



Limber Pine Monitoring at Craters of the Moon National Monument and Preserve

Observations and Results from 2011-2013

Natural Resource Report NPS/UCBN/NRR—2018/1823



ON THE COVER

Limber pine (*Pinus flexilis* E. James) at Craters of the Moon National Monument and Preserve. Photograph by Devin Stucki, NPS.

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Abstract

Limber pine (*Pinus flexilis*) is susceptible to several threats including the introduced pathogen white pine blister rust (WPBR; *Cronartium ribicola*), the native mountain pine beetle (MPB; *Dendroctonus ponderosae*), and the native parasitic plant dwarf mistletoe (*Arceuthobium cyanocarpum*). Here we describe limber pine forest dynamics in Craters of the Moon National Monument and Preserve, Idaho (CRMO) including species composition and structure, cone production, and incidence and infection severity of WPBR, MPB, and dwarf mistletoe. We surveyed trees in 50 x 50 m plots (n=93), providing baseline estimates of limber pine stand structure within CRMO. Overall, limber pine stands at CRMO have a low proportion of dead trees (~5%). There are currently no observed WPBR infections and very few trees are affected by MPB. Dwarf mistletoe remains a widespread stressor, infecting about a third of limber pine trees. Dwarf mistletoe infection was associated with higher average annual precipitation, higher basal area of dead limber pine, and larger tree diameters. Ovulate cone production was associated with larger tree diameters and higher average annual minimum temperatures. A decrease in ovulate cone production was associated with higher basal area of live and dead limber pine and with presence of dwarf mistletoe infection. Crown kill estimates were higher with larger tree diameters and presence of dwarf mistletoe infection. Our initial results show that limber pine at CRMO are experiencing lower levels of WPBR and MPB and similar levels of dwarf mistletoe compared to other limber pine sites within the range of the species.

List of Acronyms

CRMO: Craters of the Moon National Monument and Preserve

DBH: diameter at breast height

MPB: mountain pine beetle

NPS: National Park Service

TPH: trees per hectare

UCBN: Upper Columbia Basin Network

WPBR: white pine blister rust

Introduction

Limber pine (*Pinus flexilis* E. James) is a widely distributed conifer that inhabits a variety of landscapes throughout western North America (Steele 1990). It is found across a wide elevation range, occurring at low elevation sites as well as in alpine and treeline habitats (Webster and Johnson 2000). In these harsh environments, limber pine acts as a foundational species (Tomback and Achuff 2010) and plays an important role in snowpack retention and acting as a nurse tree (Baumeister and Callaway 2006).

Limber pine is susceptible to several forest stressors including the invasive pathogen white pine blister rust (*Cronartium ribicola* J. C. Fisch; hereafter WPBR), which has caused large scale devastation to five-needle white pines throughout the Pacific Northwest and Intermountain Region (Schoettle et al. 2008b; Burns et al. 2011; Klutsch et al. 2011). In addition to WPBR, limber pine is also sensitive to mountain pine beetle (*Dendroctonus ponderosae* Hopkins, 1902; hereafter MPB), drought (Kendall et al. 1996; Achuff 1997), and fire suppression (Schoettle 2004a, 2004b). An additional stressor, dwarf mistletoe (*Arceuthobium cyanocarpum* A. Nelson ex Rydb.), is considered the second most important threat to limber pine other than WPBR (Kearns and Jacobi 2007; Taylor and Mathiasen 1999). Some species of dwarf mistletoe (e.g., *A. cyanocarpum*) are especially virulent and have caused widespread mortality of limber pine in the Rocky Mountains (Mathiasen and Hawksworth 1988).

The degree to which these threats are impacting limber pine stands varies geographically and over time. In Craters of the Moon National Monument and Preserve (CRMO), where this study takes place, we did not find evidence of WPBR and only minimal evidence of MPB within plots. WPBR was first identified within CRMO in 2006 where it appeared to be restricted to a single site situated in a mesic canyon near the extreme northern park boundary. CRMO resource management staff has actively engaged in an eradication effort comprised of WPBR early-detection surveys and the removal of infected branches and trees. The program tentatively appears to be a success as no further active WPBR infections have been found in CRMO since 2013. While the incidence of WPBR infection in CRMO is low, and non-existent within plots at CRMO, mean WPBR infection rates range from 0% to 49% infected trees per plot in the Rocky Mountains of Colorado, Wyoming, and Montana (Burns et al. 2011). As of 2009, MPB induced mortality was observed in 51.7% (15 of 29) sites in northern Colorado (Klutsch et al. 2011). In Alberta, limber pine plots resurveyed 5-6 years after installation demonstrated increases in the proportion of trees infected with WPBR (74% to 88%) as well as the proportion of dead individuals (32% to 35%; all causes combined) (Smith et al. 2013).

Objectives

Understanding current population demography and factors associated with diseases, pests, and reproduction is important for developing effective management strategies for limber pine. This study increases our understanding of limber pine by: (1) characterizing the current population size, size distribution, and pest and pathogen incidence for living limber pine in CRMO, and (2) identifying

topographic, tree-level, and stand-level factors associated with dwarf mistletoe infection and ovulate cone production for limber pine.

Methods

Plot Establishment

This study uses data collected in CRMO during the summers of 2011-2013. Here, limber pine is found across ~1,260 ha (20% of the woodland associations in the park; Figure 1). Plot design and sampling followed the NPS Pacific West Region Five Needle Pine Protocol (McKinney et al. 2012).

Plots were established and sampled at CRMO in a series of three panels, each panel consisting of 30 plots, starting with Panel 1 in 2011. In 2013, three additional plots (n=33) were established and surveyed because of an issue with road access which restricted access to several plots. Access was restored to the restricted plots and the three additional plots were added to Panel 3.

The sampling points for all three field seasons were generated using the Generalized Random Tessellation Stratified (GRTS) algorithm (Stevens and Olson 2004) in a geographic information system (GIS). In addition, an oversample of points was also drawn using the GRTS algorithm to support any eventual site rejections.

The sampling frame was limited to exclude slopes greater than 35° and locations further than 2 km from a road or trail. Sites were rejected if (1) no limber pine were found, or (2) sampling the area would result in unsafe working conditions (e.g., terrain that was too steep to work on). The GRTS points generated in the GIS were used as the southwest corner (plot origin) of the 50 m x 50 m plots if one or more limber pine ≥ 1.37 m in height were found within the plot boundary. If there were no limber pine individuals in a plot, an offset procedure was employed by drawing a random distance (between 5 and 100 m) and azimuth (between 0° to 359°) from a list of random numbers. Lastly, if the offset procedure did not generate a useable plot, a new point was used from the oversample described above. Additional details on plot locations, oversample plots used, and the GRTS algorithm can be found in McKinney et al. (2012).

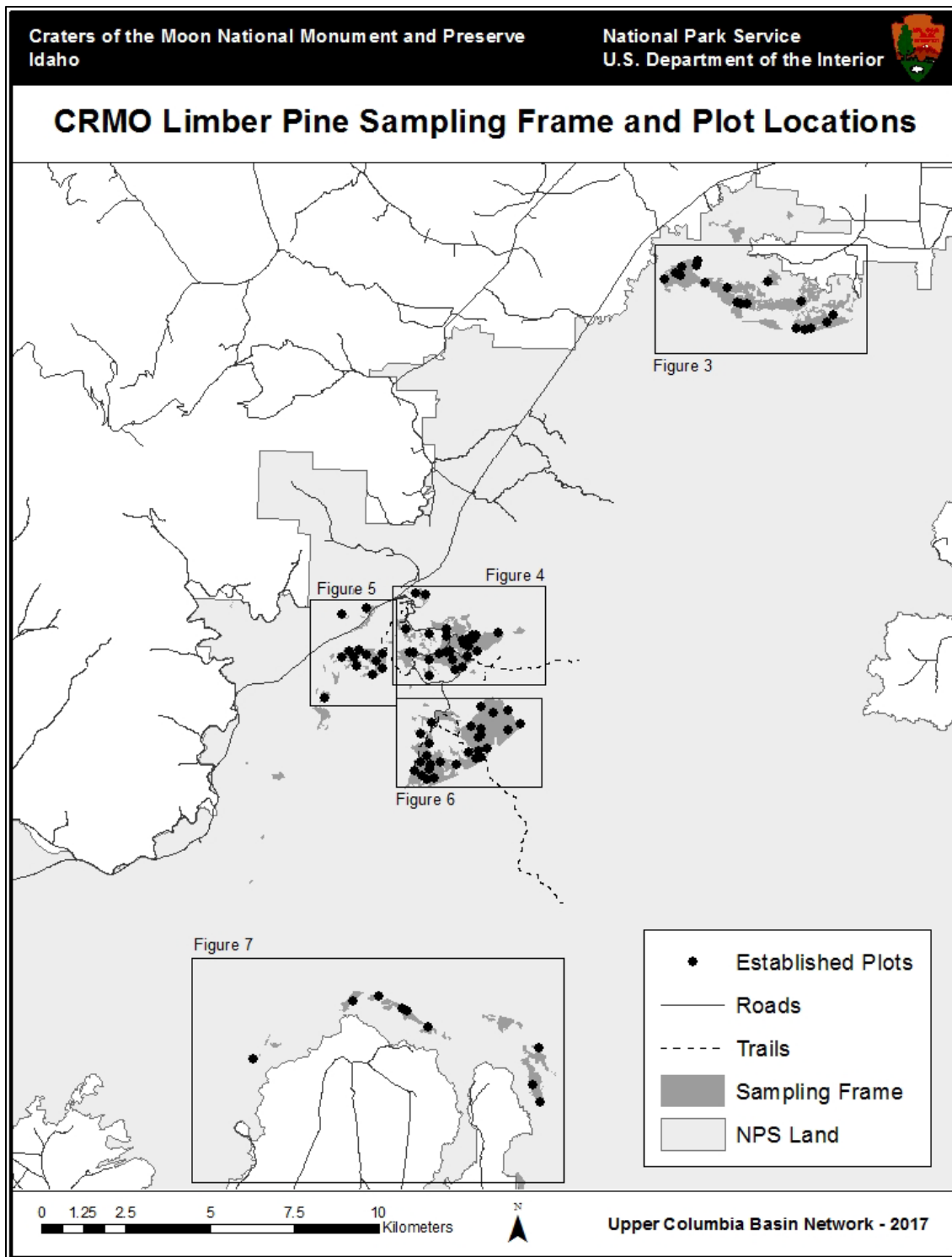
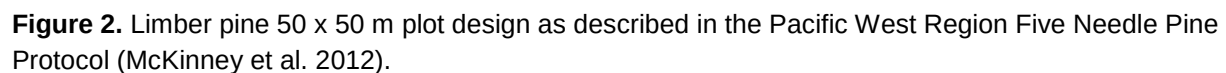


Figure 1. Limber pine monitoring sampling frame and established plot locations ($n=93$) within Craters of the Moon National Monument and Preserve (CRMO; light grey). The sampling frame (dark grey) includes all areas of the park within 2 km of roads and trails that have been mapped by Bell et al. (2009) as *Pinus flexilis* woodland. Plots were established from 2011-2013.

Each 50 m x 50 m plot consists of five 10 m x 50 m subplots and nine regeneration plots (Figure 2). Within plots, all trees ≥ 1.37 m in height were identified to species and tagged with a unique identification number. The diameter at breast height (DBH) and height of each tree was recorded. In addition, each limber pine was assessed for symptoms of WPBR and dwarf mistletoe and signs of MPB. Standing dead trees ≥ 1.37 m in height were also tagged with unique identification numbers and the height and DBH measured and recorded. Seedlings (trees < 1.37 m in height) were counted by species and height class in each of the nine regeneration plots.



We provide general summaries of the structure of limber pine stands in our plots including size distributions of trees (both alive and dead), the proportion of dead trees, ovulate cone production, and recruitment. In addition, we summarized the prevalence of dwarf mistletoe across the plots. We calculated the proportion of average crown kill by averaging all values of percent crown kill recorded for the lower, middle, and upper portions of each tree.

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using the logit link function and (3) the average proportion of crown killed using beta regression. Beta regression is a favorable approach to modeling proportions that fall between 0 and 1 but not values of exactly 0 or 1. The proportion average crown killed included proportions of 0 and 1 and therefore, we used a common transformation of the dependent variable that constrains the distribution to values that occur within the interval (0, 1) (Smithson and Verkuilen 2006).

Climate data (annual precipitation and annual minimum temperature average normals spanning from 1981-2011) were sampled for each plot location at a spatial resolution of 800 m (~30 arc seconds) from the Parameter-elevation Regression on Independent Slopes Model developed by the PRISM Group at Oregon State University (Daly et al. 1994, 2000, 2002; PRISM Climate Group 2004).

We chose to include covariates that represented abiotic and biotic drivers of dwarf mistletoe infection, ovulate cone production, and crown kill. These stand-level variables included elevation (m), longitude, basal area per hectare dead limber pine (m^2/ha), and basal area per hectare living limber pine (m^2/ha), 30-year average normals for annual precipitation (mm), and annual minimum temperature ($^{\circ}\text{C}$) (Table 1). We also included the tree-level covariate tree DBH (cm) for each model and dwarf mistletoe (y/n) for the model predicting the probability of producing ovulate cones and proportion crown kill.

Table 1. Stand- and tree-level variables included in generalized linear mixed effects models (GLMMs) or generalized linear models (GLM) conducted for all dependent variables in Craters of the Moon National Monument and Preserve (CRMO).

Type	Code	Description
Stand-level variables	Longitude	Longitude (minutes, degrees, seconds)
	Live limber pine	Live limber pine (basal area; m^2/ha)
	Dead limber pine	Dead limber pine (basal area; m^2/ha)
	Precipitation	Annual precipitation (30-year average normals)
	Minimum temperature	Minimum temperature (30-year average normals)
Tree-level variables	DBH	Diameter at breast height (cm)
	Cones	Ovulate cones (y/n)
	Mistletoe	Dwarf mistletoe infection (y/n)
	Proportion crown kill	Proportion of average crown kill

For the model predicting the average proportion crown kill we chose to use data from 2013 only ($n=471$), excluding data from 2011 and 2012. This was done for two reasons: 1) in 2011 field crews observed crown kill on limber pines with mistletoe only, excluding limber pine without infection, and 2) in 2012 field crews did not record crown kill estimates.

For both models, we began by rescaling continuous covariates such that each were standardized around a mean of 0.0 and a standard deviation equal to that of the unscaled variable. Standardizing

variables aids in the interpretation of coefficients, especially if they are on different scales (Gelman 2008). Standard errors, P-values, and 95% confidence intervals were also generated for each model. To determine the sensitivity of candidate models (the number of correctly classified trees) we used the area under the receiver operating characteristic (ROC) curve (Saveland and Neuenschwander 1990). Receiver operating characteristic (ROC) curve (AUC [area under curve]) >0.80 suggest excellent model discrimination (i.e., the ability of the model to correctly classify those with and without the cones; Hosmer and Lemeshow 2000). To assess model fit, we computed both marginal and conditional R^2 for models employing the binomial distribution ($R^2_{GLMM_m}$ and $R^2_{GLMM_c}$ Nakagawa and Schielzeth 2013) and pseudo R^2 values for models employing the beta distribution (Ferrari and Cribari-Neto 2004).

We assessed both models for overdispersion, a common problem associated with modeling count data, where the variance of the response variable is greater than the mean (Hilbe 2011). All statistical analysis were performed in R version 3.2.3 (R Development Team 2015). We used the glmer function in the R library lme4 (Bates et al. 2015) for models utilizing the binomial distribution and we used the function glmmADMB in the R package glmmADMB (Fournier et al. 2012) for beta regression.

Results

A total of 1576 live trees ≥ 1.37 m in height were measured across the 93 plots established between 2011 and 2013, of which 1445 were limber pine, 72 were Rocky Mountain juniper (*Juniperus scopulorum*), and 59 were Douglas-fir (*Pseudotsuga menziesii*; Table 2). We recorded 62.15 (SD $\pm$ 75.71) living limber pines per hectare (ha; Figures 3-5), 3.09 (SD $\pm$ 10.30) living juniper trees per ha, and 2.53 (SD $\pm$ 24.05) Douglas-fir trees per ha (Table 2). Juniper was found in 13 plots (14% of plots), 12 of which occurred in the northern most section of plots and 1 in the central section of plots while Douglas fir was found in 2 plots (2.1% of plots) both in the central portion of plots on north facing slopes. On average, 4.97% (SD $\pm$ 10.33%) of limber pine trees ≥ 1.37 m in height were dead, and 16.6% of the total limber pine basal area was dead (Table 2, Figures 3-7). Most living limber pine were small, with only 5% of trees being >40 cm DBH (Figure 8). A total of 41 seedlings were found in the 93 plots (Figure 9). Because seedlings are only assessed in regeneration plots, and these cover 81 m² in each plot (Figure 2), we estimated an average of 54 seedlings per ha.

Table 2. Summary statistics of living and dead trees sampled in 93 plots in Craters of the Moon National Monument and Preserve (CRMO). Mean values among plots (n=93) and 1.0 standard deviations (SD) are shown.

Metric	Mean	SD
Live limber pine trees (# individuals/ha)	62.15	75.71
Live Rocky Mountain juniper trees (# individuals/ha)	3.09	10.30
Live Douglas fir trees (# individuals/ha)	2.53	24.05
Live limber pine trees (basal area; m ² /ha)	1.72	2.08
Live Rocky Mountain juniper trees (basal area; m ² /ha)	0.06	0.30
Live Douglas fir trees (basal area; m ² /ha)	0.24	2.33
Dead limber pine (# individuals/ha)	3.52	8.31
Dead limber pine (basal area; m ² /ha)	0.28	0.62
Live limber pine infected with dwarf mistletoe (basal area; m ² /ha)	0.84	1.71

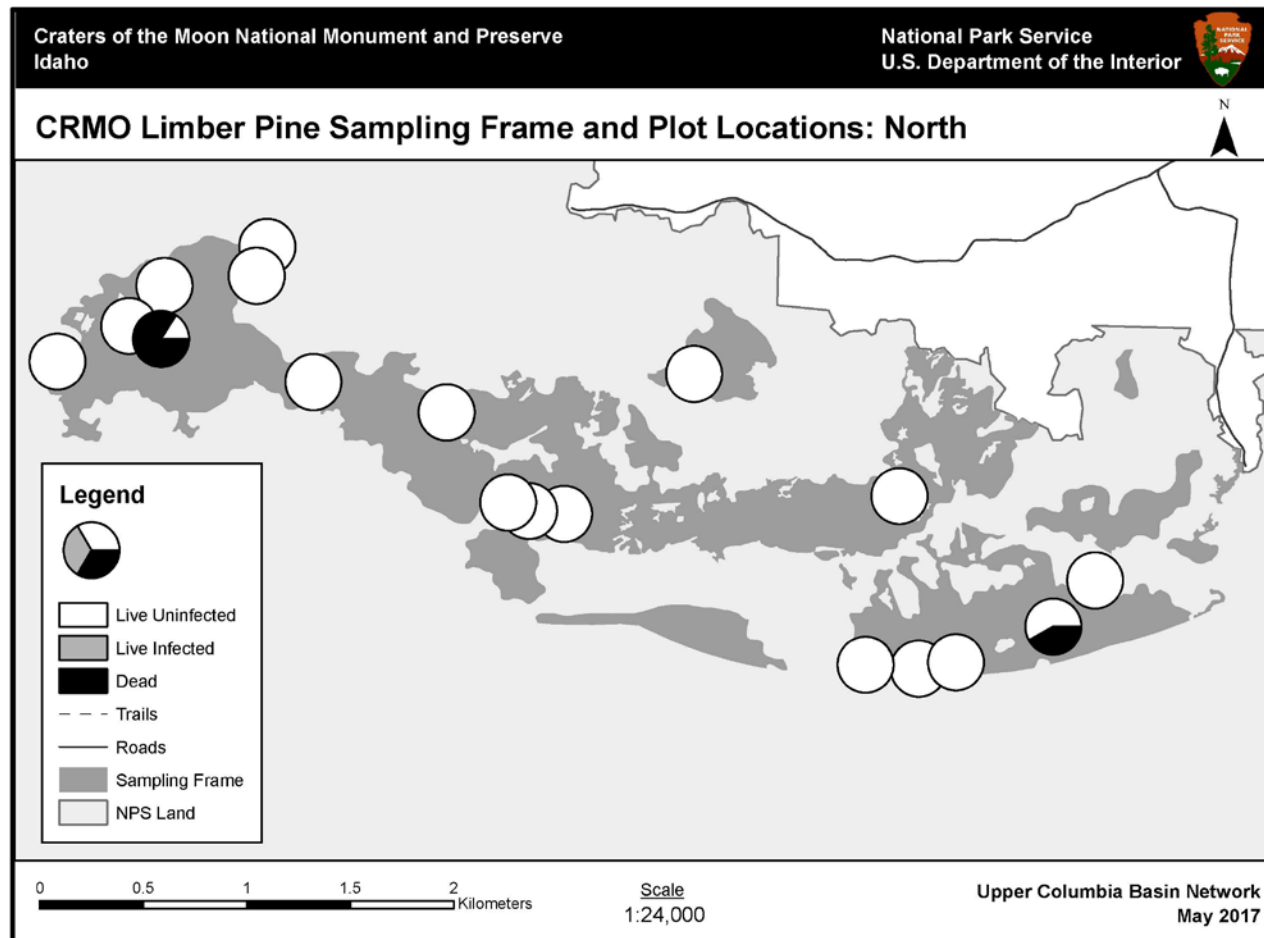


Figure 3. Relative proportion of limber pine (PINFLE) basal area at monitoring sites in the northern part of the sampling frame (near the town of Arco, ID) at Craters of the Moon National Monument and Preserve (CRMO). Plots were established from 2011-2013. Dead = dead limber pine (black), Live Uninfected = live limber pine uninfected by dwarf mistletoe (white), and Live Infected = live limber pine infected by dwarf mistletoe (grey).

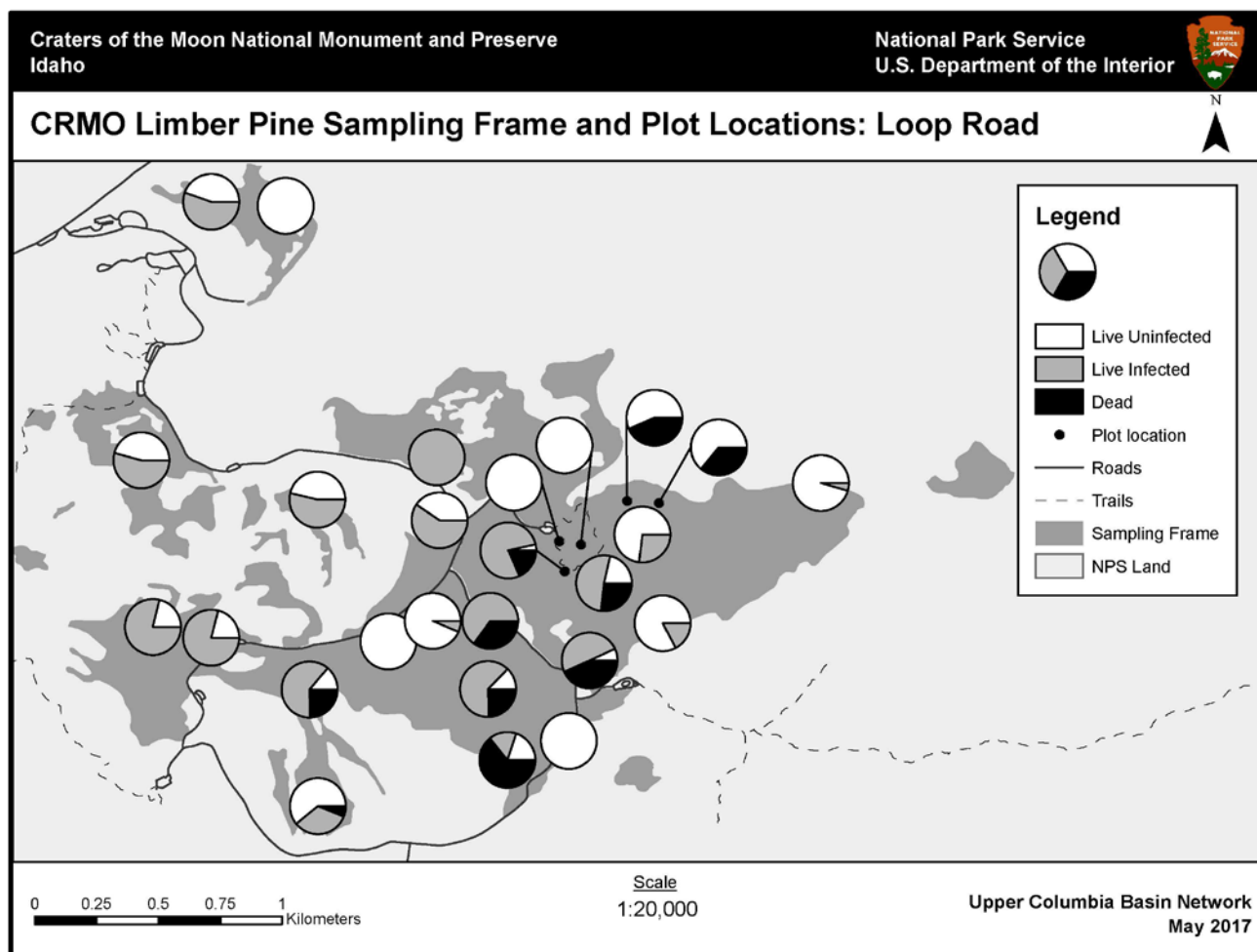


Figure 4. Relative proportion of limber pine (PINFLE) basal area at monitoring sites near the Visitor Center and along the Loop Road at Craters of the Moon National Monument and Preserve (CRMO). Plots were established from 2011-2013. Dead = dead limber pine (black), Live Uninfected = live limber pine uninfected by dwarf mistletoe (white), and Live Infected = live limber pine infected by dwarf mistletoe (grey).

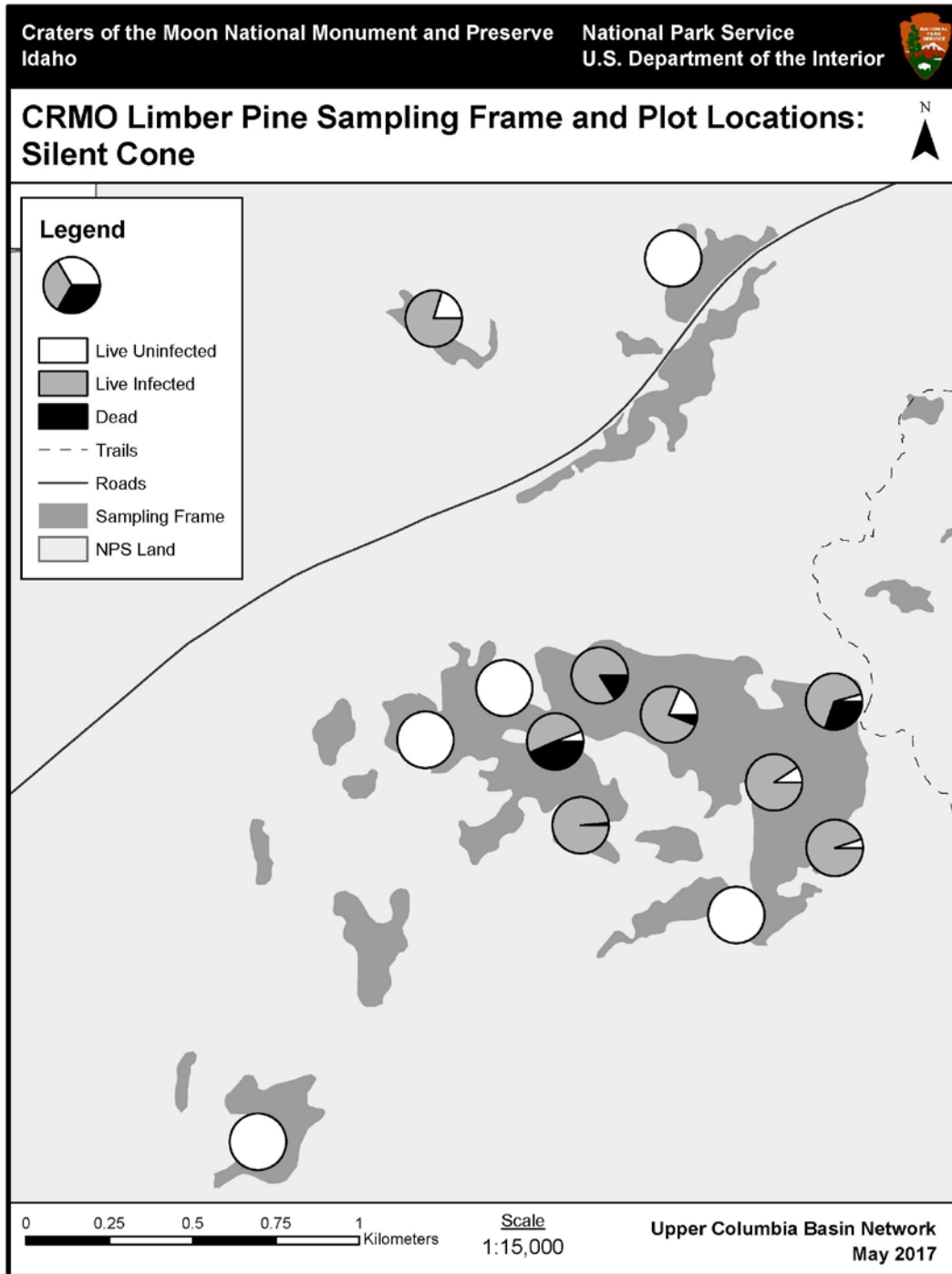


Figure 5. Relative proportion of limber pine (PINFLE) basal area at monitoring sites near Silent Cone and Grassy Cone at Craters of the Moon National Monument and Preserve (CRMO). Plots were established from 2011-2013. Dead = dead limber pine (black), Live Uninfected = live limber pine uninfected by dwarf mistletoe (white), and Live Infected = live limber pine infected by dwarf mistletoe (grey).

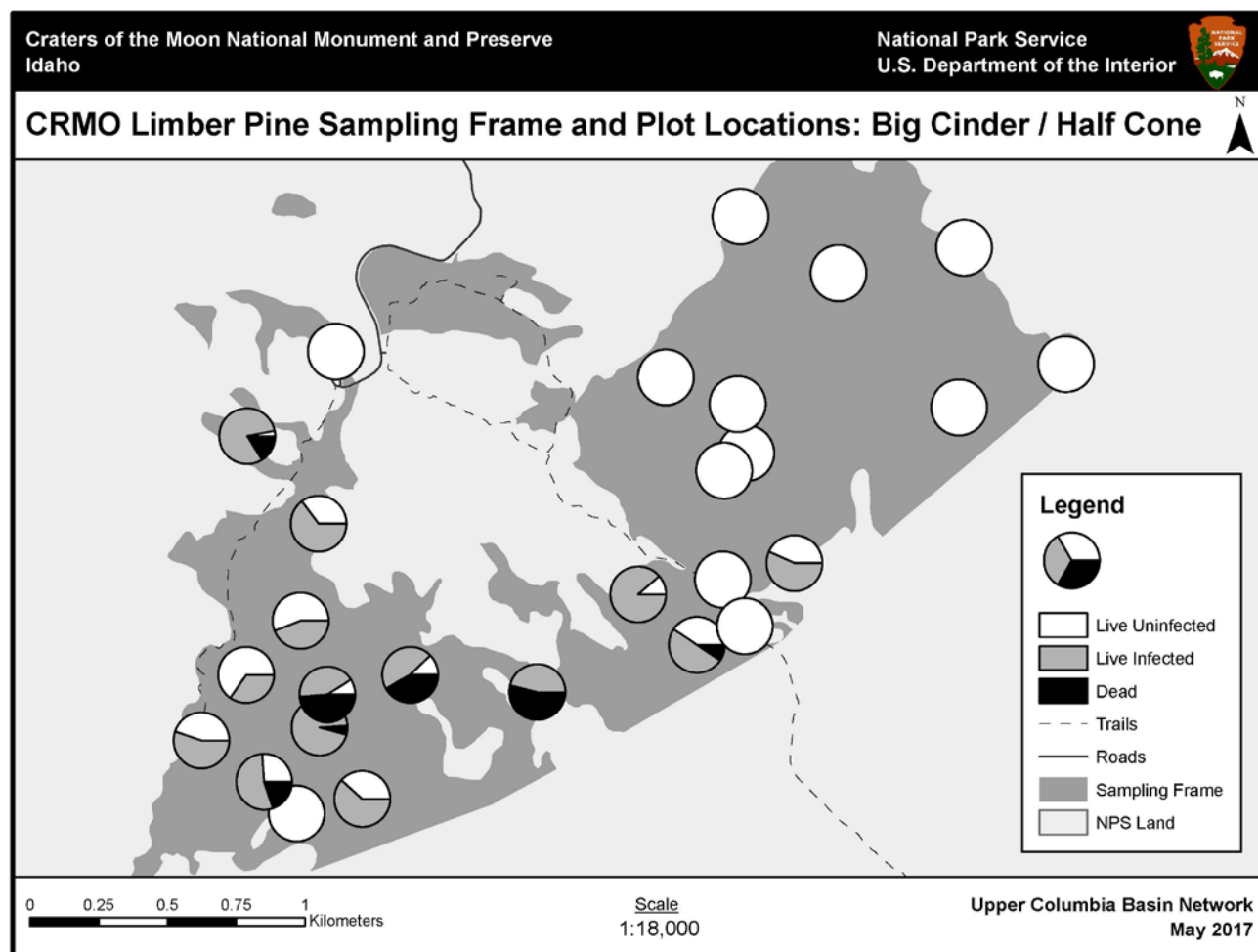


Figure 6. Relative proportion of limber pine (PINFLE) basal area at monitoring sites near Big Cinder Butte and Half Cone at Craters of the Moon National Monument and Preserve (CRMO). Plots were established from 2011-2013. Dead = dead limber pine (black), Live Uninfected = live limber pine uninfected by dwarf mistletoe (white), and Live Infected = live limber pine infected by dwarf mistletoe (grey).

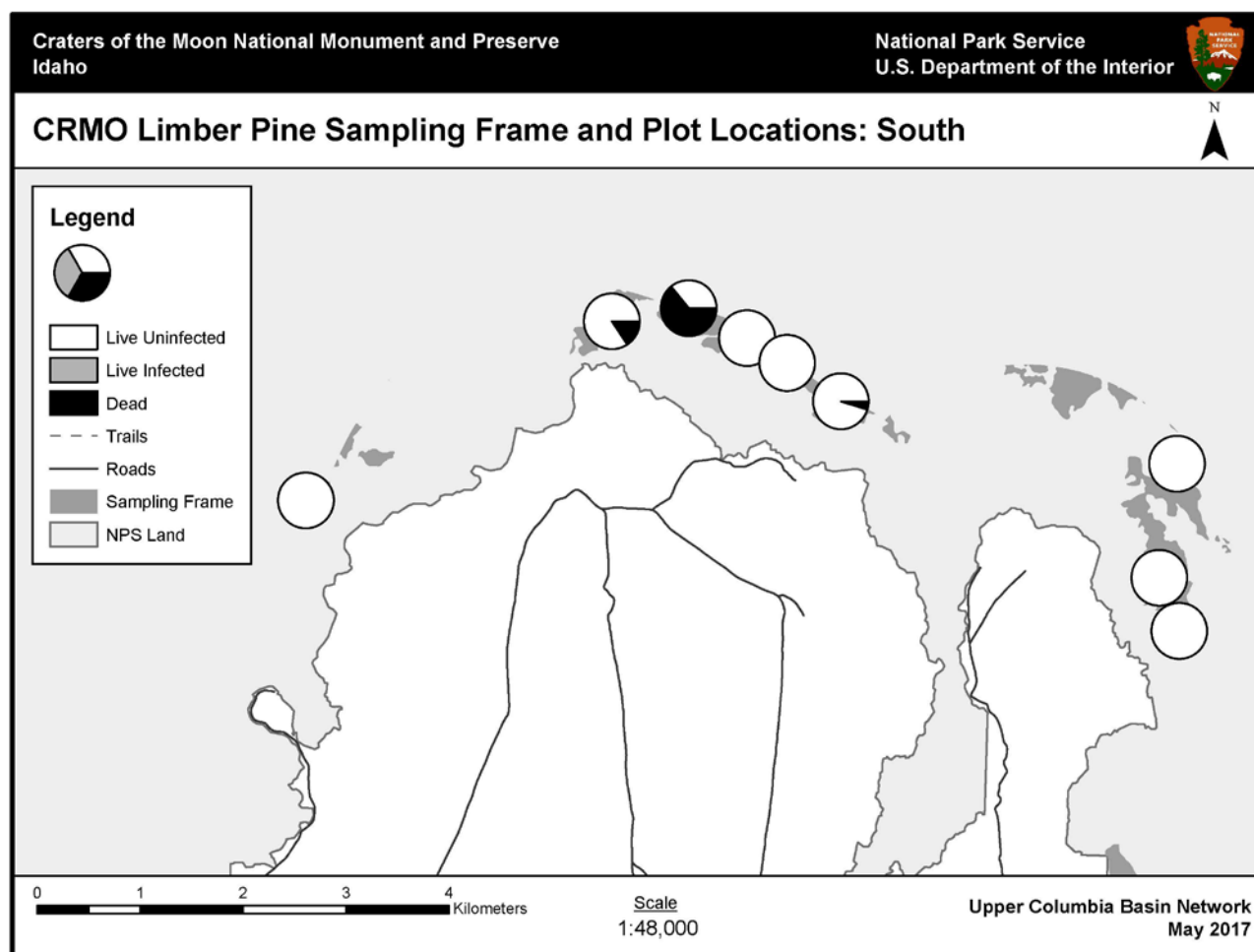


Figure 7. Relative proportion of limber pine (PINFLE) basal area at monitoring sites near Laidlaw Park at Craters of the Moon National Monument and Preserve (CRMO). Plots were established from 2011-2013. Dead = dead limber pine (black), Live Uninfected = live limber pine uninfected by dwarf mistletoe (white), and Live Infected = live limber pine infected by dwarf mistletoe (grey).

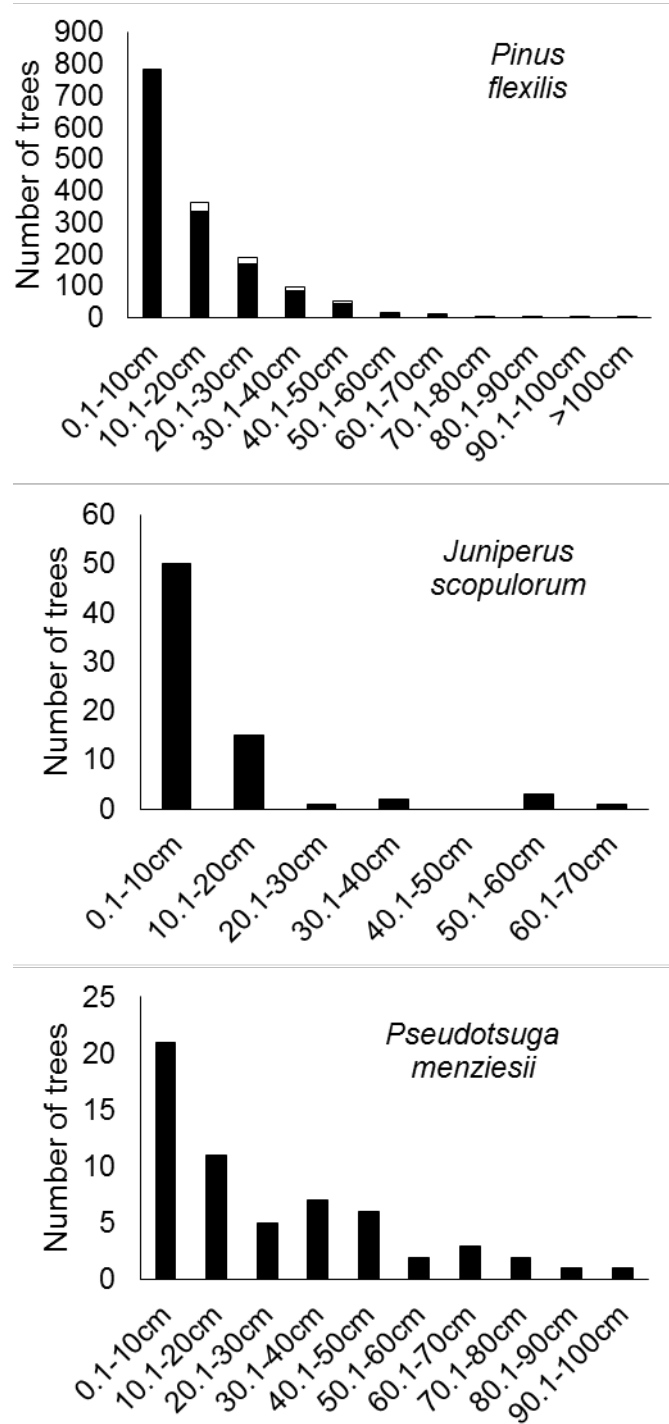


Figure 8. Size distributions of all species found in monitoring plots established during 2011-2013 at Craters of the Moon National Monument and Preserve (CRMO). Black bars represent living trees and white bars represent dead trees.

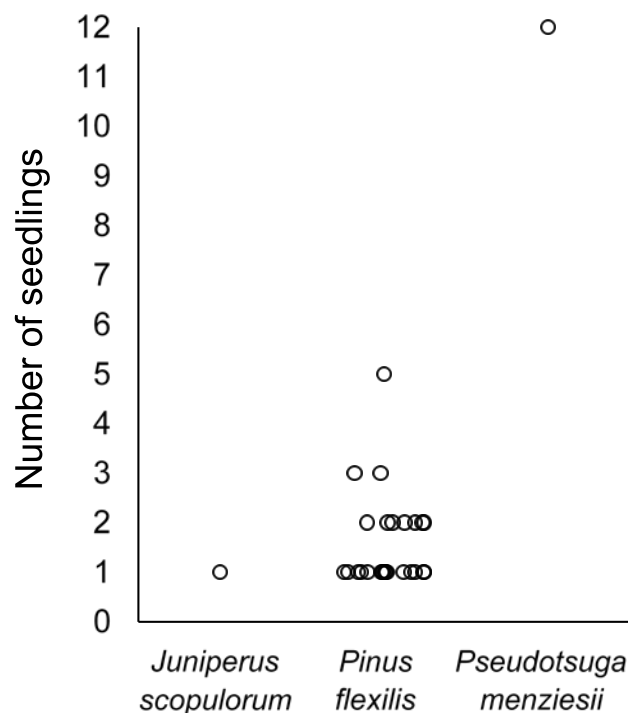


Figure 9. Number of seedlings in 93 limber pine monitoring plots in Craters of the Moon National Monument and Preserve (CRMO). Points are jittered to allow easier viewing.

The incidence of dwarf mistletoe infection ranged from 0% (of trees in a plot) to 100%, and the average basal area (m^2/ha) of infected live limber pine was 0.84 ($\text{SD} \pm 1.71$; Figures 3-5). Of the 1445 live trees assessed, 525 showed signs of dwarf mistletoe infection. Meanwhile, MPB infestations were largely absent with only 7 of 1445 (<1%) living limber pines showing MPB sign. The average proportion crown kill among plots surveyed in 2013 was 17.15% ($\text{SD}=10.41\%$; $n=471$). Of the 82 dead trees that could be identified as limber pine, 1 (1%) died from a broken stem, 5 (6%) from mountain pine beetle, and 13 (16%) from dwarf mistletoe. The remainder (63 trees, 77%) died from unknown causes (Table 3). Summary statistics of unstandardized covariates included in each of the three generalized linear mixed effects models are presented in Table 4.

Increases in precipitation (0.76) were strongly correlated to increases in elevation while increases in minimum temperatures exhibited a weaker correlation with increases in elevation (0.56).

The probability of observing dwarf mistletoe on living limber pine increased with tree size (DBH: cm) ($\beta=1.324$, 95% CI=1.064 to 1.601), basal area of dead limber pine ($\beta=0.777$, 95% CI=0.114 to 1.495), and precipitation ($\beta=3.497$, 95% CI=1.413 to 9.752; Table 5). The model predicting the occurrence of dwarf mistletoe on living limber pine provided excellent model discrimination and correctly classified 84% of all observed cases ($\text{AUC}=0.922$, error rate= 0.162). The $R^2_{\text{GLMM}_m}$ and $R^2_{\text{GLMM}_c}$ for this model were 0.604 and 0.855, respectively.

The probability of observing ovulate cones increased with tree size (DBH:cm) ($\beta=2.152$, 95% CI=1.846 to 2.481) and average annual minimum temperature ($\beta=0.596$, 95% CI=0.149 to 1.073) and

decreased for trees with dwarf mistletoe ($\beta=-0.456$, 95% CI=-0.804 to -0.111) or in plots with greater basal area of both dead ($\beta=-0.380$, 95% CI=-0.575 to -0.179) and live limber pine ($\beta=-0.349$, 95% CI=-0.599 to -0.102; Table 5). The model predicting the occurrence of cones of living limber pine provided moderate model discrimination and correctly classified 79% of all observed cases (AUC=0.856, error rate=0.203). The $R^2_{\text{GLMM}_m}$ and $R^2_{\text{GLMM}_c}$ for this model were 0.560 and 0.590, respectively.

Our model indicated that the average proportion of crown kill was associated with previous dwarf mistletoe infection ($\beta=0.442$, 95% CI=0.260 to 0.624) and larger tree size (DBH:cm) ($\beta=0.242$, 95% CI=0.158 to 0.326). The pseudo r-square value for this model was 0.158.

Table 3. Number of individual limber pine trees (n=82) and percentage of trees dying from particular mortality agents in 93 plots in Craters of the Moon National Monument and Preserve (CRMO).

Cause of mortality	Number of trees	Percent mortality
Broken stem	1	1%
Mountain pine beetle	5	6%
Dwarf mistletoe	13	16%
Unknown	63	77%

Table 4. Summary statistics of elevation and the unstandardized covariates included in each of the three generalized linear mixed effects models (GLMMs) in Craters of the Moon National Monument and Preserve (CRMO). The values below represent averages and standard deviations for each covariate across all plots (n=93) except for values concerning the average proportion crown kill where the data presented represents values for plots recorded in 2013 only (n=33).

Type	Variable	Mean (SD)
Stand-level variables	Elevation	1762.96 ($\pm$ 76.65)
	Longitude	-113.52 ($\pm$ 0.04)
	Living limber pine (basal area; m ² /ha)	1.72 ($\pm$ 2.08)
	Dead limber pine (basal areal; m ² /ha)	0.28 ($\pm$ 0.62)
	Average annual precipitation (mm)	355.88 ($\pm$ 35.89)
	Average annual minimum temperature (°C)	-1.33 ($\pm$ 0.52)
Tree-level variables	DBH	13.97 ($\pm$ 13.95)
	Average proportion crown kill	17.15 ($\pm$ 10.41)

Table 5. Estimated effects of site characteristics from the best supported generalized linear mixed effects model (GLMM) of the probability of dwarf mistletoe, the probability of producing ovulate cones, the proportion of average crown kill for limber pine in Craters of the Moon National Monument and Preserve (CRMO). *P*-values indicate significance of the Wald Z-test statistic.

Site characteristics	Metric	Est	Std. Error	<i>P</i>	95 % CI
Incidence of dwarf mistletoe	DBH	1.324	0.137	<0.001	(1.064 – 1.601)
	Basal area dead limber pine	0.777	0.340	0.023	(0.114 – 1.495)
	Precipitation (mm)	3.497	1.673	0.037	(1.413 -- 9.752)
	Average annual min temp	-1.415	1.132	0.211	(-3.541 – 1.468)
	Basal area live limber pine	0.732	0.467	0.117	(-0.188 -- 1.712)
	Longitude	-0.973	0.864	0.260	(-2.561 – 1.123)
Production of ovulate cones	DBH	2.152	0.161	<0.001	(1.846 – 2.481)
	Basal area dead limber pine	-0.380	0.099	<0.001	(-0.575 – -0.179)
	Basal area live limber pine	-0.349	0.124	0.005	(-0.599 – -0.102)
	Average annual min temp	0.596	0.232	0.010	(0.149 – 1.073)
	Dwarf mistletoe	-0.456	0.177	0.010	(-0.804 – -0.111)
	Longitude	0.308	0.251	0.219	(-0.213 – 0.787)
	Precipitation (mm)	-0.171	0.385	0.621	(-0.912 – 0.467)
Average proportion crown kill	DBH	0.242	0.043	<0.001	(0.158 – 0.326)
	Dwarf Mistletoe	0.442	0.093	<0.001	(0.260 – 0.624)
	Basal area dead limber pine	0.064	0.044	0.156	(-0.022 – 0.150)
	Precipitation (mm)	-0.123	0.150	0.413	(-0.417 – 0.171)
	Basal area live limber pine	-0.023	0.056	0.698	(-0.133 – 0.087)
	Average annual min temp	0.063	0.103	0.544	(-0.139 – 0.265)
	Longitude	-0.116	0.097	0.236	(-0.306 – 0.074)

Discussion

Results from this study have provided important information about the status of limber pine in CRMO: (i) trees in areas with greater precipitation are more likely to have dwarf mistletoe infections, (ii) tree size is an important indicator for ovulate cone production, dwarf mistletoe infection, and crown kill, and (iii) trees with dwarf mistletoe infections are less likely to produce ovulate cones and more likely to contain higher crown kill estimates. In addition, we found that trees growing in greater densities of dead limber pine were more likely to have dwarf mistletoe infections. The majority of trees sampled were living limber pines less than 40cm DBH, yet, Douglas fir constituted the majority of basal area of living trees (concentrated within panel 1, plot 27). Plot level mortality rates were low (5%; see Results) and for most dead trees (77%; Table 3) the cause of death could not be determined.

Our models indicated that dwarf mistletoe infections were more likely in areas that experienced greater precipitation. In our study, increases in precipitation were strongly correlated to increases in elevation (see Results). Trees experience harsher conditions at higher elevations and are more sensitive to changes in climate (Millar et al. 2007), which may leave them more susceptible to dwarf mistletoe infections. Drought-like conditions, in conjunction with mistletoe infections, decrease tree vigor and may predispose trees to mountain pine beetle infestations, resulting in widespread tree mortality (Millar et al. 2007). In stands with greater densities of dead limber pine, we observed greater numbers of living limber pine infected with dwarf mistletoe (Table 5). The apparent relationship between increasing stand density and dwarf mistletoe infection is consistent with the findings of other studies in regions south of CRMO (Cleaver et al. 2015; Millar et al. 2007). In addition, we also found that increases in tree DBH are associated with dwarf mistletoe infections (Table 5). Others have reported similar findings in the southern and central Rocky Mountains and have attributed this relationship to larger surface area available for dwarf mistletoe colonization during seed dispersal (Cleaver et al. 2015). In our study, crown kill estimates were higher in trees that had existing dwarf mistletoe infections and trees with larger DBH.

Ovulate cone production varied with average annual minimum temperatures and our models indicated that trees experiencing hotter minimum temperatures were more likely to produce ovulate cones (Table 5). The apparent relationship between cone production and temperature may be a result of favorable growing conditions as trees experience less cold-stress, or due to lower incidences of dwarf mistletoe found in areas with higher average minimum temperatures. In this study, areas that experienced the highest minimum temperatures occurred on the east side of the park at the lowest elevations. Stand conditions associated with decreases in ovulate cone production include greater densities of both dead and living limber pine (Table 5). Increases in the number of dead limber pine could indicate mortality from dwarf mistletoe (16% in this study), which we also found to be negatively affecting cone production. Furthermore, increases in the densities of living and dead trees may be due to increased competition for light and other resources, and may result in limited cone production. Limited cone production due to high tree density has been documented for whitebark pine in the Rocky Mountains (McCaughy and Tomback 2001) and Southern Cascades (Jackson 2016). Furthermore, ovulate cone production was also associated with trees of larger DBH (Table 5). Limber pine delay reproduction until they reach maturation, around 50 years after seedling

establishment (Schoettle 2004a), and during this period of growth, the tree increases in width and height, allowing for more access to sunlight. Lastly, our models indicated that the probability of producing ovulate cones was decreased for trees with concurrent dwarf mistletoe infection (Table 5). Other stressors, including WPBR, have been acknowledged as reducing the cone bearing potential of infected trees (Kearns and Jacobi 2007). Other research has also shown that dwarf mistletoe infections reduce reproduction, growth, quality, and longevity of the infected host (Geils and Hawksworth 2002).

Conclusions

In this study we document the current state of limber pine forests in CRMO using data collected from 93 long-term monitoring plots established during the 2011-2013 summer field seasons. Limber pine is the dominate tree species found within the plots, though Rocky Mountain juniper and Douglas-fir trees are also present. Overall, limber pine woodlands at CRMO have a low proportion of standing dead trees (~5%). There are currently no observed WPBR infections and very few trees are affected by MPB. Dwarf mistletoe remains a widespread stressor within limber pine stands and more than a third of all limber pine within the study area are infected. Increasing elevations, high basal area of dead limber pine, and trees with larger DBH were associated with an increased probability of dwarf mistletoe infection. Crown kill estimates were associated with presence of dwarf mistletoe and larger DBH. Ovulate cone production was associated with trees of larger DBH and locations with higher minimum temperatures, and a decline in cone production was associated with increased basal area of dead and living limber pine, and dwarf mistletoe infection. These results are consistent with studies of limber pine from other areas including the Sierra Nevada and Rocky Mountains (Cleaver et al. 2015; Millar et al. 2007). Continued long-term monitoring of these established plots will provide further opportunities to assess the status and trend of the unique limber pine population in CRMO, information that may be applicable to other peripheral forests bordering the Snake River Plain in Southeast Idaho.

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Appendix A. Location information and site characteristics for limber pine monitoring plots established in CRMO in 2011, 2012, and 2013.

Table A1. Plots with recorded aspect and slope values of 0° represent relatively flat or undulating lava flow terrains with no apparent overall slope or aspect.

Plot ID	Panel	Year Established	Elevation (m)	Aspect (°)	Slope (°)
1	1	2011	1655	0	0
2	1	2011	1658	0	0
3	1	2011	1828	340	5
4	1	2011	1823	0	19
5	1	2011	1655	0	0
6	1	2011	1774	80	4
7	1	2011	1820	228	21
8	1	2011	1773	76	9
9	1	2011	1652	0	0
11	1	2011	1811	0	0
12	1	2011	1666	0	0
13	1	2011	1647	0	0
14	1	2011	1795	0	0
15	1	2011	1906	86	18
16	1	2011	1681	0	0
17	1	2011	1654	0	0
19	1	2011	1780	0	0
20	1	2011	1753	188	2
21	1	2011	1652	0	0
22	1	2011	1771	0	0
23	1	2011	1797	215	6
24	1	2011	1772	48	3
27	1	2011	1899	40	27
28	1	2011	1671	0	0
30	1	2011	1865	248	14
91	1	2011	1828	272	11

Table A1 (continued). Plots with recorded aspect and slope values of 0° represent relatively flat or undulating lava flow terrains with no apparent overall slope or aspect.

Plot ID	Panel	Year Established	Elevation (m)	Aspect (°)	Slope (°)
92	1	2011	1769	45	4
93	1	2011	1641	0	0
94	1	2011	1796	48	5
95	1	2011	1755	0	0
31	2	2012	1828	20	14
35	2	2012	1780	0	0
36	2	2012	1756	0	0
37	2	2012	1649	0	0
40	2	2012	1785	32	7
42	2	2012	1776	0	0
43	2	2012	1822	0	0
44	2	2012	1622	0	0
47	2	2012	1833	38	10
48	2	2012	1695	0	0
51	2	2012	1807	356	12
52	2	2012	1756	0	0
53	2	2012	1651	0	0
55	2	2012	1790	260	6
56	2	2012	1783	43	11
58	2	2012	1837	10	7
59	2	2012	1828	134	16
60	2	2012	1696	0	0
96	2	2012	1704	340	3
99	2	2012	1776	320	7
100	2	2012	1753	0	0
101	2	2012	1652	0	0
103	2	2012	1807	220	10
104	2	2012	1751	0	0
106	2	2012	1776	2	3
107	2	2012	1854	11	23

Table A1 (continued). Plots with recorded aspect and slope values of 0° represent relatively flat or undulating lava flow terrains with no apparent overall slope or aspect.

Plot ID	Panel	Year Established	Elevation (m)	Aspect (°)	Slope (°)
109	2	2012	1650	0	0
110	2	2012	1645	0	0
111	2	2012	1838	304	9
112	2	2012	1754	0	0
61	3	2013	1650	0	0
62	3	2013	1859	45	12
63	3	2013	1751	0	0
64	3	2013	1700	0	0
66	3	2013	1786	0	0
67	3	2013	1817	96	20
69	3	2013	1651	0	0
71	3	2013	1880	316	20
75	3	2013	1785	0	0
76	3	2013	1751	0	0
78	3	2013	1785	0	0
79	3	2013	1800	42	6
82	3	2013	1858	350	12
83	3	2013	1820	222	15
87	3	2013	1799	38	0
88	3	2013	1770	45	5
90	3	2013	1774	0	0
114	3	2013	1760	0	0
115	3	2013	1810	290	30
116	3	2013	1761	45	5
117	3	2013	1649	0	0
118	3	2013	1876	133	19
119	3	2013	1886	230	10
122	3	2013	1646	0	0
123	3	2013	1789	320	12
124	3	2013	1756	0	0

Table A1 (continued). Plots with recorded aspect and slope values of 0° represent relatively flat or undulating lava flow terrains with no apparent overall slope or aspect.

Plot ID	Panel	Year Established	Elevation (m)	Aspect (°)	Slope (°)
147	3	2013	1867	276	18
149	3	2013	1651	0	0
150	3	2013	1967	24	20
151	3	2013	1767	0	2
152	3	2013	1694	0	0
156	3	2013	1823	0	17
159	3	2013	1817	0	25

Appendix B. Measured variables and collected data for white pine monitoring according to McKinney et al. (2012).

Table B1. White pine monitoring variables.

Variable	Data Recorded
Species	Tree (nominal)
Diameter	Tree (cm)
Height	Tree (m)
Status	Tree (live or dead)
Crown kill	Each of three parts of a tree (%)
Active canker	Each of three parts of a tree (present/absent)
Inactive canker	Each of three parts of a tree (present/absent)
Rust infection	Tree (presence/absence of active or inactive canker)
Pine beetle	Tree (present/absent)
Dwarf mistletoe	Tree (present/absent)
Female cones	Tree (present/absent)
Seedlings	9 m ² plot; number of each of three size classes by species

Appendix C. Summary statistics for 93 limber pine monitoring plots established in Craters of the Moon National Monument and Preserve (CRMO) in 2011, 2012, and 2013.

Table C1. Summary statistics for limber pine plots. Live PINFLE infected refers to presence/absence of dwarf mistletoe infection on tree.

Plot ID Number	Live PINFLE (#)	Dead PINFLE (#)	Dead PINFLE (%)	Live PINFLE infected (#)	Live PINFLE infected (%)	Live PINFLE with cones (#)	Live PINFLE with cones (%)
1	2	0	0	0	0	2	100
2	2	0	0	0	0	1	50
3	16	0	0	5	31	10	63
4	73	0	0	62	78	54	68
5	6	0	0	0	0	2	33
6	3	0	0	0	0	2	67
7	3	0	0	0	0	3	100
8	32	0	0	17	50	23	68
9	3	0	0	0	0	3	100
11	3	0	0	0	0	1	33
12	4	0	0	0	0	3	100
13	3	0	0	0	0	0	0
14	2	0	0	0	0	0	0
15	54	0	0	45	79	14	25
16	4	0	0	0	0	4	80
17	3	0	0	0	0	0	0
19	9	0	0	0	0	6	67
20	13	0	0	0	0	4	29
21	7	0	0	0	0	7	58
22	18	0	0	0	0	11	65
23	1	0	0	0	0	1	100
24	21	0	0	1	5	12	57
27	13	0	0	8	67	5	42
28	1	0	0	0	0	0	0

Table C1 (continued). Summary statistics for limber pine plots. Live PINFLE infected refers to presence/absence of dwarf mistletoe infection on tree.

Plot ID Number	Live PINFLE (#)	Dead PINFLE (#)	Dead PINFLE (%)	Live PINFLE infected (#)	Live PINFLE infected (%)	Live PINFLE with cones (#)	Live PINFLE with cones (%)
30	16	0	0	2	11	13	72
31	69	13	19	68	99	10	14
35	13	0	0	0	0	6	46
36	7	4	57	6	86	6	86
37	11	0	0	0	0	11	100
40	30	9	30	13	43	14	47
42	9	0	0	0	0	7	78
43	22	0	0	13	59	19	86
44	1	0	0	0	0	1	100
47	24	0	0	10	42	22	92
48	3	0	0	0	0	2	67
51	106	1	1	32	30	70	66
52	11	0	0	1	9	4	36
53	4	0	0	0	0	3	75
55	11	0	0	2	18	10	91
56	7	0	0	0	0	3	43
58	74	1	1	5	7	42	57
59	24	0	0	13	54	18	75
60	9	1	11	0	0	9	100
61	5	0	0	0	0	4	80
62	8	1	13	5	63	5	63
63	6	1	17	0	0	4	67
64	1	1	100	0	0	1	100
66	9	0	0	0	0	8	89
67	9	0	0	0	0	8	89
69	6	0	0	0	0	2	33
71	39	5	13	28	72	26	67
75	14	0	0	0	0	10	71

Table C1 (continued). Summary statistics for limber pine plots. Live PINFLE infected refers to presence/absence of dwarf mistletoe infection on tree.

Plot ID Number	Live PINFLE (#)	Dead PINFLE (#)	Dead PINFLE (%)	Live PINFLE infected (#)	Live PINFLE infected (%)	Live PINFLE with cones (#)	Live PINFLE with cones (%)
76	5	5	100	2	40	5	100
78	5	0	0	0	0	3	60
79	16	0	0	5	31	10	63
82	57	4	7	54	95	45	79
83	4	0	0	0	0	3	75
87	43	0	0	24	56	29	67
88	6	0	0	0	0	6	100
90	15	0	0	0	0	14	93
91	13	1	8	7	47	6	40
92	19	0	0	5	25	16	80
93	13	0	0	0	0	5	42
94	17	0	0	10	53	15	79
95	5	1	20	0	0	4	57
99	58	0	0	0	0	23	79
100	4	0	0	1	25	4	100
101	2	0	0	0	0	1	50
103	17	0	0	3	18	17	100
104	6	0	0	1	17	6	100
106	22	5	23	3	14	14	64
107	7	0	0	2	29	4	57
109	5	0	0	0	0	3	60
110	9	1	11	0	0	7	78
111	15	3	20	9	60	8	53
112	4	0	0	0	0	3	75
114	9	0	0	0	0	8	89
115	31	5	16	25	81	21	68
116	4	1	25	4	100	4	100
117	5	0	0	0	0	1	20
118	14	0	0	2	14	13	93

Table C1 (continued). Summary statistics for limber pine plots. Live PINFLE infected refers to presence/absence of dwarf mistletoe infection on tree.

Plot ID Number	Live PINFLE (#)	Dead PINFLE (#)	Dead PINFLE (%)	Live PINFLE infected (#)	Live PINFLE infected (%)	Live PINFLE with cones (#)	Live PINFLE with cones (%)
119	8	0	0	5	63	5	63
122	1	0	0	0	0	0	0
123	41	0	0	15	37	32	78
124	8	1	13	3	38	5	63
147	18	5	28	17	94	11	61
149	5	1	20	0	0	4	80
150	15	3	20	13	87	11	73
151	2	0	0	1	50	1	50
152	2	1	50	0	0	2	100
156	46	4	9	23	50	35	76
159	15	4	27	9	60	7	47

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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