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Decomposition Rates for Hand-Piled Fuels

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Abstract

Hand-constructed piles in eastern Washington and north-central New Mexico were weighed periodically between October 2011 and June 2015 to develop decay-rate constants that are useful for estimating the rate of piled biomass loss over time. Decay-rate constants (k) were determined by fitting negative exponential curves to time series of pile weight for each site. Piles at the Washington site ($k = 0.027$/year) decomposed significantly more slowly than piles at the New Mexico site ($k = 0.064$/year). Significant differences in k for each site may be a function of a between-site variation in pile composition (with or without large woody material), the environmental dissimilarities between sites (Mediterranean climate regime in Washington vs. monsoonal climate regime in New Mexico), or a combination of factors.

Keywords: hand piles, decay-rate constant, fractional mass loss, fuels management, Washington, New Mexico.

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Introduction

Many conifer-dominated forests with historically low-severity fire regimes in the Western United States are at risk of stand-replacing wildfires (e.g., Fulé et al. 2004, Noss et al. 2006). To reduce the likelihood of uncharacteristically severe wildfire in these forests, fuel reduction treatments, which typically consist of removal of small-diameter trees, are being implemented widely. These types of fuel reduction treatments produce large amounts of unmerchantable woody material and elevated surface fuel loadings (Agee et al. 2000, Finkral and Evans 2008, Fulé et al. 2002, Hjerpe et al. 2009). Currently, there are few commercial markets for this material, so it is commonly piled by hand or with heavy machinery and burned on site (Evans and Finkral 2009, Han et al. 2010).

In addition to biological and ecological effects, research on pile burning is expanding to address key topics such as smoke emissions and carbon dynamics. Because of concerns about smoke and air quality in particular, fire, fuel, and air-quality managers must understand and be able to quantify fuel loading accurately to best estimate and manage emissions when piles are burned (Weise and Wright 2014, Wright et al. 2010). Besides potentially affecting downwind air quality, piling and pile burning also affect terrestrial ecosystem carbon pools and fluxes (DeLuca and Aplet 2008, Finkral et al. 2012, Forbes et al. 2006, González-Pérez et al. 2004).

As with broadcast prescribed burning and wildland fires, smoke emissions from pile burning are affected by the amount and physical characteristics of the fuels involved, which change over time as existing fuel particles decompose. Little is known about how the physical characteristics, particularly the fuel loading, of hand-piled fuels change over time. As part of a larger experiment to document how time-since-piling and season-of-burning influence fire behavior and fire effects (Wright et al. 2015), we constructed and periodically weighed hand piles located at one site each in eastern Washington and north-central New Mexico to determine rates of decay. Because smoke emissions are a function of fuel loading and fuel consumption (Hardy et al. 2001), knowledge about the rate of decay can be used to more accurately estimate the biomass of piles as they age and the resulting emissions when they are burned.

Methods

Study Areas

Two study sites, one each on the Naches Ranger District of the Okanogan-Wenatchee National Forest in eastern Washington and on the Santa Clara Pueblo in north-central New Mexico, were selected for study. Both sites were in dry conifer forests that had been recently thinned of small diameter (<20 cm diameter at breast height; d.b.h.) trees to reduce stand density. Thinning debris at both sites had been piled by hand during fuel management operations; piles were approximately 2.5 to 3 m in diameter and 1.2 to 1.5 m tall (fig. 1). Piles at the Washington site included tops, branchwood, and 2-m-long pieces of bole wood up to approximately 20 cm in diameter. In contrast, piles at the New Mexico site were composed of <7.6-cm-diameter woody material only (branches and small tops), as the area had been made available for firewood collection prior to piling.

The Washington site is located on a small, flat bench in an area of gently sloping terrain (5- to 15-percent slope, easterly aspect) at 1140 m elevation above Rimrock Lake, approximately 50 km southeast of Mount Rainier in the eastern Cascade Range (N46° 39′ 25.9″; W121° 09′ 26.6″). The area is characterized by a Mediterranean climate regime with warm, dry summers (mean July–August maximum temperature of 23 °C; July–August precipitation of 3 cm) and cold, wet winters (mean December–February minimum temperature of -5 °C and precipitation of

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Figure 1—Typical hand piles approximately 6 years after piling at the study site in central Washington.

43 cm), with most precipitation falling as snow (Prism Climate Group 2016). The site is in a mixed-conifer stand comprised of 15- to 20-cm d.b.h. ponderosa pine (*Pinus ponderosa* Lawson and C. Lawson), western larch (*Larix occidentalis* Nutt.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), with scattered, remnant, old-growth (70- to 125-cm d.b.h.) ponderosa pine and western larch. The stand was thinned to a basal area of 10.0 m²/ha in 2011; small trees of all species were cut during the thinning. Thinning debris was piled by hand at a density of 90 piles/ha.

The New Mexico site is located on relatively flat terrain at 2400 m elevation 20 km west of Española, in the Jemez Mountains (N36° 0′ 56.4″; W106° 16′ 59.9″). The area is characterized by hot summers (mean July–August maximum temperature of 27 °C) and cold winters (mean December–February minimum temperature of -9 °C), and receives 56 cm of precipitation annually, with approximately half of it coming in the summer and early fall during the monsoon period (Prism Climate Group 2016). The site is in a mature ponderosa pine stand (±29 cm d.b.h.) that was thinned to a basal area of 18.5 m²/ha in 2011; thinning debris (ponderosa pine branches and tops only) was piled by hand at a density of 50 piles/ha.

Field Methods

We built five hand piles at each study site atop galvanized steel frames. The steel frames were constructed of 2 m × 2 m chainlink fence panels and reinforced with two galvanized steel cross braces joined to the panel edges with split-T braces (fig. 2). Galvanized wire mesh (6-mm diameter hole size) was attached to each panel frame with steel wire to minimize material loss through fine branch breakage and needle excision as piles aged. The entire assembly was weighed (tare weight) before building the pile on top of it.

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2-m x 2-m chain-link fence panel covered with 6-mm diameter galvanized steel hardware cloth wired to the frame

3.5-cm diameter galvanized steel fence post attached to outer frame with split-T fencing connectors

Pile diameter

Numbered steel tag wired to corner of frame to allow long-term monitoring
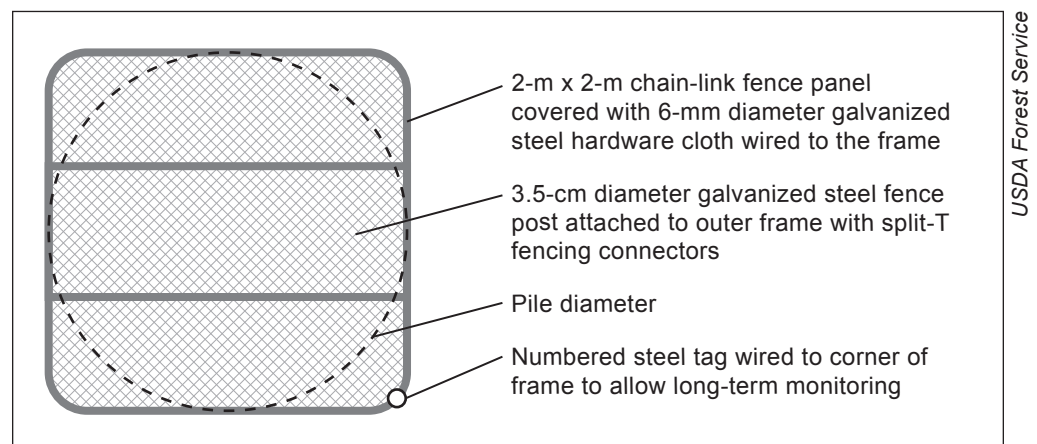
Figure 2—Pile frame assembly.

Hand piles were paraboloid, 1.8 m in diameter, and 1.2 m high when built. Thinning debris was placed on top of the chain-link panel assemblies until the pile reached its 1.2-m build height. Piles at the Washington site were constructed based on contract piling specifications that are typical on the Okanogan-Wenatchee National Forest and closely matched those created during the fuel management operations that immediately preceded the start of this study. The Washington piles were composed of alternating layers of small (<7.6-cm diameter) and large (7.6- to 20-cm diameter) fuels of mixed species (ponderosa pine, western larch, Douglas-fir, and grand fir), and were covered with a layer of waxed craft paper. The waxed craft paper is intended to keep the pile center dry to facilitate ignition during the spring and fall when weather conditions are moist and when most pile burning occurs in Washington. Piles at the New Mexico site only included ponderosa pine branchwood and tops less than approximately 8 cm in diameter and were not covered. We attempted to build piles of comparable volume, weight, and size class composition within each site.

When built, and approximately every 6 months thereafter for a period of almost 4 years, each pile was weighed intact by lifting the frame assembly a short distance off the ground using a hand-operated chain hoist with an attached 500-kg-capacity hanging scale (Intercomp CS750). The frame assembly was suspended from a 4.2-m-tall aluminum utility tripod (Spanco ATA-02-1107)[2] with 1000-kg-capacity centered over each pile by nylon slings attached to each corner of the frame (fig. 3).

Moisture-content subsamples were collected during pile construction and at the time of each remeasurement and were used to adjust all field weights to a common oven-dry basis. Three to five subsamples each from the surface and the interior of adjacent sacrificial piles (i.e., piles scattered throughout the stand that were created during piling operations immediately preceding the beginning of this study) were collected in heavy-gauge, resealable plastic bags and weighed shortly after collection. Subsamples were returned to the laboratory, oven-dried at 100 °C to a constant weight (at least 48 hours) and reweighed to determine the ratio of dry weight to wet weight for use in correcting field weights to a dry-weight basis. In addition to collecting material from the surface and the interior of sacrificial piles, at the Washington site, moisture content subsamples were further stratified by size class (<7.6 cm in diameter and >7.6 cm in diameter). A volume-weighted (and size-weighted for the Washington site) moisture ratio ($\overline{m}$) was calculated and multiplied by the field weights to adjust to an oven-dry basis (eq. 1). We assumed that moisture content subsamples collected from the surface of adjacent sacrificial piles represented an outer 0.5-m-thick shell for each pile. This outer shell accounted for 35 percent of the pile's volume, with the remainder of the pile's volume (65 percent) represented by the interior moisture content subsamples.

[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

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Figure 3—Pile suspended from tripod during periodic remeasurement.

$$\overline{m} = \left\{ \frac{w_s}{w} \times [(v_e \times m_{se}) + (v_i \times m_{si})] \right\} + \left\{ \left(1 - \frac{w_s}{w} \right) \times [(v_e \times m_{le}) + (v_i \times m_{li})] \right\} \qquad (1)$$

Where

$\overline{m}$ = the volume- and size-weighted net-dry:net-wet weight moisture ratio,

w = the starting oven-dry weight of the pile,

w_s = the starting oven-dry weight of fuel particles <7.6 cm in diameter in the pile,

v_e = the proportion of the pile's volume included in a 0.5-m-thick shell on the surface (i.e., 0.35),

v_i = $1 - v_e$ (i.e., 0.65),

m_{se} = the ratio of net-dry:net-wet weight of moisture subsample particles <7.6 cm in diameter from the exterior, or surface, of the pile,

m_{si} = the ratio of net-dry:net-wet weight of moisture subsample particles <7.6 cm in diameter from the interior of the pile,

m_{le} = the ratio of net-dry:net-wet weight of moisture subsample particles 7.6 to 20 cm in diameter from the exterior, or surface, of the pile, and

m_{li} = the ratio of net-dry:net-wet weight of moisture subsample particles 7.6 to 20 cm in diameter from the interior of the pile.

Analysis

The rate of pile mass loss was modeled by fitting a negative exponential curve to the mean fractional mass loss for the periodic remeasurements from each site (eq. 2) as in Olson (1963).

$$X_t/X_0 = e^{-kt} \qquad\qquad (2)$$

Where

X_t = the oven-dry weight at time t (in years),

X_0 = the starting oven-dry weight,

k = the fractional mass loss or decay-rate constant, and

t = the time since piling (in years).

Decay rate constants were derived for individual piles (i.e., replicates) and also for the mean of all decay rate measurements for each of the New Mexico and Washington sites. Mean decay-rate constants for the New Mexico and Washington sites were compared statistically with the Mann-Whitney U test (Zar 1984), the non-parametric equivalent of the two-sample t-test.

Results and Discussion

The experimental hand piles monitored for this study showed a trend of decreasing weight over time (tables 1 and 2). On average, piles lost 10 percent and 17 percent of their starting weight after 45 months for the Washington and New Mexico sites, respectively. Although a variety of model forms have been proposed to represent biomass decomposition (see Harmon et al. 1986 for a thorough discussion on this

Table 1—Actual changes in hand-pile weight over time at the Washington state site

Date	Mean pile weight[a]	Sample size
	Kilograms ± SE	n
October 2011[b]	160.6 ± 3.8	5
June 2012	153.4 ± 4.0	5
October 2012[c]	179.6 ± 5.9	5
May 2013	153.4 ± 3.6	5
October 2013	154.5 ± 2.9	5
July 2014	148.2 ± 4.1	4
June 2015	143.5 ± 4.8	4

[a] Oven-dry weight.
[b] Starting weight.
[c] Rainy day; likely that moisture content subsamples did not adequately account for surface moisture and properly adjust for dry weight; data point not used in model development.
SE = standard error.

Table 2—Actual changes in hand-pile weight over time at in New Mexico site

Date	Mean pile weight[a]	Sample size
	Kilograms ± SE	n
October 2011[b]	74.9 ± 5.3	5
April 2012	70.8 ± 4.3	5
November 2012	68.5 ± 4.1	5
March 2013	65.8 ± 4.6	5
October 2013	62.9 ± 4.8	5
February 2014	63.0 ± 4.0	5
June 2015	61.7 ± 4.4	5

[a] Oven-dry weight.
[b] Starting weight.
SE = standard error.

topic), the decay rate of hand-piled fuels at our study sites was well-represented with site-specific, single, negative exponential models (fig. 4). Site-specific models explained more than 80 percent of the variance in the data ($r^2 = 0.82$ for Washington and 0.83 for New Mexico), at least for the relatively early stages of decomposition (first 4 years) monitored in this study. The decay rate constant, k, was 0.027/year and 0.064/year for the Washington and New Mexico sites, respectively. The shape and slope of the curve, which is determined by the product of the exponents in equation 2, was significantly steeper for the New Mexico site than the Washington site (Mann-Whitney $U_{v(5, 5)} = 25$, $p = 0.01$), indicating a more rapid rate of mass loss over time in New Mexico.

Harmon et al. (1986) suggested that larger logs decay more slowly than smaller logs, branches, and twigs, but acknowledge that this size/decay rate relationship has not been found for all forested systems or studies. Piles at the Washington site were 43 ± 6 percent (mean $\pm$ standard deviation) bole wood >7.6 cm in diameter; none of the piled material in New Mexico was >7.6 cm in diameter. Based on our empirically derived values of the decay-rate constant, it appears that piles with a large woody material component (i.e., the Washington site) decay more slowly than piles with only small-diameter branchwood, tops, and needles (i.e., the New Mexico site).
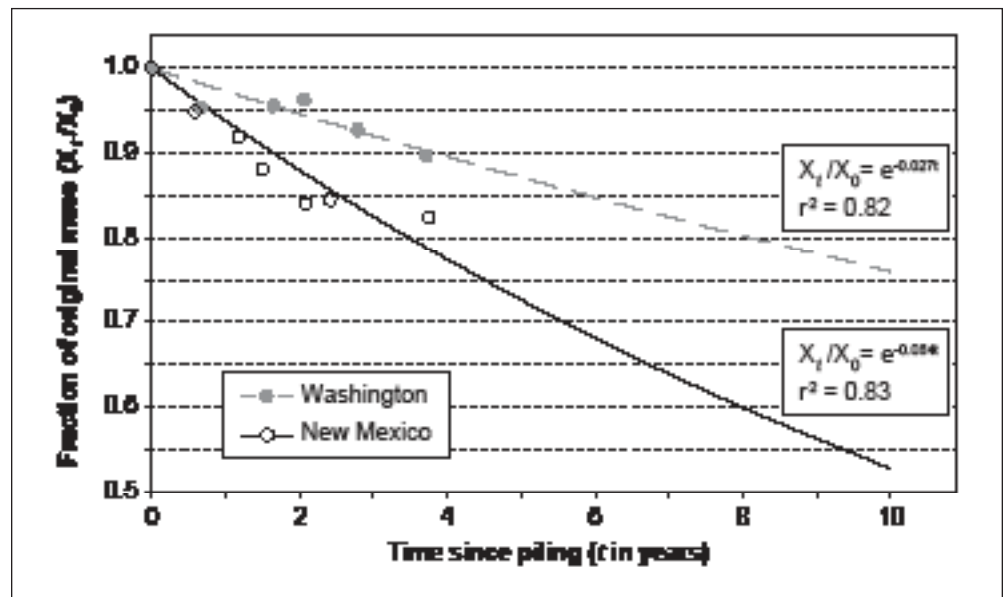

Figure 4—Mass loss of hand-piled biomass as a function of time, in years, for sites in Washington and New Mexico, with modeled mass loss projected for 10 years. The decay constant (k) and the coefficient of determination (r^2) are indicated for each site-specific negative exponential model.

Leaf litter and woody material decomposition have been widely studied in wet and moist conifer forests in the western United States, especially in the western Cascade Range (e.g., Edmonds 1987, Harmon et al. 1986, Spies et al. 1988). Information about litter and woody material decomposition is limited for dry conifer forests, however, which are widespread across the intermountain West where thinning, piling, and burning is a common forest and fuel management practice. Based on the limited information available in forest types comparable to our study sites, it appears that the decay-rate constants for whole hand piles observed in this study are intermediate between the faster rates observed for coniferous leaf litter (k = 0.08-0.20/year) (Hart et al. 1992, Stohlgren 1988) and the slower rates observed for solid wood in different size classes (k = 0.010/year) (Erickson et al. 1985), as we would expect of a pile that includes both types of material.

Litter and wood of different species have been shown to decay at different rates (Daubenmire and Prusso 1963, Edmonds 1987, Erickson et al. 1985). The piles in New Mexico were constructed entirely of ponderosa pine and it was a major component of the piles at the Washington site as well; however, the Washington site also included logs, branches, twigs, and needles of Douglas-fir, western larch, and grand fir. Species composition was not a factor in the design for this study, so we cannot say whether, or to what degree, it affected our observed differences in decay rate between sites.

In addition to material type (i.e., leaf litter vs. woody material, hardwood vs. conifer, etc.), moisture and temperature conditions influence how quickly vegetative matter decomposes (Erickson et al. 1985, Harmon et al. 1986, Hart et al. 1992, Jenny et al. 1949, Prescott et al. 2004, Zell et al. 2009). In general, warm, wet conditions favor and accelerate decomposition. While both study sites are in dry conifer forests dominated by ponderosa pine, they experience different climate regimes. The New Mexico site is characterized by a monsoonal climate pattern in which most of the precipitation falls as rain during the warm summer months, whereas the Washington site is characterized by a Mediterranean climate and receives most of its precipitation in the cold winter months in the form of snow. The coincidence of warm temperatures and summer monsoon moisture in New Mexico may provide for microclimates that are relatively more conducive to decomposition activity and a faster rate of decay than those found in Washington, where warm temperatures are temporally separated from moist conditions owing to the Mediterranean climate pattern (Hart et al. 1992).

It is a common practice in the Pacific Northwest to cover piles in an attempt to keep a portion of the pile dry and thereby facilitate ignition during wetter times

of the year when fuel managers prefer to conduct pile burning. Maintaining drier conditions within the pile by covering would theoretically slow decomposition. This supports the pattern we observed wherein the covered piles in Washington decomposed more slowly than the uncovered piles in New Mexico; however, our measurements of pile moisture content periodically throughout the study (table 3), show that fuels are not consistently significantly drier in the interior than on the surface of piles in Washington (paired two-sample t-test for difference between pile interior and pile surface) for large ($t_{v(7)} = 0.03$, $p = 0.97$) and small size classes ($t_{v(7)} = 0.96$, $p = 0.37$) of fuel particles. Thus, although the practice of covering piles may maintain a sufficient quantity of fuel in a dry, ignitable condition to justify the practice for operational purposes, based on our observations it appears as though the waxed craft paper used in this study did not maintain a consistently drier pile interior over the course of the study—a condition that would theoretically slow decomposition. Further work to document the fuel moisture dynamics of covered (and uncovered) piles is necessary to understand how within-pile moisture conditions affect decay rate.

Stand conditions (e.g., clearcut vs. mature forest, young forest vs. old growth, etc.) have also been shown to affect decomposition rate (Klemmedson et al. 1985, Prescott et al. 2004). Whether differences in decay rate are a function of the chemical qualities of the biomass inputs (e.g., from mature trees vs. young trees, from hardwoods vs. conifers, etc.) or the microclimate (e.g., with or without canopy coverage, northern vs. southern aspects, on or off the ground, etc.) is an open discussion in the literature worthy of additional study. As both of our sites were in established, forested stands, however, we were not able to assess the effects of

Table 3—Mean moisture content by size class for samples collected from the interior and the surface of piles in Washington

| | Percentage of moisture content | | | |
| | <7.6 cm diameter | | ≥7.6 cm diameter | |
Date	Interior	Surface	Interior	Surface
October 2011	21.6	31.0	59.3	70.0
June 2012	24.1	25.9	81.7	53.3
October 2012[a]	28.3	57.5	28.4	39.0
May 2013	31.2	37.8	40.3	42.0
October 2013	21.1	36.2	24.8	31.3
May 2014	36.0	22.7	36.0	36.3
July 2014	12.8	10.0	17.0	17.3
June 2015	24.3	15.4	34.7	32.0

[a] Rainy day; likely that moisture content subsamples included moisture from particle surfaces.

overstory structure on decomposition of hand-piled fuels. Given the widespread use of piling as a forest management practice throughout the Western United States, further research is warranted to better understand the manner in which stand- and species-level variables affect decay rates; for instance, whether piles in clearcuts decay at a different rate than piles in intact forest or in thinned stands.

Our results document a difference in the rate of decomposition for hand-piled fuels in Washington and New Mexico, although the nature of the experimental design does not allow us to definitively attribute a cause to the difference. Piles with a large woody material component in Washington decayed more slowly than those composed solely of small-diameter branchwood in New Mexico. This is to be expected given that the New Mexico piles were weighted more heavily, in a relative sense, to faster decomposing small woody material and needle litter. Similarly, assuming that the monsoonal weather pattern in New Mexico is relatively more conducive to decomposition than the Mediterranean climate of eastern Washington, the larger decay-rate constant we measured for the New Mexico site is to be expected. The observed differences in decay rate between sites may be related to differences in pile composition (both size class and species), differences in environmental conditions attributed to climate regimes, different within-pile microclimates related to covering or stand structure, or a combination of these and potentially other factors not measured in this study. Future research should be conducted to isolate and examine these and other factors.

Management Implications

It is quite common for piles to age on the landscape for a period of time before they can be burned. As piles age they both compress and gradually lose mass—changes that affect the quantity and quality of smoke emissions. The site-specific decay constants (k) reported in this study can be used to adjust pile weights as piles age so that fuel characteristics (i.e., loading and bulk density), fuel consumption, smoke emissions, and charcoal production can be estimated based on pile weights at the time of burning rather than the time at construction (box 1). It should be noted, however, that the decay constants reported herein are based on hand piles composed of variable-diameter, dry mixed-conifer species in Washington and of small-diameter ponderosa pine in New Mexico. Further study to clarify which factors are driving decomposition in piled fuels (i.e., climate regime, species composition, piece size distribution, overall pile size, covering, etc.) is necessary before these values can be generalized beyond the cases reported in this study.

The total amount of carbon emissions (i.e., carbon lost to the atmosphere through decomposition processes plus carbon emitted to the atmosphere during combustion)

Box 1: Steps to Estimate the Change in Pile Weight Over Time

Step 1—Determine the weight of your pile when built. The *Piled Biomass and Emissions Calculator* (http://depts.washington.edu/nwfire/piles/) will allow you to estimate the starting pile weight based on simple measurements of pile dimensions. See Wright et al. (2010) for additional details about estimating hand pile weight.

Step 2—Select the decay constant (k) that suits your situation. The decay constant for Washington (0.027/year) is probably most appropriate for piles with a large woody material component, and the decay constant for New Mexico (0.064/year) is probably most appropriate for piles comprised only of smaller branches.

Step 3—Determine the amount of time (t) that has passed (in years and fractions of a year) since the pile was created. This assumes that the pile was created from fresh logging or thinning slash (within approximately 3 months of harvesting).

Step 4—Calculate the fractional mass loss by using the k and t values from steps 2 and 3 (above) in equation 2. Below is the generic form of eq. 2 for use in a spreadsheet.

Fraction of pile remaining = EXP(-k * t)
Example—To calculate the dry weight of a 40-month-old, 2-m diameter, half-sphere-shaped, coniferous hand pile in Washington that includes large woody material:
Starting dry weight = 156.6 kg
k = 0.027/year
t = 40 months ÷ 12 months/year = 3.33 years
Fraction of pile remaining = EXP(-0.027 * 3.33) = 0.9125
Dry weight remaining = 0.9125 * 156.6 kg = 142.9 kg

will be comparable for new piles and old piles. The effects of pile burning on air quality in general and on downwind receptors in particular, however, could potentially be reduced to some degree by allowing biomass loss and reductions in fuel loading through decomposition to occur for a period of time before burning (box 2). Forest and fuel management decisions that undertake piled slash disposal through decomposition, however, must also consider the risk involved with delaying pile burning or not burning piles at all. While choosing not to burn will potentially eliminate a large, short-duration pulse of smoke and carbon emissions, this only occurs if the piled landscapes do not burn in wildland fires before the piles have fully decomposed. This kind of a strategy could be viable in mesic and wet forest types with very long fire-return intervals and low probability of wildfire occurrence. In dry forest types that are characterized by relatively high-frequency fire regimes, however, such as those documented in this study, wildfires are inevitable and piles create concentrations of fuel that burn with elevated intensity, which could limit suppression options, affect firefighting success (Evans and Wright, in press), injure residual trees (Safford et al. 2009), and remove the control over timing and dispersion of emissions from combustion that accompanies prescribed pile burning (Hardy et al. 2001).

Box 2—Potential Emissions From Burning Fresh and Aged Hand Piles

Piles lose mass over time, affecting the amount of fuel available for consumption and potential smoke emissions during burning.

Example—What is the potential difference in particulate matter (PM) and carbon dioxide (CO_2) emissions for fresh (aged 0 years) and 4-year-old piles for a 15-ha burn unit with 65 piles/ha in New Mexico, where piles are mostly branches and other small-diameter woody debris with a 100-kg starting dry weight, and where 90 percent of the piled biomass is consumed during burning?

The following calculations assume that the emissions produced per unit mass of fuel consumed for the various components of smoke (i.e., the emissions factors) are the same for fresh and aged piles, even though combustion efficiency, proportion of combustion by combustion phase (i.e., flaming and smoldering combustion), and the resulting emissions factors are likely affected by increases in pile bulk density and other physical and chemical changes that occur as piles age. To simplify this example the below-noted comparison only takes into account changes in pile weight over time.

This example also assumes that 70 percent of the fuel consumption occurs during the flaming phase of combustion and 30 percent during the smoldering phase of combustion. Fire-average PM and CO_2 emission factors are 1663.7 kg/Mg of fuel consumed and 10.95 kg/Mg of fuel consumed, respectively (based on the aforementioned combustion phase weighting and combustion phase-specific emissions factors in Wright et al. 2010). See Hardy (1996) and Hardy et al. (2001) for a more thorough discussion of combustion and emission factors.

Fresh piles—
Total unit biomass = 15 ha × 65 piles/ha × 100 kg/pile = 97.50 Mg
Consumed fuel = 97.50 Mg × 0.9 consumption rate = 87.75 Mg
PM emissions = 87.75 Mg × 10.95 kg/Mg = 961 kg
CO_2 emissions = 87.75 Mg × 1663.7 kg/Mg = 145 990 kg

Aged piles—
$k = 0.064$/yr; $t = 4$ years
Fraction of piles remaining = EXP(-0.064 * 4) = 0.7741
Dry weight remaining = 0.7741 * 97.50 Mg = 75.47 Mg
Consumed fuel = 75.47 Mg × 0.9 consumption rate = 67.92 Mg
PM emissions = 67.92 Mg × 10.95 kg/Mg = 744 kg
CO_2 emissions = 67.92 Mg × 1663.7 kg/Mg = 112 999 kg

Difference—
PM = 961 kg – 744 kg = 217 kg less PM for 4-year-old piles
CO_2 = 145 990 kg – 112 999 kg = 32 991 kg less CO_2 for 4-year-old piles
Approximately 23 percent lower emissions when burning 4-year-old piles

Acknowledgments

English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	.621	Miles
Hectares (ha)	2.47	Acres
Square meters per hectare (m^2/ha)	4.37	Square feet per acre
Kilograms (kg)	2.205	Pounds
Megagrams (Mg)	1.102	Tons
Degrees Celsius (°C)	1.8 °C + 32	Degrees Fahrenheit

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