wildlife habitat fragmentation, introduction of exotic vegetation, and increased risk of landslides and gullying (Switalski et al. 2004). Increased sediment delivery from roads to streams commonly results in decreased aquatic habitat quality. Impacts of sediment loading on habitat include filling of pools, increased fine sediment in gravel river beds, and channel widening with a concomitant decrease in shade (Furniss et al. 1991). In response to these threats from roads, public and private land managers are removing roads to restore ecosystem functions and processes. Road decommissioning or removal mitigates the physical and ecological impacts of roads by decreasing long-term erosion rates, restoring natural drainage patterns and hillslope contours, and facilitating regrowth of forests.

Although road decommissioning decreases the erosion risk from roads (Madej 2001), the activity itself produces carbon dioxide (CO_2) through the use of heavy equipment and manipulation of vegetation. To accomplish road removal, heavy equipments, such as bulldozers, excavators, and dump trucks, are used to excavate buried stream channels and reshape disturbed hillslopes and trees along the road alignment are cut down. To date, the implications of these road treatments on carbon budgets have not been assessed. In recent years, public policy increasingly has focused on carbon emissions and sequestration, especially as influenced by human activity, and the effects of carbon cycling on global warming. For example, the U.S. Department of Interior requires that "each bureau and office of the Department must consider and analyze potential climate change impacts when undertaking long-range planning exercises, … and making major decisions regarding potential use of resources under the Department's purview" (Secretarial Order No. 3289, 14 September 2009). The National Park Service (NPS) Pacific West Region's "Vision for Climate Change" states that park operations will be carbon neutral by 2016. As part of this effort, the NPS is evaluating the carbon costs and savings of its resource management activities. Through the first major

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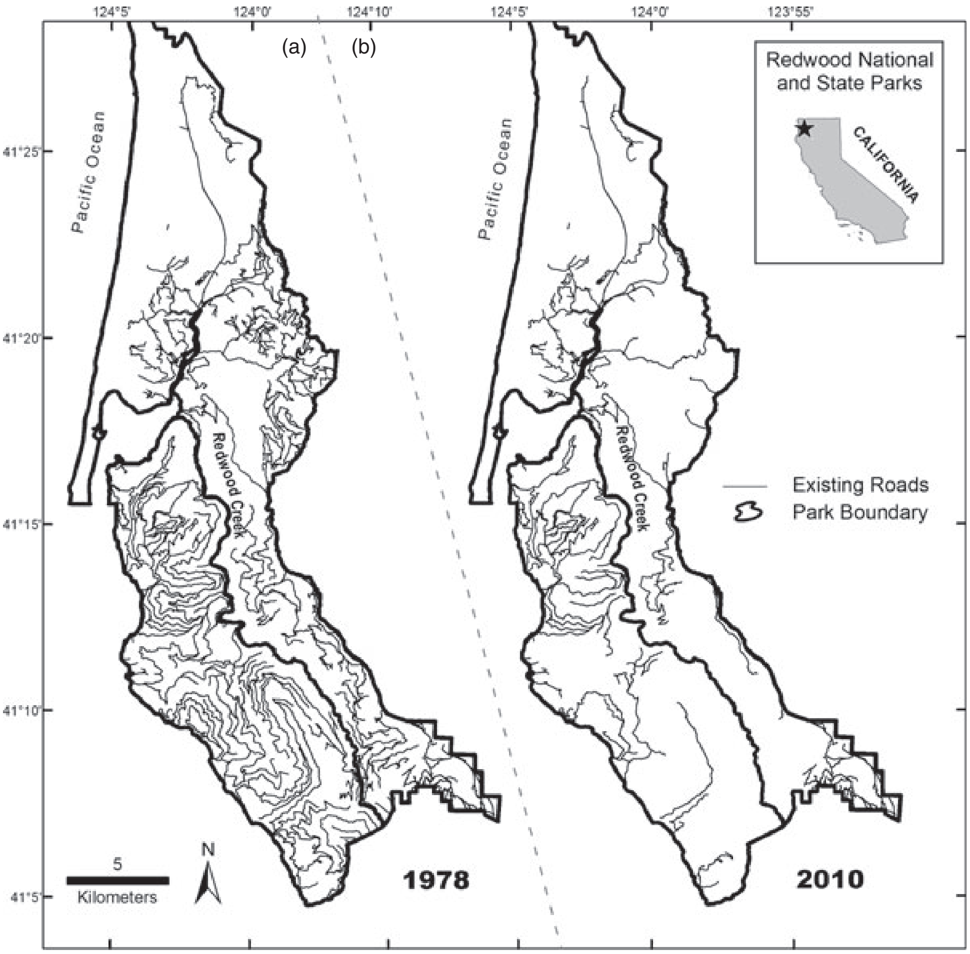

Figure 1. Presence of roads in RNP in (a) 1978 and (b) 2010. About 425 km of roads were decommissioned during this time period.

road decommissioning program in the United States, Redwood National Park (RNP) has treated 425 km of abandoned logging roads since 1978 (Fig. 1a & 1b). Road decommissioning has implications for the carbon budget because various aspects of the work (fuel consumption, removal and regrowth of vegetation, soil development, and prevention of soil erosion) can represent carbon sources or sinks. Furthermore, the rate of vegetation growth and soil development can change dramatically following the decompaction and recontouring of a road, also influencing C stocks over time. The purpose of this article is to assess the relative carbon costs and savings associated with decommissioning and revegetation of forest roads over a 30-year period in north coastal California by quantifying heavy equipment and vehicle fuel consumption, vegetation removal and regrowth, soil development, and reductions in soil erosion following road removal.

Methods

Site Description

RNP is located in the downstream third of the Redwood Creek watershed in north coastal California and was established in 1968 to preserve ancient stands of coast redwood *(Sequoia sempervirens)*. Redwood Creek drains an area of 720 km^2 and is underlain by the highly erodible rocks of the Franciscan Assemblage, mostly sandstones, mudstones, and schist. Soils on steep stable hillslopes derived from these bedrock types are primarily Haplohumults and Palehumults, and Dystrudepts on unstable slopes, based on recent soil mapping (United States Department of Agriculture, Natural Resources Conservation Service [USDA-NRCS] 2008). The basin receives an average of 2,000 mm of precipitation annually, most of which falls as rain between October and March. In 1978, RNP was expanded to encompass 15,000 ha of recently logged lands. Most of the redwood forest on this land had been tractor logged, which resulted in an extensive network of unpaved haul roads and tractor trails (skid roads). The newly expanded park included more than 650 km of abandoned haul roads, which were causing accelerated erosion (Janda et al. 1975). The road removal program began when, as part of the park expansion in 1978, Congress passed Public Law 95-250, which directed the NPS to reduce human-induced erosion on the newly acquired lands. Since then, about 425 km of roads have been treated within park boundaries.

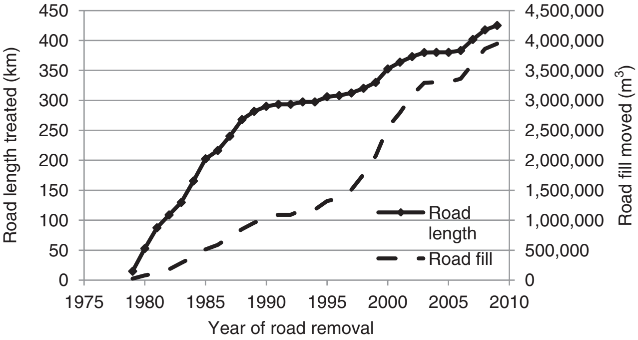

Figure 2. Cumulative length of treated roads and cumulative volume of all road fill material that was excavated or recontoured in RNP between 1979 and 2009. In the early period, less road fill was moved for a given length of treated road, whereas after 1995 more road fill was moved for a unit road length.

Road Removal Techniques

Road treatment techniques have evolved during the 32-year course of the program, which is reflected in the amount of road fill excavated or recontoured during treatment (Fig. 2). Length of road treated per year varied according to budget constraints. Early attempts (1978 to the mid-1980s, 210 km) focused on decompacting the surface of unpaved roads, removing culverts, and pulling back road fill from streambanks (Fig. 3a–c). Road surfaces were "ripped" to increase soil infiltration, but the road fill forming the road prism largely was left in place. Typically 200–500 m^3 of road fill were moved for every kilometer of road treated. Road prisms (the area of ground encompassing road drainage ditches, shoulders, driving surface, and fillslopes) at that time were unvegetated, and the forests adjacent to the road prisms generally were not disturbed by heavy equipment work.

As the road removal program progressed, resource managers recognized that more intensive excavation work was needed to control erosion and they began prescribing partial outsloping of the road surface (90 km of road). This involved excavating fill from the outboard edge of the road and placing the material in the inboard ditch at the base of the cutbank. This technique required more earth-moving (1,000–2,000 m^3 of road fill/km of treated road). By 1995, the preferred road removal treatment was full recontouring of the road prism to mimic the natural hillslope contours (outsloping) and to transport unstable road fill to more stable locations (export outsloping, 125 km). Total outsloping involved moving an average of 6,000 m^3 of road fill/km of treated road. To recontour flat road surfaces, swaths of trees adjacent to the road were cut down to allow for excavation of road fill (Fig. 4), and many of the boles and branches derived from this cutting were used as mulch on the road prism following heavy equipment work.

Carbon Calculations

Primary global carbon sinks involve the ocean, atmosphere, lithosphere (inorganic C in rocks), and the biosphere. In this study, we concentrate on changes in the biosphere components (vegetation and soil organic carbon [SOC]). Because the bedrock in this basin is lacking in carbonates and road-related erosion commonly does not strip bedrock from the slopes, we are assuming that the fraction of inorganic C related to road removal activities is negligible over the time scale of decades.

For this first-order estimate of a carbon budget, we are focusing on which management activities represent either carbon costs or savings (Table 1). Carbon stocks represent the amount of carbon in the forests and soils. A decrease in carbon is a loss, and if carbon is converted to CO_2 it is an emission. Forests, through the process of photosynthesis, store carbon in wood and roots as they grow. However, once trees die and decay, carbon is slowly released back into the atmosphere or stored in soil. The aboveground biomass values in old-growth redwood forests are some of the highest reported in the world, up to 3,500 megagrams (Mg) of stem biomass per hectare (Noss 2000). In most terrestrial systems, however, soil is the largest carbon reservoir. Consequently, for a carbon budget in a coniferous forest, we need to quantify the organic C in the trees, understory, and soil. (In this analysis, we report C mass in Mg, but some studies on C fluxes give the mass of CO_2, not C. To convert C mass to CO_2, one must multiply by 3.67 to account for the mass of the O_2.)

In this article, we assume that loss of soil from the restoration sites represents a carbon export from the watershed, but the role of soil erosion in carbon budgets is currently being debated in the literature. For example, if eroded soil is redistributed, deposited, or buried within the watershed, it is considered a carbon sink. In the Redwood Creek basin, steep hillslopes and narrow valleys preclude much sediment storage (Pitlick 1995). The only significant floodplain, at the mouth of the creek, has been disconnected from the channel since 1968 when flood control levees were constructed. Consequently, within-watershed sequestration of carbon derived from soil erosion is probably negligible, similar to other steepland systems (Gomez et al. 2003). The ultimate fate of this carbon once it reaches the ocean is unknown, however.

Because road removal techniques have evolved over the 32-year restoration program in RNP, the rates of heavy equipment fuel consumption, vegetation removal and regrowth, and soil erosion have also changed during this period. Carbon accounting was never part of the original restoration program goals, so quantification of a carbon budget necessarily requires some estimation from existing data sets. We examined 135 RNP project reports covering the period of 1979–2009 to determine volumes of road fill excavated from stream channels, volumes of material reshaped and transported on road prisms, and hours of heavy equipment work. Volume of road fill was converted to mass by using a bulk density value of 1.6 Mg/m^3, based on a range of bulk densities of subsoil of 1.4–1.8 measured by the NRCS (USDA-NRCS 2008). We first estimated three carbon costs: fuel consumption, removal of vegetation, and short-term soil loss. To calculate fuel consumption, we contacted heavy equipment vendors for bulldozers, loaders, excavators, dump trucks, etc. to estimate fuel consumption rates for a given piece of machinery. Both low and high estimates of fuel consumption were used to bracket

Figure 3. Typical stream channel excavation in the early 1980s. (a) Intact road prism with culvert in place. (b) Following removal of culvert and minor reshaping of streambanks. Minor excavation of stream channel did not reach the original channel bed. No mulch was used. (c) Regrowth of red alder (*Alnus rubra)* 3 years later.

probable fuel use in order to account for a range of field conditions, and a midpoint value was used. For project reports that did not specify equipment types or hours, we used a normalized value (the average C emission per cubic meter of road fill moved) from other projects implemented that year to estimate C emissions. Some types of equipment used in early years of the program (such as dragline cranes and small bulldozers) were later deemed inefficient and have not been used in recent years. From RNP records, we also knew the total number of workdays on a site, and we estimated that staff would drive pickup trucks to and from the site each work day. We used the U.S. Environmental Protection Agency's published estimates for average pickup truck mileage to calculate fuel consumption used for commuting to the restoration site.

Trees adjacent to decommissioned roads were cut down during decommissioning to facilitate heavy equipment work and recontouring of the road prism. This technique was employed more frequently in recent years than early in the restoration program, and the footprint of road removal is obvious in air photos (Fig. 5). To determine the area of forest disturbed by road decommissioning, we used color aerial imagery (National Agriculture Imagery Program) coupled with field measurements. Trees that were cut down along the road corridor contributed to C emissions because the vegetative material left on the ground was subject to decomposition over the following years. Timber harvest records and historical aerial photographs provided the ages of second-growth forests adjacent to the decommissioned road reaches. The C content of various stand ages for these second-growth redwood forests was estimated through the Carbon On-Line Estimator (COLE) (Proctor et al. 2005; National Council on Air and Stream Improvement, Inc. [NCASI] 2011). COLE estimates carbon in various pools, such as live tree, standing dead tree, and down dead wood. For this purpose, we only used the carbon content of two pools: live tree (C in boles, crowns, and coarse roots of live trees with diameter at breast height [dbh] at least 2.5 cm) and understory (C in boles, crown, and coarse roots of shrubs and trees with dbh $<$ 2.5 cm). Estimates of C in redwood forests were generated using plots from Del Norte and Humboldt counties, where RNP is located.

Some soil loss occurs after road decommissioning as excavated stream channels adjust during the first rainy season. Inventories of 41 decommissioned crossings in this region (Flanagan et al. 2012) show that post-restoration erosion was

Figure 4. Example of recent road decommissioning. The road prism is extensively reshaped, and some second-growth forest adjacent to the road alignment is cut down to facilitate outsloping. The stream channel crossing is excavated more extensively. The cut trees are left on the reshaped road alignment as mulch.

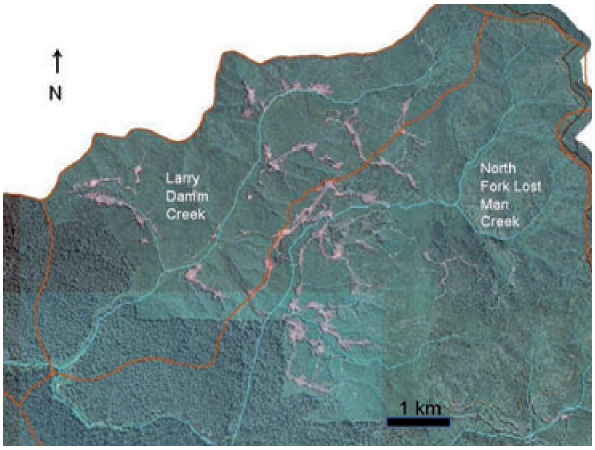

Figure 5. Aerial view of the Larry Damm and North Fork Lost Man Creek watersheds (sub-basins within the Redwood Creek watershed) showing recent ground disturbance from road decommissioning along forested road alignments.

Table 1. Carbon budget implications in road decommissioning projects.

Road Decommissioning Activities and Processes	*Carbon Cost*	*Carbon Savings*
Transportation of staff to restoration sites (fuel emissions)	X	
Use of heavy equipment in excavations (fuel emissions)	X	
Cutting trees along road alignment during hillslope recontouring	X	
Excavation of road fill from stream crossings		X
Removal of road fill from unstable locations		X
Reduces risk of mass movement		X
Post-restoration channel erosion at excavation sites	X	
Natural revegetation following road decompaction		X
Replanting trees		X
Soil development following decompaction		X

0.4–4.5% of the total volume of the excavation. On the basis of that study and our field observations, we estimated that crossings in the study area eroded 3% of the excavated volume. This soil erosion represents an export of carbon from the restoration site to the perennial stream network.

We then calculated three carbon benefits from road removal: revegetation, increased soil development, and prevention of further soil loss. Following road removal, decompacted road surfaces became colonized by vegetation. In the early 1980s, the restoration program used grass seeding, stem cuttings, transplants, and conifer and alder seedlings to revegetate the road surfaces. By the mid-1980s, RNP focused on site preparation (decompacting and retrieving buried topsoil) during heavy equipment work to encourage natural revegetation (primarily red alder [*Alnus rubra*]) rather than planting seedlings (Weaver et al. 1987). Eventually, we expect the decommissioned roads to support redwood forests, but redwood is not yet dominant on these sites. Estimates of carbon in red alder forests through COLE were based on California averages and were used to calculate carbon savings due to reforestation.

A map of total SOC for RNP has been created from a recently published U.S. Department of Agriculture-Natural Resources Conservation Soil Survey (USDA-NRCS 2008). SOC stored in the upper 2 m of soil in this area averaged 199 Mg/ha, ranging from 100 Mg/ha on steep unstable hillslopes to 400 Mg/ha in old-growth redwood forests on stable landforms. We also collected 300 soil samples at depths of 0–10 cm and 10–20 cm from road prisms decommissioned from 2000 to 2009, adjacent forests, and road fill to determine SOC. Soil samples in the <2 mm size fraction were air dried in an oven overnight at 105°C, weighed, and then combusted at 450°C to quantify C content. Average SOC in the upper 20 cm of soil on treated roads was 8 Mg/ha, and 12 Mg/ha in the young (30–50 years old) forest (compared with 35 Mg/ha in old-growth forests). We applied these values to the area of road treated to estimate SOC accumulation following road removal.

The determination of the amount of SOC "saved" due to road removal is not straightforward because we must predict erosion events that have not yet occurred. In terms of changes in carbon stores, we are concerned with the amount of soil delivered to a stream channel and exported from the system through sediment transport (Madej 2010). There are several considerations in constructing the carbon budget. First, the effectiveness of road removal in preventing soil erosion needs to be assessed after the "test" of a large storm. The largest event in the Redwood Creek basin that tested the road removal program was a 12-year storm in 1997 (Madej 2001). Consequently, we do not have information for the erosional response after an even larger storm nor for the effectiveness of road removal projects undertaken after 1997. We assume that the soil savings from recent projects will be similar to those of the late 1990s. Second, a unit of excavated road fill does not translate directly to a unit of soil prevented from eroding and entering a stream. For example, heavy equipment, by reshaping streambanks, typically excavates much more road fill from a stream crossing than would actually be delivered to the stream if a culvert failed. A recent field-based inventory of 1,250 km of roads in the Redwood Creek basin estimated that 55% of the fill volumes from excavated stream crossings represents soil erosion prevention (Bundros & Short 2011), similar to the 50% reported in an earlier study of about 100 actual road fill failures in the watershed (Best et al. 1995).

In addition to stream excavations, road decommissioning in RNP also involves outsloping the road prism to match the contours of the hillslope. Although outsloping improves revegetation, lessens the visual scarring of the road on the landscape, and restores natural drainage patterns, it is not usually prescribed to prevent sediment delivery. In contrast, on unstable road reaches where road fill cannot be stored locally, most of the road bench is removed and exported to a stable fillsite (export outsloping). On the basis of the road inventories in the Redwood Creek watershed, Bundros and Short (2011) assumed that three-fourth of the export outslope treatments were prescribed for erosion control. They further assumed that three-fourth of the material would be delivered to streams if failure occurred, based on previous landslide studies in RNP by Bloom (1998) and Curry (2007). Consequently, we used a factor of 0.55 (0.75 × 0.75) to convert total volume of export outslope material from a decommissioned road to soil savings.

Some soil loss occurs after road decommissioning as excavated stream channels adjust during the first rainy season. Inventories of 41 decommissioned crossings in this region (Flanagan et al. 2012) show that post-restoration erosion was 0.4–4.5% of the total volume of the crossing excavation. We estimated that crossings in the study area eroded 3% of the excavated volume. This soil erosion represents an export of carbon from the restoration site.

Results

From 1979 to 2009, through treatment of 425 km of road in RNP, 1,800,000 m^3 of road fill was excavated from stream channels. In addition, 1,100,000 m^3 of unstable road material was moved to stable fill sites. The cost of doing this work in terms of fuel emissions was estimated to be 3,500 Mg C. In the process of road decommissioning, 385 ha of compacted and largely unvegetated road surface was decompacted and reshaped. On the other hand, about 400 ha of trees and shrubs adjacent to the road alignments (primarily on cut- and fill-slopes) were removed during heavy equipment work. Table 2 lists the carbon content of stands of forest of various ages associated with road decommissioning sites. These values were used to calculate carbon loss when vegetation was removed during decommissioning as well as the carbon sequestration associated with a restored area as it became revegetated.

Table 2. Carbon in forest stands estimated through COLE model.

Forest Type	*Age Class (yr)*	*Live Tree (Mg/ha)*	*Understory (Mg/ha)*	*Sum (Mg/ha)*
Redwood[a]	0	0	0	0
Redwood	5	0.58	1.87	2.45
Redwood	10	3.97	3.86	7.83
Redwood	15	11.53	4.25	15.78
Redwood	20	23.57	4.29	27.86
Redwood	25	39.83	4.26	44.09
Redwood	30	59.71	4.21	63.92
Redwood	35	82.48	4.17	86.65
Redwood	40	107.39	4.13	111.52
Redwood	50	160.83	4.06	164.89
Red alder[b]	0	0	0	0
Red alder	5	4.05	7.51	11.56
Red alder	10	19.09	6.81	25.90
Red alder	15	39.40	6.11	45.51
Red alder	20	59.19	5.70	64.89
Red alder	25	75.79	5.46	81.25
Red alder	30	88.63	5.31	93.94
Red alder	35	98.09	5.21	103.30

[a] *Sequoia sempervirens.*
[b] *Alnus rubra.*

In the early days of the road restoration program, the dominant carbon costs associated with road decommissioning were the emissions from fuel consumption by the heavy equipment used to excavate road fill (Fig. 6a). Because those abandoned logging roads accessed recent clear-cuts and most equipment work was focused on unvegetated road prisms, there was little carbon cost associated with vegetation removal. In addition, older, more inefficient heavy equipment was used early in the program. Decades later, RNP's road restoration program was treating roads that traversed older second-growth forests and was outsloping a wider swath of land while fully recontouring the hillslopes. Consequently, the carbon cost associated with vegetation removal increased. By 1995, costs of vegetation removal surpassed fuel emission as the leading carbon cost.

Carbon savings associated with road decommissioning also shifted through time (Fig. 6b). Because roads treated in the early 1980s are now well vegetated, primarily with red alder, new tree growth represents carbon sequestration. Less road fill was excavated in early days of the program, but in recent years the program focused on more extensive stream crossing excavations and export outsloping. Although recently treated roads are becoming revegetated, the amount of live C and SOC on treatment sites is still low, but is expected to increase with time.

In summary, the total carbon cost for treating 425 km of road was 23,000 Mg C. Total savings as of 2009 was 72,000 Mg C. Carbon sequestration associated with these sites should increase as new forests and soils develop and mature.

Discussion

As CO_2 increases in the atmosphere, land managers are looking for strategies to sequester carbon. The original purpose of

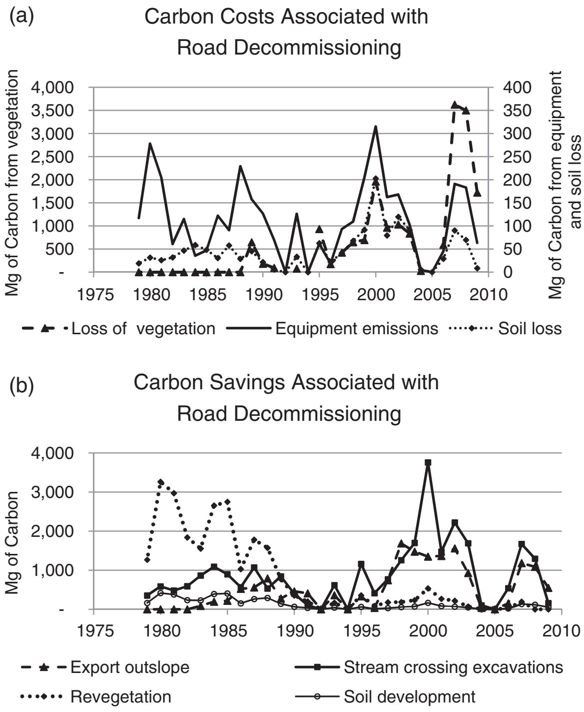

Figure 6. Carbon costs (a) and savings (b) associated with road decommissioning in RNP as of 2009.

the road decommissioning program at RNP was to decrease sediment input to the stream network. In 1978, when the program began, carbon sequestration as a goal was not considered explicitly, but it has recently come into focus. Road removal addresses many other ecological issues besides carbon costs and savings (Switalski et al. 2004), such as improved aquatic habitat and fish passage in streams, decreased forest fragmentation, and increased forest habitat for terrestrial species.

Several assumptions were used in this carbon budget. First, we assumed that all untreated stream crossings and unstable road benches would eventually fail, so that all stream excavations and export outsloping represent a soil carbon savings. Through this assumption, we may have overestimated SOC saved during road removal because not all decommissioned road segments will fail in the absence of treatment. On the other hand, road removal likely reduces the risk of landslides that extend beyond the road prism (Switalski et al. 2004), so we may have underestimated the SOC saved by landslide prevention. However, the volume of soil carbon saved through landslide risk reduction cannot be adequately estimated until treated and untreated roads are subjected to a large landslide-inducing storm. Since the beginning of the watershed restoration program in RNP in 1978, Redwood Creek has not exceeded a 12-year recurrence interval flood, whereas large landslide events in the past were associated with floods with greater than 25-year recurrence intervals (Madej 2010).

Road ripping and recontouring loosens soil and increases infiltration, which aids in revegetation (Kolka & Smidt 2004). The long-term effect on infiltration capacity is not known, however. Luce (1997) reported that surface sealing and soil settlement caused a number of ripped roads to revert to their original bulk densities after three simulated rainfall events. The effect of possible reduced infiltration capacity on the rate of reforestation on decommissioned roads in NRP is not known. Road sites are typically nutrient poor and decompacting the road surface may provide conditions conducive to weed invasion (Merriam et al. 2006). Further studies of vegetation composition on treated road prisms are needed to assess these effects.

The restored road prisms also represent a potential carbon storage site as organic matter (approximately 55% C) accumulates and forms an O horizon. In freshly decommissioned road prisms, SOC content is less than in adjacent second-growth forests. As forests develop on recently disturbed road prisms, more carbon will be sequestered in the soil column and soil productivity will likely increase. We are presently conducting soil analyses on various ages of removed roads. Future research will determine the rates and magnitudes of this mode of carbon sequestration.

Removal of vegetation during road decommissioning was found to be a key carbon cost. The cost is obviously greater as the forest stand grows older. Treating problem roads as soon after timber harvest as possible will reduce the carbon cost from vegetation removal. Carbon costs associated with fuel emissions will likely decrease in the future as equipment improvements lead to better fuel efficiency.

Implications for Practice

- Environmental planning and permitting efforts can use this approach to estimate the carbon implications of a restoration project.
- Carbon costs of road decommissioning can be reduced by using fuel-efficient equipment and minimizing vegetation loss.
- Carbon savings associated with road removal can be enhanced by implementing aggressive revegetation and soil improvement techniques.

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