NOTE / NOTE

Dwarf mistletoe effects on fuel loadings in ponderosa pine forests in northern Arizona

Chad Hoffman, Robert Mathiasen, and Carolyn Hull Sieg

Abstract: Southwestern dwarf mistletoe (*Arceuthobium vaginatum* (Willd.) J. Presl ssp. *cryptopodum*) infests about 0.9 million ha in the southwestern United States. Several studies suggest that dwarf mistletoes affect forest fuels and fire behavior; however, few studies have quantified these effects. We compared surface fuel loadings and predicted fire behavior among four levels of dwarf mistletoe infestation (none, light, moderate, and severe) in a total of 239 plots on 11 sites on basaltic soils in northern Arizona. In each plot we measured tree attributes, dwarf mistletoe rating and surface fuel loading. Stands severely infested by dwarf mistletoe had lower ($P < 0.05$) tree density and higher snag density, but higher ($P < 0.05$) total surface fuel loadings and total fuel loadings >7.62 cm and <7.62 cm, than non-infested stands. However, there were no statistical differences in any canopy fuel variables among infestation classes. Predicted fire behavior indicated that the wind speed required to promote the spread of a surface fire into the canopy was lower in severely infested stands than in non-infested stands. These results suggest that stands in northern Arizona that are severely infested with dwarf mistletoe should be priority areas for fuels treatments.

Résumé : Le faux-gui du sud-ouest (*Arceuthobium vaginatum* (Willd.) J. Presl ssp. *cryptopodum*) affecte environ 0,9 million ha dans le sud-ouest des États-Unis. Plusieurs études portent à croire que le faux-gui affecte les combustibles forestiers et le comportement du feu; peu d'études ont cependant quantifié ces effets. Nous avons comparé la quantité de combustibles de surface et le comportement simulé du feu pour quatre degrés d'infestation du faux-gui (aucune infestation et infestations faible, modérée ou forte) sur un total de 239 parcelles dans 11 stations sur un sol basaltique dans le nord de l'Arizona. Dans chaque parcelle, nous avons mesuré les attributs des arbres, le degré d'infestation par le faux-gui et la quantité de combustibles de surface. Les peuplements fortement infestés par le faux-gui avaient une plus faible densité ($P < 0,05$) avec plus de chicots, mais une quantité totale de combustibles de surface plus élevée ($P < 0,05$) et une quantité totale de combustibles >7,62 cm et <7,62 cm, que dans les peuplements sains. Cependant, il n'y avait pas de différences statistiques entre les classes d'infestation pour aucune des variables des combustibles de la canopée. Le comportement simulé du feu a indiqué que la vitesse du vent requise pour qu'un feu de surface s'étende à la cime était plus faible dans les peuplements fortement infestés que dans les peuplements sains. Ces résultats indiquent que les peuplements fortement infestés par le faux-gui devraient être des zones prioritaires pour le traitement des combustibles dans le nord de l'Arizona.

[Traduit par la Rédaction]

Introduction

Increased wildfire activity over the past 60 years has led to concerns about the effectiveness of current management practices, including fire suppression. Nowhere is this more so than in the western United States, which have experienced an increase in the relative area burned over the last 60 years (Stephens 2005). It has been suggested that stands with past insect and disease outbreaks, as well as extremely dense stands with small-diameter trees, are priority areas for fuel treatments because it is thought these areas are more likely to experience extreme fire behavior (Fulé et al. 2001, 2002). Although fire-modeling studies across the western United States have indicated that dense stands composed of small-diameter trees increase the likelihood of adverse fire behavior, the effects of insect infestations and disease on fire behavior, especially in areas infested with dwarf mistletoes (*Arceuthobium* spp.), have not been investigated (Hawksworth and Wiens 1996; Fulé et al. 2001, 2002).

Several studies have suggested that dwarf mistletoe infestations affect forest fuels and fire behavior (Koonce and Roth 1985; Godfree 2000; Conklin and Armstrong 2001; Roth 2001; Geils et al. 2002; Godfree et al. 2002). Dwarf mistletoes are thought to influence fire spread characteristics and potential fire propagation because of their effect on stand structure and forest fuel loadings (Alexander and Hawksworth 1975; Harrington and Hawksworth 1990; Conklin and Armstrong 2001). Forest fuel loadings and for-

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est structure are thought to be affected by dwarf mistletoes through two different means. First, it is assumed that dwarf mistletoes cause an increase in tree mortality relative to uninfested stands, thereby affecting stand structure by creating openings in the stand and enhancing snag density. Snags resulting from tree mortality can increase surface fuel loadings as dead trees fall to the forest floor. The increase in tree mortality may also influence in-stand fire weather variables, causing, for example, an increase in wind speed and lowering fuel moisture levels. Second, it is assumed that the witches' brooms formed in trees infected with dwarf mistletoes affect stand structure and tree flammability by lowering crown base heights and increasing the amount of flammable resin. However, few studies have attempted to experimentally quantify how varying levels of dwarf mistletoe infestation influence fuels and fire behavior (Koonce and Roth 1980, 1985; Harrington and Hawksworth 1990; Conklin and Armstrong 2001).

This study was conducted near Flagstaff, Arizona, to investigate the effects of southwestern dwarf mistletoe (*Arceuthobium vaginatum* (Willd.) J. Presl subsp. *cryptopodum* (Engelm.) Hawksworth & Wiens) on fuel loadings and potential fire behavior. Southwestern dwarf mistletoe is a common parasite of ponderosa pine (*Pinus ponderosa* Dougl. ex P. Laws. & C. Laws.) in Arizona, New Mexico, Colorado, Utah, Texas, and northern Mexico, and is considered the most widespread pathogen in the southwestern United States (Hawksworth et al. 1989; Hawksworth and Wiens 1996; Conklin 2000; USDA Forest Service 2004). The USDA Forest Service (2004) estimated that approximately 0.9 million ha of commercial ponderosa pine forest has some level of infection.

The objectives of this study were to (*i*) quantify fuel loadings and stand structure among stands varying in degree of dwarf mistletoe infestation (none, light, moderate, or severe) and (*ii*) estimate the effects of the various infestation levels on predicted fire behavior attributes using fire-behavior models. We hypothesized that severely infested stands have greater surface and crown fuel loadings and lower crown base heights than non-infested stands. We also hypothesized that increased fuel loadings in severely infested stands lead to more extreme predicted fire behavior, using NEXUS® Fire Behavior and Hazard Assessment System (Scott and Reinhardt 1999) and Fuels Management Analyst Plus® (FMAP) fire models (Carlton 2001).

Study area

The study area was in Coconino County in northern Arizona. Annual precipitation averages 54.6 cm (Western Regional Climate Center 2005), of which half is received in late-summer rains and half as winter snow (Sheppard et al. 2002). We selected 11 study sites with stands that encompassed a range of no to severe infestation by southwestern dwarf mistletoe. We selected stands that were similar in tree size, density, and basal area, slope, aspect, parent soil material, and past management history in an effort to control as many extraneous factors as possible. The 11 sites were all within 20 km of Flagstaff at elevations ranging from 2218 to 2545 m a.s.l. This elevational range captures the zone in this region that is strongly dominated by ponderosa pine. Sites had basaltic soils, slopes <10%, and dense, even-aged stands composed of >95% ponderosa pine. All sampled stands were in active cattle allotments but had not been harvested or otherwise actively managed within the last 15 years. None of the stands showed evidence of previous fuel treatments, such as scattered thinning slash or slash piles. Understory vegetation included Arizona fescue (*Festuca arizonica* Vasey), mountain muhly (*Muhlenbergia montana* (Nutt.) A. S. Hitchc.), Fendler's ceanothus (*Ceanothus fendleri* Gray), creeping barberry (*Mahonia repens* (Lindl.) G. Don), pine dropseed (*Blepharoneuron tricholepis* (Torr.) Nash), and blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffithsl). Plant habitat types were either ponderosa pine / Arizona fescue or ponderosa pine / mountain muhly (USDA Forest Service 1997).

Methods

We sampled a total of 239 plots on 11 study sites during 2004 and 2005. On each of the 11 study sites a minimum of five 20 m by 20 m plots were selected at each of four levels of dwarf mistletoe infestation (none, light, moderate, and severe). We estimated the severity of dwarf mistletoe infestation using the six-class dwarf mistletoe rating (DMR) system (Hawksworth 1977). Classes were assigned as follows: non-infested (stand DMR = 0), lightly infested (stand DMR = 0.1–2.0), moderately infested (stand DMR = 2.1–4.0), and severely infested (stand DMR = 4.1–6.0).

On each study site, an initial starting point was arbitrarily selected along a road. Then two randomly generated numbers, for an azimuth and a distance, were used to locate the first plot from the starting point. After data were collected on the first plot another random azimuth and distance were used to locate the next plot and so on until at least five plots were established in each of the four infestation classes. An even distribution of infestation classes was achieved by visually estimating the stand DMR in each plot before data collection. If a plot was estimated to be in an infestation class for which five plots had already been completed, it was not sampled, and another random distance and azimuth were generated for establishing the next plot corner. Plots were at least 30.5 m apart.

For all trees in a plot with a diameter at breast height (DBH, i.e., diameter outside bark 1.4 m above the ground on the uphill side of the tree) ≥10 cm, we recorded tree diameter (to the nearest 0.25 cm), tree height (to the nearest 0.3 m), DMR, and height to the lowest live branch (to the nearest 0.3 m). The lowest quintile canopy base height was calculated for each plot and averaged by infestation class and is defined as the lowest 20% of the range of crown base heights (Fulé et al. 2001, 2002). We calculated average tree diameter, DMR, height, crown ratio, basal area per hectare, stems per hectare, and snags per hectare for each plot and then averaged plot data by dwarf mistletoe infestation class for each site.

Downed and dead woody debris and litter and duff depths were measured along four 15.2 m planar transects in each plot (Brown 1974). A random number between 0.3 and 3.9 was generated for the distance (m) from the initial plot corner to the start of the first transect. The next three planar transects were systematically placed at 3.9 m intervals from the original transect alternating to opposite sides of the plot.

We inventoried fine woody debris for three size classes (0–0.64, 0.65–2.54, and 2.55–7.62 cm diameter) (Brown 1974). These size classes correspond to 1, 10, and 100 h fuel-moisture time lag classes, while course woody debris (>7.62 cm diameter) corresponds to the 1000 h time lag class (Fosberg 1970). We tallied 1 and 10 h fuels in the first 1.8 m of each fuel transect, 100 h fuels in the first 3.1 m, and 1000 h fuels along the entire 15.2 m length. We measured duff and litter depth at the 0.3, 1.8, and 3.1 m marks along each transect.

Fuel loadings were calculated using FMAP software (Carlton 2001). Planar intercept data were directly input into the down woody debris program in FMAP and fuel loadings were calculated using the methods outlined in Brown (1974). Fuel loadings (Mg·ha^{-1}) were calculated according to fuel size classes <7.62 cm diameter (1, 10, and 100 h fuels) and >7.62 cm diameter (1000 h fuels) for each plot and then averaged by dwarf mistletoe infestation class on each of the 11 sites.

Fire-modeling and fire-transition analysis

Fire behavior was modeled with NEXUS, which links separate models of surface and crown fire behavior to assess crown fire potential for a given stand (Scott and Reinhardt 1999). The NEXUS system relies on Rothermel's (1972, 1991) equations to predict fire rate of spread and Byram's (1959) equation to predict fireline intensity. These are the equations most commonly used in the United States for estimating fire behavior attributes (Pastor et al. 2003).

NEXUS uses canopy fuel loadings, crown base height, weather conditions, and a fuel model to predict fire behavior. We used the lowest quintile (20%) of the range of measured low live branches on a given plot as an estimate of canopy base height (Fulé et al. 2002). Canopy fuel loadings were calculated using allometric equations in FMAP (Carlton 2001). These equations estimate total canopy mass, 1, 10, 100, and 1000 h canopy fuel loadings, total canopy fuel, canopy fuel for crown fire, and crown bulk density for each tree, based on DBH, total tree height, crown ratio, and species (Stephens and Moghaddas 2005). Fuel models were designated as either 9, if total fuel loadings were <22.4 Mg·ha^{-1} or 10 if fuel loading was >22.4 Mg·ha^{-1} (Anderson 1982). Table 1 lists the fire-model variables and their definitions and units, and references used in fire-behavior predictions and crown fuel loading calculations in FMAP and NEXUS.

Fire behavior was predicted for the upper 80th and 97.5th percentile weather conditions. Weather conditions were obtained using the Fire Family Plus® program (Bradshaw and Brittain 1999) to calculate the 80th percentile weather conditions between May and September and the 97.5th percentile weather conditions for the month of June in the Coconino National Forest, Arizona, over the last 37 years (1968–2004) (Table 2). The 80th percentile weather conditions were obtained for the fire season to represent moderate fire weather for the region, while the 97.5th percentile weather conditions were calculated for the month of June, which historically has the most severe fire weather conditions and represents extreme weather conditions for this region (Fulé et al. 2002).

Predicted fire-behavior characteristics (flame length, fireline intensity, rate of spread, torching index, and crowning index) and proportion of fire types (active crown fire, passive crown fire, conditional crown fire, and surface fire) were calculated by modeling data from each sampled plot separately (for definitions see Table 1).

Statistical analysis

We averaged response variables from each plot by dwarf mistletoe infestation class for each of the 11 sites for statistical analyses; thus, $n = 11$ per class, or $n = 44$ overall, for statistical comparisons. We used Bartlett's test statistic to test for homogeneous variances for all measured variables. If variances were homogeneous, we tested for significant differences among infestation classes using analysis of variance (ANOVA). Following a statistically significant ANOVA result ($\alpha = 0.05$), we used Tukey's multiple comparison procedure to separate means. If variances were heterogeneous, we used Welch's test (Milliken and Johnson 1984) followed by a Dunnett's T3 multiple-comparison procedure (Dunnett 1980*a*, 1980*b*) to separate means.

Results

There were no significant differences in basal area ($P = 0.06$), diameter ($P = 0.39$), tree height ($P = 0.64$), canopy base height ($P = 0.16$), or 20% percentile canopy base height ($P = 0.07$) among infestation classes (Table 3). However, the average number of live trees per hectare was significantly lower ($P = 0.03$) in plots severely infested with dwarf mistletoe than in non-infested stands but did not differ from that in moderately or lightly infested stands. Severely infested stands had a higher ($P = 0.001$) number of snags per hectare than stands in all other dwarf mistletoe infestation classes.

Surface and canopy fuel loadings

Total fuel loading was greater ($P = 0.001$) in severely infested stands than in stands in other dwarf mistletoe infestation classes (Fig. 1). Total fuel loading in severely infested stands was, on average, at least four times greater than in lightly infested and non-infested stands. Total fuel loading in moderately infested stands was also greater ($P = 0.001$) than in lightly and non-infested stands.

Total fuel loading for fuels <7.62 cm diameter was greater ($P = 0.001$) in severely infested stands than in lightly and non-infested stands but similar to the average fuel loading in moderately infested stands (Fig. 2). A breakdown of <7.62 cm diameter fuels into time-lag fuel size classes indicated no statistical differences in average 1 h ($P = 0.92$) and 10 h ($P = 0.10$) fuel loadings among infestation classes (Table 4). Average 100 h fuel loadings were higher ($P = 0.001$) in severely infested stands than in lightly and non-infested stands, but did not differ from 100 h fuel loading in moderately infested stands.

Mean fuel loading of >7.62 cm diameter fuels was higher ($P = 0.001$) in severely infested stands than in stands in all other infestation classes and was higher in moderately infested stands than in lightly infested or non-infested stands

Table 1. Fire-model variables and references used for fire-behavior predictions in Fuels Management Analysis Plus (FMAP) and the NEXUS Fire Behavior and Hazard Assessment System.

Fire-model variable	Model	Definition	Units	References
Fire rate of spread	FMAP and NEXUS	Final rate of forward spread of fire	$m \cdot min^{-1}$	Rothermel 1972, 1991
Fireline intensity	FMAP and NEXUS	Rate of heat release in flaming front per unit length of fire front	$kW \cdot m^{-1}$	Byram 1959
Surface flame length	FMAP and NEXUS	Distance between flame tip and midpoint of flame depth at base of flame	m	Byram 1959
Canopy fuel loading (1, 10, 100, and 1000 h woody fuels and canopy foliage biomass (needles))	FMAP	Mass of canopy fuel load per unit area by time-lag size class	$Mg \cdot ha^{-1}$	Brown 1978; Reinhardt et al. 2000
Canopy fuel for crown fire	FMAP	Foliage biomass plus 50% of 1 h woody canopy fuel load	$Mg \cdot ha^{-1}$	Brown 1978; Reinhardt et al. 2000
Canopy bulk density	FMAP	Mass of available canopy fuel per unit of canopy volume	$kg \cdot m^{-3}$	Brown 1978; Reinhardt et al. 2000
Fire type	FMAP and NEXUS	Surface fires burn in the surface fuel layer; passive crown fires move vertically into the crowns of one or more trees but do not spread horizontally; active crown fires move horizontally and vertically through the canopy; conditional crown fires occur where active crown fires are possible in a stand but crown-fire initiation is not predicted to occur	Surface fire, passive and active crown fire, and conditional crown fire	Alexander 1988; Van Wagner 1993
Torching index	NEXUS	Wind speed at 6 m height at which some kind of crown fire (passive or active) is expected	$km \cdot h^{-1}$	Rothermel 1972; Van Wagner 1977
Crowning index	NEXUS	Wind speed at 6 m height at which an active crown fire is possible	$km \cdot h^{-1}$	Van Wagner 1977; Rothermel 1991

Table 2. The upper 80th percentile fire weather from May to September and the upper 97.5th percentile fire weather for the month of June for the Coconino National Forest from 1968 to 2004.

Weather parameter	80th percentile weather conditions	97.5th percentile weather conditions
Wind speed at 6 m height ($km \cdot h^{-1}$)	20.1	42.0
Wind direction (of origin)	Southwest	Southwest
Fuel moisture (%)		
1 h	5.8	2.9
10 h	9	4.7
100 h	11.9	6.6
1000 h	13.7	9.3
Herbaceous	50.6	51.1
Woody	115	82.2
Foliar	100	100

(Fig. 3). Average fuel-bed depth (P = 0.37) and duff depth (P = 0.85) did not vary significantly among dwarf mistletoe infestation classes (Table 4). Canopy fuel variables, including canopy foliage mass (P = 0.06), 1, 10, 100, and 1000 h canopy fuels (P > 0.05), total canopy fuel (P = 0.08), canopy fuel for crown fire (P = 0.11), and canopy bulk density (P = 0.10) also did not vary among dwarf mistletoe infestation classes (Table 5).

Fire-behavior models

Fire-behavior predictions indicated that there were no significant differences among infestation classes under either the 80th or the 97.5th percentile weather condition in predicted fire rate of spread (P = 0.56, P = 0.99), fireline intensity (P = 0.81, P = 0.50), or flame length (P = 0.62, P = 0.58) (Table 6) or in predicted crowning index (P = 0.58, P = 0.33).

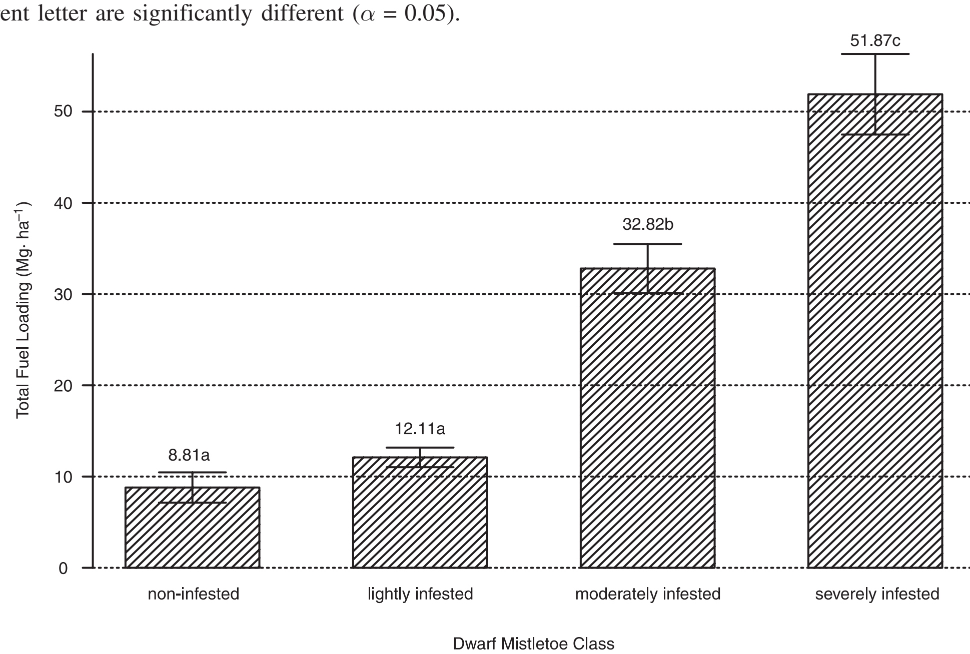
However, the torching index, i.e., the wind speed required to promote the spread of a surface fire into the canopy, was significantly lower (P = 0.001) in severely infested stands than in non-infested stands for the 80th percentile weather condition (Table 6). Under the 97.5th percentile weather condition, both severely and moderately infested classes (P = 0.001) had lower torching indexes than non- and lightly

Table 3. Characteristics of stands classified by dwarf mistletoe infestation class on 11 sites in northern Arizona.

	Dwarf mistletoe infestation class			
Stand characteristic	Non-infested (DMR = 0.0)	Lightly infested (DMR = 0.1–2.0)	Moderately infested (DMR = 2.1–4.0)	Severely infested (DMR = 4.1–6.0)
DBH (cm)	29.2a (3.8)	30.7a (4.6)	31.8a (3.3)	31.5a (3.1)
Total tree height (m)	15.3a (1.4)	15.9a (1.6)	15.9a (1.3)	15.9a (1.3)
Basal area ($m^2 \cdot ha^{-1}$)	45.8a (10.2)	46.1a (10.6)	43.2a (9.9)	36.5a (8.12)
Trees (no.$\cdot ha^{-1}$)	107.9a (39.9)	116.9ab (47.3)	84.2ab (22.3)	69.8b (14.8)
Snags (no.$\cdot ha^{-1}$)	4.6a (1.6)	4.9a (2.9)	10.7a (6.23)	16.5b (7.9)
Lowest live branch (m)	6.9a (1.1)	7.1a (0.9)	6.5a (1.2)	6.2a (1.0)
Lowest quintile (20%) canopy base height (m)	4.5a (0.8)	4.8a (0.7)	4.1a (1.0)	3.8a (0.9)

Note: Means followed by a different letter in a row are significantly different (α = 0.05). Values in parentheses are standard deviations.

Fig. 1. Total fuel loading by dwarf mistletoe infestation class (mean with standard error) for the Coconino National Forest, Arizona. Means followed by a different letter are significantly different (α = 0.05).



infested classes. Our modeling results also indicated that under severe weather conditions, as dwarf mistletoe infestation increased from the non- and lightly infested classes to the moderately and severely infested classes, the proportion of fires predicted to be active or passive crown fires doubled.

Discussion

Our results show that increased levels of dwarf mistletoe infestation were associated with increased surface fuel loadings, which contributed to differences in predicted fire behavior. Koonce and Roth (1985) quantified surface fuel loadings in plots with different levels of western dwarf mistletoe (*Arceuthobium campylopodum* Engelm.) in ponderosa pine on four study sites in central Oregon. The only significant difference they reported was higher loadings of fuels <7.62 cm diameter in stands severely infested with dwarf mistletoe compared with their pooled data for non-infested / lightly infested stands. For fuels >7.62 cm diameter, loadings did not vary significantly among dwarf mistletoe infestation levels, ranging from a low of 18.4 $Mg \cdot ha^{-1}$ in their severely infested study sites to a high of 33.2 $Mg \cdot ha^{-1}$ in moderately infested study sites. Unfortunately, the low sample size and other confounding variables in their study make a comparison with our results invalid.

Our results indicated that stands severely infested with dwarf mistletoe were characterized by significantly higher total fuel loadings for fuels both <7.62 cm and >7.62 cm in diameter. We were unable to find published data on fuel loads in ponderosa pine stands infested with dwarf mistletoe in the Southwest. Sackett (1979) measured natural fuel loadings in 62 non-infested ponderosa pine stands in the Southwest and his findings for 1, 10, 100, and 1000 h fuel loadings were similar to our estimates for the non-infested class (Table 3). Furthermore, fuel-bed depths in our study were similar to those reported by Ffolliott et al. (1968): approximately 3.3 cm (Table 3). Therefore, our estimated fuel

Fig. 2. Fuel loading of <7.62 cm diameter fuels by dwarf mistletoe infestation class (mean with standard error) in the Coconino National Forest, Arizona. Means followed by a different letter are significantly different (α = 0.05).

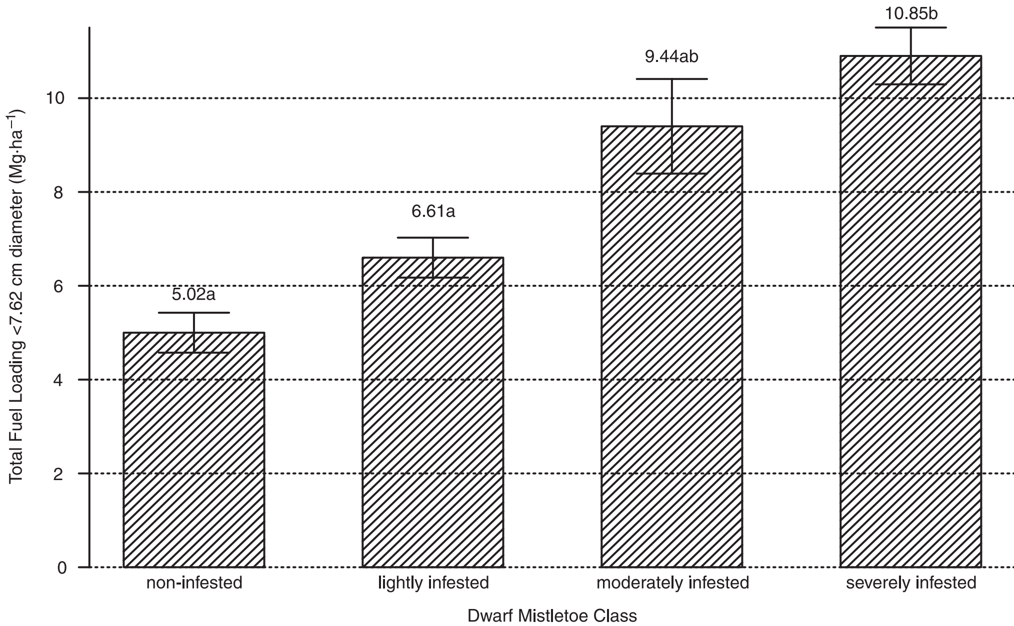


Table 4. Average surface fuel loadings, fuel-bed depth, and duff depth by dwarf mistletoe infestation class in northern Arizona.

	Dwarf mistletoe infestation class			
Surface fuel loading	Non-infested (DMR = 0.0)	Lightly infested (DMR = 0.1–2.0)	Moderately infested (DMR = 2.1–4.0)	Severely infested (DMR = 4.1–6.0)
1 h fuels (Mg·ha^{-1})	0.45a (0.2)	0.43a (0.2)	0.47a (0.2)	0.47a (0.2)
10 h fuels (Mg·ha^{-1})	1.79a (0.4)	2.26a (0.8)	2.33a (0.6)	2.35a (0.5)
100 h fuels (Mg·ha^{-1})	3.09a (1.4)	4.12a (1.3)	5.49ab (2.9)	6.93b (1.8)
Fuel-bed depth (cm)	3.45a (0.6)	3.43a (0.6)	3.81a (0.7)	3.96a (1.4)
Duff depth (cm)	2.20a (1.0)	1.88a (0.5)	2.06a (0.9)	2.21a (1.1)

Note: Means followed by a different letter in a row are significantly different (α = 0.05). Values in parentheses are standard deviations.

loadings and fuel-bed depths for ponderosa pine stands infested with dwarf mistletoe are reasonable because they are similar to the results of these studies of non-infested ponderosa pine stands in the Southwest.

Brown et al. (2003) reviewed published data on optimum fuel loadings for >7.62 cm diameter fuels in relation to commonly stated management objectives for warm, dry ponderosa pine forests in western Montana. Assuming similar optimum fuel loadings for the Southwest, none of the stands we sampled had average >7.62 cm diameter fuel loadings above optimum ranges for fire hazard (0–56 Mg·ha^{-1}), soil heating (0–78 Mg·ha^{-1}), or wildlife (2–67 Mg·ha^{-1}). In contrast, 73% of the severely infested stands and 27% of the moderately infested stands that we sampled had >7.62 cm diameter fuel loadings above their suggested optimum range for productivity and historical fuel loadings (both 11.2–22.4 Mg·ha^{-1}), while none of the lightly and non-infested stands were outside these ranges.

The severely infested stands that we sampled had significantly higher snag densities than the lightly or non-infested stands. Similar findings have been reported for central Colorado (Bennetts et al. 1996), central Oregon (Roth 2001), and northern Arizona (Parker 2001). Although snag densities are not currently included in fire or fuel models, snags do influence canopy fuels while they are standing and contribute to the increase in surface fuel loadings after they fall. While snags do ultimately contribute to the increase in surface fuel loadings in ponderosa pine stands infested with dwarf mistletoe, they also provide habitat for cavity-nesting birds and other wildlife (Tinnin 1984; Bennetts et al. 1996; Mathiasen 1996; Parks et al. 1999; Parker 2001). In addition to higher snag densities, the severely infested stands also had lower tree densities than the non-infested stands. The more open conditions in severely infested stands can lead to lower relative humidity and higher surface wind speeds (Agee et al. 2000). As a consequence of the altered microclimate on these sites compared with more closed stands, drier dead fuel and higher wind speeds potentially contribute to the increase in fire rate of spread (Agee et al. 2000)

Fire models such as NEXUS are composed of a collection of equations that estimate fire behavior in a given stand (Pastor et al. 2003). Fire models are largely dependent upon

Fig. 3. Fuel loading of >7.62 cm diameter fuels by dwarf mistletoe infestation class (mean with standard error) in the Coconino National Forest, Arizona. Means followed by a different letter are significantly different (α = 0.05).

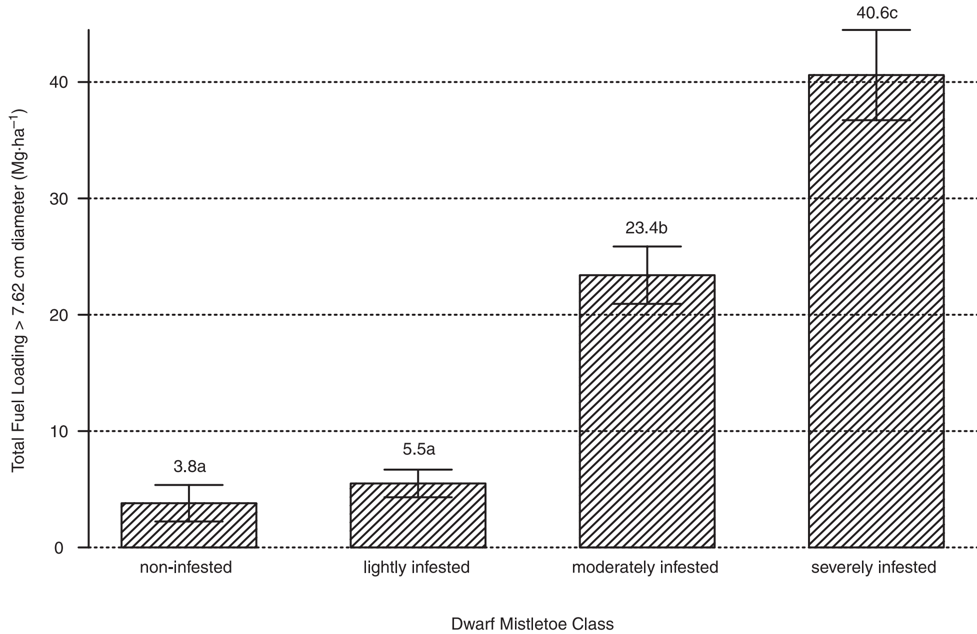


Table 5. Canopy fuel loadings according to dwarf mistletoe infestation class in northern Arizona.

	Dwarf mistletoe infestation class			
Canopy fuel loading	Non-infested (DMR = 0.0)	Lightly infested (DMR = 0.1–2.0)	Moderately infested (DMR = 2.1–4.0)	Severely infested (DMR = 4.1–6.0)
Canopy foliage mass ($Mg \cdot ha^{-1}$)	14.54a (3.5)	14.12a (3.0)	12.91a (2.7)	11.32a (2.7)
Canopy fuel ($Mg \cdot ha^{-1}$)				
1 h	1.37a (0.4)	1.30a (0.4)	1.21a (0.4)	1.03a (0.3)
10 h	20.00a (4.3)	19.77a (3.6)	19.08a (4.4)	16.29a (3.7)
100 h	16.07a (3.6)	17.62a (3.5)	16.94a (3.0)	14.15a (3.2)
1000 h	5.67a (1.8)	6.41a (1.7)	6.28a (1.3)	5.07a (1.3)
Total	58.23a (12.2)	59.54a (11.1)	56.69a (11.3)	48.26a (10.6)
Canopy fuel For crown fire ($Mg \cdot ha^{-1}$)	15.23a (3.7)	14.77a (3.2)	13.52a (3.6)	11.84a (2.8)
Canopy bulk density ($kg \cdot m^{-3}$)	0.1650a (0.05)	0.1490a (0.05)	0.1426a (0.04)	0.1202a (0.03)

Note: Means followed by a different letter in a row are significantly different (α = 0.05). Values in parentheses are standard deviations.

three sets of variables — weather conditions, stand properties, and fuel characteristics — and therefore actual fire behavior will differ from predictions. Thus, fire-model results should be viewed in terms of relative differences in predicted behavior. Comparing fire-behavior predictions among stands with different levels of dwarf mistletoe infestation, under a common weather scenario, provides a basis for assessing relative differences in potential fire behavior.

Our results indicated no differences in two of the most important input variables used in fire models, canopy fuel loadings and canopy base height, among infestation classes. Thus, differences in fire-behavior predictions are primarily due to the use of different fuel models within the dwarf mistletoe infestation classes, and are a reflection of differences in measured woody fuels. However, our canopy fuel loadings are probably underestimated because they are estimated on the basis of standardized relationships between a given tree diameter and crown characteristics, and therefore would not account for additional crown volume contributed by witches' brooms on an infected tree. Several authors have suggested that resin from dwarf mistletoe infection increases flammability, but quantitative data are not available (Alexander and Hawksworth 1975; Koonce and Roth 1980, 1985; Harrington and Hawksworth 1990; Conklin 2000; Geils et al. 2002). The accuracy of fire-behavior models will be enhanced by adjusting estimates of these critical fire-related parameters for stands infested with dwarf mistletoe.

These results suggest that higher levels of dwarf mistletoe infestation are associated with increased surface fuel loadings and a decreased torching index, and thus especially severely infested stands in northern Arizona should be priority areas for fuel treatments. However, the effects of dwarf mistletoe infestation on fuel loadings and fire behavior need to be investigated further. Additional studies of ponderosa pine forests infested with dwarf mistletoe across the Southwest and other host–parasite combinations and forest ecosystems are needed. The results of this study should be used cautiously outside northern Arizona.

Table 6. Predicted fire behavior for the upper 80th and 97.5th percentile fire weather conditions in northern Arizona by dwarf mistletoe infestation class, using the lowest quintile (20%) canopy base height.

Weather condition and DMR class	Fire type	Fire rate of spread ($m \cdot min^{-1}$)	Fireline intensity ($kW \cdot m^{-1}$)	Flame length (m)	Torching index ($km \cdot h^{-1}$)	Crowning index ($km \cdot h^{-1}$)
80th percentile						
Non-infested	2% (6.0) CCF, 98% (5.7) SF	1.8a (0.4)	323.2a (542.4)	1.0a (0.7)	89.1a (15.9)	40.2a (8.7)
Lightly infested	2% (6.0) CCF, 98% (6.1) SF	1.8a (0.4)	338.3a (574.1)	1.0a (0.7)	91.6a (12.5)	43.6a (10.1)
Moderately infested	2% (6.0) CCF, 3% (6.3) PCF, 95% (8.1) SF	1.8a (0.4)	439.9a (636.8)	1.2a (0.7)	71.5ab (19.1)	43.2a (7.8)
Severely infested	2% (6.0) CCF, 8% (8.8) PCF, 90% (9.4) SF	1.8a (0.4)	545.0a (631.7)	1.3a (0.7)	62.4b (23.0)	46.1a (12.2)
97.5th percentile						
Non-infested	5% (12.3) PCF, 5% (12.6) SF, 11% (13.1) ACF, 79% (21.7) CCF	29.3a (3.9)	18 166.5a (4968.5)	17.8a (3.9)	66.8a (12.1)	29.3a (6.6)
Lightly infested	13% (16.2) ACF, 16% (11.7) SF, 71% (22.3) CCF	27.5a (3.7)	16 845.2a (4837.4)	16.6a (3.9)	67.4a (9.44)	34.3a (7.9)
Moderately infested	6% (12.3) SF, 12% (17.2) PCF, 26% (21.2) ACF, 56% (31.2) CCF	28.8a (3.6)	18 512.4a (4575.2)	17.9a (3.5)	51.5b (14.7)	32.4a (5.9)
Severely infested	4% (12.0) SF, 20% (24.3) PCF, 38% (27.7) ACF, 38% (35.6) CCF	29.1a (3.4)	19 993.3a (4729.1)	18.8a (3.7)	43.0b (18.3)	34.6a (9.3)

Note: Mean values in a column (blocked by percentile weather) followed by the same letter are not significantly different ($\alpha = 0.05$). Values in parentheses are standard deviations.

*SF, surface fire; PCF, passive crown fire; CCF, conditional crown fire; ACF, active crown fire.

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