Influence of road reclamation techniques on forest ecosystem recovery

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Road reclamation has emerged as an integral part of ecological restoration strategies, particularly on public lands. However, there are no consistent techniques for how road reclamation should be implemented to restore ecosystem structure and function. Resource managers are hindered by critical research gaps regarding the linkages between, as well as the effects of different restoration actions on, above- and belowground ecological and hydrological properties. In the western US, we examined how two road reclamation methods (recontouring and abandonment) affect ecosystem properties relative to "never-roaded" areas. Recontoured and abandoned sites displayed similar aboveground properties but exhibited notable differences in belowground properties, including soil hydraulic conductivity, organic matter, total carbon, and total nitrogen, among others. Our findings suggest that recontouring can dramatically accelerate recovery of above- and belowground properties so they resemble never-roaded reference conditions. In contrast, abandoning roads generates above- and belowground properties that follow a different path to recovery.

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Resource managers increasingly rely on restoration activities to accelerate ecosystem recovery and to rehabilitate ecosystem function after a disturbance (Hobbs and Cramer 2008). Although forest and stream restoration in the US has grown into a billion-dollar annual economy (Bernhardt *et al*. 2005), relatively little quantitative information is available regarding the success of restoration projects in rehabilitating ecosystems. Understanding how restoration activities influence the rate of recovery of ecosystem properties is a critical first step toward optimizing restoration efforts (Birch *et al*. 2010).

Ecosystem responses to disturbance and their trajectories toward recovery involve complex biological, chemical, and physical interactions. A growing body of theoretical and empirical research suggests that ecosystems often do not respond smoothly to change, and that ecosystem recovery may require a different pathway back to the initial state, also referred to as reference conditions (Scheffer *et al*. 2009). For example, restoring aboveground forest structure may not be sufficient to allow this ecosystem to return to its original state and function. Other factors, such as belowground soil properties and processes, may affect the pathway to recovery and could result in an alternative final ecosystem state, with ecological composition and functions that differ from unperturbed reference conditions (Kardol and Wardle 2010).

Among the most pressing current challenges facing managers of public lands is how to mitigate the impacts of the many roads that are now surplus to management needs (Leu *et al*. 2008). Concerns over the detrimental effects of erosion and resource damage due to unmaintained roads provided the impetus for most road decommissioning projects on public lands; as a result, most research has focused on mitigation of road-associated sedimentation and hydrologic impacts (Switalski *et al*. 2004). Although identifying erosion and sedimentation impacts is important, this narrow focus may overlook how road decommissioning affects ecological and hydrological linkages that exert critical control over ecosystem recovery. Resource managers developing integrated ecosystem restoration programs have many options for decommissioning a particular road, ranging from passive closure (abandoning the road and allowing revegetation to occur naturally over time; Figure 1) to the most intensive approach (recontouring the existing road and reshaping the hillside to its original contours; Figure 2). However, little information is available to help managers decide how to administer a decommissioning project so as to achieve ecosystem recovery. Failure to understand how different road reclamation treatments influence ecological and hydrological properties may limit the ability to predict whether an ecosystem will recover to a pre-disturbance state or whether it will cross a critical threshold and progress to an alternative state (Suding *et al*. 2004).

Here, we examine the effectiveness of different road decommissioning techniques for rehabilitation of ecological and hydrological systems in densely roaded forest ecosystems. Our overarching hypothesis is that restoration designs that fail to explicitly address both above- and belowground ecosystem structure and function may result in recovery to alternative states that have diminished ecological and hydrological functions relative to a "never-roaded" forest. Figure 3 conceptualizes how recov-

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Figure 1. *Typical abandoned forest roads in the project area, with natural revegation occurring (a) after 10 years and (b) after 30 years.*

ery trajectories toward a desired functional state (ie similar to never-roaded sites) may differ between two methods of restoration: abandoned roads and roads that are actively reclaimed by recontouring. Specifically, we predict that recontouring will accelerate recovery of critical ecosystem properties, such as vegetative succession, soil organic matter (SOM), nutrient stocks, and hydrologic properties of the soil, toward never-roaded reference conditions. We also predict that abandoned roads will recover aboveground vegetative cover similar to that of never-roaded conditions, but belowground characteristics – such as SOM and the ability of water to move through soil – will be diminished as compared with the desired values of never-roaded sites.

Materials and methods

Study area

We integrated our research with a landscape-scale restoration partnership between the Nez Perce Tribe (NPT) and the Clearwater National Forest (CNF) in the upper Lochsa Basin, a tributary of the Clearwater River in northern Idaho, located in the CNF (WebFigure 1). The study area was densely roaded, ranging from 2–24 km of roads per square kilometer (McClelland *et al.* 1997). Roads were built to support timber harvests in the 1950s and 1960s, and have been abandoned for 30–40 years (McClelland *et al.* 1997). To date, this restoration program has decommissioned over 960 km of surplus roads. We established 150-m transects along road treatments to assess how key properties change across a recontour age gradient to show how recovery progresses over time (R1, R5, and R10 represent 1, 5, and 10 years after recontour, respectively) and compared these treatments with never-roaded sites and abandoned sites (a total of 25 road sites). We controlled for other factors (eg geology, topography, climate, and biota) to the best extent possible. The study sites are underlain by the geologic formation known as the Idaho Batholith (McClelland *et al.* 1997). The soils were granitic with a volcanic ash cap generally classified as Andisols (McDaniel and Wilson 2007). The sites experience similar climate, with an average maximum and minimum annual temperature of 28°C and –9°C, respectively, and with a mean annual precipitation of 130 cm (McClelland *et al.* 1997). Slopes ranged from 30–45%.

Aboveground recovery

We followed vegetation data-collection protocols already in use by CNF and the NPT. In brief, we established 150-m line transects that crisscrossed the axis of the road with direction changes every 30 m, and recorded plant functional groups as grass, forb, shrub, tree, or invasive plant every meter and estimated percent cover at five stratified random point locations using 5-m^2 quadrats along each transect. We added transects to compare vegetative succession on roads abandoned for 10 and 30 years (A10 and A30 in Figure 4, respectively).

Belowground recovery

Along each transect, we excavated five soil pits (0.5 m × 0.5 m, to 1-m depth) at stratified random point locations (at 15 m, 30 m, 75 m, 95 m, and 140 m). We collected

A Connor, Clearwater National Forest

Figure 2. *Abandoned roads (a) before recontour, (b) during recontour, and (c) 3 years after recontour.*

soil samples by depth (the upper layer or organic [O] horizons occurred from 0 to 5 cm, the middle layer or mineral [A] horizons occurred from 8 to 40 cm, and the lower layer or C horizons [see description below] occurred below 40 cm); at least three samples were taken in each depth range and homogenized. O horizons consisted of undecomposed to partially decomposed litter. A horizons contained humified organic matter and mineral soil. Horizons with little evidence of soil development and lacking other properties of O, A, or weathered (B) horizons were designated as C horizons (eg a decomposed granitic subsurface horizon). Within each soil pit, we characterized rooting depth and collected soil samples for physical and chemical analysis. For recontoured roads that had negligible profile development in the A horizon, a single homogenized sample from 0.1 to 0.5 m was collected.

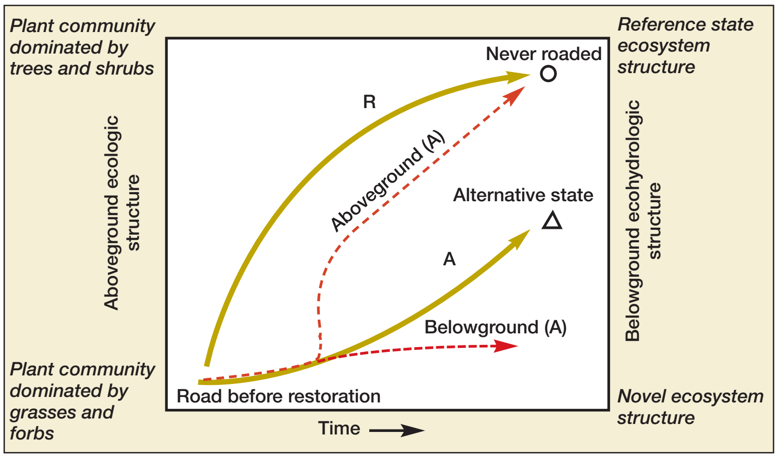

Figure 3. *Coupled ecohydrologic properties will determine ecosystem recovery after road removal. Recontouring roads will accelerate recovery to reference conditions, while abandoning a road may result in decoupling above- and belowground recovery trajectories, resulting in recovery to an alternative functional state. R = recontoured roads; A = abandoned roads. Time represents the years and decades of the recovery period (ie time from the initial restoration treatment). Dashed arrows represent a hypothetical decoupling of above- and belowground recovery trajectories for abandoned roads, whereas solid arrows represent hypothetical recovery trajectories contrasting the two methods of road reclamation (abandon versus recontour).*

Soil biogeochemical and physical properties

Soil cores were processed to determine bulk density (ρ_b) (ie soil mass per unit volume) and other chemical properties following standard protocols (Robertson 1999). We determined saturated hydraulic conductivity (K_s), a quantitative measure of a saturated soil's ability to transmit water, using a Reynold's Tank flow apparatus. Soils were analyzed for SOM content through the use of loss on ignition techniques requiring heating to 360°C for 4 hours (Robertson 1999). We also analyzed 30-mg samples for total carbon (TC) and total nitrogen (TN) using an Elemental Analyzer (Model EA1110, CE Instruments, Wigan, UK). Finally, soils were extracted for nitrogen (N) pools and process rates following methods described in Lohse and Matson (2005). In brief, available soil nitrate (NO_3^-) and ammonium (NH_4^+) pools were determined by extracting soils in 2N potassium chloride (a 1:5 soil-to-extract ratio) upon return from the field and by performing a second extraction after a 7-day aerobic incubation in the laboratory. Net mineralization rates were calculated by subtracting the initial inorganic N (NO_3^- + NH_4^+) from final pools and dividing by the incubation period. Net nitrification was determined by subtracting initial NO_3^- pools from final pools and again dividing by the incubation period. We measured NO_3^--N and NH_4^+-N using a Smartchem Discrete Analyzer (Westco Scientific Instruments, Brookfield, CT).

Data analysis

Data from separate soil pits along the same transect were averaged, and each metric was given one value per transect. We used a one-way analysis of variance (ANOVA) to test for significant differences in means among groups and the Tukey-Kramer post-hoc test to evaluate the significance of differences between each pair of treatment types.

Results

Aboveground recovery

As expected, both abandoned roads and never-roaded reference sites had less bare ground and higher herbaceous cover than recontoured sites (Figure 4). A10 roads had more bare ground (45 ± 8.7%, $F_{5,25}$ = 3.4, P = 0.01), fewer

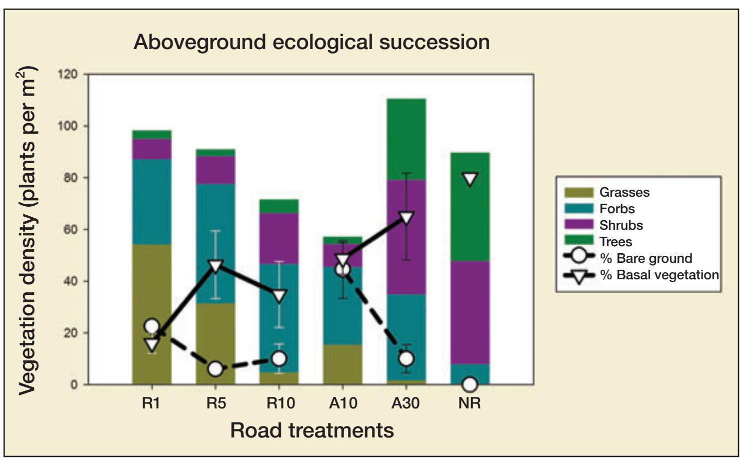

Figure 4. *Changes in plant cover and functional group composition over time and between treatments. R = recontoured; A = abandoned; NR = never roaded. Error bars indicate standard error.*

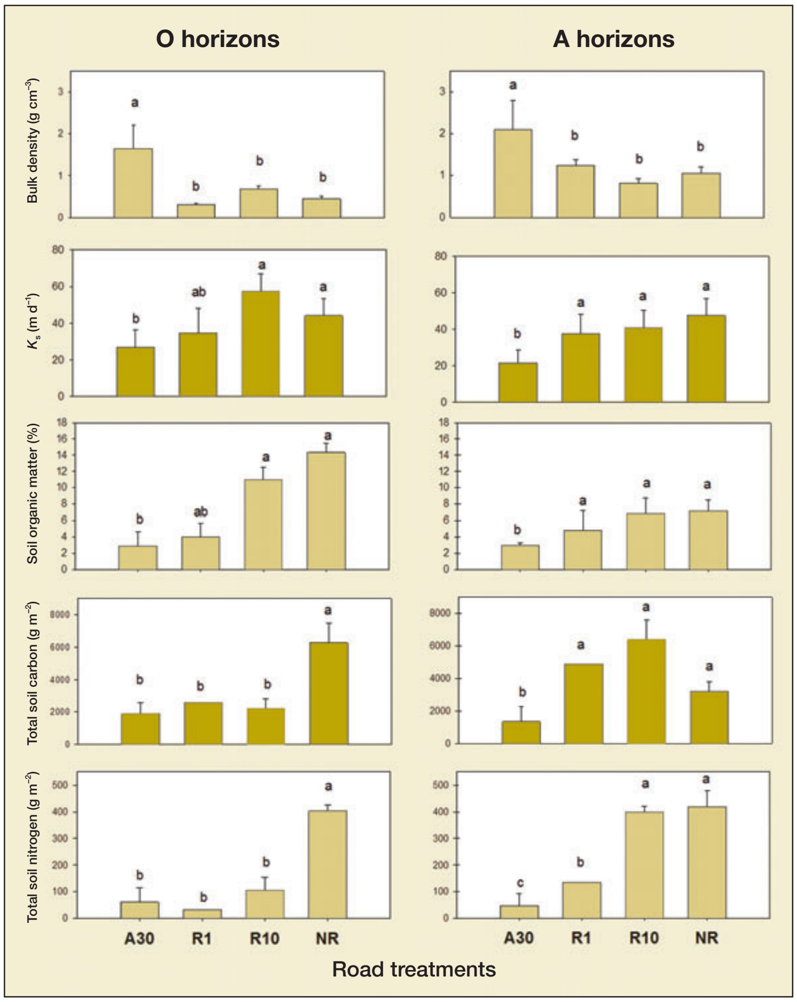

Figure 5. *Compiled results for soil characteristic data, showing differences in values by treatment and compared across two depths in the soil profile. Left panels = O (upper) horizons; right panels = A (lower) horizons. For all treatments,* n = 5*, except R1 where* n = 3*; statistical difference determined by ANOVA with* P < 0.05 *and direction of difference determined by post-hoc Tukey test. Significantly different values are indicated by lowercase letters, where a is greater than b, b is greater than c, and so forth. Error bars indicate standard error.*

shrubs (8 ± 4.7%, $F_{5,25}$ = 5.5, P = 0.009), fewer trees (2.5 ± 0.9%, $F_{5,25}$ = 3.7, P = 0.01), and more grasses (16.4 ± 4%, $F_{5,25}$ = 18.9, P < 0.0001) as compared with never-roaded areas (no bare ground, 39 ± 3.3% shrubs, 42 ± 8% trees, less than 1% grasses). By contrast, A30 roads were not significantly different in shrub and tree density as compared to never-roaded transects, with 23 ± 12% and 22 ± 8% coverage of shrubs and trees, respectively. However, there was significantly more bare ground remaining (10 ± 8%, $F_{5,25}$ = 3.4, P = 0.01) on the oldest abandoned roads (A30).

Average percent of bare ground along recontoured road transects decreased with each successive year after treatment, from 22% in R1 to 10% in R10 (Figure 5). Conversely, percent basal vegetation increased from an average of 16% in R1 to 35% in R10. Concurrently, plant functional groups transitioned from grass- and forb-dominated to higher percentages of shrubs and trees, with cover percentages closer to those of never-roaded areas. R10 roads had more trees (5 ± 2.9%) and shrubs (44 ± 12%, $F_{5,25}$ = 5.5, P < 0.001) than A10 roads and were not significantly different from A30 and never-roaded sites.

Belowground recovery

Soil physical properties and processes

Soils at never-roaded sites were relatively deep (>100 cm), had strong O horizons from 0- to 5-cm depth, and had weak to modest A horizons from 5- to 50-cm depth, overlying a granitic C horizon at 50–100 cm. In contrast, soils on A30 roads were shallow, typically 20- to 25-cm depth, with a weak O horizon in the upper 2 cm, a shallow A horizon, and a granitic C horizon at 25-cm depth. Roots on A30 roads were constrained to the upper 15 cm (10 ± 0.45 cm). In contrast, never-roaded sites and recontoured roads had rooting depths that extended below the limits of soil pit excavations (>60–75 cm).

Average ρ_b and K_s were statistically different among restoration treatment groups, most notably in the A horizons (Figure 5). We used the Hydrus 1-D software (Šimůnek *et al.* 2008) to simulate infiltration capacity and time to runoff generation for each treatment under a typical summer precipitation event, using measured K_s and ρ_b values and soil texture. The simulated time to runoff generation after a 1-hour storm event was significantly different between treatments, with runoff occurring in the first 0.2 hours of the storm on A30 roads and never on R10 roads (WebFigure 2).

Soil biogeochemical properties and processes

Average SOM percent, TC, and TN were significantly different among restoration treatments, with recontoured sites having higher TC and TN as compared to A30 roads in the lower horizons (Figure 5). Summed over the total depth of the sampled soil horizons, soil carbon (C; kg m^{-2}) and soil N (kg m^{-2}) were significantly higher at the recontoured sites (R10 = 17.66 ± 3.5 kg C m^{-2}, 1.03 ± 0.34 kg N m^{-2}) as compared to abandoned sites (A30 = 3.12 ± 0.67 kg C m^{-2}, 0.09 ± 0.03 kg N m^{-2}) but not significantly different from never-roaded areas (19.53 ± 2.34 kg C m^{-2}, 1.23 ± 0.21 kg N m^{-2}) (TC: $F_{2,7}$ = 4.6, P = 0.02; TN: $F_{2,7}$ = 3.1, P = 0.01).

Soil N pools and process rates also varied across restoration treatments, most strongly within the A horizons (Figure 6). Specifically, extractable NH_4^+ pools were significantly higher in the recontoured sites than A30 but not significantly different than never-roaded areas ($F_{4,23}$ = 4.8, P = 0.005). Consistent with these patterns, net mineralization rates in the lower horizons were significantly higher in the recontoured sites as compared to A30 but not in never-roaded sites ($F_{4,23}$ = 3.2, P = 0.01).

Soil C:N ratios were significantly higher along abandoned roads (32:1 ± 15:1) as compared with C:N ratios in never-roaded areas (14:1 ± 5:1) and R10 treatments (21:1 ± 13:1), which were not significantly different (O horizon: $F_{2,7}$ = 19.79, P = 0.0013). The one exception was the lower A horizon of the abandoned roads, which was similar (35:1) to other treatments (lower A horizons: $F_{1,7}$ = 0.52, P = 0.52).

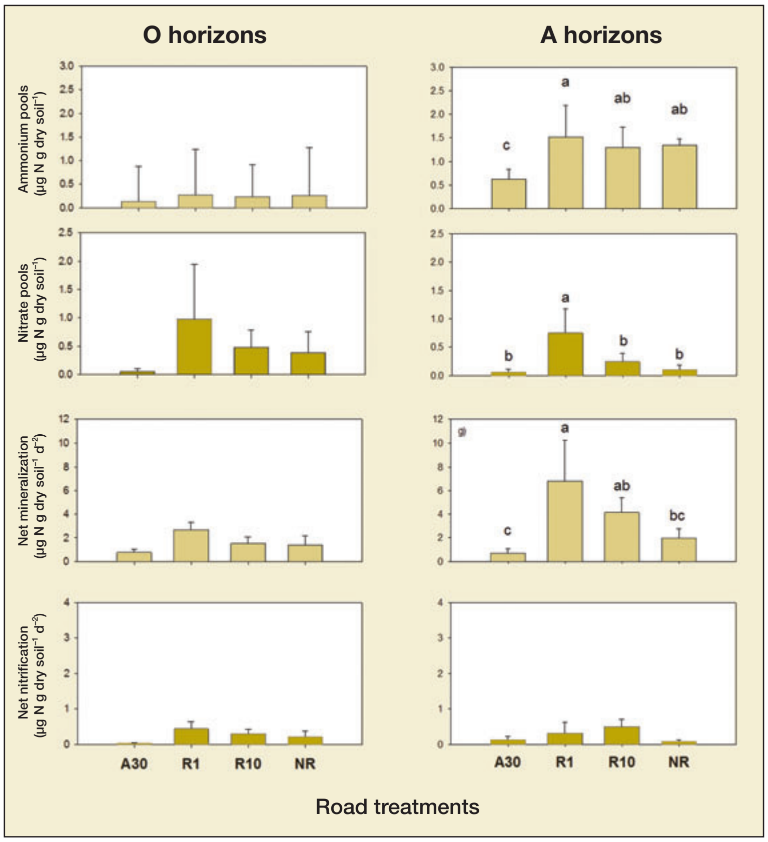

Figure 6. Nitrogen pools and fluxes compared between upper (left panels) and lower (right panels) soil layers across treatments. Ammonium pools in the surface soil horizons were not significantly different; however, pools in the A (lower) horizons were based on Welch's T test for comparing group means with unequal variances ($F_{3,2}$ = 10.46, P = 0.04); lowercase letters indicate significant differences. The other pools and processes exhibit similar trends in extractable nitrate pools, net mineralization, and rates of net nitrification, with the strongest differences in the A horizon. Error bars indicate standard error.

Discussion

To our knowledge, this is the first study to evaluate how road restoration treatments influence the recovery of coupled above- and belowground ecosystem structure and processes. We found that patterns of recovery were markedly different among the treatment approaches at the road scale. In practice, resource managers often use restoration of aboveground vegetation structure as the criterion for restoration success. In our study, the trajectory of plant succession on abandoned roads and recontoured roads followed similar trends to other research conducted on passively restored roads (Madej 2001; Foltz *et al.* 2009), although our data suggest that vegetation succession to shrubs and trees may be slower on abandoned roads as compared with recontoured roads. However, ecosystem recovery belowground differed markedly from that aboveground. The strong differences in belowground properties following road abandonment result in an effective decoupling of the recovery trajectories of above- and belowground ecohydrological properties (Figure 3). Together, these findings support the prediction that recontouring accelerates the rehabilitation of key ecohydrologic properties toward reference dynamics.

Results from our study also showed that recontouring increased SOM, TC, and TN pools to levels similar to those of never-roaded sites, while TC and TN pools remained low along abandoned roads. Soil organic matter is a key ecosystem property that exerts control on secondary succession, water-holding capacity, hydraulic properties, and nutrient dynamics. Research quantifying accumulation rates of SOM following disturbance indicates that it can take thousands of years for SOM to accumulate to steady-state levels, particularly in forested ecosystems (Wang *et al.* 1999). In this context, our research suggests that active recontouring can dramatically accelerate the recovery of soil properties by hundreds to thousands of years, as compared with never-roaded reference areas. In contrast, belowground properties and processes along abandoned roads remain in a degraded state even 30 or more years after road closure and revegetation.

The observed differences in hydrologic property recovery were striking, with significantly higher ρ_b, strongly constrained rooting depths, and significantly lower K_s on A30 roads as compared to never-roaded and recontoured sites. Previous research has demonstrated that abandoned roads, even after many years of passive revegetation, have higher soil ρ_b than adjacent never-roaded areas (Luce 1997; Foltz *et al.* 2009). In a study contrasting recontoured roads, roads with their surfaces decompacted only, and recently abandoned roads, Kolka and Smidt (2004) found lower soil ρ_b and less erosion and runoff on treated roads as compared with abandoned roads. Luce (1997) concluded that roads decompacted and left in place have ρ_b values that are initially similar to never-roaded areas, but after only 1 year, recovery is slowed and regresses back to pretreatment states. In contrast to their results, we found that ρ_b values on recontoured roads decreased significantly 1 to 10 years after recontouring, suggesting that this treatment initiates a hydrologic recovery process that may not be possible with less intensive treatments. Modeling how different hydrologic properties may influence runoff and water storage underscores the potential importance of the varied hydrologic recovery trajectories of the two different road treatments. In the modeled response to a typical summer storm (5 cm per hour), runoff occurs within the first 12 minutes of the storm on A30 roads, whereas no runoff occurs within the first hour on R10 roads (WebFigure 2).

In areas with road densities comparable to those within the CNF, different road restoration treatments have implications for C and N storage and cycling at hillslope and watershed scales. In one watershed in the Lochsa Basin, for example, active road recontouring reduced the density of abandoned roads from 2 km per square kilometer to 0.4 km per square kilometer. Extrapolating soil TC estimates to a hillslope, we estimate that soil TC storage was approximately 2.33×10^7 g C per road kilometer (to 25-cm depth) prior to active recontouring. After treatment, we conservatively estimate soil TC storage increased sixfold, to 6.5×10^7 g C per road kilometer (to 25-cm depth). The same trends are seen for soil N. Abandoned roads have approximately 6.96×10^5 g N per road kilometer, and this amount increases by an order of magnitude to 7.16×10^6 g N (to 25-cm depth). These major differences in soil C and N storage have potentially important implications for climate-change mitigation. With thousands of kilometers of roads being recontoured each year across the US, this may represent a substantial C sink, as a result of both higher soil C and increased rooting depth relative to sites that have undergone passive restoration techniques. Thus, road reclamation may serve as an important management approach to mitigate the potential impacts of climate change.

Research shows that complex linkages among subsurface ecosystem properties, including how C and N interact with water storage and runoff to control rates of nutrient cycling, are critical to an ecosystem's post-disturbance recovery (Lohse *et al.* 2009). The major differences in hydrologic function, SOM, soil C, and soil N resulting from the two decommissioning approaches suggest that abandoned roads may be moving to an altered ecosystem state, characterized by diminished capacity for nutrient cycling, water storage, and other key ecosystem functions. Indeed, higher soil C:N, smaller N pools, and decreased C and N process rates seen along the abandoned roads may indicate that these sites are moving toward N limitation. Additional research beyond plant functional groups evaluated in this study is warranted to determine whether these belowground differences in ecological and hydrological processes influence other metrics of aboveground recovery, such as aboveground plant composition, diversity, and productivity. Previous research suggests that differences in N processes and rates may be the strongest control on recovery potential of an ecosystem (Turner *et al.* 2004). The change in functional potential could have cascading consequences for ecosystem recovery and resilience to other disturbances (Suding *et al.* 2004).

Importance

Land management paradigms, particularly on public lands, have shifted from resource extraction to a focus on restoration that will result in ecosystems that are resilient to climate change and other disturbances. To support these efforts, both scientists and managers need more information on how to design restoration efforts that restore ecosystem function. The initial expense of road decommissioning and restoration can be a major issue for managers working with limited budgets. In general, intensive restoration approaches, such as full recontouring, are considerably more expensive than simply abandoning a road. Managers must weigh initial economic costs with both short- and long-term ecosystem benefits.

Although more expensive as compared with road abandonment, recontouring may be the only way to restore both above- and belowground ecosystem processes, accelerating the recovery of these forest ecosystems by decades to millennia. Our findings also suggest that manual groundtruthing or remotely sensed aboveground assessments are inadequate to evaluate the benefits derived from active restoration (Birch *et al.* 2010). Restoration techniques that fail to restore above- and belowground properties and processes may lead to an altered ecosystem with different functional processes and potential (Kardol and Wardle 2010). Further studies are needed to help scientists and managers understand how these differences in ecosystem properties may translate into differences in ecosystem function and how these findings may apply in other landscapes.

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