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Post-harvest slash burning in coniferous forests in North America: A review of ecological impacts

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A B S T R A C T

Increasing drought and changing temperatures drive researchers to seek more efficient and effective means to aid management of coniferous forests across the western United States. Thinning allows for effective removal of biomass, but with few options to remove the residual slash from the treatment unit after saleable timber is taken away, pile burning has become a favored method of debris removal. Pile burning has greater efficiency and reduced removal cost as compared to air curtain burning or whole tree removal. In this review, we synthesize the current knowledge on the effects of slash pile burning on soil physical properties, soil nutrients, impacts to understory vegetation and tree regeneration, animal responses to pile burning, and the variety of remediation techniques for burn scar areas. Forest composition and age, climate, and fire intensity have the greatest impact on the outcomes of pile burning. Pre-fire ecosystem dynamics influence the changes to soil structure and nutrient profile, where native vegetation can either capitalize on changes such as altered nitrogen pathways, or be outcompeted by nonnative species. We hypothesize that vegetation adaptations to the natural fire interval may play a role in recovery from these high-intensity burn piles, and with further research, could assist managers in improved remediation efforts. We identify existing gaps in our knowledge of the ecosystem effects of slash pile burning, and to suggest some management-centered areas for further research.

1. Introduction

Slash pile burning is prevalent in logging operations throughout the western United States and Canada (Owen et al., 2009; Fornwalt and Rhoades, 2011). Harvesting methods that leave slash near roads favor pile burning as the primary disposal technique for most projects (Thorpe and Timmer, 2005; Bont and Church, 2018). Pile burning is most often used to remove debris from the forest floor and is generally the preferred method for land managers to dispose of any non-harvested woody material (Kalabokidis and Omi, 1998). Management activities such as thinning, salvage logging, and other fuels reduction efforts create significant amounts of woody residue that would otherwise create extreme fuel hazards in the future. Pile burning is an efficient and effective technique to reduce future fire risk and extreme fire behavior (Peterson et al., 2005; Jang et al., 2017), and it can be used under a wide variety of climate and topographic conditions (Seymour and Tecle, 2004). In addition to fuels reduction, pile burning is often used to facilitate seedbed preparation for new plantings (Rab, 1996).

Although pile burning emits smoke that contains various air pollutants (Jang et al., 2017), many smoke management programs across the western United States still favor pile burning over broadcast burning (Hardy, 1996). While there are some negative impacts of smoke to nearby population centers, pile burning provides faster and more efficient fuel consumption than a broadcast burn that may smolder over a large area for an extended period of time. Pile burning can be used under a much broader range of weather conditions, with more options to reduce smoke to nearby populations (Hardy, 1996). Pile burning is also more economically feasible, especially in the wildland-urban interface (WUI) and in areas without access to a biomass energy facility, such as northern Arizona (Farnsworth et al., 2003; Jang et al., 2017). In the western United States and Canada, piles are often burned on site in late fall and winter, when conditions are favorable to control fire, reduce scorch, and minimize smoke (Farnsworth et al., 2003). Farnsworth and others (2003) acknowledged that pile burning, even under ideal or snowy conditions, produces extreme temperatures at the soil surface that can adversely affect soil processes and biota beneath the piles. Despite the danger, they propose burning only when conditions guarantee 90% or greater consumption, to prevent “unsightly” residue (Fig. 1) that may also hinder regrowth of vegetation in some cases, such as the dry ponderosa pine forests of northern Arizona (Farnsworth et al., 2003).

Pile burns cause changes to underlying soil and vegetation, but there is little agreement over the extent of potential long-term effects or the timescale of complete community recovery after pile burns (Korb et al., 2004; Rhodes and Fornwalt, 2015; Rhodes et al., 2015). There are strict regulations in place to minimize permanent changes to soil chemical and

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biological properties or understory vegetation resulting from silvicultural treatments; therefore, the majority of slash pile research is focused on management practices and pile scar remediation and rehabilitation (Korb et al., 2004; Creech et al., 2012; Rhoades et al., 2015; DeSandoli et al., 2016). While Hardy (1996) offers a method for estimating volume and biomass of slash piles to determine smoke production for federal management activities, fuel type (not pile diameter) is more important in predicting potential changes in ecosystem functions during the burning phase (Busse et al., 2013). Federal regulation requires that management activities do not permanently degrade soil processes, and in some areas, severely burned soil or permanent soil erosion or degradation are limited to 15% of the total treatment area (Rhoades et al., 2015). Because hand piles are smaller and take up a relatively small area of a treatment unit as compared to machine piles, they are less frequently studied for ecological outcomes or for rehabilitation plans under this regulation (Rhodes et al., 2015). Today, sites in Arizona commonly contain upwards of 44 piles per hectare on state and federal lands, with pile sizes ranging between 3 and 6 m in diameter and covering anywhere between 2% and 8% of the land area per acre in thinned sites (Mott and Hofstetter, unpublished data: Fig. 2). These calculations include only the surface area impacted by pile burning and not mechanical damage such as skid trails or soil compaction. This theoretical figure is a small and highly localized example of a larger forest management process. Hardy (1996) defined pile construction for federal land managers and Evans and Wright (2017) offer insights into the effects of piles on unplanned wildfire, but there is little research on the total area of slash piles within a treatment unit. We recommend further research into the spatial arrangement and total areas of slash piles for both ecological impacts and further improvements in slash disposal techniques and efficiency.

The purpose of this review is to synthesize current knowledge on the impacts of slash pile creation and burning in forest ecosystems on outcomes like plant and fungal survival and growth, nutrient dynamics, and intervention requirements to improve overall ecosystem recovery, and to identify potential gaps in that knowledge for future research efforts (Fig. 3). The scope of this review is generally limited to forests of the western USA and Canada, with several related examples included from the high latitude forests of Europe and South Africa. We review the impacts of 1) pile structure and composition prior to burning and 2) temperatures in slash pile burns on soil structure and select nutrients, understory herbaceous and shrub recovery, tree regeneration, invasibility and nonnative plant establishment, and finally, vertebrate and arthropod diversity in slash pile burn scars.

The initial literature search for this review topic utilized the full university library online search for all databases, plus a Google Scholar search to capture any articles that may not appear in scientific search engines (commercial reports, news links to primary literature, etc.). Primary keywords were slash piles, thinning, slash burning, pile burning, forest thinning, and high severity fire. After evaluating the initial literature list, we requested assistance from our university librarian to capture any other research or reports that did not appear in our first search. Some extra search terms and variations, including slash, all possible variations of pile, piles, piling, piled, logging residue(s), and all possible variations of burn, burns, burned, burning, and fire. We used these keywords in both a topic and a title search, and limited geography to narrow our search to regional interest, which yielded several additions to our literature list. The next iteration of searches included multiple levels of tracking references or citations in papers on our list through to deeper reference lists. Through this process, we felt confident in our assessment of available literature when we stopped finding new papers and achieved nearly 100% overlap between our reference list and the references available in all further searches and papers we reviewed on the topic.

2. Slash pile burning effects on soil structure and chemistry

2.1. Pile construction

Piling slash after harvest, whether clearcut or selection cutting, has significant impacts on the landscape and soil characteristics of the forest. Forest harvest and slash treatment or site preparation practices frequently disrupt organic and mineral soil, remove protective mulch and decaying debris layers, increase soil water content, temperature and light intensity at soil surface, cause nutrient loss through leaching, volatilization, and increased surface erosion, and alter microbial community composition (Waldrop et al., 2003). Building piles can cause additional soil disturbances such as compaction, displacement, or rutting, depending on soil type and climate, and the methods used to create piles (Jang et al., 2017). Slash piles are built by cutting crews during the thinning operation and left for land managers to dispose of after cutting operations are complete. Many agencies rely on fuel management and fire personnel to make decisions on length of drying and on burn timing, meaning piles are often left for at least one year to dry out for sufficient consumption during burning (Evans and Wright, 2017). In some cases, where weather and funding limit number of piles able to be safely and effectively burned in one season, piles may sit upwards of three to four years, or never get burned at all (M, Nabel and P. Mercer, personal communication). Depending on location and climate, hand piles may cure over the course of one season with complete combustion as they are burned, where complex machine-built piles with integrated soil and debris take longer to dry out and not combust completely when they are burned (Wright et al., 2019).

Regardless of construction method, slash piles of all sizes alter soil surface temperatures and solar exposure. In the boreal forest, slash cover reduces soil warming and keeps soil cooler during vegetative periods, and slash from some species can even keep soils at slightly higher temperatures during winter (Moroni et al., 2009). In Norway spruce (*Picea abies (L.) Karst.*), Scots pine (*Pinus sylvestris L.*) and silver birch (*Betula pendula Roth.*), minimum and maximum temperatures under slash piles were 2 °C lower than controls at the edge, with a maximum average temperature difference of 5 °C in the center (Törmänen et al., 2018). Temperature changes under piled material are also closely linked

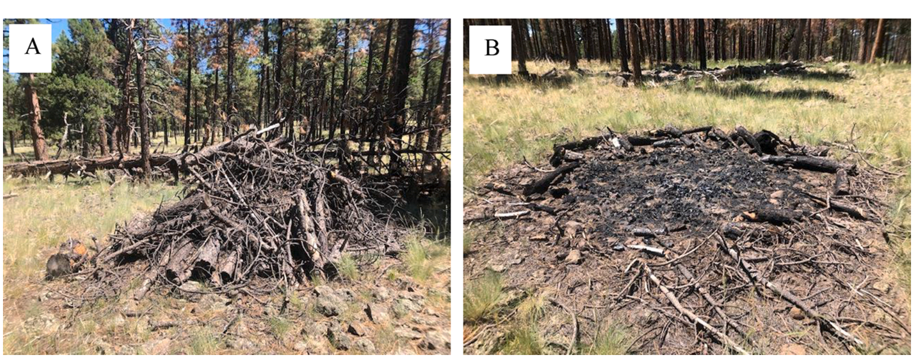

Fig. 1. Example of typical slash piles in northern Arizona thinning and pile burning projects. **A.** Post-thinning ponderosa pine slash pile on Centennial Forest near Flagstaff, Arizona. This pile measures approximately 3.5 m in diameter and 1.5 m high with mixed large- and small-diameter fuels. **B.** Adjacent pile of similar size and structure 9 months after burning. This pile scar is representative of recent pile burns across northern Arizona, with residual coarse woody debris as potential habitat for multiple taxa and complete lack of vegetation within the entire burn scar.

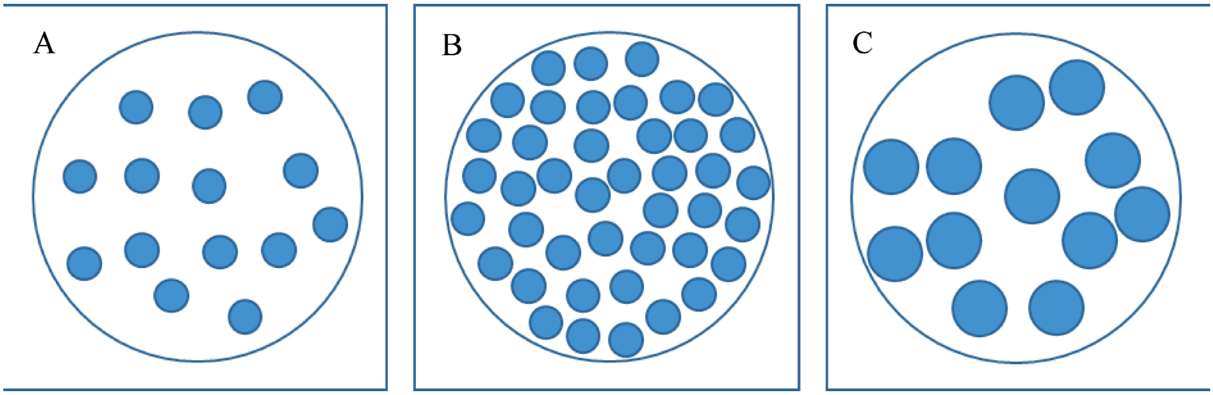

Fig. 2. Theoretical spatial representation of slash piles below and above threshold limits on a 0.4 ha (1 acre) circular plot. A) Average number (n = 14) and size (5 m diameter) of pile scars in an example a northern Arizona forest, covering approximately 6% of the land area. B) Number of piles (n = 42) of average size with approximately 16% of area affected. C) Number of piles (n = 12) of largest measured size (8 m diameter) with approximately 17% of area affected. Pile size and number in both B and C surpass the 15% area threshold for federal limits of damage to the management unit.

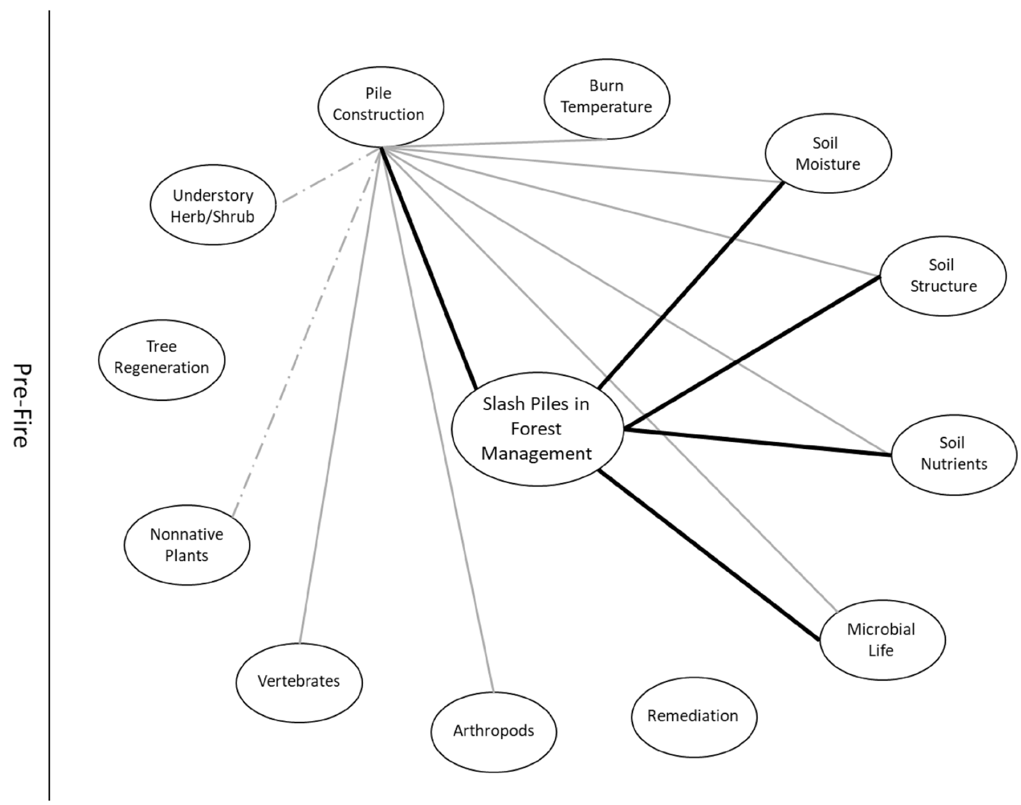

Fig. 3. Figure showing relationships between topics in slash pile burning literature regarding the pre-fire, immediate aftermath, and long-term studies in western ecosystems. Heavy black lines indicate topics mentioned in slash pile literature for the timeframe. Grey solid lines indicate interactions that are studied in available literature. Dashed grey lines indicate interactions that are referenced or hypothesized in literature, but not yet thoroughly investigated. Absence of lines indicates an interaction not yet investigated in the literature. Outcomes of all interactions are also likely dependent on climate, ecosystem type, fire intensity, and density of piles on the treatment unit.

to soil respiration, indicating that piling can have an impact on soil processes, even if left unburned (Moroni et al., 2009). Piled, unburned slash also alters soil nutrient dynamics in the soil beneath the piles. Harvesting tends to reduce soil and microbial carbon (Sullivan et al., 2008; Dore et al., 2010), but slash piles add a pulse of nutrients in addition to temperature fluxes and may increase respiration potential in the organic layer underneath the pile (Moroni et al., 2007; Zhang et al., 2018). Further work in slash pile construction and seasoning (drying period prior to burning) may yield further changes to soil properties in a variety of ecosystems.

There is some debate as to whether the tree species composing slash matters to chemical processes, as some species affect pH, microbial composition, and nutrient leaching more than others (Moroni et al., 2007; Törmänen et al., 2018). All piles alter processes associated with both carbon and nitrogen cycles, including increased net nitrogen mineralization and nitrification of underlying soil, organic matter content, carbon mineralization, and pH (Törmänen et al., 2018). These outcomes, however, are affected by the length of time slash remains in

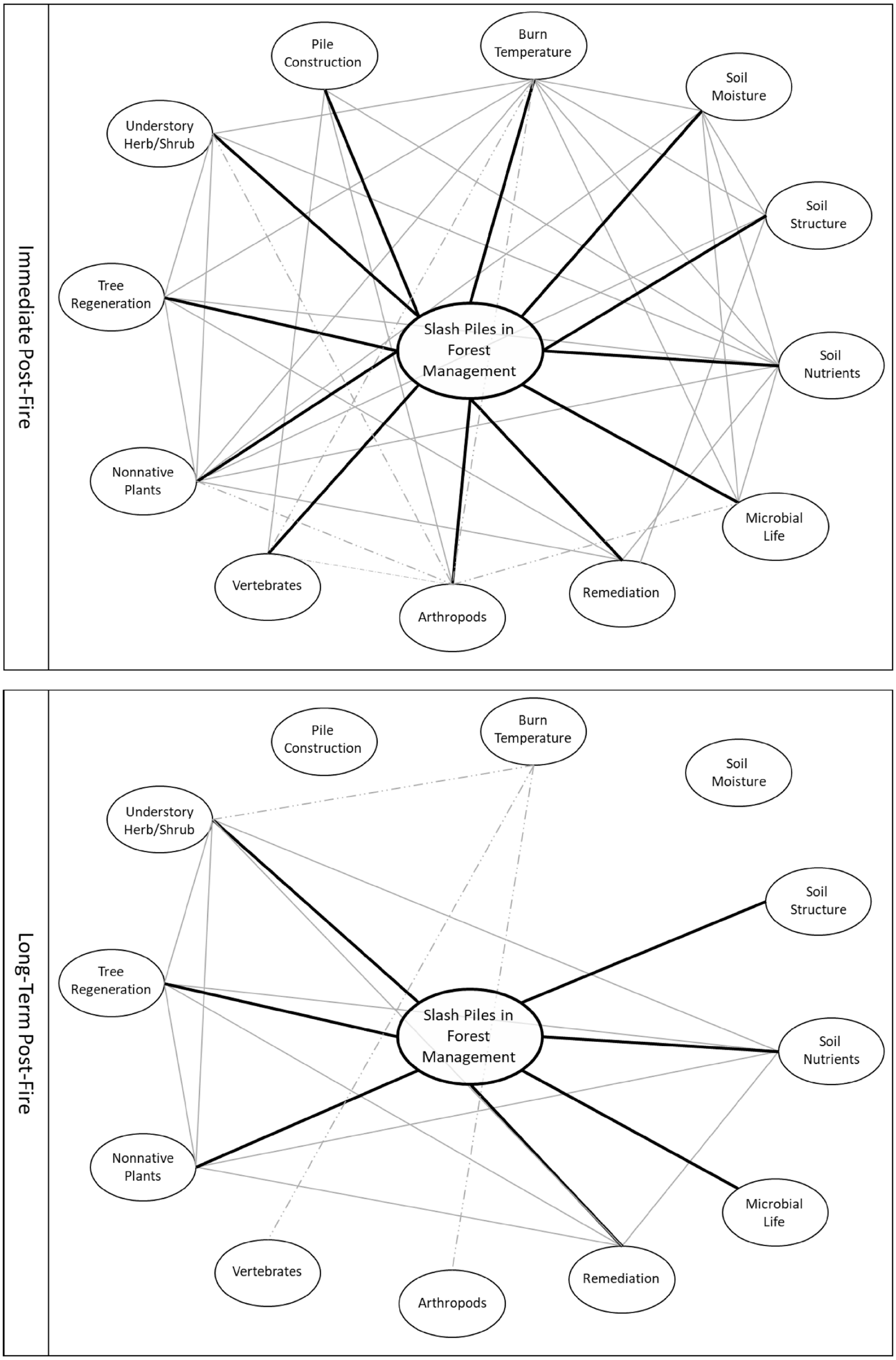

Fig. 3. (*continued*).

the forest and the time of year, as local climate conditions dictate precipitation and decay rate, which further alter soil conditions beneath slash piles. Fuel consumption during burning is impacted by pile age and season of burn (Wright et al., 2019). Piles tend to compact over time, becoming lower in height but with minimal loss of biomass. This compression may not affect fuel consumption but could affect peak flame height or fire intensity, and therefore show different impacts to both above- and belowground resources (Wright et al., 2019).

2.2. Burn temperatures

The greatest ecological effect of burning slash piles is the elevated surface temperature under heavily concentrated fuel loads. Excessive heat created by burning debris affects soil properties and plant and animal survival. The physiological responses of biota impacts future species composition and invasibility (Gifford, 1981) which is a great concern for use of this management technique (Korb et al., 2004; Jiménez Esquilin et al., 2007). Slash piles generate heat that transfers directly to the soil via conduction, as piles are physically adjacent to the soil surface (Neary et al., 1999). This concentrated fuel allows heat to penetrate further into the soil than occurs in a high-temperature but fast-moving wildfire. Soil damage is limited to the area directly underneath the piles (Seymour and Tecle, 2004), with burn temperatures differing based on ecosystem, climate, and soil type (Table 1). Soil moisture content can also be a critical factor for heat transfer and impact on soil properties (Jang et al., 2017). Temperatures often reach over 300 °C in the center of the pile under the highest fuel load, and over 175 °C at the outer edges of small piles (Busse et al., 2010; Jiménez Esquilín et al., 2007; Owen et al., 2009). Creech and others (2012) found instantaneous temperatures over 1000 °C immediately after pile ignition. Most studies use 60 °C as the lethal temperature limit, as these temperatures kill seeds, roots, and other plant tissues, regardless of burn duration (Gifford 1981; reviewed in Neary et al., 1999; Busse et al., 2010; Massman et al., 2012; Jang et al., 2017). Some microorganisms are sensitive to temperatures as low as 50 °C, and temperatures in the 120–160 °C range kill nearly all living organisms (Busse et al., 2010; Massman et al., 2012). Temperatures of 500 °C and higher cause irreversible physical, chemical, mineral, and hydrologic changes in soil (Massman et al., 2012). While fuel type, ecosystem characteristics and pile size determine the heat intensity and duration of heating, nearly all piles generate temperatures that kill most soil biota (Neal et al., 1965; Gifford, 1981; Switzer et al., 2012; Jang et al., 2017).

Lethal temperatures are easily observed in the top few centimeters of soil across all studies (Busse et al., 2010; Massman et al., 2012), but extreme heating can occur deep into soils under large slash piles, up to 1.3 m deep in some cases (Jang et al., 2017). Extreme temperatures that penetrate soils can destroy seed reserves and plant tissue at depths that would normally protect these tissues from surface disruption (Rhoades and Fornwalt, 2015). However, temperatures that would cause instantaneous plant tissue death can be measured up to 0.5 m deep up to 24 h after a slash pile fire is extinguished (Creech et al., 2012). Another study showed that soil temperatures remain elevated relative to adjacent control plots for 18 months at 0.15 m in the soil (Massman et al., 2006). These high temperatures easily disrupt biological processes for vegetation, soils, and any animals dwelling near the surface of the soil (Fig. 3).

2.3. Soil physical properties

Severe burning has significant impacts on soil at all levels of organization, including texture, structure, and soil stability. Soil type is an important variable in understanding the effects of pile burning on an ecosystem, due to differential heat transfer and thermal conductivity of different soil types (Oswald et al., 1998; Jerman et al., 2004). Texture has little impact on fire effects (Oswald et al., 1998; Busse et al., 2010), and both texture and bulk density are relatively unchanged by fire in this system (Oswald et al., 1998). However, in other studies, slash pile burning altered the particle size distributions under intense soil heating, increased silt and reduced clay fractions after intense soil heating under burned slash piles (Rab, 1996). Rab (1996) attributed the difference in soil responses to soil texture, organic matter content, moisture content and fire duration and intensity among different studies and ecosystem conditions (Rab, 1996). There may also be further significant mineralogical changes that otherwise lead to altered thermal conductivity (Nobles et al., 2010). For example, burned soils retained heat more than controls, with summer burn plot temperatures elevated nearly 20° after one year at a depth of 15 cm (Neal et al., 1965; Massman et al., 2006).

Extreme heating under slash pile burns alters soil stability by removing the soil litter layer and organic matter, stimulating aggregate breakdown and reducing overall aggregate stability in the post-fire environment, where lighter broadcast burning does not (Gifford, 1981; Rab, 1996; Ross et al., 2012; Shanklin, 2014). Cation exchange capacity and electrical conductance are also disrupted by high temperatures and changes to underlying soil structure (Gifford, 1981; Shanklin, 2014). Loss of aggregate stability and changes to particle size distribution lead to slower infiltration and contribute, along with chemical changes, to increased susceptibility to surface repellency, and erosion potential in forest systems and conifer-invaded grasslands (Rab, 1996; Seymour and Tecle, 2004; Halpern et al., 2014). High intensity fire also reduces macroscopic pore volume in most soil types, and significantly reduces percolation and infiltration as compared to unburned soils (Tarrant, 1956). Everett et al., (1995) used sand pits placed under piles, which were then burned, to examine effects of burning on surface and sub-surface soils. Over 60% of their replicates exhibited hydrophobicity and some attributes of allelopathic activity. Allelopathic compounds are released by plants that affect the growth of neighboring plants. These chemicals, such as monoterpene hydrocarbons from slash material, are released during high intensity fire and released into the soils beneath. The hydrophobic and allelopathic layers in the soils decrease infiltration and plant establishment and growth in the burn scar (Everett et al., 1995). If the severe burn occurs only in small, scattered patches, the net effect of slash pile burning on the ecosystem functions may not be highly detrimental and erosion control is not a problem; an exception to this is

Table 1
Maximum and average surface temperatures in pile burns on different forest types. Exact temperature data are difficult to acquire due to limited range of temperature paints and expense of highly-sensitive thermocouples.

Forest type	Location	Number of piles	Average temperature	Maximum reported temperature	Reference
Interior Douglas-fir Dry Mild	British Columbia, CAN	N = 6 (3 large piles, 3 small piles)		715 °C for large piles, 203 °C for small piles	Switzer et al., 2012
Mixed conifer	California, USA	N = 60	534 °C ± 17	867 °C	Busse et al., 2010
Mixed conifer	California, USA	N = 18 per burning trial (5)	162 °C at 1 cm depth	389 °C	Jang et al., 2017
Mixed conifer	Oregon, USA	N = 3 (small, medium, and large)		537 °C	Neal et al., 1965
Mixed conifer and low-elevation pine	California, USA	N = 29	428 °C ± 54 for wood, 344 °C ± 64 for slash, 406 °C ± 66 for small diameter slash	715 °C	Busse et al., 2013
Ponderosa pine and mixed conifer	Colorado, USA	N = 2		300 °C	Jiménez Esquilín et al., 2007
Pinyon-juniper	Utah, USA	N = 46 (piles and interspace)		777 °C 10 cm above surface, 288 °C 2.5 cm soil depth	Gifford, 1981
Hardwood and longleaf pine uplands	Georgia, USA	N = 8		1000 °C	Creech et al., 2012

on steep (16 + degrees) slopes (Tarrant, 1956; Xiu-hai et al., 2000).

2.4. Changes to soil moisture

Extreme temperatures from concentrated fuel loads alter physical and chemical attributes of soil within pile scars compared to unburned controls (Busse et al., 2010; Massman et al., 2012; Rhoades et al., 2015; Rhoades and Fornwalt, 2015). One soil property that may allow managers to predict and mitigate soil damage prior to burning is moisture. Soil moisture may play a role in protecting the upper horizons from extreme heat. Burning when duff is damp can protect the soil by reducing surface temperatures, but moisture content of the soil itself is more important (Frandsen and Ryan, 1986). Pre-fire soil moisture has a large influence on post-fire cation exchange capacity (Oswald et al., 1998) and may influence both nutrient loss and pH changes on pile scars (Klemmedson, 1976; Johnson et al., 2011). Soil moisture as low as 20% can dampen heat transfer to deeper soils in masticated fuels, in addition, large fuels may still require damp soils to safely burn (Busse et al., 2010). Burning when soil is moist can protect some soil components, but heating of water in moist soil can cause biological damage before the non-biological soil components reach damaging temperatures (Busse et al., 2013). Some of the most common changes in soil characteristics after burning are reviewed here. Though many studies find no immediate water loss in burned soils (reviewed in Neal et al., 1965), both soil moisture and water-holding capacity decrease significantly throughout the year (Neal et al., 1965). This is generally due to a common phenomenon after high-intensity fire in forest systems: hydrophobicity in surface soils. Slash pile burn scars are no exception. Water loss in these soils is due to decreased permeability of surface soils and loss of organic layer due to extreme heating, with the greatest water loss in the first five centimeters of soil (Neal et al., 1965).

2.5. Soil chemistry and nutrient profiles

High temperatures and soil moisture alter soil pH in burn scars, though pre-fire pH has a large influence on potential changes in pH and cation exchange capacity (Oswald et al., 1998). pH may be unchanged (Oswald et al., 1998) or increased (Korb et al., 2004; Creech et al., 2012; Shanklin, 2014) at the surface of burn scars. Fire typically initiates a temporary rise in pH within days after burning, and slowly decreases over time, but can remain elevated for as long as 6 months to one year after fire as compared to controls (Tarrant, 1956; Neal et al., 1965; Gifford, 1981; Switzer et al., 2012).

Nutrient retention and soil fertility are also impacted by pile burning. As early as the 1960s, researchers realized that severity of changes in soil nutrients, much like aggregation and pH, were tied to fire intensity (Neal et al., 1965). The composition of the slash pile in both species and fuel type (i.e. large diameter xylem versus small slash and leafy material) determines the nutrients released to the soil during burning. Nutrients react very differently across different vegetation types, and fuel characteristics and intensity can dictate which nutrients are released or converted to either useable or unavailable forms (Gifford, 1981). In general, losses of organic matter, total N, P, and K are greatest in high-intensity fire, but are also affected by less intense fires such as broadcast burning (Xiu-hai et al., 2000). Some changes to nutrients seem initially beneficial to vegetation, but after a year or two, the advantage is lost (Neal et al., 1965).

One major nutrient that is important for plant and animal life is nitrogen. In some ecosystems, there is little change in N content of surface ash after pile burning (Klemmedson, 1976), where many other studies show that soil nitrogen below the pile is sensitive to fire intensity. Pile burn scars have significantly reduced total N as compared to controls, likely due to volatilization during the fire, and increase in leaching losses and transformation to inorganic and available forms in the immediate aftermath of the fire (Neal et al., 1965; Klemmedson, 1976; Rab, 1996; Nadel et al., 2007; Halpern et al., 2014; Rhoades et al., 2015). In general, high-intensity fire tends to reduce total N but increase inorganic and available forms of N (such as ammonium, Nadel et al., 2007; Fornwalt and Rhoades, 2011) as compared to unburned areas (Neal et al., 1965; Covington et al., 1991; Rab, 1996; Nadel et al., 2007; Halpern et al., 2014; Rhoades et al., 2015). In some other systems, fire scars created by ponderosa pine slash pile burns show significant reduction in total N, and ammonium was over 4 times higher than unburned areas (Wolfson et al., 2005; Jang et al., 2017). In ponderosa pine, available forms of both N and C remain higher outside of pile scars for up to 4 years after burn (Korb et al., 2004; Shanklin, 2014). In some systems, however, total N shows a slight increase in the immediate aftermath of fire, with a general decline over time (Neal et al., 1965; Ross et al., 2012). Ross and others (2012) found that in pinyon-juniper piles, percent total nitrogen was higher in pile burns versus broadcast burn or controls, but only in the top two centimeters of soil. Difference in N transformation is most likely tied to both soil structure and surface vegetation composition in different ecosystems.

High-intensity fire can benefit plants for a short period of time by transforming previously unavailable nutrients to available forms (Neal et al., 1965). Thorpe and Timmer (2005) found that in the boreal forest, some pile burns generally improved soil fertility. Pile burns raised soil pH from 4.2 to 5.4 and increased exchangeable K, Ca, and Mg to levels exceeding conifer seedling requirements (Thorpe and Timmer, 2005). Similarly, a less-intense fire created a short-term benefit for planted seedlings in a Norway spruce clearcut, due to retained N and available minerals with decreased competition (Jönsson and Nihlgård, 2004). Low intensity burning also increases the amount of acid soluble P_2O_5 and exchangeable K, and high-intensity burning increases these available forms of potassium even more (Tarrant, 1956). Phosphorus levels rose to nearly four times in pile burn scars compared to unburned controls in the year following the burn and remained elevated over two fold after 6 years (Creech et al., 2012).

Soil characteristics and organic matter play an important role in nutrient retention. Johnson and others (2011) found that total C and N in surface soils after fire decreased in a mixed conifer site but not in an adjacent meadow site. Total C was lower in burned versus control soils at both 5 and 15 cm depth in Colorado ponderosa pine forest (Jiménez Esquilín et al., 2007). Similar to N dynamics, organic C increased significantly in the pinyon-juniper system but returned to previous levels within one year (Gifford, 1981). Other critical plant nutrients show different dynamics across forest type and climate. For example, potassium concentration was the only significant change across soil properties in mixed conifer (Jang et al., 2017), but several studies show an increase in PO_4^{+3}, Ca^{2+}, and Mg^{2+} throughout burned treatments in Douglas-fir and ponderosa pine forest types (Switzer et al., 2012; Wolfson et al., 2005).

2.6. Microbiota and fire

High-intensity fire has a significant impact on soil microbial activity (reviewed by Neary et al., 1999; Switzer et al., 2012, and Gongalsky et al., 2012). Loss of soil structure, change in soil moisture, nutrient loss and altered pH reduce the biomass of fungi and bacteria (Haskins and Gehring, 2004; Jiménez Esquilín et al., 2007; Switzer et al., 2012). Microbial communities and fungal respiration in burn scars remain lower than control plots for over a year, in some cases up to 15 months, likely related to pH (Neal et al., 1965; Jiménez Esquilín et al., 2007). In some studies, bacteria begin to increase after 6 months, with the largest increase in lower-intensity burn areas or plots with significantly increased soil moisture (Neal et al., 1965). In addition, carbon dioxide increases significantly in burned plots compared to unburned controls. Carbon dioxide levels start much lower in burned soils, but increase sharply over time, likely following increased bacterial activity due to changing soil moisture, depending on ecosystem (Massman et al., 2006).

3. Impacts of slash burning on vegetation

3.1. Understory herbaceous vegetation and shrub recovery

Plants demonstrate a wide variety of responses to fire disturbances, often linked to disturbance intensity. Vegetation recovery in high-severity burn scars is both ecosystem- and species-dependent for trees and understory vegetation. Succession is also affected by intensity of soil disturbance and soil temperatures on burned sites (Zabowski et al., 2000; Selmants and Knight, 2003). Across 5 forest types, researchers find that high-intensity burn plots have much lower plant cover than all other forms of disturbance, such as mastication or prescribed burning (Griffis et al., 2001; Owen et al., 2009). Burn scars are nearly always initially denuded (DeSandoli et al., 2016) and retain a significantly higher proportion of bare soil compared to unburned areas (Fornwalt and Rhoades, 2011), which can persist for months in some systems (Korb et al., 2004). In most cases, low plant cover persists for upwards of 2 years, and any initial plant community may show reduced survival over time (Owen et al., 2009). Rhoades and others (2015) found that native plant cover was still 30% lower than cover on adjacent unburned areas after five years in a lodgepole pine stand (Rhoades et al., 2017).

Most current research monitors plant cover in burn scars to determine related ecosystem function, such as soil stability or protective cover, and not for information on community composition or individual species. Vegetation cover in pile burn scars is often measured by soil exposure (Halpern et al., 2014) or percent cover (Scherer et al., 2000; Fornwalt and Rhoades, 2011; Creech et al., 2012; Castoldi et al., 2013), where complete lack of vegetation makes proportion of area exposed an easily repeatable spatial method to measure change over time, or by vegetation biomass for ecosystems where vegetation returns immediately, and biomass is a better indicator of recovery (Shanklin, 2014). Both methods show significant differences in burned and unburned areas over periods of months to years (Scherer et al., 2000; Fornwalt and Rhoades, 2011; Creech et al., 2012; Castoldi et al., 2013; Halpern et al., 2014; Shanklin, 2014). Measuring total surface cover, along with plant abundance, species richness, and diversity are complicated to measure, but potentially important to fully characterize burn scar vegetation recovery as a management goal. Future work that combines several of these techniques in one study would allow some interpretation across ecosystems and time scales, whether natural or assisted regeneration of burn pile scars.

In general, high intensity fire leads to greatly diminished understory species richness and diversity across a variety of ecosystems, with the lowest diversity in the center of the burn plot where the temperatures are highest (Scherer et al., 2000; Fornwalt and Rhoades, 2011; Creech et al., 2012; Castoldi et al., 2013; Halpern et al., 2014; Shanklin, 2014). High-intensity fire is more likely to kill plant species with shallow rhizomes or runners, and the surface seed bank is destroyed by high temperatures (Halpern et al., 2014). Seed viability and plant propagule availability may be the limiting factor for some dry forests that are not so evolutionarily adapted to stand-replacing fire, such as Arizona and Colorado ponderosa pine systems (Korb et al., 2004; Shanklin, 2014). Korb and others (2004) found significantly more viable seeds outside of burn plots than within, and most viable seeds within burn plots were ruderal or nonnative. In both of these settings, burn scar recovery does somewhat reflect the surrounding vegetation, but with very different plant composition. In a lodgepole pine forest (*Pinus contorta* var. *latifolia*), plant cover in openings created by burn piles was actually higher than the surrounding regenerating forest in a study examining 50-year old burn openings (Rhoades and Fornwalt, 2015). This could very well be a natural response in the lodgepole pine system, where the forest is adapted to stand-replacing, high-intensity fire, with cones and seedlings that rely on hot temperatures and bare mineral soil for regeneration. Many understory plants in forest ecosystems are adapted to moderate- to high-intensity wildfire, but high temperatures of pile burns may even exceed the hottest wildfire in a concentrated area (Fornwalt and Rhoades, 2011).

3.2. Tree regeneration

High severity burn scars, such as those left by slash piles, are particularly challenging for native conifer regeneration. Physical properties of the site, burn intensity, and associated temperatures or disruption of the associated microflora have long been implicated in low tree regeneration (Fuller et al., 1955). However, in forest systems such as some lodgepole pine, where high-severity fire is necessary for reproduction through serotinous cones and reduced competition, high-intensity slash pile burning is advantageous for establishment and growth of new seedlings (Rhoades and Fornwalt, 2015). In other systems, such as ponderosa pine, comparison of slash pile scars to broadcast burns reveals that high intensity fire is detrimental, while low intensity broadcast burn is beneficial (Xiu-hai et al., 2000; Rhoades and Fornwalt, 2015).

Elevation is a significant contributor to success in post-fire seedling establishment, likely due to complex interactions between temperature, moisture, soil type, and species composition. Montane fire scars show some seedlings recover more quickly than in subalpine fire scars, due to differences in species, soils, moisture, and growing season, which may also contribute to ecosystem resiliency (Selmants and Knight, 2003). Still, burn pile scars that had no remediation efforts in montane systems supported severely diminished seedling density as compared to adjacent unburned areas (Scherer et al., 2000; Fornwalt and Rhoades, 2011; Halpern et al., 2014). In a similar study of Mediterranean pine system with oak and shrub understory, burning increased pine seedling density, with a correlation between number of cones and distance to seed tree (Castoldi et al., 2013). However, though there was a significant increase in seedling density on burned sites, they found a much higher species richness in control plots, though more species were exclusive to burned versus unburned plots (Castoldi et al., 2013). Thorpe and Timmer (2005) found 17% first-season mortality in jack pine seedlings planted on control plots in the boreal forest, with significantly lower mortality of seedlings in burn plots, leading them to believe that seedlings planted in burned sites at higher latitudes might be more stress tolerant or that ash input promoted microbial activity to increase N mineralization and release of plant-available P (Thorpe and Timmer, 2005).

Seedling height growth is often used as measure of site quality in post-fire regeneration. As expected, less fire-adapted species such as Douglas-fir seedling height growth after pile burning is less than broadcast burn (Minore, 1986), and significantly lower than unburned controls, where lodgepole pine growth is best with slash pile burn residues (Zabowski et al., 2000). However, both Douglas-fir and lodgepole pine show greater growth by volume index (as measured by DBH) after 2 years in slash pile burns than in crushed and retained slash, though there was no significant difference after 4 years (Lacey and Ryan, 2000). This implies that the initial nutrient availability of slash pile burns could, in fact, benefit some tree species during early regeneration.

3.3. Nonnative plants and invasibility

Changes in soil structure, soil chemistry, and nutrient profiles due to pile burning influence invasibility and post-fire plant community structure (Haskins and Gehring, 2004; Korb, Johnson and Covington, 2004). As compared to surrounding controls, broadcast burning or concentrated disturbance such as pile burning may favor establishment of either agronomic plants or other nonnative plants, in especially nutrient-rich or unbalanced nutrient environments like pile burn scars (Haskins and Gehring, 2004; Scherer et al., 2000; Korb et al., 2004; DeSandoli et al., 2016; Rhoades et al., 2015). Similarly, the additional moisture retained in burn scars through lack of evapotranspiration loss and elevated soil temperatures likely improved germination of exotic species, where loss of native seedbank allowed nonnatives to become early colonizers and outcompete less fire-adapted native plants (Wolfson et al., 2005). The loss of litter layer can also change the invasibility of a forest stand. The physical presence of litter in a healthy forest system can inhibit establishment of nonnative plants and change overall community structure. Many native plants are adapted to frequent fire intervals and reduced litter, but non-native plants create a thick litter layer that inhibits native plant establishment, so loss of litter is beneficial to native plants (Faist, 2015). However, the loss of litter may also reduce the pool from which to recruit native seeds (Faist, 2015). Korb and others (2004) found significantly more viable seeds outside of burn plots than within, and most viable seeds found within burn plots were ruderal or non-native. In pinyon-juniper woodlands of the same region, up to 90% of established plants in pile burn scars were non-native species, with increased numbers of non-natives established on the edges of burn scars (Owen et al., 2009). Other studies show no significant presence of nonnative plants in the center of burn scars after two years (Shanklin, 2014) or nonnative plants only in adjacent unburned areas (DeSandoli et al., 2016). Halpern and others (2014) found no nonnative plants in the burn scars in a lodgepole pine system, and speculated that the most common nonnatives in this ecosystem may prefer shade, which is less common in a canopy structure altered by thinning and pile burning projects, or that patchy distribution and distance to seed sources reduced dispersal and establishment across the site. Nonnative plant establishment changes biotic, abiotic, and even economic components of an ecosystem (DeSandoli et al., 2016), impeding natural ecosystem processes through competition for resources and changing the community composition in their favor (Creech et al., 2012). Nonnatives also tend to be ruderal species, with high reproductive output and highly competitive seeds, capable of rapid dispersal and establishment in pile burn scars (Haskins and Gehring, 2004).

3.4. Remediation of pile burn scars and nonnative plants

Piling and burning can increase establishment and germination for nonnative plants in some ecosystems, and different remediation techniques may be necessary in different ecosystems (Robichaud et al., 2000). Unfortunately, many common rehabilitation methods intended to stabilize soils and restore vegetation communities after intense heating are often responsible for introduction of nonnative plants or are ineffective at preventing nonnative establishment (DeSandoli et al., 2016; Table 2). Miller and Seastedt (2009) argued that disturbed ponderosa pine ecosystems promoted non-natives (mostly forbs), and mastication treatments allowed rapid spread and establishment of nonnatives (Faist, 2015). Residue-based rehabilitation techniques vary in effectiveness in improving soil stability and productivity (Rhoades et al., 2017), and in some cases, nonnative plant cover and richness are no different in untreated scars than surrounding unburned areas (Rhoades and Fornwalt, 2015). Mulching techniques offer some erosion control, soil moisture retention, and control of nonnative plant cover, but may also suppress native plants and reduce available inorganic N in some ecosystems (Fornwalt, 2012; Shanklin, 2014; Rhoades et al., 2015). Thus, the effectiveness of mulching will depend upon the target vegetative species (Rhoades et al., 2017), as well as the supporting communities, such as mycorrhizal fungi, invertebrates, etc. in the system. Furthermore, overall success of mastication and mulching efforts is patchy and needs more research (Table 2); mastication of woody debris and litter alter the seed bank, and ground cover alters the ability of some native species to germinate (Faist, 2015).

In contrast to some other conventional post-fire treatments, seeding has a significant impact on future plant biomass (Shanklin, 2014) and plant composition (Fornwalt, 2012) in many systems (Table 2). For example, in the aftermath of the Fourmile Fire in Colorado, non-native

Table 2

Effects of remediation techniques within forest types on plant cover, growth, or species richness. Effects are based on results from research on plant recovery on pile burns across several remediation techniques and forest types. Data are reported as increase (↑), decrease (↓), or no change (→) as compared to unburned controls, as measured by cover, growth, or species richness (depending on specific study methods). Boxes without systems mean that no data or information is available for that particular response and forest type from scientific literature. Lodgepole pine, jack pine, and subalpine forests were combined into one category due to shared patterns of recovery, likely due to similar ecosystem adaptations and responses to high severity fire. All other forest types showed mixed results, likely due to a mixed severity natural fire regime and consequent varied success across multiple remediation techniques.

		Forest Type											
		Pinon-juniper			Ponderosa pine			Mixed conifer (Douglas-fir dominated)			Lodgepole pine, jack pine, and subalpine forest		
		Total	Native	Non-native	Total	Native	Non-native	Total	Native	Non-native	Total	Native	Non-native
Remediation Techniques	No remediation	↓[1] ↑[2]	↓[1] →[2]	↑[1] ↑[2]			↑[5]	↓[8] ↓[9]	↓[8]	→[8]	↑[11]	↑[11]	→[11] →[12]
	Planting (trees)							↓[10]			↑[10] ↑[14]		
	Seeding (understory)	↑[3] ↑[4]	↑[3]	→[3]	↑[6]	↑[6] ↑[7]	→[6] ↓[7]					↑[12] →[13]	→[13]
	Live soil amendment + seed				→[6]	↓[6] ↑[7]	→[6] ↓[7]						
	Scarification + seed											↑[12]	↓[12]
	Mulch/straw cover + seed											↑[12]	↓[12]
	Comments	one study showed native decrease and nonnative increase to neutral at 6 years						one study showed total increase to neutral in 7 years, native remained negative					
	Papers referenced	[1]Owen et al 2009; [2]Haskins and Gehring 2004; [3]Havarilla et al 2017; [4]Ross et al 2012; [5]Wolfson et al 2005; [6]DeSandoli et al 2016; [7]Korb et al 2004; [8]Halpern et al 2014; [9]Scherer et al 2000; [10]Minore 1986; [11]Selmants and Knight 2003; [12]Rhoades and Fornwalt 2015; [13]Rhoades et al 2017; [14]Thorpe and Timmer 2004											

grasses made up 90% of plant cover in seeded treatment plots (Fornwalt, 2012), a common occurrence where high levels of seeded grasses used in stability treatments impeded native plant establishment (Fornwalt, 2012). Some of the greatest plant cover in montane systems came from soil scarification and seeding (Fornwalt and Rhoades, 2011), though effects can be somewhat variable depending on forest type (Shanklin, 2014). Seeding and mulching or combined treatments often assume an increase in total plant cover from just those two methods (Fornwalt, 2012), without considering the added function of invertebrates or fungi. Frequently, the seeded species show poor establishment and survival, and little overall cover within the first year (Fornwalt, 2012), with early successional native plants most negatively impacted (Fornwalt, 2012). In general, vegetation-focused treatments (seeding, surface treatments, and mulching) in the dry ponderosa pine forests have unwanted effects on short-term abundance of nonnative plant cover in pile burn scars. In some cases, however, seeding significantly increases plant cover and species richness as compared to other treatments, such as mulching and scarification. Researchers found that in the pinyon-juniper ecosystem, they can achieve 18% plant cover at year two after burning by seeding. Plant cover increased to 66% by year six, with potential for recovering native species to outcompete non-native species, though cheatgrass remained three times higher in pile burns as compared to controls (Havrilla et al., 2017). Despite the challenge of non-native species, seeding in some ecosystems may allow understory vegetation to re-establish and contribute to soil stabilization more in pile burn scars than other treatment efforts.

4. Impact of slash burning on animal communities

4.1. Vertebrates

Forest treatments that create or remove slash alter habitat for small vertebrates, with both positive and negative effects. Three studies (Chambers, 2002; Converse et al., 2006a; Converse et al., 2006b) show that small vertebrates use slash and coarse woody debris for nesting cover, hiding cover, or food sources, such as conifer seeds or insects. Opportunistic habitat users, such as deer mice, will likely decrease in the area as piles decay or are burned. Early studies hypothesized that mice populations could be reduced from logged areas by burning slash, as mice were thought to negatively impact tree regeneration in Douglas-fir management operations (Tevis, 1956). After burning slash piles, researchers concluded that mice still crossed open burned areas to find other islands of habitat or simply to explore a newly created habitat structure (Tevis, 1956). Adding piles to the landscape can increase small mammal abundance for a short period of time, but some animals actually prefer lower structural complexity and higher openness after piles are burned, such as grasshopper mice and kangaroo rats in pinyon-juniper woodlands (Severson, 1986). Many birds also show an affinity for unburned slash piles. Small songbirds use slash piles for foraging, nesting, or perch sites from which to observe the area (Franzreb and Ohmart, 1978; Hutto et al., 1991; Gorenzel et al., 1995). Many small ground-foraging birds such as towhees, sparrows, and juncos are frequently observed foraging within 1 m of slash piles (Gorenzel et al., 1995) and will immediately move into the cover of the pile when disturbed or threatened by predators. In some cases, bird abundance decreases sharply in the area after piles are removed. Franzreb and Ohmart (1978) reported a significant increase in both house wrens and juncos in a logged area with piles, but a rapid decline in junco numbers after slash piles were burned. Finally, some reptiles, such as lizards, show a positive response to thinning and burning within two years of treatment, but authors concluded that no single treatment type will create ideal conditions for all lizard species (Sutton et al., 2014). The diverse reptilian species of different forest types may require as many microhabitats and microclimates for each species to thrive (Sutton et al., 2014). While there is some significant research on the use of intact slash piles for vertebrates, more research is needed to determine the impact of post-fire pile burn scars on vertebrate communities (Kalies et al., 2012).

4.2. Surface arthropods

Few studies address the impact of slash pile burning on surface arthropods, which are a critical part of biodiversity and ecosystem functioning across all forest types (Schowalter, 1986; Patton et al., 2014). Plant materials in the pile provide nutritional resources for a large number of wood infesting insects (Six et al., 2002; Hayes et al., 2008; Hedin et al., 2008). Slash piling and post-fire burn scars allows refuge sites for a number of surface arthropods, as close proximity to unburned soil allows them to move into safe areas from which to re-colonize burned areas (Nadel et al., 2007). It is, however, unknown how or when surface arthropods might return to these high severity burns that are devoid of plant life. Many studies address the impact of high-severity fires on arthropods, and some consider single arthropod groups in recolonization of burned areas after fire (Carabids: Holliday, 1991; Rainio and Niemela, 2003; Villa-Castillo and Wagner, 2002; Lange et al., 2014; Orthopterans: Hochkirch and Adorf, 2007; Hahn and Orrock, 2015; Bergmann and Chaplin, 2018). Some studies show arthropods remaining in residual slash after wildfire (Nadel et al., 2007), demonstrating the importance of coarse woody debris to arthropod biodiversity. In many cases, slash piles are not fully consumed by the fire, and may provide habitat for recolonizing insects in surrounding residue.

Fire intensity is a critical variable in both plant and arthropod recovery, and vegetation succession patterns can profoundly influence arthropod recovery (Vasconselos et al., 2017). In many systems, the new arthropod community depends on the pre-fire habitat and mortality of various groups. The surviving arthropods likely dictate the pattern of succession in burned areas, as residual populations may have a previously unknown competitive advantage in the new habitat (Saint-Germain et al., 2005; Sasal et al., 2010). In almost all systems, survivors and immigrants are forced to adjust to simplified habitat structure, which may be good for some species but not for others (Sackmann and Farji-Brener, 2006). Some xylophagous and predatory insects benefit from openness and debris, while others require vegetation recovery or a particular habitat structure (Kaynas and Gurkan, 2005). Research from mixed-conifer, boreal, and deciduous forest systems show variable effects on overall abundance after prescribed burns, but researchers often observe an increase in diversity or complete change in community composition (Ferrenberg et al., 2006; Nadel et al., 2007). There may be lower abundance in high intensity fire, but more unique species in burned plots compared to unburned controls (Niwa and Peck, 2002; Saint-Germain et al., 2005).

5. Conclusions

Despite the obvious economic and application advantages, the effects of pile burning are often seen for decades after the harvest treatment, even if forest regeneration appears well-established in treated areas. Selmants and Knight (2003) noted that remnants of piles were still evident after 30–50 years in Wyoming lodgepole and Engelmann spruce forest, easily recognizable by circular patterns with low vegetation density and with charcoal and charred debris still visible. While rehabilitation of large slash piles is frequently required due to extreme temperatures and significant permanent soil damage, small piles are largely unstudied in the context of ecosystem restoration (Rhoades et al., 2015; Rhoades and Fornwalt, 2015). Some studies indicate that intense heating of pile burns may have broader implications for these forest ecosystems. With many hundreds of piles on each site, the sheer volume of pile scars on the landscape may reduce habitat for native species (Seymour and Tecle, 2004), which would adversely impact overall ecological functions and processes.

Slash piling and burning is one of the most efficient ways to remove logging residue from the landscape to help meet timber and fuels management objectives. Fuel management will continue to be critically important under changing climate and drought conditions (Governor's Forest Health Councils, 2007), especially in the southwestern United States in projects like the Four Forests Restoration Initiative (Robles et al., 2014; 4fri.org). To better manage our forest ecosystems under changing conditions, we need to better understand the impacts of fuel management treatments on the ecosystem as a whole, from the ground up. Slash pile burning has significant impacts on the surface vegetation, litter layer, soil composition and nutrients, and the animals that dwell in the understory, especially arthropods. These effects can be significant if pile burns occur across thousands of acres each year. Research on slash pile burning reveals that the recovery of soil and vegetation is very system dependent. Ecosystems that are well-adapted to stand-replacing fire, such as lodgepole pine, may require less intensive management to recover from high severity fire in heavily loaded slash piles. Other systems, such as more xeric and lower elevation ponderosa pine forests of the Southwest USA, may require a different approach to both slash pile burning and overall restoration management after fire.

We recommend further research into the effects of slash pile burning and post-fire recovery, especially as it relates to surface vegetation and arthropods and the interactions between them (Fig. 3). It is possible that these systems will recover over a period of time, but we need repeated, testable hypotheses to evaluate current and future community composition, as well as future impacts on these sites. As we noted in Table 2, some of the most common research in slash piles, vegetation recovery, is still in early stage of study with more to learn on overall impacts on ecosystem function and vegetation community composition over longer time periods. One key point for future research in vegetation recovery will be determining the best way to measure both spatial and community data to improve reproducibility and comparison across ecosystem types, as the current body of work uses a wide array of techniques depending on specific research goals. The overall research on the impacts of slash pile burning on animals is also limited. We need a better understanding of these small high-severity fire scars from a more balanced ecosystem perspective. We need to determine if ecosystems will return to the former state, or have greater impacts on the surrounding ecosystem, which is likely to take longer than the time required for a single dissertation or thesis. We created a framework (Fig. 3) to represent the major topics found in the pile burn literature and reviewed thus far, with interactions among those topics either investigated by at least one paper, hypothesized in at least one paper, or not mentioned in any literature. We recommend a long-term and interdisciplinary approach to increase the body of work on these topics as they relate to management through use of pile burning and the interactions among them, to understand how each component interacts and effects long-term forest succession and stability at landscape scales. Climate change will continue to impact forest regeneration after fire, and understanding how small pieces of forest recover after high-severity fire may be the key to increasingly successful forest restoration policy and techniques.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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