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1 Article

2 Overstory Tree Mortality in the Ponderosa Pine and 3 Spruce-Fir Ecosystems, Following a Drought in 4 Northern New Mexico

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14 **Abstract:** Drought-caused tree dieback is an issue around the world as climates change and many
15 areas become dryer and hotter. A drought from 1998-2004 resulted in a significant tree dieback
16 event in many of the wooded areas in portions of the Jemez Mountains and the adjacent Pajarito
17 Plateau in northern New Mexico. The objectives of this study were to evaluate and quantify the
18 differences in tree mortality before and after a recent drought in the ponderosa pine and spruce-fir
19 ecosystems, and to assess the effect of mechanical thinning on ponderosa pine mortality.
20 Significant increases in mortality were observed in the unthinned ponderosa pine ecosystem.
21 Mortality varied significantly between species and within size classes. Mechanical thinning of
22 ponderosa pines reduced overstory mortality to non-significant levels. A lack of rainfall, snowfall,
23 and increases in daily minimum temperature contributed most to the mortality. Adaptive
24 management, including the use of thinning activities, appear to moderate the impact of climate
25 change on ponderosa pine forests in this region, increasing the long-term health of the ecosystem.
26 The impact of climate change on the spruce-fir ecosystems may accelerate successional changes.

27 **Keywords:** Aspen, White fir, Douglas-fir, succession, Jemez Mountains

28

29 1. Introduction

30 Prolonged below-normal precipitation and above-normal temperatures from 1998-2004 led to
31 drought over an extensive swath of the Northern Hemisphere mid-latitudes, with a significant tree
32 dieback in many of the wooded areas in the American Southwest. Fifteen months of depleted soil
33 water content resulted in significant mortality of the dominant overstory of piñon pine (*Pinus edulis*)
34 [1,2,3]. A similar event occurred in northern New Mexico in the 1950s when the ecotone between
35 semiarid ponderosa pine forest and piñon-juniper woodland shifted location extensively (2 km or
36 more) and rapidly (<5 years) through ponderosa pine mortality in response to a severe drought [4],
37 and more recently, similar drought-related mortality in ponderosa pine and mixed conifer forests
38 have also been reported [5,6].

39 Most tree death is episodic and irregular [7]; this is especially true in dieback cases. These
40 essentially episodic but unpredictable events appear to occur somewhat regularly throughout
41 geologic time. The causes of dieback are case by case due to the differing conditions of each area,
42 but long-term climatic change has been suggested as a major cause of stand-level dieback [8].

43 The invasion of woody species into areas they did not historically inhabit and the general
44 increase of tree density in areas already forested has created greater water stress in many areas of the

45 American Southwest. This in turn could mean that the water stress caused by drought would be
46 exacerbated due to the excess amount of woody species. For ponderosa pine, the spatial pattern of
47 mortality corresponded directly to elevation/moisture gradients. Mortality of ponderosa pine was
48 apparently widespread on drier, lower-elevation sites across the drought-affected region.
49 Moreover, the effects of the drought have persisted. There is little evidence of ponderosa pine
50 re-establishment in recent decades in spite of favorable climatic conditions [9]. In Northern Arizona
51 and Northern New Mexico a more recent drought caused substantial tree dieback in many species,
52 with piñon pine being the most affected [10, 11]. The proximal cause of the mortality for most of
53 the trees was apparently infestation by bark beetles; such outbreaks are tightly tied to
54 drought-induced water stress [1]. It was found that piñon seedlings exhibited the lowest levels of
55 mortality during severe drought while mature tree mortality exceeded 50%. Aerial surveys of the
56 Southwest in 2003 showed that 12,191 km² of piñon and ponderosa pine had experienced substantial
57 mortality, correlated with abnormally low precipitation and high temperatures. Piñon mortality
58 greatly exceeded juniper mortality during 1996 and 2002 [11]. It was hypothesized that such high
59 mortality could result in bottleneck events that reduce genetic variation or favor drought-adapted
60 genotypes [10], and that this rapid die-off could have a number of important, interrelated ecological
61 implications such as large changes in carbon stores and dynamics, near-ground solar radiation,
62 runoff and erosion, genetic structure of the dominant tree species, and land surface microclimate
63 feedbacks to the atmosphere. Such rapid shifts in vegetation may represent abrupt, rapid, and
64 persistent shifts in not only ecotones, but also in dominant vegetation cover and associated
65 ecosystem processes [1].

66 The Los Alamos region, located on the east slopes of the Jemez Mountains of northern New
67 Mexico, is relatively free of human-caused disturbance, contains a large elevational gradient of
68 habitats, has a history of strong environmental assessment, and has an abundance of data available
69 in both vegetation structures and meteorology [12,13].

70 We assessed the mortality of the Ponderosa pine (*Pinus ponderosa*) and the Spruce-fir
71 (*Picea-Abies*) communities that occurred in the Los Alamos regions of Northern New Mexico during
72 the 2000-2003 drought period, and the effect of mechanical thinning on ponderosa pine mortality.
73 Our hypothesis was that the different communities would have different mortalities in response to a
74 drought event, and that mechanical thinning on the ponderosa pine community would reduce the
75 mortality caused by increased soil water competition during the drought.

76 2. Materials and Methods

77 2.1. Study Area

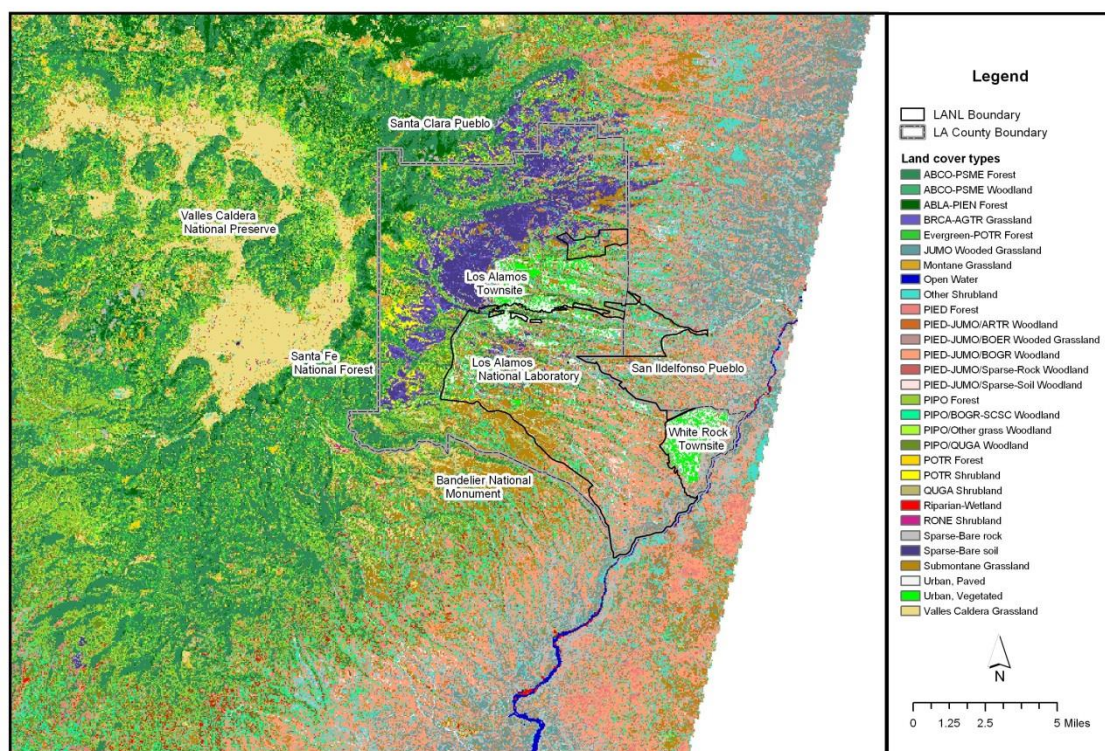
78 The study area was in the eastern portions of the Jemez Mountains and the adjacent Pajarito
79 Plateau. This includes the Los Alamos National Laboratory (LANL), the Los Alamos townsite, White
80 Rock and surrounding environs (Figure 1). In addition to LANL, the major landowners and land
81 managers of this region include the Santa Fe National Forest, Bandelier National Monument, Los
82 Alamos County, the Pajarito Ski Area and the Valles Caldera National Preserve. Approximately
83 29,542 ha (73,000 ac) are within this region. The area descends into White Rock Canyon and
84 borders the Rio Grande to the east. To the west, Los Alamos County ascends to the Sierra de Los
85 Valles, a segment of the rim of the Valles Caldera, remnants of an ancient volcano. In between
86 White Rock Canyon and the Sierra de Los Valles, the highly dissected Pajarito Plateau is the
87 dominant landform. The eastern border of the county is at its lowest elevation, approximately 1,631
88 m (5,350 ft). The highest peak is Pajarito Mountain, at 3,182 m (10,441 ft).

89 In general, the precipitation increases with elevation in the Los Alamos region. At the
90 lowest elevations in White Rock Canyon, the annual precipitation is approximately 241 mm
91 (9.5 inches), at higher elevations in the Sierra de los Valles, the annual precipitation averages
92 762 mm (30 inches) or more. During the winter months, annual snow depths at higher
93 elevations can exceed 127 cm (50 inches). The precipitation levels can vary widely from

94 year to year [14]. Annual precipitation levels at Los Alamos ranged from 173 mm to 770
 95 mm (6.8 inches to 30.3 inches). Snowfall also varies considerably from year to year, from
 96 the minimum 236 mm to 3891 mm (9.3 inches to 153.2 inches).

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98 Significant increases in temperatures and decreases in total precipitation occurred during the
 99 drought, even though no significant reductions in annual snow pack was found.



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101 **Figure 1.** The eastern Jemez Mountains, including the region of interest to this study. The
 102 abbreviated species in the legend are included within the list of species in Appendix A. Source: [10].

103 2.2 Vegetation Types

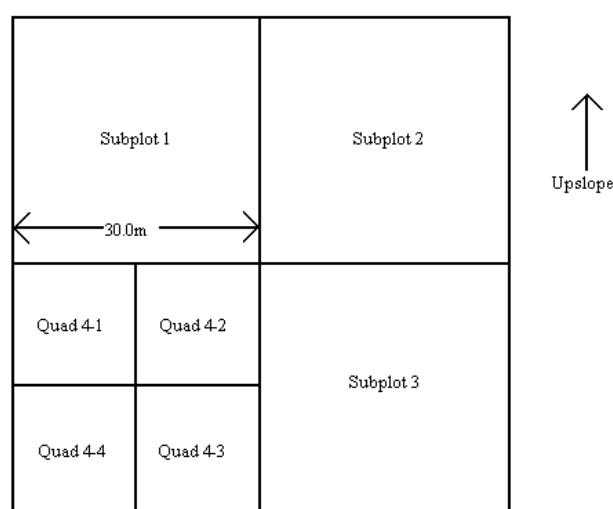
104 From low to high elevations, the predominant vegetation types in this study area consist of
 105 juniper savannas, piñon-juniper woodlands, ponderosa pine forests, mixed-conifer forests, and
 106 spruce-fir forests [15, 16]. Aspen forests and a variety of grasslands and shrublands may also be
 107 found. Areas that were severely burned by the Cerro Grande Fire during the late spring of 2000
 108 were bare ground or sparse vegetation immediately after the fire, but recovered to grasslands or
 109 shrublands within a few years [17].

110 2.3. Field Methods

111 The field methods described here are synthesized from previous work in the area [12,13]. We
 112 conducted a stratified random sample, using multi-spectral, remotely sensed and digital elevation
 113 model (DEM) data to identify potential plot locations within the targeted communities as shown in
 114 Figure 1. Following the automated stratification procedure, individual sites were selected for further
 115 analysis on the ground. Each site was checked to verify the homogeneity of topographic, soil and
 116 vegetational conditions for a distance on 60 m in all four cardinal direction. If these conditions were

117 not met, the site was rejected and either a new randomly selected point was located in the field or the
 118 original point was replaced by the nearest homogeneous area of vegetation. A nested, randomized
 119 plot layout and sampling design was utilized. This was accomplished by defining a macroplot that
 120 consists of four subplots (Figure 2). The macroplot consisted of a square area, 60 m on each side,
 121 and oriented parallel to the slope contours. The horizontal and vertical compass bearings, as well
 122 as their respective back bearings, were recorded. The plot center was permanently marked with
 123 rebar.

124 The subplots were numbered sequentially in a clockwise direction, with the subplot number 1
 125 located in the upper left corner of the macroplot. In this fashion, subplot 1 and subplot 2 were
 126 always upslope, whereas subplot 3 and subplot 4 were always downslope. Two of these subplots
 127 were randomly selected for further sampling.
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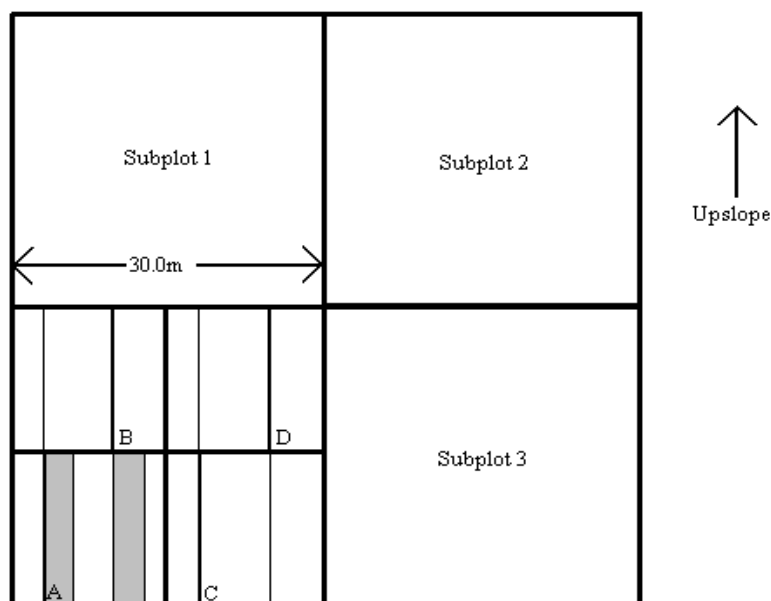


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132 **Figure 2.** Representative macroplot layout and subplot numbering scheme. The macroplot scale is
 133 60 m by 60 m. The subplots are numbered sequentially in clockwise direction beginning with the
 134 upslope-left subplot. The quads are numbered sequentially in a clockwise direction. The layout of
 135 subplots 1, 2 and 3 are similar.

136 Each of the two subplots selected for sampling was further divided into quads and three of the
 137 four quads were randomly selected for detailed sampling. Trees greater than 3 m (10 ft) tall and
 138 other overstory characteristics were measured in each quad of the two subplots. Most of the other
 139 parameters and site descriptors were measured in the quad, in strip plots, or along line transects
 140 within the quad.

141 To optimize the sampling of shrubs and small trees that were less than ten feet tall, a system of
 142 strip plots was selected. This was accomplished by assessing the density of shrubs and small trees
 143 in the less than 3 m size height class and selecting an appropriate strip plot scheme. More compact
 144 combinations of strip plots and sub-strip plots were used for plots that have numerous seedlings,
 145 saplings and small shrubs. Moderate combinations were used for typical forested conditions.
 146 Extensive combinations of strip plots and sub-strip plots were used for sparsely forested or
 147 non-forested plots that had few seedlings, saplings or small shrubs. Using the optimal plot size that
 148 was selected and recorded, two line transects were constructed in each quad, and also used to
 149 construct the strip plots. In Quad A, the first (left) line transect was used to create the first strip plot
 150 (A), and in Quad B, the second (right) line transect was used to create the second strip plot (B). In
 151 either case, this is done with a 15-m tape that extends from the lower boundary of the quad to the
 152 upper boundary. The 15-m tape was parallel to its companion line-transect tape and separated by a
 153 distance as prescribed by the size of the strip plot, 1 m, 2 m, or 3 m (Figure 3).



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Figure 3. General layout of line transects and strip plots for a representative subplot.

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2.4 Sampling Methods

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Sampling occurred between 1998 and 2005 to capture a range of years, overlapping the drought in question. All plots overstory densities ranged from 500-800 trees per hectare, depending on the community type and site conditions. Thinning targets ranged from 50-1500 trees per hectare, again depending on which community was thinned. Thinned plots were within management areas to be thinned, and occurred across the range of years. They were not set up as paired to non-thinned plots, nor was proximity to unthinned plots measured.

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From the center of each subplot, the slope (%), aspect (degrees), elevation (m above MSL), topographic position (ridge, upper slope, mid slope, lower slope, bench or flat, or drainage bottom), plus horizontal and vertical configuration (convex, concave, straight, or undulating) were recorded. Strip plots were used to sample all trees and shrubs that met specific height criteria. The strip plots were used to sample all trees and shrubs above 0.6 m tall but less than 3 m in height. Information recorded for each individual includes the species, live or dead status and total height. Overstory trees and shrubs were defined as those that were ≥ 3 m tall. Overstory was recorded by species and either live or dead. For dead trees, the species, diameter at breast height (DBH), and the total height were recorded. For each live tree the previous information was always collected and the number of multiple stems, if any, was also recorded. DBH were recorded to the centimeter and height to the decimeter.

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2.5 Data Summarization and Analysis

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Thirty plots representing unthinned ponderosa pine (*Pinus ponderosa*) forests and sixteen plots representing spruce-fir (*Picea-Abies*) forests were analyzed, as well as sixteen plots for thinned ponderosa pine forests. Sixteen plots were used for direct measurement of spruce-fir drought mortality. Only prominent tree species within each of these vegetation types were analyzed. For ponderosa pine forests, this was limited to ponderosa pine; for spruce-fir forests, corkbark fir (*Abies lasiocarpa*), white fir (*A. concolor*), Engelmann spruce (*Picea engelmanni*), quaking aspen (*Populus tremuloides*), and Douglas-fir (*Pseudotsuga menziesii*). The spruce-fir data was also broken down into the two major habitat types, (*Picea engelmanni/Erigeron eximius*, Engelmann Spruce/forest fleabane) Pien/Erex and (*Abies lasiocarpa/Vaccinium myrtillus*, Subalpine fir/Myrtleleaf blueberry) Abla/Vamy.

184 Each tree sampled in the plot was categorized to species, live or dead status, and height and/or
185 diameter size. For trees less than or equal to 3 m (10 ft) tall, height was used, as defined by the
186 following upper boundaries of each class: 0.3 m (1 ft), 0.6 m (2 ft), 2 m (6 ft), and 3 m.

187 For trees greater than 3 m (10 ft) tall, DBH size classes were used, as defined by the following
188 upper boundaries of each class: 10 cm (4 in), 20 cm (8 in), 30 cm (12 in), 40 cm (16 in), 50 cm (20 in), 60
189 cm (24 in), 71 cm (28 in), 81 cm (32 in), and ≥ 81 cm.

190 These data were collected and organized by subplot. A mean percent mortality was calculated
191 for each species and size class per subplot. Thus, a zero represented zero percent mortality. Plots
192 were organized by the year of the sample. The plot samples were also categorized by premortality
193 (before 2002) and postmortality (2002 and later).

194 A Two-Sample One-Tailed t Test and a Wilcoxon Paired-Sample One-Tailed t Test was used to
195 determine if there were any significant increases in tree mortality with respect to drought response.
196 For the Wilcoxon Paired-Sample One-Tailed t Test the earliest eight samples were compared with
197 the eight post drought samples. This was because there is no geographic or numerical bias and also
198 this limits the effect of the upcoming drought on the pre-drought data. These tests produce P
199 values that are small enough to shield the study from Type I Error. The same techniques were also
200 used to compare the drought response in both thinned and un-thinned areas to determine if
201 thinning relieved the trees of enough competition to reduce mortality. Also, Canonical
202 Correspondence Analysis (CCA) was used to interpret the weather's effect on each of the ecozones.
203 CCA analysis was carried out using PC-ORD Version 5 software [18], using calendar year data.

204 3. Results

205 3.1 Mortality

206 With the exception of the smallest class, all size classes (0-40 cm DBH) as well as the largest class
207 of unthinned ponderosa pine were found to have significantly greater mortality post-drought.
208 Since no significant differences with respect to pre and post-drought measurements for thinned
209 ponderosa pine were found (Table 1), CCA analyses were not run. However, Wilcoxon
210 paired-sample one-tailed t tests found significant greater mortality post-drought (Table 2).

211 The only size classes that were found to be significantly different with respect to mortality pre
212 and post-drought in Spruce-fir were the DBH size classes of 20-30 and 30-40 cm (Table 1), with
213 greater mortality recorded post-drought. While no size classes were found to be significant for the
214 Abla/Vamy Habitat Type, the 10-20, 20-30, and 30-40 cm size classes were found to be significant
215 greater post-drought in the Pien/Erex Habitat Type (Table 3).

216 Table 1. Results for two-sample one-tailed *t* test ran on unthinned ponderosa pine, thinned ponderosa pine, and Spruce-fir. Ht/DBH=Height/Diameter
 217 breast height; Pre=Pre-drought; Post=Post-drought.

Ht./DBH Class	0.6-3m		0-10cm		10-20cm		20-30cm		30-40cm		>40cm	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Unthinned Ponderosa												
Mean % Mortality	10.4	18.2	10.0	19.0	5.6	17.1	1.2	11.4	0.2	11.7	2.3	13.5
t-stat		-1.606		-2.179		-3.246		-3.855		-4.166		-2.012
t-stat 0.05		1.706		1.706		1.699		1.699		1.699		1.701
<i>P</i> value	0.10> <i>P</i> >0.05		0.0025> <i>P</i> >0.01		<i>P</i> <0.0005		<i>P</i> <0.0005		<i>P</i> <0.0005		0.05> <i>P</i> >0.025	
Thinned Ponderosa												
Mean % Mortality	0.0	0.0	0.0	4.8	0.0	16.6	0.0	3.8	0.0	1.7	0.0	8.2
t-stat		0.0		-0.509		-0.836		-0.589		-0.564		-1.046
t-stat 0.05		1.895		1.895		1.796		1.771		1.761		1.761
<i>P</i> value	<i>P</i> <0.25		<i>P</i> <0.25		<i>P</i> <0.25		<i>P</i> <0.25		<i>P</i> <0.25		0.10> <i>P</i> >0.05	
Spruce-fir												
Mean % Mortality	16.5	11.2	32.5	25.2	17.0	26.6	4.9	12.9	0.2	7.7	6.9	18.9
t-stat		0.046		0.766	0.147	1.673		-1.885		-2.053		-1.34
t-stat 0.05		1.685		1.673				1.674		1.677		1.696
<i>P</i> value	<i>P</i> <0.25		0.25> <i>P</i> >0.1		0.1> <i>P</i> >0.05		0.05> <i>P</i> >0.02		0.25> <i>P</i> >0.1		0.10> <i>P</i> >0.05	

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Table 2. Results for Wilcoxon paired-sample one-tailed *t* test run on ponderosa pine. DBH=Diameter breast height.

DBH class	0-10cm	10-20cm	20-30cm	30-40cm
T+	3	1	3	3
t-stat 0.05	$T_{0.05(1),8=5}$	$T_{0.05(1),8=5}$	$T_{0.05(1),8=5}$	$T_{0.05(1),8=5}$
<i>P</i> value	$P=0.025$	$P=0.01$	$P=0.025$	$P=0.025$

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Table 3. Results for two-sample one-tailed *t* test run on Habitat Types in Spruce-fir zone. Ht/DBH=Height/Diameter breast height; Pre=Pre-drought; Post=Post-drought; Mort.=mortality. Number (N) is sample size.

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Ht./DBH Class	0.6-3m		0-10cm		10-20cm		20-30cm		30-40cm		>40cm	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
<u>Abla/Vamy(16)</u>												
Mean % Mortality	9.5	5.0	33.9	9.3	15.8	13.1	0.9	1.7	0.0	0.0	0.0	11.1
t-stat	0.470		0.216		0.380		.984		0.0		-0.500	
t-stat 0.05	1.943		1.782		1.782		1.771		.860		2.920	
<i>P</i> value	$P>0.25$		$P>0.25$		$P<0.25$		$P<0.25$		$P<0.25$		$P>0.25$	
<u>Pien/Erex (48)</u>												
Mean % Mortality	17.7	13.2	32.1	23.6	17.3	31.5	5.7	12.4	0.3	9.4	7.3	9.4
t-stat	0.535		0.771		-1.749		-1.722		-2.025		-1.296	
t-stat 0.05	1.696		1.683		1.681		1.684		1.685		1.688	
<i>P</i> value	$P<0.25$		$0.25>P>0.10$		$0.05>P<0.025$		$0.05>P<0.025$		$0.05>P<0.01$		$P>0.25$	

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Table 4. Results for two-sample one-tailed *t* test ran on individual species in the Spruce-fir zone. Ht/DBH=Height/Diameter breast height; Pre=Pre-drought; Post=Post-drought. (N) = number in sample for each species. NA = No data for those size classes for those species.

Ht./DBH Class	0.6-3m		0-10cm		10-20cm		20-30cm		30-40cm		>40cm	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
<u>Engelmann Spruce</u>												
Mean % Mortality	20.1	22.9	14.4	12.4	5.0	11.7	1.0	10.2	0.0	7.1	0.0	0.0
t-stat		-0.251		0.406		-1.394		-2.158		-1.075		0.0
t-stat 0.05		1.796		1.761		1.761		1.761		1.771		1.771
<i>P</i> value		<i>P</i> >0.25		<i>P</i> >0.25		0.10> <i>P</i> >0.05		0.025> <i>P</i> >0.01		0.25> <i>P</i> <0.10		<i>P</i> >0.025
<u>Douglas-fir</u>												
Mean % Mortality	7.8	5.0	5.4	27.3	3.9	16.3	5.6	23.2	0.0	0.0	19.4	36.1
t-stat		0.3		-2.151		-1.463		-1.307		0.0		-0.634
t-stat 0.05		1.86		1.796		1.782		1.771		1.796		1.860
<i>P</i> value		<i>P</i> <0.25		0.05> <i>P</i> <0.025		0.10> <i>P</i> <0.05		0.25> <i>P</i> <0.15		<i>P</i> <0.25		<i>P</i> >0.25
<u>White fir</u>												
Mean % Mortality	0.0	14.7	19.4	5.3	2.0	28.6	NA		NA		NA	
t-stat		-1.430		0.767		-2.332						
t-stat 0.05		1.895		1.833		1.895						
<i>P</i> value		0.10> <i>P</i> <0.05		0.25> <i>P</i> >0.10		0.025> <i>P</i> >0.01						
<u>Aspen</u>												

Mean % Mortality	NA	85.2	69.2	48.3	55.6	10.5	12.7	NA	NA
t-stat			1.045		-0.660		-0.303		
t-stat 0.05			1.782		1.761		1.761		
<i>P</i> value			0.25> <i>P</i> >0.10		<i>P</i> <0.25		<i>P</i> <0.25		

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The only size class for white fir that was found to have significantly greater mortality post-drought was the 10-20 cm DBH class, for Engelmann spruce only the 20-30 cm class, and for Douglas-fir only the 0-10 cm class. No size classes for aspen that were found to be significantly different (Table 4).

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3.2 Measurement of Drought Induced Mortality

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While total mortality of all trees in the Spruce-fir communities ranged from 2.3-5.4% across the five species, the percent mortality of that which was drought induced ranged from 21.7 to 75.0 % for the conifer species, but only 8.5% for aspen (Table 5).

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Table 5. Direct measurement of drought induced mortality for all Spruce-fir species in 2005.

Species	% of Mortality Induced by Drought	Total % Mortality
Corkbark fir	75.0	2.3
White fir	25.0	1.7
Engelmann spruce	39.1	4.2
Aspen	8.5	5.4
Douglas-fir	21.7	3.0

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3.3 Canonical Correspondence Analysis

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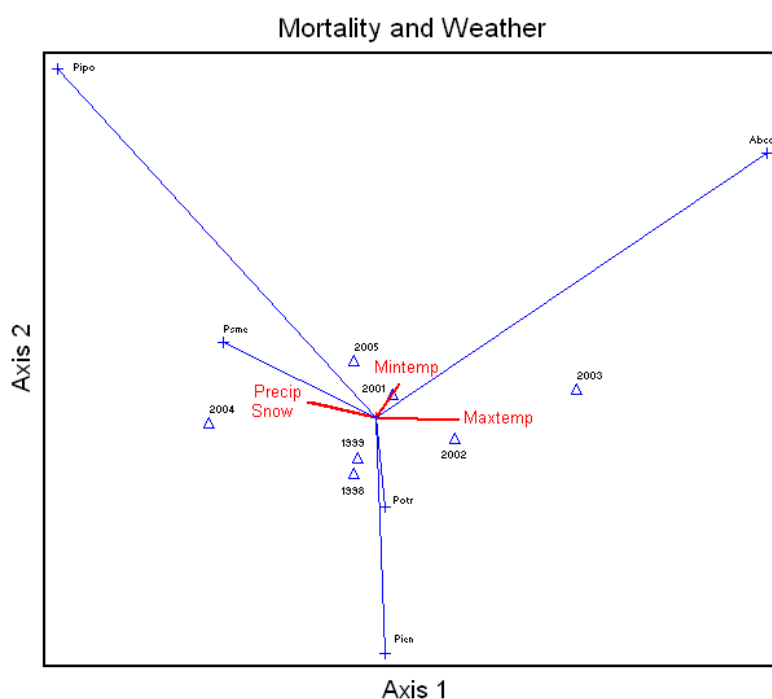
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Average percent mortality of all species (annual mortality) correlated to the annual (calendar year) snow, rainfall, and average daily maximum and minimum temperatures showed that unthinned ponderosa pine mortality was highly related to rainfall and snow (Figure 4). Douglas-fir mortality was to a lesser extent further related to snow and rainfall, and white fir mortality was highly related to increases in temperatures. Aspen and Engelmann spruce do not show much correlation due to high pre-drought mortalities.



250

251

252

Figure 4. Canonical Correspondence Analysis Ordination on average percent mortality of all species measured in the study area by year and correlated to the calendar year snow (Snow) and rainfall

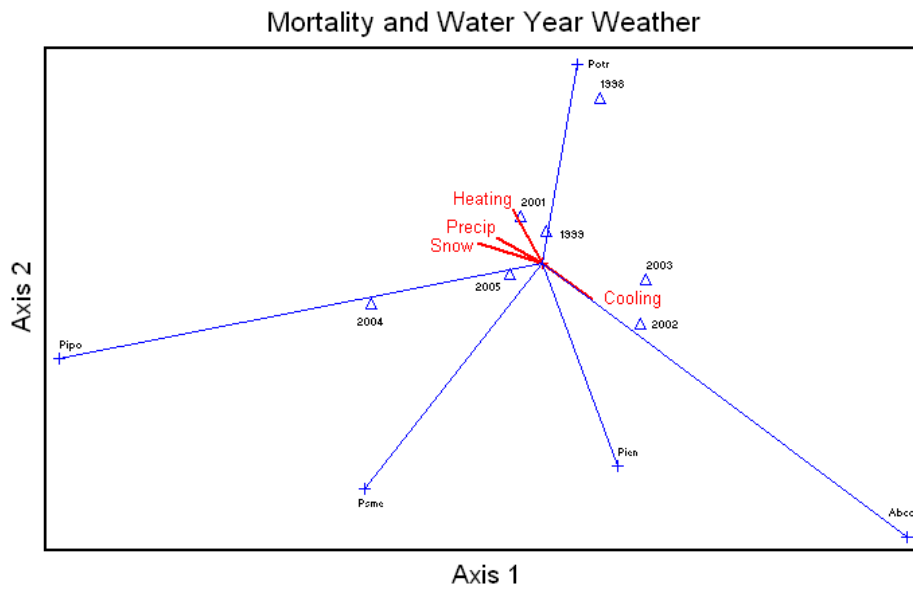
253 (Precip) and average daily maximum (Maxtemp) and minimum (Mintemp) temperatures . Xxx =
 254 year, Abco = Abies concolor, Pipo = Pinus ponderosa, Potr = Populus tremuloides, Psme =
 255 Pseudotsuga menziesii, Pien = Picea engelmannii.

256

257 Average percent mortality of all species was correlated to the annual water year snow, rainfall,
 258 and number of heating and cooling degree-days (Figure 5). Unthinned ponderosa pine mortality,
 259 and Douglas-fir to a lesser extent, was highly related to rainfall and snow. White fir mortality was
 260 highly related to increases in temperatures, and aspen showed a relationship to heating days.
 261 Engelmann spruce showed a positive relationship to cooling days.

262

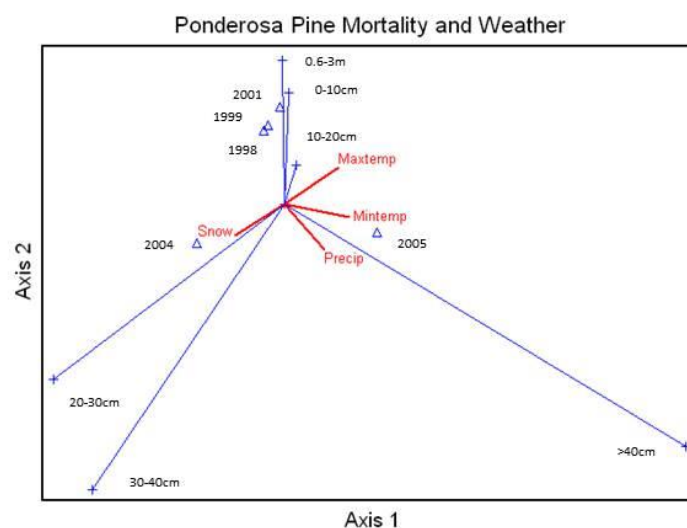
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264

265 **Figure 5.** Canonical Correspondence Analysis Ordination on average percent mortality of all the
 266 species by year and correlated to the water year snow (Snow) and rainfall (Precip) and the number of
 267 heating (Heating) and cooling (Cooling) degree days. . Xxx = year, Abco = Abies concolor, Pipo =
 268 Pinus ponderosa, Potr = Populus tremuloides, Psme = Pseudotsuga menziesii, Pien = Picea
 269 engelmannii

270 Average percent mortality of unthinned ponderosa pine size classes was correlated to the
 271 annual (calendar year) snow, rainfall, and average daily maximum and minimum temperatures
 272 (Figure 6), and that the mortality in the larger size classes was highly related to rainfall and snow.
 273 The three smallest size classes showed some relation to maximum temperature.



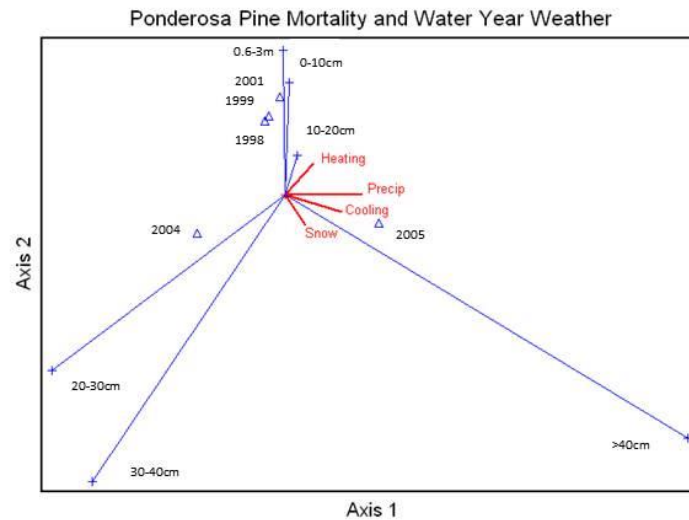
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275 **Figure 6.** Canonical Correspondence Analysis Ordination on average percent mortality of the
 276 different ponderosa pine size classes by year and correlated to the calendar year snow and rainfall
 277 and average daily maximum and minimum temperatures. Snow = Snow accumulations, Cooling =
 278 lower temperatures, Heating = warmer temperatures, Precip = precipitation amounts. Xxxx = year,
 279 xx-xxm = height class, xx-xxcm = diameter class.

280

281

282 Average percent mortality of unthinned ponderosa pine size classes was correlated to the
 283 annual water year snow, rainfall, and number of heating and cooling degree-days (Figure 7), with
 284 the largest size class heavily affected by snow, rainfall, and the number of cooling days. This
 285 ordination also shows a relation to snowfall with the 20-30 and 30-40 cm DBH size class.



286

287 **Figure 7.** Canonical Correspondence Analysis Ordination on average percent mortality of all
 288 ponderosa pine size classes measured in the study area by year and correlated to the water year
 289 snow and rainfall and the number of heating and cooling degree days. Snow = Snow accumulations,
 290 Cooling = lower temperatures, Heating = warmer temperatures, Precip = precipitation amounts. Xxxx
 291 = year, xx-xxm = height class, xx-xxcm = diameter class.

292 4. Discussion

293 There were substantial differences in the pre-drought stands and the post-drought unthinned
 294 ponderosa pine stands. The average percent mortality was approximately ten percent higher in the
 295 post-drought stands with larger ponderosa pine trees more significantly impacted by the drought.
 296 The drought had a significant impact on ponderosa pine mortality. The primary factors influencing
 297 the mortality were decreases in precipitation and increases in temperature. There were no
 298 significant differences in the pre-drought stands and the post-drought thinned ponderosa pine
 299 stands. This is very different from the unthinned ponderosa pine data, suggesting that the thinning
 300 process significantly reduced ponderosa pine mortality.

301 When analyzed by size class, irrespective of species, the data showed significant differences in
 302 the 20-30 and 30-40 cm DBH size classes, but not for ponderosa pine. The main difference between
 303 the two sets of data is that the spruce-fir data showed substantial mortality in the pre-drought years.
 304 There are several potential reasons for this occurrence. The stands in the spruce-fir sites were
 305 characteristically denser than the ponderosa pine sites, and therefore were already experiencing
 306 more competition. The spruce-fir sites were at the stage of stand development where a second
 307 phase stem exclusion process was becoming more pronounced. The first stage occurred earlier in
 308 stand development, where overtopped or suppressed trees had died. Now, older trees were again
 309 experiencing competition stress. As a result, successional changes were still occurring in the
 310 spruce-fir stands whereas most of the ponderosa pine stands were older and showing less
 311 successional changes. There was substantial mortality recorded in both pre and post-drought

312 years, possibly a product of ongoing successional processes. As a whole, this ecozone did react to
313 the drought although in a more understated way when compared to ponderosa pine or the
314 piñon/juniper [1].

315 When the spruce-fir data was broken down into the two major habitat types, the Pien/Erex
316 habitat type showed some significant differences while the Abla/Vamy habitat type did not. The
317 mortality increases in the size classes of 10-20, 20-30, and 30-40 cm were found to be significantly
318 different in the Pien/Erex habitat type. The difference in mortality significance between the two
319 habitat types is most likely due to their respective positions along the elevational gradient of the
320 area. The Pien/Erex habitat type is usually situated in the lower areas of the Spruce-fir ecosystem
321 and is therefore more susceptible to drought-induced influences while the Abla/Vamy habitat type is
322 usually situated in the higher areas.

323 The only significant differences in mortality for the individual species were the 0-10 cm in
324 Douglas-fir, 10-20 cm class in white fir, and 20-30 cm class in Engelmann spruce. There was
325 substantial pre-drought mortality, especially in the smaller size classes. This is most likely due to
326 the increased competition for resources in the stands and therefore increased stress on the trees.
327 The most interesting feature of the aspen data set is the large amount of mortality in both pre and
328 post-drought years. There was 85% average percent mortality in the pre-drought size class of 0-10
329 cm DBH and a 48% average percent mortality in the pre-drought size class of 10-20 cm DBH. The
330 reason for the high pre-drought mortality is most likely due to the fact that aspen is an early
331 successional species, and it appeared to be suffering from competition from encroaching, slower
332 growing later successional species. There were large percentages of dead trees that were killed by
333 the drought (>20%) for all species except aspen. Aspen's small percent of dead trees killed by the
334 drought is most likely due to pre-drought mortality. Aspen did have the largest total percent
335 drought mortality. This is most likely due to a smaller total number of aspen trees, aspen's short
336 lifespan, and also the encroachment of later successional species such as Engelmann spruce and
337 white fir.

338 There was a strong correlation between ponderosa pine and Douglas fir mortality and
339 precipitation. Mortality increased with a decrease in precipitation, but there was a time lag
340 between initial mortality (drought), recorded mortality (data collection), and the increase in
341 precipitation post-drought. Mortality in the white fir followed average minimum and maximum
342 temperatures with a large portion of the mortality recorded in 2003 and 2005, when the temperatures
343 were highest. Both aspen and Englemann spruce's mortality vectors followed decreases in average
344 minimum temperature. This is due to both species having substantial mortality in the pre-drought
345 measurements. Like aspen, much of the Engelmann spruce stands was at mid-succession. This
346 has resulted in relatively higher mortality in the smaller size classes of Engelmann spruce. Most of
347 the mortality recorded in Engelmann spruce was recorded in the later years when temperatures had
348 dropped after the drought.

349 Mortality in ponderosa pine and Douglas-fir are heavily influenced by precipitation and snow,
350 with decreases in precipitation resulting in increases in mortality. White fir and Engelmann spruce
351 mortality followed increases in cooling days. It would seem to be counterintuitive but this is due to
352 the hottest years having the most cooling degree days; more days with an average temperature
353 above 65°F.

354 It has been estimated that almost 90 percent of the total annual water yields in the Rocky
355 Mountain Region, which includes Arizona and New Mexico, are derived from snowmelt [19].
356 These results also show the relationship between tree health and the monsoonal season. In some
357 cases in southwestern US and northwestern Mexico, over half the water used by vegetation may
358 come from the monsoonal rains. It shows that nearly all size classes in ponderosa pine are heavily
359 affected by water year snowfall. The largest size classes shows evidence of lag time in response to
360 water year snowfall.

361 5. Conclusions

362 The significant differences in drought-induced mortality by the different size classes within the
 363 different species were an important result of this study. As the region experiences a greater number
 364 and intensity of drought events, major changes in the regional forest structure in the future most
 365 likely will occur, with cascading impacts on wildlife, water, and the public. While tree dieback is a
 366 natural occurrence, human involvement in the management of forested areas has changed the
 367 interaction between the vegetation and its environment [20]. In the American Southwest, issues
 368 such as timber management, fire exclusion, overstocked stands, livestock grazing, and climate
 369 change have all contributed to a movement away from historic conditions in these areas [21].
 370 Drought played a significant role in unthinned ponderosa pine mortality in Northern New Mexico.
 371 This is no surprise as it has been estimated that snowpack in the Rockies can contain approximately
 372 5,103,630 acre-feet (6.3 billion cubic meters) of water [22]. While the pre and post-drought
 373 measurements were highly significant in the unthinned plots, the analysis of the thinned data
 374 showed no significance at all. This is an important implication because it shows that upon the onset
 375 of a drought the overstory mortality can be reduced through mechanical thinning.

376 The drought increased all of the mortality percentages in the spruce-fir zone with the exception
 377 of the two smallest size classes. The main difference between the ponderosa pine data and the
 378 spruce-fir data is that the spruce-fir had substantial amounts of pre-drought mortality. The
 379 Pien/Erex habitat type had significant increases in mortality suggesting that this habitat type is more
 380 susceptible to drought.

381 Precipitation was highly correlated to the mortality in the larger size classes of ponderosa pine
 382 as well as Douglas-fir. The species that characteristically occupy higher elevations such as white fir
 383 and Engelmann spruce were most heavily affected by temperature changes. Lag times between the
 384 stress event and actual death were evident in the ordination but the conclusions are clear. It may be
 385 possible to lessen the mortality in future dieback events through a systematic reduction of stressors
 386 such as overpopulation of trees through mechanical thinning or the use of prescribed fire.

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392 **Conflicts of Interest:**

393 **Appendix A. Plant species that are common to land cover classes of the Jemez** 394 **Mountains in Northern New Mexico.**

Code	Scientific name	Common name
ABCO	<i>Abies concolor</i>	White fir
ABLA	<i>Abies lasiocarpa</i>	Subalpine fir
ACGL	<i>Acer glabrum</i>	Mountain maple
ACMI	<i>Achillea millefolium</i>	Western yarrow
AGTR	<i>Agropyron trachycaulum</i>	Slender wheatgrass
ANPA	<i>Antennaria parvifolia</i>	Small-leaf pussytoes
ARFR	<i>Artemisia franserioides</i>	Ragweed sagebrush
ARLU	<i>Artemisia ludoviciana</i>	Louisiana wormwood
ARTR	<i>Artemisia tridentata</i>	Big sagebrush
ARUV	<i>Arctostaphylos uva-ursi</i>	Kinnikinnik
ATCA	<i>Atriplex canescens</i>	Four-wing saltbush
BADI	<i>Bahia dissecta</i>	Yellow ragweed
BOER	<i>Bouteloua eriopoda</i>	Black grama

BOGR	<i>Bouteloua gracilis</i>	Blue grama
BLTR	<i>Blepharoneuron tricholepis</i>	Pine dropseed
BRCA	<i>Bromus carinatus</i>	Mountain brome
BRCI	<i>Bromus ciliatus</i>	Fringed brome
CAGE	<i>Carex geophila</i>	White Mountain sedge
CAMI	<i>Carex microptera</i>	Small-wing sege
CAOC	<i>Carex occidentalis</i>	Western sedge
CAUT	<i>Carex utriculata</i>	Northwest Territory sedge
CEMO	<i>Cercocarpus montanus</i>	Mountain mahogany
CHNA	<i>Chrysothamnus nauseosus</i>	Chamisa
CHVI	<i>Chrysopsis villosa</i>	Hairy golden aster
CLPS	<i>Clematis pseudoalpina</i>	Rocky Mountain clematis
DAPA	<i>Danthonia parryi</i>	Parry's danthonia
DECA	<i>Deschampsia caespitosa</i>	Tufted hairgrass
EREX	<i>Erigeron eximius</i>	Forest fleabane
ERFO	<i>Erigeron formosissimus</i>	Beautiful fleabane
FAPA	<i>Fallugia paradoxa</i>	Apache plume
FEAR	<i>Festuca arizonica</i>	Arizona fescue
FEID	<i>Festuca idahoensis</i>	Idaho fescue
FEOV	<i>Festuca ovina</i>	Sheep fescue
FETH	<i>Festuca thurberi</i>	Thurber fescue
FRVE	<i>Fragaria vesca</i>	Woodland strawberry
FRVI	<i>Fragaria virginiana</i>	Mountain strawberry
GECA	<i>Geranium caespitosum</i>	Rose crane's bill
HOVU	<i>Hordeum vulgare</i>	Barley
JUBA	<i>Juncus balticus</i>	Baltic rush
JUMO	<i>Juniperus monosperma</i>	One-seed juniper
KONI	<i>Koeleria nitida</i>	Junegrass
LAAR	<i>Lathyrus arizonicus</i>	Arizona lathyrus
LOMU	<i>Lolium multiflorum</i>	Italian ryegrass
LUCA	<i>Lupinus caudatus</i>	Spurred lupine
MUMO	<i>Muhlenbergia montana</i>	Mountain muhly
MUWR	<i>Muhlenbergia wrightii</i>	Spike muhly
OPER	<i>Opuntia erinacea</i>	Grizzly-bear prickly-pear cactus
PAMY	<i>Pachystima myrsinites</i>	Mountain lover
PIEN	<i>Picea engelmannii</i>	Engelmann spruce
PIED	<i>Pinus edulis</i>	Piñon
PIFL	<i>Pinus flexilis</i>	Limber pine
PIPO	<i>Pinus ponderosa</i>	Ponderosa pine
POFE	<i>Poa fendleriana</i>	Mutton grass

POFR	<i>Potentilla fruticosa</i>	Shrubby cinquefoil
POHI	<i>Potentilla hippiana</i>	Woolly cinquefoil
POPA	<i>Poa palustris</i>	Fowl bluegrass
POPR	<i>Poa pratensis</i>	Kentucky bluegrass
POTR	<i>Populus tremuloides</i>	Quaking aspen
PSME	<i>Pseudotsuga menziesii</i>	Douglas fir
PSMO	<i>Pseudocymopterus montanus</i>	Yellow mountain parsley
PTAQ	<i>Pteridium aquilinum</i>	Bracken fern
QUGA	<i>Quercus gambelii</i>	Gambel oak
QUUN	<i>Quercus undulata</i>	Wavy leaf oak
RHTR	<i>Rhus trilobata</i>	Skunkbush sumac
RICE	<i>Ribes cereum</i>	Wax currant
RONE	<i>Robinia neomexicana</i>	New Mexico locust
SAEX	<i>Salix exigua</i>	Coyote willow
SCSC	<i>Schizachyrium scoparium</i>	Little bluestem
SMST	<i>Smilacina stellata</i>	Star Solomon's plume
STCO	<i>Stipa comata</i>	Needle and thread
THFE	<i>Thalictrum fendleri</i>	Fendler meadowrue
THTR	<i>Thelesperma trifidum</i>	Green thread
VAMY	<i>Vaccinium myrtillus</i>	Myrtle-leaf blueberry
VIAM	<i>Vicia americana</i>	American vetch

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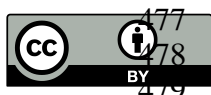
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