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Pile burning creates a fifty-year legacy of openings in regenerating lodgepole pine forests in Colorado

Charles C. Rhoades *, Paula J. Fornwalt

US Forest Service, Rocky Mountain Research Station, United States

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ABSTRACT

Pile burning is a common means of disposing the woody residues of logging and for post-harvest site preparation operations, in spite of the practice's potential negative effects. To examine the long-term implications of this practice we established a 50-year sequence of pile burns within recovering clear cuts in lodgepole pine forests. We compared tree, shrub and herbaceous plant abundance and documented indicators of soil degradation in openings where logging residue was piled and burned as part of post-harvest site preparation and the adjacent forests regenerating after clear cutting. We found that pile burning creates persistent 10–15 m diameter openings with lower tree densities (<500 trees ha^{-1}; stems >2.54 cm diameter at 1.4 m height) compared to surrounding regenerating pine stands (2000–5000 trees ha^{-1}). Low tree seedling and sapling densities (stems <2.54 cm diameter at 1.4 m height) in the openings (10–20% of regenerating forest), suggest they will remain poorly-stocked into the future. We observed evidence of high severity burning, including layers of soil charcoal and hardened red soil across the time series, but no sign that water infiltration, compaction or other indicators of soil degradation were consistent barriers to plant recolonization. Forb and graminoid cover, for example, was higher in the burn scar openings compared to regenerating forests. Pile burn openings are formed by the loss of pine seed during burning and short-term soil changes, but it is uncertain what factors maintain the openings during subsequent decades. As conducted for site preparation, the herbaceous plant-dominated openings are not extensive (<5% cover within clear cut units), and we found few invasive, non-native plants and no indication that soil conditions were sufficiently altered to explain 50 years of poor tree regeneration. Nevertheless, persistence of the openings and recent increases in the number and size of piles from fuels and bark beetle salvage treatments has prompted resource managers to consider options for utilization and on-site retention of harvest residue.

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1. Introduction

Slash burning has long been used to reduce wildfire risk and to promote tree regeneration after harvesting in western North American forests (Isaac and Hopkins, 1937; McCulloch, 1944; Boe, 1956). Historic wildfires in the Pacific Northwest (Wells, 2004), Northern Rockies (Lyman, 1947), and elsewhere, that ignited in cutover forests with heavy slash accumulations resulted in a general policy of piling and burning slash to dispose of woody residue to reduce fuel loads. Recent growth of biomass energy markets that utilize small-diameter material (Fahey et al., 2010; Klockow et al., 2013) and development of equipment for conducting on-site fuel reduction treatments (Rummer et al., 2003; Hartsough et al., 2008) broaden options for disposing woody residue, yet pile burning remains a common slash disposal method. For example, in northern Colorado where bark beetle outbreaks in lodgepole pine forests have resulted in a rapid increase in treatments to reduce woody fuels and tree fall hazards, salvage dead timber, and regenerate new forests (Collins et al., 2010), the inventory of piles that await burning exceeds 140,000 (US Forest Service, 2012, R2, unpublished records).

The influence of slash pile burning on soil temperature (Roberts, 1965) and soil chemical and physical properties (Tarrant, 1956a; Dyrness and Youngberg, 1957) have been researched for more than 50 years. The quantity, arrangement and moisture content of fuels within burn piles are intended to promote complete combustion and as a result, the short-term effects of pile burning are more severe in concentrated areas than those of either wildfire or broadcast burning (Ahlgren and Ahlgren, 1960; Wells et al., 1979; DeBano et al., 1998; Wan et al., 2001). The temperatures that

* Corresponding author at: US Forest Service, Rocky Mountain Research Station, 240 W. Prospect, Ft Collins, CO 80526, United States.
E-mail address: crhoades@fs.fed.us (C.C. Rhoades).

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penetrate the soil beneath burning slash piles (Massman et al., 2008; Busse et al., 2010) can destroy seed reserves and plant tissues (Keeley and Fotheringham, 2000) and change physical, chemical and biological soil properties (Certini, 2005). The extreme heating often has immediate effects on soil microbes, acidity, organic matter and plant nutrients (Fowells and Stephenson, 1934; Tarrant, 1954 and Tarrant, 1956a; Covington et al., 1991; Wan et al., 2001). Elevated levels of plant-available soil nutrients and exposed mineral soil in pile burn openings can improve plant seeding growth (York et al., 2009) favor establishment of weedy, non-native species (Haskins and Gehring, 2004; Korb et al., 2004; Creech et al., 2012) and threaten water quality through nutrient leaching and surface runoff (Johnson et al., 2011) for months to years following combustion. Loss of aggregate structure, decreased water infiltration and formation of hardened, red soils are common in the surface soils of pile burn scars and may last for multiple years after burning (Isaac and Hopkins, 1937; Tarrant, 1956b; Dyrness and Youngberg, 1957; Ulery and Graham, 1993; Ketterings et al., 2000).

Federal regulations (National Forest Management Act of 1976; US P.L. 94-588) stipulate that management activities must not permanently degrade the productive capacity of soils. Where severe soil damage (defined by severe burning, compaction, erosion, or displacement) occurs or its spatial extent exceeds 15% of a treatment unit, rehabilitation may be warranted (US Forest Service, 2006). The negative consequences of pile burning are most apparent for large piles constructed at log landings and timber processing areas often along permanent roads, where soils are influenced by a combination of topsoil displacement, compaction and fire effects. These areas are high priority for rehabilitation, typically involving mechanical decompaction and seeding of herbaceous plants (US Forest Service, 2012). In contrast, burn scars created on federal land during site preparation and scars from smaller, mechanical- and hand-built pile burns are rarely considered priorities for rehabilitation.

Land managers require information about the long-term consequences of pile burning to evaluate rehabilitation needs or justify alternatives to pile burning. To address this knowledge gap, we used US Forest Service (USFS) stand activity records, aerial photographs and local knowledge to develop a 50-year record of site preparation pile burning after clear cutting (Fig. 1), and then we quantified tree regeneration, understory plant cover and indicators of soil degradation in pile burn openings and adjacent forests. This project did not attempt to disentangle the ecological processes responsible for maintaining the forest openings; such work is the aim of on-going experimental studies and pile burn rehabilitation research (Fornwalt and Rhoades, 2011; Rhoades et al., unpublished data).

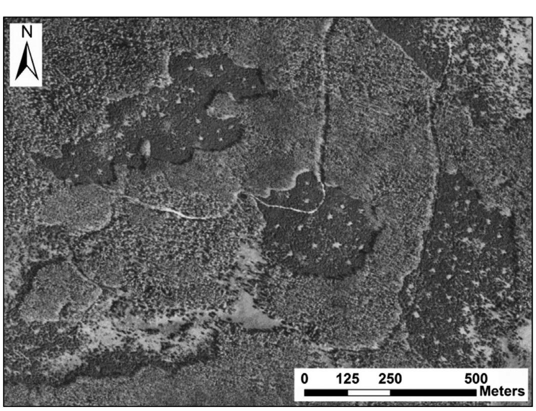

Fig. 1. Pile burn scars created during post-harvest site preparation in lodgepole pine clear cuts conducted during 1986 on the Parks Ranger District, Medicine Bow–Routt National Forests. The 2011 photograph is centered near 40°26′39″N; 106°4′10″W at 2815 m elevation. The US Department of Agriculture image may be accessed at: www.googleearth.com.

2. Methods

The study was conducted in northern Colorado on USFS land administered by the Medicine Bow–Routt National Forests. Study sites span a 500 km^2 portion of the Parks Ranger District at a mean elevation of 2900 m. Total annual precipitation averages 660 mm (Willow Creek Pass, SNOTEL Site, Natural Resources Conservation Service, 2012; National Climate Data Center, 2012). Mean annual temperature is 3 °C with average January minima and July maxima of −9 and 15 °C, respectively. Soils are formed in sandstone, siltstone and conglomerate residuum and colluvium and are moderately deep and well-drained to excessively well-drained. The most abundant soil types are loamy-skeletal, Typic Cryoboralfs and sandy-skeletal, Typic Cryochrepts. The area is part of the Southern Rocky Mountain Steppe Ecoregion (Bailey, 1998). Lodgepole pine (*Pinus contorta* var. *latifolia*) is the dominant tree species in the area, growing in relatively pure, even-aged stands on southerly aspects, lower elevation and flatter landscape locations. Lodgepole grows in association with subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*) and quaking aspen (*Populus tremuloides*) on mesic north-facing slopes and higher elevations (Collins et al., 2011).

Lodgepole pine forests in this region are typically regenerated with clear cut harvests (Lotan and Critchfield, 1990; USFS, 1998). Post-harvest site preparation activities, consisting of piling and burning logging debris, aim to reduce surface fuel loads and create a seedbed to stimulate tree recruitment and ensure adequate stocking in regenerating forests (Lotan and Perry, 1983). Site preparation slash piling is conducted with a tractor-mounted brush rake, blade or grapple hook. Pile burning typically occurs within a few years of harvesting and during winter months when there is adequate snow cover to reduce the risk of unintended ignition. Post-burn, rehabilitation is limited to large piles located on log landing sites along haul roads where high severity burning and soil compaction are evident (USFS, 2006 and 2012); piles created by site preparation are distributed more evenly within clear cut harvest units and are not usually rehabilitated.

We used USFS stand activity records to locate harvest units where pile burn operations had been conducted; such records extend from the present to the 1960s for the Medicine Bow–Routt National Forests. Within historic harvest areas pile burn openings were identified on true-color aerial photographs and individual pile locations were transferred to digital media using GIS software (ArcGIS V. 10, ESRI, Redlands, CA). Photographs taken at multiple times after harvesting helped confirm pile scar locations within regenerating forests. We limited sampling to clear cut, lodgepole pine stands and piles created during post-harvest site preparation that were subsequently burned but not rehabilitated. To facilitate comparisons, we avoided burn scars created on logging decks where the large pile size, proportion of large wood and degree of soil compaction differ from piles made within harvest units.

Stand treatment records for the Medicine Bow–Routt National Forests include 1761 treatments units where pile burning was conducted from the 1960s through the 2000s (Fig. 2a). Over that period, treatments were conducted on 180 km^2 of forest land, primarily as clear cut harvests (∼70%). Treatment activity peaked during the 1980s and 1990s when harvesting and pile burning were conducted on 5000 and 10,000 ha, respectively. Our aerial photography survey identified 7500 site preparation scars, averaging from 500 to 5000 per decade over the past 50 years (Figs. 1 and 2b).

We randomly selected 10 harvest units per decade from the 1960s through the 2000s. In each of 50 harvest units we randomly selected five individual pile burn openings. The 50 clear cut units

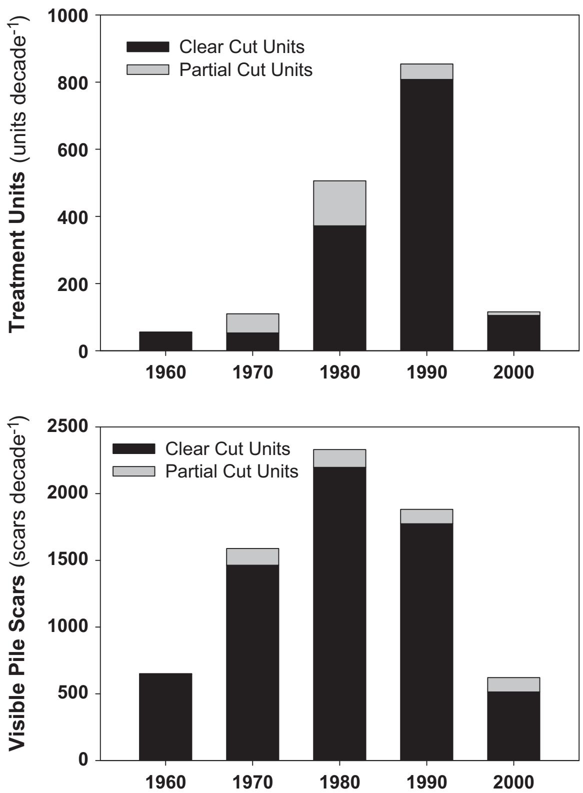

Fig. 2. Pile burn activity per decade on the Medicine Bow–Routt National Forests. Data show counts of clear cut harvest units where pile burning was conducted and individual pile burn scars visible on 2011 aerial photography.

ranged from 2.4 to 194 ha in size (15 ha average) and contained from 3 to 69 visible pile scars. On average there were 22.5 scars per harvest unit or 2.2 scars per ha. Harvest units were located on slopes ranging from 10% to 14% on average; slope did not exceed 30% on any unit. The perimeter of pile burn openings was delineated by the presence of partially-charred logs and surface char. The diameter of each opening scar was measured along the longest and a perpendicular dimension. Sound and rotten logs (1000 h fuel size classes) were enumerated on the longest dimension in each pile.

Trees and understory plants were measured in 3 m radius paired plots centered in each pile burn opening and adjacent, regenerating forest. Each adjacent forest plot was 20 m from the edge of the pile burn opening, generally along a uniform slope contour, avoiding visible remnants of rutting or other soil disturbance. Diameter at breast height (DBH; 1.4 m height above ground) was measured for trees >2.54 cm DBH. Trees <2.54 cm DBH were tallied for the following height classes: 0–15 cm, 16–76 cm, and >75 cm and <2.54 cm DBH. We visually estimated graminoid, forb and shrub cover and identified common species in four systematically-located 1 m^2 quadrats per scar and forest pair. Cover of exposed mineral soil, rock, litter, moss, stumps, and downed coarse wood (100 and 1000 h fuel size classes) was also estimated within the quadrats. The depth of organic soil layers (litter + duff) was measured at the corners of each quadrat. We also noted the presence of trees with open pine cones within and immediately surrounding the plots.

Water infiltration was measured in pile openings and adjacent regenerating forests using a field infiltrometer (Robichaud et al., 2008). Three replicate measurements were taken at 2 cm depth in mineral soil after carefully removing organic soil layers. Resistance to water drop penetration was rated at the same depths and locations (DeBano, 1981). Resistance ratings were assigned based on the length of time that a water drop remained on the soil surface as follows: none <10; weak 10–40; moderate 40–180; severe >180 s, respectively. We noted heat-reddened soil, char layers and resistance to shovel penetration as an index of soil compaction at one corner of each 1 m^2 quadrat.

Statistical analyses compared tree regeneration, shrub and herbaceous plant abundance and indicators of soil degradation between pile openings and the surrounding forest and across time since harvesting. Measurements from 1 m^2 quadrats were composited within each pile opening prior to analysis. Water infiltration replicates were composited similarly. We used a generalized linear mixed model analysis of variance with location (scar opening vs regenerating forest) and decade as fixed effects to examine differences between pile openings and the surrounding regenerating forest (SPSS V. 19, IBM Corp., Armonk, NY). Levene's statistic was used as a test of homogeneity of variance and data were log-transformed when needed. Statistical significance was assigned for F-test p values less than $\alpha = 0.05$. We used least-squares regression to evaluate changes in the surrounding forests and openings with time since harvesting and pile burning. Candidate models were compared using adjusted r^2 and Akaike information criterion (AIC) to balance goodness of fit and model complexity.

3. Results

Pile scar diameter averaged 10–15 m during separate decades across the time series; the largest and smallest openings were 21 and 7 m in diameter, respectively. Based on an average area (139 m^2) and density, pile openings covered 3.1% of recovering clear cuts on average, but exceeded 8% in some units. Charred logs (1000 h lag fuel size class) and stumps were evident in ~90% and 50% of the pile openings, respectively, extending throughout the 50 year time period. Rotten, charred logs became more abundant than sound charred logs in piles created in the 1980s and earlier. In contrast, both sound and rotten charred logs were rare in surrounding, regenerating forest.

The density of trees (>2.5 cm DBH) in pile burn openings averaged 366 t ha^{-1} across the time series, 10% of the density in the regenerating forests (Fig. 3a). In the regenerating forest surrounding the pile burn scars, tree density increased rapidly for two decades after harvesting; tree density was highest in units harvested 3 decades ago and declined as expected in the older units (tree density (t ha^{-1}) = $-4449 + 5937x - 944x^2$; $r^2 = 0.35$; $p < 0.001$). Lodgepole pine comprised >90% of all trees. Lodgepole pines reached 11 m in height and 12 cm in DBH on average in areas cut during the 1960s. Trees with open cones were noted in regenerating forests of all age classes. The few trees growing within the pile scars had larger diameter in general than those in the regenerating forests.

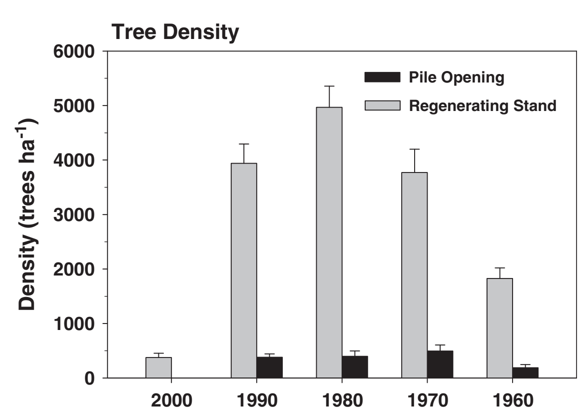

Fig. 3a. Tree density (tree diameter >2.54 cm DBH) in regenerating clear cuts and pile burn openings within Colorado lodgepole pine forests. Data are means and standard error sampled in 3 m radius plots in 10 clear cut harvest units per decade and 5 pile openings-forest pairs per unit.

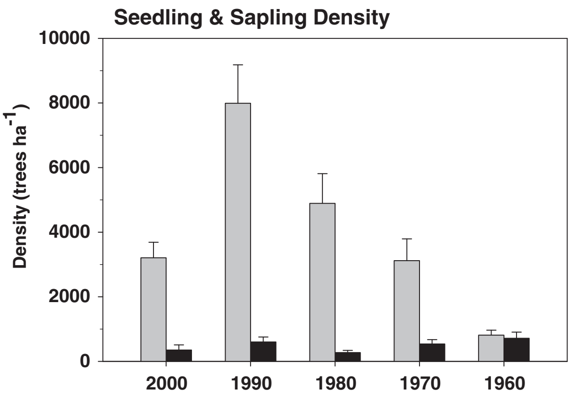

Fig. 3b. Tree seedling and sapling density (tree diameter <2.54 cm DBH) in regenerating clear cuts and pile burn openings within Colorado lodgepole pine forests. Data are means and standard error sampled in 3 m radius plots in 10 clear cut harvest units per decade and 5 pile openings-forest pairs per unit.

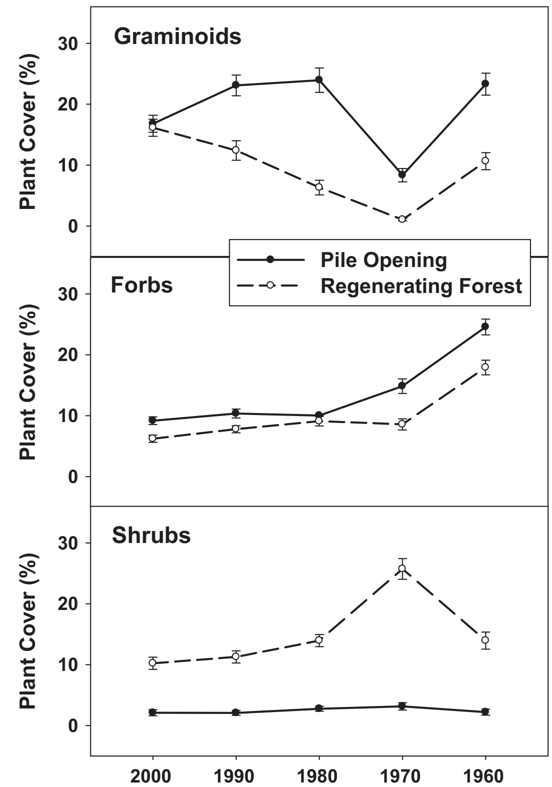

Fig. 4. Graminoid, forb and shrub cover in regenerating clear cuts and pile burn openings within Colorado lodgepole pine forests. Data are means and standard error from 1 m^2 quadrats in 10 clear cut harvest units per decade, 5 pile openings-forest pairs per unit and 4 quadrats per location.

The density of seedlings and saplings (trees <2.54 cm DBH) was also reduced within pile burn openings (Fig. 3b). Total seedling and sapling density was 496 t ha^{-1} on average, 8–20% of that in regenerating forests and the difference was significant except between the oldest pile openings and stands. The density of the 2 smaller height classes (0–15 cm and 16–76 cm) were 3 times higher in 1960s and 1970s compared to the newer pile openings, though there were no statistically significant trends with time since harvest overall. In the regenerating forests, total seedling and sapling density more than doubled the 2 decades after harvesting and then declined uniformly. The largest height class (>75 cm height and <2.54 cm DBH) comprised 84% of these trees.

Graminoid and forb cover was generally higher in pile scar openings than the surrounding forest (Fig. 4). Graminoid cover in the pile openings was double or more that of the surrounding forests for all but the 2000s decade. There was no significant temporal trend in the openings, as opposed to the general decline in graminoid cover in the recovering forest (graminoid cover = $29.9 - 14.1x + 2.0x^2$; $r^2 = 0.15$; $p < 0.001$). Forb cover was significantly higher in pile openings for all except the 1980s decade, and forb cover increased across the time series in both locations (forb cover in piles = $14.4 - 6.0x + 1.6x^2$; $r^2 = 0.15$; $p < 0.001$; forb cover in surrounding forest = $9.6 - 3.5x + 1.0x^2$; $r^2 = 0.09$; $p < 0.001$). Like tree abundance, shrub cover was significantly depressed in the pile burn openings compare to the recovering forest.

The probability of occurrence of many of the dominant species increased one or two decades after treatment (Table 1). Sedges (*Carex* spp.), common yarrow (*Achillea millefolium*), pussytoes (*Antennaria* spp.) and lupines (*Lupinus* spp.) were more likely to be present in pile scars that were more than a decade old. The forbs strawberry (*Fragaria* spp.) and heartleaf arnica (*Arnica cordifolia*) were 2 and 3 times more common and the woody plants rose (*Rosa* spp.) and whortleberry (*Vaccinium* spp.) were 3 and 4 times more common during the latter 3 decades after pile burning. Grasses and the non-native forb common dandelion (*Taraxacum officinale*) were uniformly common over time. The native fringed thistle (*Cirsium centaureae*) was most common the first 3 decades since burning, but it occurred in pile scars of all ages. The non-native musk thistle (*Carduus nutans*) occurred in only 2 piles, but surprisingly these were older treatment areas.

Shrubs were more commonly encountered in regenerating forests compared to pile burn openings (Table 1). Whortleberry, rose and kinnikinnick (*Arctostaphylus uva-ursi*) were found in 64%, 51% and 36% of regenerating forest sites, overall. The forbs heartleaf arnica and fireweed (*Chamerion angustifolium*) were well represented in the understory of the regenerating clear cuts (58% and 47% of plots, respectively). We found no non-native thistle in surrounding forests, though common dandelion occurred as commonly in the regenerating forests as it did in the pile burn openings.

The extent of bare, mineral soil in the pile openings was 2–3 times higher than that in the surrounding forest across the 50 year period (Fig. 5). Its cover declined linearly with time since treatment in the burn scars (cover = $47.7 - 5.6x$; $r^2 = 0.09$; $p < 0.001$), but only to the level found in the unburned forest sites the decade after harvesting. Organic soil (litter + duff) cover was 15% in the burn scars on average, or 25–30% of that measured in the surrounding forest. Similarly, the depth of the organic soil layer in the pile openings was 28% of that measured in the regenerating forests. Shovel penetration sampling at each 1 m^2 quadrat found small patches of heat-reddened soil in 23% of the piles burned during the 2000s, and similar patches dating back to the 1960s. Char layers (1–3 cm thick) were present in most piles, regardless of age. Water infiltration was significantly higher in the pile burn openings throughout the time series (Fig. 6). The water drop penetration test also found little evidence of penetration resistance within the burn scars (Fig. 6). In contrast, resistance to water drop penetration was moderate to severe in 40% of the surrounding forest plots.

4. Discussion

4.1. Pile burn legacy: what maintains the openings?

The openings created by pile burning conducted for post-harvest site preparation may have a longer landscape legacy than clear cutting itself. Soil degradation is an obvious candidate to have caused and maintained the openings given the well-documented effects of severe burning. As opposed to the short-lived alterations

Table 1
Frequency of occurrence of common understory plants in pile burn openings and surrounding, regenerating forests in northern Colorado lodgepole pine forests. Plant presence in pile opening and surroundings forest pairs was recorded at ten harvest areas per decade.

	Pile openings						Regenerating forest					
	2000	1990	1980	1970	1960	All	2000	1990	1980	1970	1960	All
	Frequency of occurrence (%)						Frequency of occurrence (%)					
Graminoids												
Grasses	90	96	79	62	92	84	57	54	28	24	63	45
Carex spp.	25	42	32	50	47	39	69	66	19	18	20	39
Forbs												
Achillea millefolium	40	66	53	72	57	58	14	24	17	8	18	16
Fragaria virginiana	21	38	53	60	84	51	14	22	47	14	39	27
Chamerion angustifolium	25	18	21	42	51	32	33	52	36	46	67	47
Antennaria spp.	0	20	51	46	31	30	2	20	17	4	4	9
Taraxacum officinale[a]	23	32	21	32	20	26	20	20	17	6	24	18
Arnica cordifolia	8	8	23	34	22	19	41	54	57	58	80	58
Lupinus spp.	6	20	15	22	20	17	14	38	9	18	27	21
Lathyrus latifolius	0	2	19	0	20	8	0	4	21	4	29	11
Anaphalis margaritacea	4	4	2	20	8	8	4	6	0	6	4	4
Cirsium centaureae	4	14	9	0	4	6	0	2	2	0	4	2
Carduus nutans[a]	0	0	0	2	2	1	0	0	0	0	0	0
Woody Plants												
Rosa spp.	10	16	62	32	29	30	43	56	83	36	37	51
Vaccinium spp.	6	8	26	46	14	20	67	50	49	88	61	64
Arctostaphylos uva-ursi	2	12	0	14	2	6	41	26	36	54	22	36
Mahonia repens	0	6	6	4	0	3	18	14	21	14	6	15
Juniperus communis	0	0	9	2	0	2	6	12	30	8	8	13
Shepherdia canadensis	2	0	0	6	2	2	20	10	19	12	16	16
Rubus ideaus	2	6	0	0	0	2	4	2	2	0	0	2
Artemesia tridentata	6	4	0	0	0	2	0	0	0	0	0	0

[a] Non-native to the continental US (Weber and Wittmann, 2012).

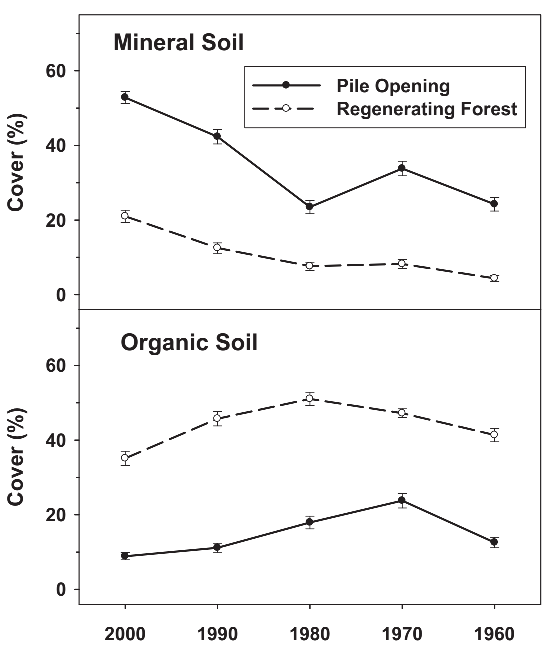

Fig. 5. Mineral and organic soil cover in regenerating clear cuts and pile burn openings within Colorado lodgepole pine forests. Data are means and standard error from 1 m^2 quadrats in 10 clear cut harvest units per decade, 5 pile openings-forest pairs per unit and 4 quadrats per location.

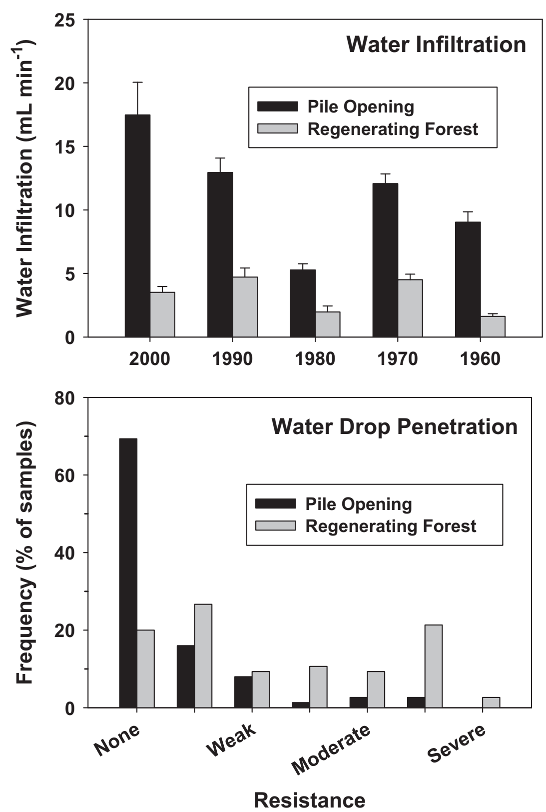

Fig. 6. Water infiltration and water drop penetration resistance in regenerating clear cuts and pile burn openings within Colorado lodgepole pine forests. Data are means and standard error for infiltration rates and frequency of water drop resistance classes in 5 clear cut harvest units per decade and 3 pile openings-forest pairs per unit.

in plant-available soil nitrogen, microbial processes and mycorrhizal inoculum potential after pile burning (Covington et al., 1991; Haskins and Gehring, 2004; Esquilin et al., 2007) those for soil acidity, cations and phosphorus may last longer (Rhoades et al., 2004 [3–6 yrs]; Creech et al., 2012 [6 yrs]; Vogl and Ryder, 1969 [15 yrs]). Effects of severe burning on clay mineralogy and the soil physical properties can persist for years (Vogl and Ryder, 1969; Ulery and Graham, 1993; Ketterings et al., 2000); we found small patches of heat-reddened soil throughout the time series. The openings supported a diverse assortment of native herbaceous plants, and where trees occurred in openings they were larger on average than those growing in the regenerating forest. If pile burning initially decreased water infiltration, that effect disappeared, prior to the first decade we sampled; water infiltration was in fact significantly higher in the pile burn openings throughout the measured chronosequence (Fig. 6). Similarly, we have observed that short-term pile burn effects on inorganic soil nitrogen (increase) and water infiltration (decrease) lasted less than two years in Colorado Front Range forests (Rhoades et al., unpublished data). We observed soil mounding in the majority of piles (84%), though this was not associated with soil compaction and did not vary in any clear manner over time. Based on the measurements conducted, we found no indication that soil conditions were sufficiently altered by pile burning to explain 50 years of poor tree regeneration within the openings.

In the absence of significant soil degradation, we have identified other biotic and abiotic factors likely to maintain the pile burn openings. Combustion of the pine seed contained within piled logging residue explains the short-term lack of seedling colonization of the burn scars. In contrast, the forest surrounding the piles regenerated from seeds in unburned logging slash and the soil seed bank (Lotan and Critchfield, 1990). During subsequent decades, poor tree regeneration in the openings may have resulted from limited seed dispersal, competition between trees and herbaceous plants, site microclimate or herbivory. Lodgepole pine develops viable seed after 5–10 years (Lotan and Critchfield, 1990), and we observed mature cones in the regenerating forests surrounding pile openings at all the study locations. Lodgepole seed can disperse 60–100 m from mature trees (Boe, 1956; Perry and Lotan, 1977), so dispersal from the edge of the clear cuts and trees regenerating within the cuts would contribute seeds to the openings. Plant cover in the openings is greater than in the regenerating forests (Fig. 4), yet there is significant exposed mineral soil (Fig. 5), so plant competition or scarcity of mineral seedbed cover does not appear widespread. The exposed openings and potentially warmer and drier soils are not likely to be more extreme than conditions found immediately after clear cutting, though the faster infiltration that persisted in the openings throughout the study period is likely to create drier soils that may inhibit pine seed germination (Fig. 6). We observed signs of wildlife activity (northern pocket gopher [*Thomomys talpoides*]; elk [*Cervus canadensis*]) in most pile openings, and the diverse understory species may concentrate animal activity and increase herbivory damage on tree seedlings. None of the individual factors (soil, seed dispersal, competition, abiotic factors, herbivory) seem to adequately explain the persistent pile burn openings, though simultaneous or sequential combinations of them might. Experimental manipulations will help identify the combination of factors that maintain the openings and guide the design of effective rehabilitation practices.

4.2. Management implications

The well-stocked stands surrounding the pile burn openings attest to the efficacy of clear cutting for regenerating lodgepole pine in the Southern Rockies (Lotan and Perry, 1983; Lotan and Critchfield, 1990). Post-harvest, site preparation pile burning was conducted on about 18,400 ha of the Medicine Bow–Routt National Forests from the 1960s through the end of the 2000s. Equally well-stocked stands occur in nearby areas where site preparation pile burning is uncommon, so it is uncertain to what extent the practice contributed to the regeneration success (Alexander and Edminster, 1981; Shepperd et al., 2004). Lodgepole pine commonly regenerates into dense stands in the Southern Rockies, so post-harvest manipulations are rarely required to achieve adequate stocking levels (Alexander, 1966).

Site preparation pile burning created more than 45,000 individual piles and between 500 and 600 ha of openings on the Medicine Bow–Routt National Forests during the past 50 years that have remained visually evident on aerial photographs. Our survey found that on average pile burn openings occupy 3% of harvest areas and that they do not appear to have significant negative effects on soil productivity. However, we limited our assessment to pile openings created by site preparation in upland stands, so this work does not fully reflect the density, size, location and effects of pile burns generated by other types of management. Salvage operations in beetle-killed lodgepole pine forests, generate larger amounts of non-merchantable woody residue. This material is typically accumulated in larger piles (~16 m mean pile diameter (n = 80 piles); Rhoades, unpublished data) at log processing and loading areas and burned. Conversely, smaller piles created during hazard tree removal, right-of-way clearing, ladder fuel reduction and other treatments can cover more than 15% of a treatment unit (8% median and 34% maximum cover; Busse et al., 2013). Roadside treatment units commonly occur in lower landscape positions where they are more likely to spread weed populations (Creech et al., 2012) and threaten sensitive riparian, wetland or stream habitats (Johnson et al., 2011). Both the larger piles on log decks and smaller piles in along stream and road corridors are more likely to be high priorities for rehabilitation (USFS, 2006, 2012) than pile burns openings created in upland areas during site preparation.

As currently implemented for site preparation in upland sites, pile burning has few clearly negative consequences for invasive species or soil degradation and the herbaceous plant-dominated openings appear to create wildlife habitat and enhance native plant species diversity to these lodgepole pine ecosystems. Our study documents the longevity of pile burning effects; like road building these persistent openings contribute to the cumulative effect of management within forest landscapes. In the Southern Rockies, the increased number and size of piles in sensitive habitats has become a growing concern for resource managers and the public and has prompted study of treatment alternatives that retain or utilize rather than burn woody reside.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2014.10.011. These data include Google maps of the most important areas described in this article.

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