

Burning Characteristics of Western Conifer Needles

Abstract

The needles from thirteen species of western conifers were burned to compare flammability of nonwoody fuels. The following burning characteristics were measured in a completely randomized design ANOVA: maximum flame height, flame time, ember time, burn time, percent combusted, and mean rate of weight loss. The burning characteristics tested in this study address important aspects of nonwoody fuel flammability in coniferous forests. Ponderosa pine, Jeffrey pine, Monterey pine, coast redwood, knobcone pine, giant sequoia, and sugar pine ranked in the upper half of most of the burn categories. These highly flammable species are prominent in communities for which fire return intervals are two to four decades. Lodgepole pine, western redcedar, Douglas-fir, Pacific silver fir, subalpine fir, and western hemlock seldom ranked in the upper half of any of the burn categories. The needles of these species are less flammable than the upper group of seven. The fire return intervals for the communities in which they grow are commonly two or more centuries.

Introduction

Most forest communities in Washington, Oregon, and California experience fire at some time in their developmental history. For some, the fire return interval (FRI) is about one to three decades, whereas for others the FRI is one to three or more centuries. Fire is a natural environmental factor affecting forest communities, but the effects of fire are determined by fuel loading, size class, arrangement, and chemical composition. These fuel characteristics are affected by other community characteristics.

When feedback from natural community characteristics limits the frequency, intensity, or severity of fire, the relationship may be considered homeostatic (*sensu* Odum 1969; e.g., fire-stable). Stability is a measure of homeostasis (Holling 1973), the ability of the component species to tolerate a disturbance and maintain the niche structure of the community. Forests that historically met the definition of fire-stable are characterized by: 1) short FRI (Agee 1993, Pyne et al. 1996); 2) species with highly flammable fuels because of fuel chemistry and low fuel moisture (Mutch 1970, Bond and Midgley 1995); 3) frequent ignition events from lightning (Komarek 1968, Keeley 1977, Agee 1994); 4) low intensity, low severity surface fires (Agee 1989); 5) species with fire-adaptive characteristics, allowing individual plants to survive the fire (Agee 1993, Pyne et al. 1996). Further reference to fire-stable forests in this paper are to historical fire regimes.

Ponderosa pine, Jeffrey pine, and giant sequoia dominate forests with fire-stable characteristics (Sweeney 1967, Vogl 1967, Weaver 1967, Kilgore 1972, Habeck and Mutch 1973, Kilgore and Taylor 1979, Arno 1980, Madany and West 1980, Bonnicksen and Stone 1982, Arno and Peterson 1983, Swetnam and Dieterich 1983, van Wagtenonk 1983, Agee et al. 1990, Swetnam 1993, Agee 1994). Sugar pine often exists as a subordinate member of fire-stable communities (Kilgore 1972; van Wagtenonk 1983; Thomas and Agee 1986).

Communities controlled by fire are not homeostatic with fire, but the individual species in the community still must respond to the disturbance. Resilience is a measure of persistence (Holling 1973, Fonda 1976, Westman and O'Leary 1986), the ability of the component species to persist on the site. Many species exist in forest communities that are involved with fire on a stand-replacing scale. Such fires often burn with high intensity and high severity (Agee 1993). Individual trees are killed by stand-replacing fires, yet the species persist on the site. Such forests, for which the prefire species return to the postfire site, are termed fire-resilient. Forests that historically met the definition of fire-resilient are characterized by: 1) long FRI (Agee 1993, Pyne et al. 1996); 2) species with less flammable fuels (Mutch 1970, Bond and Midgley 1995); 3) infrequent ignition events; 4) high intensity, moderate to high severity, stand-replacing fires (Agee 1989); 5) species that lack fire-adaptive characteristics and generally survive on the postfire site

by seed germination (Agee 1993; Pyne et al. 1996). Further reference to fire-resilient forests in this paper are to historical fire regimes.

Monterey pine, coast redwood, knobcone pine, lodgepole pine, Douglas-fir, and subalpine fir dominate forests with predominantly fire-resilient characteristics, although each forest type also has been known to support low intensity, low severity surface burns (Vogl 1967, 1973; Fonda and Bliss 1969; Vogl et al. 1977; Fonda 1976; Arno 1980; Romme and Knight 1981; Agee and Smith 1984; Stuart 1987; Finney and Martin 1989; Romme and Despain 1989; Agee et al. 1990; Greenlee and Langenheim 1990; Morrison and Swanson 1990; Taylor and Fonda 1990; Agee 1991, 1994; Brown and Swetnam 1994; Wetzal 1995).

Western redcedar, Pacific silver fir, and western hemlock are associated with forest types that burn infrequently, usually with high severity, stand-replacing fires (Fonda and Bliss 1969; Arno 1980; Hemstrom and Franklin 1982; Agee et al. 1990; Agee 1993, 1994).

Agee (1993) classified Pacific Northwest conifers according to the strategies by which they adapt to low severity fires (Table 1). Resisters generally dominate fire-stable communities, whereas the other strategies listed in Table 1 are adaptations for species that dominate fire-resilient communities, or are sensitive to fire at any age. Agee (1993) cautioned that researchers should be aware that most species cannot be classified according to merely one of these strategies. Tree species respond differently to fire, depending on tree age and fire severity. For instance, older trees

of coast redwood, Douglas-fir, Monterey pine, and western redcedar can resist low severity fires (i.e., a fire-stable strategy), but perish as young trees or in high severity fires (i.e., a fire-resilient strategy).

In any community in which fire is an ecological factor, the fire must start and continue to burn. Four requirements must be met at the time of the fire: 1) flammable fuels; 2) sufficient fuel loads to carry the fire through the community; 3) low environmental moisture; 4) ignition sources.

In this work we focus on measures of flammable fuels, specifically nonwoody fuels from species associated with fire-stable and fire-resilient conifer forests (Table 1). Mutch (1970) burned nonwoody fuels to formulate a hypothesis that natural selection favored the development of highly flammable species that perpetuate the fire environment. Taylor and Fonda (1990) employed the methods used by Mutch (1970) to assess burning characteristics of fuels in subalpine fir forests on Hurricane Ridge in Olympic National Park. Because they burned reasonably intact samples of the litter layer that had accumulated on the forest floor, their litter layers mixed some woody fuels with the largely nonwoody fuels. To our knowledge, no other studies exist that tested burning characteristics of nonwoody fuels to describe their contribution to the fire status of forests.

We studied in a fire chamber burning characteristics of the needles from 13 conifer species from forests in Washington, Oregon, California, and Nevada as indicators of flammability. Flammability has four components: ignitability,

TABLE 1. Species sampled and collection sites. Botanical nomenclature follows Hickman (1993). The strategy used by mature trees to resist low severity fire is based on information provided in Agee (1993).

Common name	Latin name	Strategy	Collection site
Coast redwood	<i>Sequoia sempervirens</i>	Resister	J. P. Burns Park (Big Sur), CA
Douglas-fir	<i>Pseudotsuga menziesii</i>	Resister	Cascade Mountains (Wenatchee), WA
Giant sequoia	<i>Sequoiadendron gigantea</i>	Resister	Sequoia National Park (Giant Forest), CA
Jeffrey pine	<i>Pinus jeffreyi</i>	Resister	Carson Range (Lake Tahoe), NV
Knobcone pine	<i>Pinus attenuata</i>	Evader	Siskiyou Mountains (Cave Junction), OR
Lodgepole pine	<i>Pinus contorta</i>	Evader	Olympic National Park (Deer Park), WA
Monterey pine	<i>Pinus radiata</i>	Evader	Monterey Peninsula, CA
Pacific silver fir	<i>Abies amabilis</i>	Avoider	Cascade Mountains (Stevens Pass), WA
Ponderosa pine	<i>Pinus ponderosa</i>	Resister	Cascade Mountains (Roslyn), WA
Subalpine fir	<i>Abies lasiocarpa</i>	Avoider	Olympic National Park (Deer Park), WA
Sugar pine	<i>Pinus lambertiana</i>	Resister	Siskiyou Mountains (Cave Junction), OR
Western hemlock	<i>Tsuga heterophylla</i>	Avoider	Olympic Peninsula (Sappho), WA
Western redcedar	<i>Thuja plicata</i>	Avoider	Lake Padden Park (Bellingham), WA

combustibility (intensity), sustainability, and consumability (Martin et al. 1994). Our work relates to intensity (flame height), sustainability of the fire (flame time, ember time, and burn time), and consumability of the fuel (percent consumption and mean rate of weight loss). We sought answers to two research questions: 1) are differences in burning characteristics among the species significant? 2) how do these 13 species contribute to the fire environment of the communities in which they grow?

Methods

We followed the methods in Mutch (1970) and Taylor and Fonda (1990). The experiment was designed as a completely randomized design ANOVA, with the species constituting the 13 treatments. Significant differences among the species for each burning characteristic were determined by a Newman-Keuls multiple range test (Zar 1996). The significance level was set at 5% before testing began. The data for percent combusted were transformed by arcsin before analysis. We burned 10 samples of each species, for a total of 130 burns.

Species and collection sites are listed in Table 1. Needles from all species were gathered from nearly pure batches from several different locations at each site, then allowed to dry in the lab. Needles for the burn tests were separated from the forest debris and stray needles of other species mixed in the sample.

We used ~15-g samples of conifer needles in the test burns. Samples were placed in aluminum trays and dried at 103°C for 72 hr. Samples were removed from the ovens and allowed to equilibrate for 2-3 min, then weights were adjusted by removing needles until the sample to be burned weighed 15.0 to 15.3 g. Moisture content at time of burning was 1.5-2.7%.

The fire chamber was 1 m² by 3 m tall, with a four-story exhaust chimney. Excessive draw from the chimney over the fire bed was prevented by a series of baffles in the chimney, and air movement was controlled by a fan in the chimney. Mean air velocity equaled 9.96±0.9 cm sec⁻¹, based on 25 measurements using a Barnant Company Tri-Sense meter (Model 637-0000).

The fuel bed was arranged on the floor of the chamber in a 35 x 35 cm grid formed by eight

strings dipped in xylene. All fuel beds were < 5 cm high. Strings were ignited, and two timers were started when fuels first ignited. Maximum flame height was judged by comparing the highest point reached by flames against a meter stick at the rear of the fire chamber. At this point, the room lights were extinguished so that we could judge flame and burn times.

The first timer was stopped when all flames were extinguished (= flame time). The second timer was stopped when the last ember was extinguished (= burn time). The difference between these two is ember time.

Percent fuel combusted was determined by weighing the ashes, after removing the unburned bits of string, then dividing consumed weight by initial weight. Mean rate of weight loss was calculated as mg lost over burn time.

The six categories shown in Table 2 were calculated from the burn data. Regardless of the results of the multiple range test (MRT), species were ranked in order from the top species (#1) to the bottom species (#13) for each category. For each species, we added the ranked values for each burning characteristic to create a single list of combined flammability ranks, as shown in Table 3. In our judgment, each characteristic contributes to the interpretation of fire effects in a forest, so that they have equal weights. The means of all treatments are provided in Table 2 for readers who wish to create their own ranking.

Results

Jeffrey pine had significantly higher flames than any other species, followed by ponderosa pine (Table 2). Means for both species exceeded 60 cm. Jeffrey pine had the four highest flames (87 cm max) of the 130 individual burns in this study. Maximum height for an individual ponderosa pine burn was 75 cm. The differences among coast redwood, Monterey pine, sugar pine, and knobcone pine were not significant, nor were the differences among lodgepole pine, giant sequoia, western redcedar, and Pacific silver fir. The flames for Douglas-fir and western hemlock (no significant difference) and subalpine fir were the shortest of the species tested. Subalpine fir had significantly shorter mean flame height than any other species. Maximum flame height for subalpine fir was 22 cm.

TABLE 2. Means of burning characteristics resulting from ten test burns for each species.

MAXIMUM FLAME HEIGHT (cm)												
JP	PP	RW	MP	SP	KP	LP	GS	WRC	PSF	DF	WH	SAF
76.7	69.3	59.4	58.3	55.6	55.6	43.2	42.6	42.4	38.4	26.2	24.6	16.7
FLAME TIME (sec)												
GS	SP	LP	WRC	DF	KP	PP	MP	SAF	PSF	RW	WH	JP
148.5	128.5	121.8	113.2	105.8	99.2	92.4	82.6	79.8	79.8	73.4	68.4	64.7
EMBER TIME (sec)												
MP	JP	RW	GS	KP	PP	WRC	LP	SP	SAF	PSF	WH	DF
328.3	326.7	317.3	242.6	206.3	149.7	130.7	118.7	103.2	91.8	84.8	43.6	21.8
BURN TIME (sec)												
MP	JP	RW	GS	KP	WRC	PP	LP	SP	SAF	PSF	DF	WH
410.9	391.4	390.8	386.1	305.6	243.9	242.1	240.5	231.8	171.6	164.6	127.6	112.1
% COMBUSTED												
PP	JP	RW	MP	KP	SP	GS	LP	WRC	PSF	DF	SAF	WH
91.1	90.1	86.1	85.1	84.7	77.1	75.8	73.0	45.7	32.0	26.6	25.6	18.8
MEAN RATE OF WEIGHT LOSS ($\mu\text{g}/\text{sec}$)												
PP	SP	LP	KP	JP	RW	DF	GS	MP	WRC	PSF	WH	SAF
58.2	50.9	49.3	42.0	35.3	33.5	31.6	30.4	30.3	29.9	29.4	26.8	23.4

Means connected by underline are not significantly different. Species abbreviations: DF = Douglas-fir; GS = giant sequoia; JP = Jeffrey pine; KP = knobcone pine; LP = lodgepole pine; MP = Monterey pine; PP = ponderosa pine; PSF = Pacific silver fir; RW = coast redwood; SAF = subalpine fir; SP = sugar pine; WH = western hemlock; WRC = western redcedar.

The flames for giant sequoia lasted significantly longer than any other species tested (Table 2). Four of the ten trials exceeded 160 sec, with a maximum of 187 sec. Otherwise, there was much overlap in the MRT for mean flame times, and the remaining species exhibited a continuum of times. There were no significant differences among the seven species with less than 95 sec mean flame time (ponderosa pine, Monterey pine, subalpine fir, Pacific silver fir, coast redwood, western hemlock, and Jeffrey pine).

Ember times for Monterey pine, Jeffrey pine, and coast redwood were not significantly different. Mean ember times for these species exceeded 300 sec (Table 2). Maximum ember times for individual burns for Jeffrey pine and coast redwood were 454 sec; for Monterey pine, 418 sec. This upper group was followed by giant sequoia and knobcone pine (not significantly different), for which mean ember times were in the 200 sec range. A large group, ranging from 84-150 sec includes ponderosa pine, western redcedar, lodgepole pine, sugar pine, subalpine fir, and Pacific silver fir. The maximum ember time for an individual burn for the species in this group was 242 sec (ponderosa pine). There were no significant differences between western hemlock and Douglas-fir, for which mean ember times were significantly shorter (< 50 sec) than any other species.

There were no significant differences in mean burn time among Monterey pine, Jeffrey pine, coast redwood, and giant sequoia, all of which had significantly longer mean burn times than the other nine species (Table 2). Each of the top species had at least three individual burns that exceeded 400 sec. Knobcone pine was significantly different from all other species, but shorter than the upper group. No knobcone pine burn exceeded 355 sec. Western redcedar, ponderosa pine, lodgepole pine, and subalpine fir composed the middle group, the means of which were in the mid-200 sec range. The group with the shortest burn times comprised subalpine fir, Pacific silver fir, Douglas-fir, and western hemlock. Mean burn times in this group were < 200 sec, significantly shorter than the other species. Maximum burn time among these four species was 203 sec (subalpine fir).

Mean percent fuel combusted was not significantly different between ponderosa pine and Jeffrey

pine, both of which had greater values than any of the other species (Table 2). The minimum percent consumed for any individual burn for these two species was 87% (ponderosa pine). There were no significant differences among coast redwood, Monterey pine, and knobcone pine. Sugar pine and giant sequoia were not significantly different. The minimum single burn value among these five species was 65% (giant sequoia). Lodgepole pine lost >70% fuel, but ranked significantly below sugar pine and giant sequoia. Western hemlock had significantly less mean fuel combusted than any other species, and maximum fuel combusted for an individual western hemlock burn was 22%. Douglas-fir and subalpine fir (not significantly different) ranked just above western hemlock. Western redcedar and Pacific silver fir, both significantly different from other species, averaged less than 50% fuel combusted.

Ponderosa pine fuel was consumed at a significantly higher mean rate than any other species (Table 2). Ponderosa pine also produced the two highest individual rates (80 and 73 $\mu\text{g}/\text{sec}$). There were no significant differences among sugar pine and lodgepole pine, for which maximum individual rates were 62-63 $\mu\text{g}/\text{sec}$. Knobcone pine was the fifth species to lose more than a mean of 40 $\mu\text{g}/\text{sec}$, with a maximum value of 46 $\mu\text{g}/\text{sec}$. The remaining species constitute a large group among which there was much overlap in the MRT and largely no significant differences. They lost weight at a mean rate of < 40 $\mu\text{g}/\text{sec}$.

The combined ranking based on burning characteristics (Table 3) indicates how well the needles of these 13 species will contribute to fire. The top seven species are separated by only 9 points, whereas the bottom six species are separated by 37 points. Ponderosa pine and Jeffrey pine are separated by one point. These two species ranked in the upper half of every burning characteristic except flame time. Monterey pine, coast redwood, and knobcone pine are separated by merely four points. Giant sequoia and sugar pine are separated by two points. All of these species contribute well to fire. With a few exceptions, they were in the upper half of the burning characteristics (Table 2). The species at the bottom of Table 3 (Douglas-fir, Pacific silver fir, subalpine fir, and western hemlock) were the bottom four species in every category except flame time. These four species contribute poorly to fire.

TABLE 3. Combined ranking of species based on six burning characteristics.

RANK	SPECIES	POINTS
1	Ponderosa pine	24
2	Jeffrey pine	25
3	Monterey pine	27
4	Coast redwood	29
5	Knobcone pine	31
6	Giant sequoia	32
7	Sugar pine	33
8	Lodgepole pine	37
9	Western redcedar	45
10	Douglas-fir	59
11	Pacific silver fir	63
12	Subalpine fir	67
13	Western hemlock	74

Discussion

The burning characteristics tested in this study address important aspects of nonwoody fuel flammability in coniferous forests. Flame height, flame time, ember time, and burn time measure the intensity and duration of a burnable condition in the needles, so that a spreading fire can be supported. Percent combusted and mean weight loss rate indicate how much of the fuel bed will be involved with fire and how quickly the fuel will be consumed. No single characteristic defines flammability, especially on the community level, when only nonwoody fuels are considered. Taken together, however, the characteristics in Table 2 speak to the role of fire in the forests in which these 13 species are dominant. The top ranked species in these categories are prominent in forests in which fire is common. Some of these forests are fire-stable, others are fire-resilient with FRI on the order of a few decades.

Ponderosa pine and Jeffrey pine, the top two ranked species (Table 3) grow in forests with short FRI. Studies of fire history in ponderosa pine at various locations in the Rocky Mountains and the Sierra Nevada and Cascade Ranges put the FRI at less than 15 yr (Arno 1980; Madany and West 1980; Arno and Peterson 1983; Swetnam and Dieterich 1983; van Wagendonk 1983; Agee 1994). Fires may be even more frequent in Jeffrey pine forests (Vogl 1967), and they clearly favor Jeffrey pine (Sweeney 1967; Vogl 1967). Both species are resisters (Table 1). They exist in fire-stable forests, where frequent underburns are sup-

ported largely by nonwoody fuels. The burning characteristics indicate that surface fires would be well-supported, and the fuels would be consumed rapidly and almost completely (Table 2).

Monterey pine, coast redwood, and knobcone pine are prominent members of forest stands along the northern California coast into southern Oregon. Fire is a common environmental factor in this region (Vogl et al. 1977; Stuart 1987; Greenlee and Langenheim 1990; Brown and Swetnam 1994), and the forests generally are fire-resilient. Because of serotinous cones and voluminous seed crops released by fire, Monterey pine is adapted to stand-replacing fires, although surface fires also burn in these forests (Vogl et al. 1977). Knobcone pine, with 33-50 yr FRI (Vogl et al. 1977), depends on stand-replacing fires to open serotinous cones to repopulate the postfire site (Vogl 1973). Both pines are evaders (Table 1). The FRI for coast redwood is on the order of 6-8 yr (Brown and Swetnam 1994) to 135 yr (Greenlee and Langenheim 1990), and at least in the Santa Cruz Mountains some of these fires can be extensive. Fires in forests dominated by Monterey pine and knobcone pine are much more intense and more severe than fires in ponderosa pine forests, largely because of the greater woody fuel component. Fires in coast redwood forests vary from low to high severity (Greenlee and Langenheim 1990; Brown and Swetnam 1994). Fires in all three forest types are sustained because the highly flammable nonwoody fuels ignite longer time-lag woody fuels. These three species had no significant differences among them for flame height, ranking just behind ponderosa pine and Jeffrey pine (Table 2). Furthermore, they ranked in the top five for burn time.

Giant sequoia, the number six species, grows in a series of isolated groves in the Sierra Nevada Range, for which historic FRI ranged from 5-8 yr from 500 to 800 AD and from 2-4 yr from 1000 to 1300 AD (Swetnam 1993). Similar to ponderosa pine and Jeffrey pine, the forests were fire-stable and the fires were low intensity, low severity surface burns (Kilgore 1972; Bonnicksen and Stone 1982). Giant sequoia is a resister (Table 1). Giant sequoia had a long burn time and ~76% fuel consumed (Table 2), which, coupled with the short FRI, indicates that most of the fuel consumed by natural fires was nonwoody.

The relationship between sugar pine and fire is known from studies of mixed conifer forests in the Sierra Nevada and Cascades (Kilgore 1972; van Wagtenonk 1983; Thomas and Agee 1986). Sugar pine is a prominent subordinate species in giant sequoia and ponderosa pine forests. Mature sugar pines resist fire (Table 1). Sugar pine's presence in the community depends on frequent fires removing its main competitor, white fir. The model created by van Wagtenonk (1983) showed that sugar pine seedlings were favored by an open landscape, presumably created by fire. Sugar pine density remained above 600 trees/ha through 80 yr of lightning fires at mean intervals of 8.9 yr. Sugar pine may be more susceptible to postfire insect attack than to the fire itself (Thomas and Agee 1986). Although sugar pine ranks just below giant sequoia, and considerably below ponderosa pine (Table 3), the contribution of sugar pine needles to regular fires in these forests is important. It is noteworthy that 77% of sugar pine fuel was consumed at a rate of 50.9 $\mu\text{g}/\text{sec}$, and that it had a long flame time (Table 2). Mixed with either giant sequoia or ponderosa pine needles, sugar pine enhances the flammability of the fuel load.

The bottom six species in Table 3 exist in dramatically different fire regimes from the top seven species. Fires in communities dominated by these species usually are high intensity, high severity, and stand-replacing. Lodgepole pine, Douglas-fir, and subalpine fir are associated with fire-resistant forests in the Pacific Northwest, and owe their continued dominance on the landscape to stand-replacing fires at FRI on the order of 150-200 yr or more (Fonda and Bliss 1969; Fonda 1976; Arno 1980; Agee and Smith 1984; Romme

and Knight 1981; Romme and Despain 1989; Taylor and Fonda 1990; Agee 1993). All three species are postfire invaders (Agee 1993), and depend on abundant seed crops to restore the forest community. Some lodgepole pine and Douglas-fir forests, however, are known to support surface burns on shorter intervals (Morrison and Swanson 1990; Agee 1991, 1994; Wetzel 1995). Lodgepole pine had the highest rank among these six species (Table 3), four points lower than sugar pine. Lodgepole pine needles, however, will not sustain fire in young forests for which there is little woody fuel (Romme and Despain 1989). Forests dominated by lodgepole pine, Douglas-fir, and subalpine fir rely on decades of accumulated woody fuels to support fires, rather than the less flammable needles investigated in this study.

Western redcedar, Pacific silver fir, and western hemlock are avoiders (Table 1), favored by the absence of fire (Fonda and Bliss 1969; Hemstrom and Franklin 1982; Agee et al. 1990; Agee 1993, 1994). These species are common in Pacific Northwest forests. The data in Table 2 confirm that the nonwoody fuels of these three species contribute little to the fire environment of their communities. Of the three, western redcedar contributed best to sustainability, however, they all ranked near the bottom on measures of intensity and consumability.

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