Incidence of Ponderosa Pine with Latent Dwarf Mistletoe Infections Following Timber Stand Improvement on the Mescalero Apache Indian Reservation, New Mexico

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Abstract

Southwestern dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum*) is a damaging pathogen of ponderosa pine (*Pinus ponderosa* var. *scopulorum*) in the Southwest. Aspects of the dwarf mistletoe life cycle facilitate silvicultural control methods; conversely, latent infections make complete eradication impractical. On the Mescalero Apache Indian Reservation, New Mexico, a mistletoe control project occurred on 3,300 severely infested acres from 2005 to 2006. The treatment, locally known as an application of the "knee-high rule," intended to target mistletoe infection while maintaining sufficient natural regeneration for stocking. The operation cut all ponderosa pine > 2-feet tall without compromise. In 2008, 12 fixed radius plots (0.1 to 0.2-acre) were randomly established in the project area to observe the emergence of latent infections on the ponderosa pine seedlings. Plots were re-measured in 2012 and 2015. The survival and growth of the retained cohort were prolific. Results indicated that 2.3% of natural regeneration in the study area harbored latent infections, which was lower than estimates from previous studies. Results demonstrated that implementing the strict "knee-high rule" guidelines with follow-up sanitation treatments is an effective control option for this mistletoe.

Introduction

Dwarf mistletoes (*Arceuthobium spp.*, Viscaceae) are obligate parasitic flowering plants that depend almost entirely on their host tree for water, minerals and carbohydrates. Dwarf mistletoes have the potential to significantly impact height, diameter growth and life expectancy of a severely infected tree. Dwarf mistletoes are spread by hydrostatically controlled, thermogenesis-triggered, explosive dispersal otherwise known as pressure-released seed (Hawksworth and Wiens 1996; Geils et al. 2002; Rolena et al. 2015). Spread occurs tree-to-tree and by intensification within individual infected tree crowns. When dwarf mistletoe seeds ballistic flight propels them onto a safe site of susceptible hosts, new infections may be initiated. Distribution on both the landscape and stand scale is typically patchy, with more or less discrete infection centers surrounded by areas without the disease (Conklin 2000); however, large tracks of severe infestation have been noted in the Southwest.

Several aspects of the dwarf mistletoe life cycle facilitate their control through silvicultural methods including 1) obligate parasitism— requirement of a living host, 2) host specificity— generally infect one species or a group of related species, 3) long life cycles— generations range from two to ten years or more that includes an incubation period of two to ten-years before aerial shoots develop, 4) limited seed dispersal— maximum horizontal spread distances of 33 to 49-ft. and 5) slow intensification within tree crowns— fast growing trees can outpace the infection (Muir and Geils 2002). However, the long incubation period makes it difficult to observe infected branches or stems initially and these are referred to as “latent infections”. Latent infections can considerably complicate control efforts, as it is nearly impossible to eliminate all infection in one operational entry without compromising stocking requirements. Baranyay et al. (1971) defined lag period as the period in the development of an infection from seed deposition to appearance of the first aerial shoots and noted that latency period was used to define the time from infection to reproduction for other pathogens. Typically, the lag period is two to six-years but this varies for different dwarf mistletoes (Hawksworth and Wiens 1996).

Southwestern dwarf mistletoe (SWDM) (*A. vaginatum* subsp. *cryptopodum* (Engelmann) Hawksworth and Wiens) is recognized as the most damaging pathogen in Southwestern ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelmann) forests (Hawksworth and Wiens 1996; Conklin 2000). According to Hawksworth and Wiens (1996), this dwarf mistletoe is particularly damaging to ponderosa pine in the Sacramento Mountains in south central New Mexico, central Arizona and along the Front Range in Colorado. Dr. Lake Gill of the USDA Forest Service, a renowned mistletoe researcher, stated that the worst SWDM infestation in the entire southwest was on the Mescalero Apache Indian Reservation (Mescalero) and the adjoining Lincoln National Forest (Shields 1953).

Early studies on the control of SWDM at the Fort Valley Experimental Forest (Gill and Hawksworth 1953) indicated a prolonged latent period following treatment. Hawksworth (1961) investigated the incubation period from infection to production of the first aerial shoot for SWDM and concluded that incubation periods ranged from two to eight-years with a mean of five-years. Most plants (92%) were produced three to five-years after initial infection. More recently, Conklin (2002) studied the emergence of SWDM plants from latent infections in advanced regeneration at Mescalero and reported that 18% of infections became visible between six to nine-years following treatment. His study also showed that latent infections were least common in trees ≤ 2-ft. tall at the time of the treatment and regeneration exhibited more latent infections positively correlated with height at time of release.

Hawksworth et al. (1977) stated that a century of experience has demonstrated that it is virtually impossible to eliminate dwarf mistletoe populations through partial cutting. Latent infections, infections that have not yet produced visible mistletoe shoots, are a major reason. Korstian and Long (1922) were perhaps the first to propose the idea of clearcutting and regenerating areas severely infested with SWDM; however, they stated that such conditions would seldom be encountered. Nevertheless, early mortality studies on the Mescalero (Hawksworth and Lusher 1956) indicated that commercial stands may no longer be able to reach maturity with such a high incidence and severity of the pathogen present. Artificial regeneration has been employed with limited success in the arid Southwest; therefore, refinement of silvicultural practices were required before appropriate landscape scale treatments could be implemented without compromising appropriate stocking levels (Bill Hornsby personal communication, October 2015).

The current recommendation for addressing moderate to severe SWDM infestations at Mescalero is to implement even-aged management. This consists of a commercial harvest where all host trees ≥ 9-in. diameter breast height (DBH) are removed, followed by a timber stand improvement (TSI) that consists of slashing all host trees that are > 2-ft. tall. This TSI is known locally as the "knee-high rule". The intent of this treatment (a commercial harvest followed by a TSI) is to eliminate the potential for new infections in the existing ≤ 2-ft. tall seedling component from the > 2-ft. tall component and to release the retained seedlings from suppression.

Recommendations for lightly infested stands are less intense. Mistletoe is addressed using a "30-ft. rule" (marking guideline) that harvests all saw log size (≥ 9-in.) host trees within 30-ft. of any visibly infected saw-log size tree (including the infected stem). This process is then repeated in the pre-commercial (< 9-in. DBH) size class, cutting all hosts within 30-ft. of visible mistletoe infection. These operations take place during a single tree selection cutting or the establishment or removal phase of a shelterwood with reserves. The similarity between these two management recommendations is that host trees ≤ 2-ft. tall within range of infection sources at the time of entry are maintained for stocking. Both options include follow-up walkthrough sanitation treatments to control latent infections that occur on these small trees.

The Mescalero Bureau of Indian Affairs (BIA) is exemplary at obtaining grant funding for implementation of forest health treatments as well as expanding the tribal consciousness to include contemporary knowledge of current forest health issues. Forest managers and tribal members at Mescalero understand that SWDM can be both an ecologically important species when at endemic levels providing benefits for wildlife and increasing diversity or an economically damaging tree pathogen otherwise. Less than half of the Reservation is managed as commercial timberland. Much of the steep and inaccessible land is typically not harvested and the ecological benefits of SWDM will continue to be available on these sites. Treatments to control mistletoe on potentially commercial sites where the infestation is largely attributable to past management practices will enable these stands to again be productive in support of the local rural economy. Due to the high incidence and severity of the pathogen, these treatments designed to combat it without compromising stocking are not viewed as overly aggressive.

Background

Several projects were implemented at Mescalero over the past two decades based on the above recommendations. The only practical control for dwarf mistletoes over large forested areas is through cultural treatments (Geils et al. 2002). No viable chemical or biological controls are available for treating stands (Beatty and Mathiasen 2003). Tribal consciousness of the severity of the mistletoe problem is largely responsible for the high degree of active management at Mescalero (B. Hornsby personal communication, October 2015); however, due to the occurrence of latent infections in these young seedlings ≤ 2-ft. tall, doubts remained about whether or not the treatments would result in healthy or severely infested younger stands. Based on Conklin's (2002) results, it was assumed that the number of trees with latent infections in the ≤ 2-ft. tall seedlings was low (about 6%); yet, managers speculated that if the "knee-high rule" were implemented with strict adherence to the 2-ft. height limit, the resulting occurrence of trees with latent infections would be even lower.

Paul's Canyon is located in the northeast area of Mescalero and has historically been characterized by a high incidence and severity of SWDM infestation. The canyon was initially part of the Whitetail Logging Unit where aggressive but unsuccessful mistletoe control efforts were implemented in the 1950's (Weaver and Sarlin 1950; Hawksworth and Lusher 1956). Paul's Canyon is now part of the 24,564-acre Upper Pine Tree Logging Unit, where from 2005 to 2006 a commercial timber harvest of approximately 7,500-acres was followed by a TSI utilizing the "knee-high rule" over the most severely infested 3,300-acres (Paul's Canyon). This ambitious control effort provided the unique opportunity for an observational study of the effectiveness of the current recommendations for moderate to severe SWDM-infested stands at Mescalero.

Conklin's (2002) study area was located adjacent to the Upper Pine Tree Logging Unit, which did not have a strict implementation of the "knee-high rule" guidelines. The variables that could have possibly influenced his results included new infections from mature ponderosa pine near the margins of the study area, new infections from competing trees > 2-ft. tall shown to have a higher incidence of latent infections, the use of fire for site preparation and overlooking trees ≤ 1-ft. tall. To address these variables, the Mescalero Bureau of Indian Affairs (BIA) established monitoring plots in Paul's Canyon following the strict implementation of the "knee-high rule." This provided a research opportunity to investigate the incidence of retained ponderosa pine with latent infections.

I hypothesized that the incidence of latent infections in the seedlings would be low and could be controlled and reduced even further with future sanitation retreatments. Results from the measurements nine years post treatment are presented in this paper. I investigated the possibility of converting a severely infested stand into a healthy stand by implementing a commercial harvest that removed all host species ≥ 9-in. DBH and a TSI following the "knee-high rule" guidelines. This treatment utilizes the minimally infected, existing ≤ 2-ft. tall ponderosa pine seedling component to restore the stands commercial viability.

Study Area

The Mescalero is located in the Sacramento Mountains of south-central New Mexico. The Smokey Bear and Sacramento Ranger Districts of the Lincoln National Forest border the 460,414-acre reservation to the north and south, respectively. To the east and west are a combination of both public and private lands. Local climatic factors range from an average minimum of 32.1°F to an average maximum temperature of 65.9°F. The elevation ranges between 6,500 and 12,000-ft. and the average annual precipitation varies from about 15-in. at lower elevations to more than 32-in. at higher elevations with a majority of the precipitation occurring from June-August (Hornsby 2011). Forest cover is comprised of both timber and woodland species. The managed forest area at Mescalero is approximately 185,000-acres, predominantly consisting of pine mixed, mixed conifer and ponderosa pine types (B. Hornsby personal communication, November 2015).

Methods

Prior to treatment, 172 0.01-acre circular plots were installed in the Upper Pine Tree Logging Unit on a five by five chain grid. Regeneration surveys in these plots indicated that there was sufficient natural ponderosa pine regeneration ≤ 2-ft. tall present. Sufficient stocking was determined to be 200-trees per acre (TPA) (B. Hornsby personal communication, October 2015). Over 98% of the survey plots were known to have had infected overstory trees within a distance that could have allowed infection of the pine regeneration (35-ft.).

In 2005, a commercial entry cut all ponderosa pine ≥ 9-in. DBH on 7,500 acres of the Upper Pine Tree Logging Unit. Feller bunchers were utilized to cut and pile merchantable timber and skidders were restricted to designated skid trails to limit damage to the existing ponderosa pine regeneration. Healthy crop quality Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) and southwestern white pine (*Pinus strobiformis* Engelmann) were maintained on the site.

Funding was obtained from the USDA Forest Service, Forest Health Protection, Southwestern Region and National Fire Plan, Hazardous Fuel Reduction to implement a strict application of the "knee high rule" across the most severely infested 3,300-acres. Operations began in Fall 2005 and concluded in Spring 2006. They consisted of slashing all remaining ponderosa pine > 2-ft. tall. During Spring 2007, a subsequent stand entry was made to cut any missed trees that would have been > 2-ft. tall at the time of the 2005 to 2006 operation and cut trees with visible mistletoe infection. The 2007 retreatment was a walkthrough operation. During this retreatment, very few trees were cut.

In 2008, twelve fixed radius plots were randomly established in Paul's Canyon. Initially, seven plots 0.2-acre were established; however, plot size was reduced to 0.1-acre for the remaining five plots due to high stocking. All ponderosa pine on each plot estimated to have been > 2-ft. tall during the TSI in 2006 were cut in 2008. All trees visibly infected with mistletoe were cut and tallied as infected at the time of plot installation. Remaining trees were inspected for mistletoe plants, distance and azimuth from plot center were recorded, tree heights were measured to the nearest 0.5-ft., identification tags were placed on retained trees, and crop tree quality based on growth form and apparent vigor was determined for predicting the merchantability of the future stand. Both crop and non-crop trees were retained throughout this study.

Plots were first re-measured in 2012. At this time, all trees were inspected for visible SWDM infection, height was measured to the nearest 0.5-ft., all infected trees were destroyed and crop trees were again noted. Seedlings not present in 2008 were incorporated into the study population and new sturdier identification tags were installed on all trees maintaining the original numbering. In 2015, the plots were re-measured using the same protocol as the 2012 measurement, but it was unnecessary to re-tag trees. GPS coordinates of the plots were recorded for all plot centers to facilitate plot location during future re-measurements.

Results

Based on the 2015 measurement, the average stocking of ponderosa pine across the project area was 1,058-TPA. This did not account for the additional tree species present including Douglas-fir, southwestern white pine, junipers (*Juniperus sp.*), and oaks (*Quercus sp.*) that make up lesser components of the developing ponderosa pine stands. Of the ponderosa pine stems present, 95% were determined to be of crop tree quality. Mean tree height was 4.3-ft. with a median of 4-ft. and a range of 0.5 to 11-ft.

Nine-years post treatment, a total of 51 (2.3%) of the sample trees had become visibly infected (Table 1). This number included the trees that were infected when the plots were established in 2008 and all-additional infections found during the 2012 and 2015 re-measurements (Table 2). This percentage was based on a sample size of 2,263 trees, which was the sum of all the live trees in 2015, the trees that had died from 2008 to 2015 and the infected trees that were cut during each measurement (Table 2).

Table 1. Plot size, number of sample trees, number of trees with latent infections and incidence of trees with latent infections by plot for the Upper Pine Tree Logging Unit.

Plot #	Plot Size (acres)	Sample Trees	Trees w/ Latent Infection	Incidence of Trees w/ Latent Infections (%)
1	0.2	125	7	**5.6**
2	0.2	143	0	**0**
3	0.2	527	7	**1.3**
4	0.2	94	1	**1.1**
5	0.2	467	5	**1.1**
6	0.2	251	24	**9.6**
7	0.2	370	5	**1.4**
8	0.1	43	0	**0**
9	0.1	54	0	**0**
10	0.1	50	0	**0**
11	0.1	44	2	**4.5**
12	0.1	95	0	**0**
Total	**1.9**	**2,263**	**51**	**2.3**

Table 2. The number of live trees, mortality and cut mistletoe-infected trees for each plot sampled in the Upper Pine Tree Logging Unit from 2008 to 2015.

Plot #	Live Trees 2015	Mortality 2008-2015	Mistletoe Cut 2008	Mistletoe Cut 2012	Mistletoe Cut 2015	Total
1	95	23	5	1	1	**125**
2	137	6	0	0	0	**143**
3	476	44	3	0	4	**527**
4	74	19	1	0	0	**94**
5	441	21	2	1	2	**467**
6	200	27	15	6	3	**251**
7	348	17	0	1	4	**370**
8	40	3	0	0	0	**43**
9	49	5	0	0	0	**54**
10	47	3	0	0	0	**50**
11	39	3	2	0	0	**44**
12	64	31	0	0	0	**95**
Total	**2010**	**202**	**28**	**9**	**14**	**2,263**

None of the SWDM detected in 2008, 2012 or 2015 appeared to have originated on ponderosa pine vegetation that developed after 2006. This indicated that no new infections occurred since the treatment. Because recent tissue (< 5-years old) is more susceptible to infection than older tissue (Hawksworth 1961; Hawksworth and Wiens 1996), if any new infections occurred they would likely have appeared on the younger host tissue. Twenty-eight (55%) of the trees with latent infections were seen two-years after the treatment at the time of plot installation in 2008; nine (18%) of the total number of trees with latent infections were observed six years after the treatment in 2012; and 14 (27%) of the total trees with latent infections were observed at nine-years after the treatment in 2015 (Table 2).

The highest incidence of latent infections occurred on trees in plots 1 and 6 where > 5%, but < 10%, of the sample trees were infected prior to the 2006 treatment; plot 6 had the greatest number of trees with observed latent infections (24 of 251 trees; 9.6%), which was three times higher than other plots (Table 1). Plots 1 and 3 each had seven trees with latent infections and plots 5 and 7 each had five trees with latent infections. Plot 11 had almost 5% of the sampled trees develop latent infections, but the sample size for plot 11 was relatively small because this plot was only 0.1-acre. The remainder of the plots had < 2% or no trees with latent infections, but the majority of these plots were also 0.1-acre in size. Only two trees with latent infections were recorded on the smaller 0.1-acre plots (plots 8 through 12) over the nine-year study period presenting a 0.7% incidence of observed trees with latent infections. Plot size obviously influenced the number of trees sampled and this was correlated with the number of trees on which no latent infections expressed themselves during the study. However, two plots (2 and 12) had no trees with observed latent infections during the nine-year study, but had > 90 trees sampled (143 and 95, respectively).

Total plot mortality consisted of 202-dead trees (9%) between 2008 and 2015. The majority of mortality (80%) occurred between 2008 and 2012. Rodent girdling and drought were assumed to be the primary drivers of mortality during this time period. Drought is the rule rather than the exception in the arid Southwest. Historical analysis of the Palmer Drought Severity Index (PDSI) for Mescalero over the study period indicated that the first protracted extreme drought conditions in the area occurred during 2011, 2012 and into 2013 (NOAA 2015). Therefore, drought may have largely contributed to the mortality that occurred during those years. Root diseases may have predisposed some of these trees to drought stress as both Armillaria and Annosus root diseases were observed in the area adjacent to the study site (Conklin 2002).

It is unlikely that any mortality was directly caused by SWDM infection due to the absence of aerial shoots on inspected dead trees and the cutting of all infected trees on the plots during measurements. Based on field observations, the mortality (20%) that occurred from 2012 to 2015 was primarily attributed to elk rub damage. New seedlings were found during each re-measurement even though residual trees were not yet at reproductive age. This suggested that these new trees were either overlooked previously or have since grown from a residual seed bank.

Many ponderosa pines slashed on the plots during the 2005 to 2006 treatment sprouted from epicormic buds below the cut, increasing stocking levels estimated from the pretreatment surveys. Sprouting is a natural physiological reaction of plants to disturbance that likely developed as a survival mechanism to either fire or flooding (Baker 2009). Many tree species including a variety of pines are described as having this ability to sprout from their original root-stock following disturbance. To our knowledge, ponderosa pine has never been documented to sprout. Nevertheless, 129 (5.7%) ponderosa pine trees in this study apparently sprouted post slashing. Sprouted ponderosa pine were noted in the comments section of the data entry forms when they were observationally determined to have resumed growth following the cut and it is likely that many more sprout trees were overlooked. This response from ponderosa pine may be associated with high site quality, stump size and/or the seasonality of treatments (B. Hornsby personal communication, November 2015). Further investigation is needed to definitively document the phenomenon.

Because SWDM rarely develops systemic infections, it is probable that infections on regeneration with sprouts will rarely extend into the sprouts (Hawksworth 1961). To date, one tree has been observed with a DM-infected sprout. The aerial shoots appeared both below and above where the tree had been cut indicating that the initial infection was below the cut height and the infection grew a short distance into the new sprout. Hence, trees with sprouts may be more likely to exhibit latent infections as the original cut tree was a larger target for mistletoe seed prior to treatment and an infection may have established below stump height.

Discussion

The results from this study support a general management recommendation that regeneration within SWDM-infested ponderosa pine stands should be retreated with sanitation thinning five years after an overstory removal and certainly no longer than ten years after the operation. The majority of ponderosa pines ≤ 2-ft. tall with latent infections in this study became observable two-years after implementing the “knee-high rule” treatment. Furthermore, after only six-years, more than 70% of the trees with latent infections were observed, indicating that a sanitation retreatment conducted five years after treatment would have detected and removed most of the infected regeneration. Although the number of trees with latent infections detected nine years after the treatment was completed (14) was larger than six years after the treatment (9), it is probable based on artificial inoculation experiments (Hawksworth 1961) that nearly all of the latent infections were detected less than ten-years after the treatment. However, another re-measurement is needed in order to estimate the incidence of trees that express latent infections after ten years and long-term impacts of the treatment.

Based on the estimated maximum incubation period for SWDM of eight years (Hawksworth 1961), it is probable that most, if not all, of the latent infections present in the treatment unit were expressed. It should be noted that while Hawksworth (1961) reported that an eight-year duration was the maximum incubation period based on his observations of artificially inoculated ponderosa pines, current study results indicated that a longer incubation period of at least nine-years occurred at Mescalero. This is supported by the fact that new infections were prevented following the “knee-high rule” treatment in 2006 due to the removal of all overstory and infected understory trees, the complete lack of edge effects given the projects size, plot locations in the treatment interior and the subsequent removals of all trees with emerging latent infections both on the plots during the measurements and off the plots during project area sanitation retreatments in 2007 and 2015. Therefore, although the years of infection initiations were not determined, all latent infections must have occurred prior to the 2006 treatment.

Comparison of current results with those of Conklin (2002) shows that the sample proportion of trees with latent infections observed during the current study (2.3%) from 2006 to 2015 was less than half of that observed by Conklin (2002) (5.9%) over a nine-year period. There are several differences between the studies that may account for this variation. The

Conklin (2002) study used a relatively small project area of only 120-acres, whereas this project area was around 3,300-acers, which eliminated SWDM infection from the edges of the study area. Additionally, the previous study observed latency in an array of tree sizes and although results were recorded by tree height (making it possible to estimate incidence of infection in trees ≤ 2-ft), our implementation of a strict "knee-high rule" eliminated the variable of possible new infections from > 2-ft tall trees. This study also included new trees that were discovered after the sampling plots had been established as well as trees ≤ 1-ft. tall, which Conklin (2002) did not sample. These factors could explain some of the variation in the observed incidence of trees with latent infections between the two studies for regeneration ≤ 2-ft. tall.

The general patchiness of mistletoe infestation on both the landscape and stand scale may be responsible for the plot by plot variation observed in the incidence of trees with latent infections (Hawksworth 1961; Hawksworth and Wiens 1996; Conklin 2000). Although SWDM-infestations in ponderosa pine stands on the Mescalero are often severe, the severity and size of the infestations vary across these forests (Hawksworth and Lusher 1956). Previous studies of ponderosa pine and other conifers demonstrated that the incidence and rate of infection of new regeneration were influenced by the severity of the infection in the overstory, the density of regeneration and the age or tree height of the regeneration (Hawksworth 1961; Scharpf 1969; Hawksworth et al. 1977; Parmeter 1978; Mathiasen 1998). Although limited pre-treatment data is available on the distribution and severity of SWDM in the Upper Pine Tree Logging Unit, the incidence of infected regeneration was probably influenced by the severity of SWDM in the removed overstory trees as well as the density, age and height of the regeneration prior to the treatment. For example, the relatively high incidence of trees with latent infections observed on plot 6 (9.6%) may be the result of more severe SWDM infection in the overstory removed from and around that plot, than for other plots with lower incidences of infection.

The regeneration of pine on the Mescalero is more reliable than on many sites in the Southwest, soils and seasonal precipitation patterns may be responsible for this (B. Hornsby personal communication October 2015). The survival and growth of regeneration were prolific throughout the project area. Current stocking conditions are more than an order of magnitude higher than reference conditions for the Southwest (Fulé et al. 1997). Thinning will therefore occur either by competition related mortality or operational means in the future and ample stocking will accommodate either. It should be noted that all of the mortality that occurred on the plots from 2006 to 2015 was attributed to either drought or animal damage and not to SWDM infection. Even if trees with latent infections had died, the level of mortality caused by these infections would be far below that caused by these other factors. Some of the trees that died during the study due to drought and/or animal damage may have contained unobserved latent infections.

Hawksworth and Wiens (1996) reported that trunk infections will typically kill very small trees but Conklin (2002) stated that this probably only occurs in the understory of dense stands where suppression is a factor on the Mescalero. Trunk/bole infections were the main type of infection observed on tress within the treatment area and the structure of young regeneration was probably responsible for this. In order for a new infection to be initiated, a seed must land on a safe site of a receptive host (Geils et al. 2002). In regeneration (≤ 2-ft. tall), this safe site may consist almost exclusively of the trees main stem; therefore, trunk infections are the norm rather than the exception for this size class of tree. Several infections were also observed on older branches that were present prior to 2006. All trees with any mistletoe infection were cut before they could be killed by SWDM.

Fire is an important mortality agent and natural regulator of densities in this region; however, fire is initially incompatible with this treatment due to the vulnerability of the young trees. Fire should be excluded from stands treated with the "knee-high rule" for at least ten-years or until an appropriate amount of the trees are approximately 4.5-ft. tall and large enough to likely withstand fire (Bailey and Covington 2002). Broadcast burning to decrease stocking is an option for these stands since the mean tree height is currently 4.3-ft.; however, no plans exist for implementation of prescribed burning due to the uncertain impacts of fire on the commercial value of these stands. In addition, burning in the Upper Pine Tree Logging Unit would compromise the continuation of this study. These stands, with the exception of the plots, will likely be entered within the next five to ten-years with an intermediate treatment utilizing a "free thin" cutting method with the goal of developing uneven-aged stand structure.

The strict "knee-high rule" treatment appears to be highly effective at controlling SWDM at Mescalero. By eliminating the variables identified in Conklin (2002) and implementing the treatment without compromise, we demonstrated that the occurrence of latent infections can be diminished to less than half of the infection level reported by Conklin (2002). These results demonstrated that the use of a strict "knee-high rule" treatment is a viable option for managing severely infested ponderosa pine stands prior to uneven-aged conversion. The incidence of trees with latent infections was low in this study; however, some of the infections detected during the 2015 re-measurement had just begun to produce aerial shoots. Additionally, the incidence of trees with latent infections did not taper off over time as expected (Table 2).

Future monitoring will provide a better estimate of the incidence of trees with latent infections in the treatment unit and the incubation period for SWDM on this site. Conklin (2002) and this study found that the incubation period for SWDM on the Mescalero is at least nine-years, which is one-year longer than the maximum incubation period reported for SWDM in northern Arizona (Hawksworth 1961). Although additional infections may likely be observed, it is expected that there will eventually be a definitive end to these expressions, possibly after ten-years. This is the basic reason that Hawksworth (1961) recommended retreating at five-year intervals; Conklin (2002) and my findings support this recommendation.

Thus far, we have estimated that about 2.3% of the trees ≤ 2-ft. tall in the sampled treatment area on the Mescalero were infected before the treatment was initiated. This low incidence of trees with latent infections suggests that the operations were effective in reducing SWDM infection to acceptable levels and that follow up treatments can further reduce the SWDM infection. If this treatment proves to be successful at controlling SWDM in the long term and these stands are able to develop to maturity with little of the parasite present, then managers will have an effective tool to reduce the high incidence and severity of SWDM and maximize fiber production on what were once potentially commercial lands.

Management Implications

A prolonged incubation period is the primary reason that complete eradication of SWDM is impractical in most settings. The objective of this study was to estimate the incidence of ponderosa pines with latent infections following a treatment referred to as the "knee-high rule" on the Mescalero. The results of the study demonstrated that this treatment resulted in a very low incidence of young ponderosa pines with latent infections (< 3%) and can be used to control SWDM in commercial ponderosa pine sites in the Sacramento Mountains. This management technique may be applicable in other SWDM infested pine stands due to the epidemiology of SWDM related to the dispersal and infection of regeneration.

Management of SWDM using the implementation of a strict “knee-high rule” that cuts all hosts > 2-ft. tall followed by sanitation retreatments five and ten years after the treatment may be the most economically efficient way to control SWDM in severely infested pine stands. This treatment requires sufficient natural pine regeneration ≤ 2-ft. tall prior to implementation and subsequent sanitations. In certain areas of the Southwest, regeneration is sporadic; therefore, treatments would need to be designed to capitalize on these events. Future observations at the Upper Pine Tree Logging Unit plots will provide more detailed data on the total number of retreatments required.

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