

Quantitative and qualitative approaches to assess tree vigor and stand health in dry pine forests



Nancy Grulke^{a,*}, Craig Bienz^b, Kate Hrinkevich^c, Jason Maxfield^d, Kellie Uyeda^e

^a USDA Forest Service, Pacific Northwest Research Station, 63095 Deschutes Market Rd, Bend, OR 97701, United States

^b The Nature Conservancy, 226 Pine Street, Klamath Falls, OR 97601, United States

^c DOE-ORISE, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331, United States

^d Portland State University, Biology Department, Portland, OR 97207, United States

^e San Diego State University, Biology Department, San Diego, CA 92182, United States

ARTICLE INFO

Keywords:

Tree vigor
Stand health
Stand resilience
Ponderosa pine
Forest treatments
Forest restoration
Dry pine forest
Stand management
Monitoring
Stand assessment

ABSTRACT

Despite a critical need to evaluate effectiveness of forest treatments in improving stand health, practitioners lack quantitative, repeatable metrics to assess tree vigor and stand health. We evaluated canopy and whole tree attributes of ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) related to carbon balance, water balance, and susceptibility to insects and pathogens in dry, pine-dominated forest stands during a multi-year drought, an environmental challenge to stand resilience. Metrics of trees in two unmanaged, and seven treated forested stands, in both uplands and lowlands to develop the quantitative approach. Whole tree and crown attributes including needle length and color, branchlet length and diameter, needle retention (needle ages and retention within ages), and frequency of insects, fungi, and abiotic needle damage were statistically selected to assess tree vigor. Cluster analysis of vigor attributes revealed that trees responded or persisted independently within a forest treatment; forest treatments did not necessarily yield similar tree responses within a stand. A rapid, qualitative assessment was developed to rank trees as low, average, and above-average vigor. To demonstrate an application of our approach, trees were ranked annually over six years in most stands, as well as in a stand where the prescription was adjusted due to the evaluation. The proportion of trees in the three tree vigor ranks differed, suggesting differing levels of stand health. Quantitative metrics and qualitative ranking of tree vigor could assist in selecting trees to be retained to meet specific management objectives, to evaluate treatment implementation, and to monitor post-treatment changes in stand health.

1. Introduction

Forest managers have a charge to restore and maintain resilient ecosystems with the capacity for adaptive change (Holling, 1973; North et al. 2009). The intent of restoration is to improve ecosystem function and thus resilience by managing ecosystem processes and improving biodiversity (Converse et al., 2006; Finkral and Evans, 2008; Boerner et al., 2009, Saab and Powell, 2005; Bond et al., 2012). Whether treating a stand to increase resilience to fire or environmental change, restore critical forest ecosystem function, or to provide a range of ecosystem services, the choice of retained trees is perhaps the most important decision to be made for long-term forest health. Retained trees are selected to meet a variety of objectives, including species composition, ecosystem service provisioning (Seidl et al., 2016; North and Sherlock, 2012), and resiliency to disturbance (Falk, 2017). Given

the large investment of time, effort, and expenditures in forest restoration initiatives, it is critical that standards for assessing the effectiveness of forest management activities are available (Hobbs, 2003; Hood et al., 2018). Providing objective criteria to assess tree vigor and stand health allows managers to apply adaptive management strategies, and to make mid-course corrections or large-scale changes in management direction (Lake, 2001; Hobbs, 2003; Stephens et al., 2012; Wortley et al., 2013; Hood et al., 2018).

In practice, forest treatment evaluations are generally qualitative, may be conducted many years after treatment, and are generally focused on resilience to large or returning fire (Kalies and Kent, 2016; Vaillant and Reinhardt, 2017); increased time for understory recovery (Peppin et al., 2010); and resilience to insects and disease (Kalies and Kent, 2016). The impact of forest treatments may be evaluated from the point of view of timber production, where tree vigor is defined by basal

* Corresponding author.

E-mail addresses: nancy.grulke@usda.gov (N. Grulke), cbienz@tnc.org (C. Bienz), hlinky@gmail.com (K. Hrinkevich), jasmx@pdx.edu (J. Maxfield), kellie.uyeda@gmail.com (K. Uyeda).

<https://doi.org/10.1016/j.foreco.2020.118085>

Received 3 October 2019; Received in revised form 9 March 2020; Accepted 11 March 2020

Available online 30 March 2020

0378-1127/ Published by Elsevier B.V.

area increase, but their effect on stand health, *per se*, is not assessed. Despite a critical need to assess the outcomes of forest restoration, standards for evaluation and verification of restoration efficacy and effects are lacking. The intent of this study was to identify metrics of tree vigor that could be used to quantitatively evaluate short- to long-term management effects on stand health. We focused on one of the most common forest stand types in western United States, dry pine forests, dominated by ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws).

Still operationally used today, Keen's tree vigor classification (1943) for ponderosa pine was developed and applied to rapidly identify low vigor trees 'at risk' of succumbing to western pine beetle (Keen and Salman, 1942). Tree vigor was defined by live crown ratio, tree age and size relationships, and the degree of canopy degradation. However, Keen's classification may be less applicable for evaluating tree vigor in dense, overgrown stands common today, as fundamental height to diameter ratios and canopy structure are strongly influenced by stand density (Chen and Brockway, 2017). Such structurally compromised trees may still exhibit traits of vigor such as bright green, full foliage in the upper crown, and low insect and disease frequency.

One of the most well-known approaches for evaluating stand health is described by the FIA^[1] program, which was developed to estimate and project standing biomass (timber) through time. A small proportion of stands are also more intensely evaluated (Level III), for the purpose of monitoring tree crown condition and vegetation change. Crown condition includes estimates of crown density, transparency, and die-back; live crown ratio; and crown production efficiency, a calculated index of potential tree productivity. This approach is more detailed, but similar to Keen's (1943) in the sense that crown structure and degradation are key attributes assessed. Another well-developed approach to evaluate tree health is the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP-Forests; Eichhorn et al., 2016), which focused on evaluating the impact of oxidative stress (ozone, O₃) on tree and forest health. Whereas the sample plot design and tree attributes measured are similar to that of FIA Level III, the focus on damaging agents (insects, fungi, mechanical, ungulate, fire, O₃, etc.) and their effect on different tissues of trees has been implemented. Our approach was influenced by the above approaches, but relies more heavily on physiologically-based attributes of tree vigor: those related to tree carbon balance, water balance (Tewry and Weiskittel, 2013), and evidence of current frequency of insects and disease, and abiotic damage.

The purpose of our study was to statistically identify metrics of individual tree vigor, using trees from uplands and lowlands, unmanaged and in common forest treatments with varying densities in dry pine forests. We demonstrate the approach with two applications: 1) evaluating stand health of two paired lowland stands: unmanaged and harvested, with assessments during drought and post-drought; and 2) evaluating stand health as marked, adjusted to meet management objectives, implemented, and post-harvest response in year one and two. The approach described here permits: 1) identifying low vigor trees to be removed based on quantitative tree health metrics; 2) evaluating marked retained tree vigor prior to removal; and 3) quantitatively assessing short-, medium-, and long-term post-treatment stand health based on the proportion of low, average, and above-average vigor trees in the stand. We assessed tree vigor during drought, as a tree that can maintain high vigor under such a stress, and a stand that retains a high proportion of trees with high vigor, demonstrates resilience to that stressor.

2. Study description

2.1. Study area

Tree vigor metrics were measured for ponderosa pine in a dry ponderosa pine forest in south central Oregon, U.S.A (Ponderosa Pine Series; Simpson, 2007). The study area is located in the upper Sycan

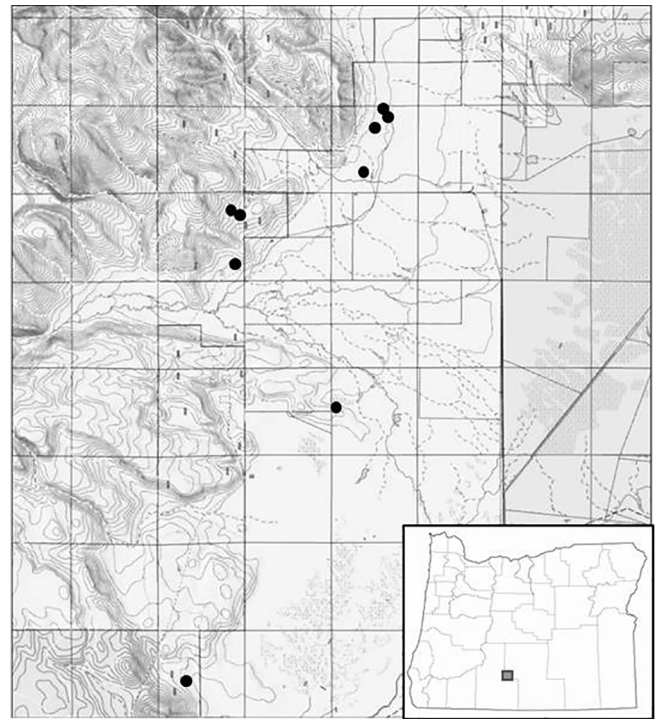


Fig. 1. Location of study area and intensively studied stands in south central Oregon.

River Watershed (HUC 6), in the Modoc Plateau and the East Cascades Ecoregions, in the headwaters of the Klamath Basin, on the divide between the Great Basin and the Klamath Basin. The area is bounded by the coordinates: NW corner: 42°52'44.96" N, 121°11'04.55" W; NE corner: 42°52'42.41" N, 121°06'36.44" W; SE corner: 42°52'33.62" N, 121°09'35.19" W; SW corner: 42°52'38.52" N, 121°14'04.46" W (Fig. 1). Annual precipitation averages 48 cm (hydrologic year: Oct 1 – Sept 30, 1998–2019), with 90% of the total falling between October and May. Known drought years include 2001, 2002, 2014, and 2015 (65%, 80%, 77%, and 83% of the 22 year average). Mean annual air temperature is 5.6 °C. Soil type in the forested lowlands adjacent to Sycan Marsh are andesitic-derived clayey loam. The most common soil type is Andyfan (60–64A), followed by Andyfan - Shakecreek series (66A–67A) (Bienz et al., 2019).

Historically, the forested areas in the study area consisted of a ponderosa pine-dominated forest that averaged 68 trees per ha (TPH), with 24% of the trees in clumps with > 15 trees, and 20% as isolated trees. Within-clump tree spacing averaged 6 m (bole center to center), and the single-storied stands had small openings between clumps. The average mature tree diameter was ca. 68 cm diameter at breast height (1.37 m; DBH). The natural fire interval averaged 58 ± 2 years, with a median of 11 years over the past 400 years based on fire scars (Bienz, 2019).

Similar to many western U.S., pine-dominated forested landscapes, there is a mosaic of unmanaged and treated stands in the study area (Bienz, 2019), all uneven age, with evidence of multiple entries (mid 1980s and 1990s^[2]) for removal of mature, black bark ponderosa pine. Currently, the stands are dominated by uneven-aged ponderosa pine, and secondarily by lodgepole pine (*Pinus contorta* Dougl. Ex. Loud). Aspen (*Populus tremuloides* Michx.), juniper (*Juniperus occidentalis* Hook.), and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) occasionally occur. In the lowland unmanaged stand, lodgepole pine is co-dominant.

Tree vigor metrics were investigated in two unmanaged stands (uplands, U NM; lowlands, L NM); two upland (U HP1, U HP2, patchy harvests in March of 2016); and four lowland forest treatments: patchy harvest in November of 2016 (L HP); even harvest in 2005 (L HE); even

Table 1
Metrics of dry pine stands in south central Oregon.

	PIPO, DBH	PIPO, TPH	ALL spp, TPH	PIPO, BA/HA	ALL spp, BA/HA	4CZDPP	H	Rx
U NM	35.2 ± 4.0	559 ± 361	(all PIPO)	61.4 ± 80.4	(all PIPO)	9.0 ± 4.2		
U HP1	34.6 ± 3.5	307 ± 50	(all PIPO)	34.8 ± 15.0	(all PIPO)	7.7 ± 4.8	3/16	
U HP2	37.5 ± 5.4	198 ± 37	(all PIPO)	14.7 ± 4.8	(all PIPO)	6.3 ± 3.5	3/16	
L NM	35.8 ± 2.3	605 ± 237	722 ± 289	27.6 ± 12.8	30.0 ± 13.8	8.3 ± 3.9		
L HP	41.2 ± 2.8	160 ± 36	(all PIPO)	18.6 ± 4.9	(all PIPO)	7.0 ± 2.7	11/16	
L HE	37.5 ± 0.8	137 ± 57	(all PIPO)	8.8 ± 3.8	(all PIPO)	4.0 ± 0.7	2005	
L HE Rx	38.5 ± 1.8	146 ± 16	(all PIPO)	17.3 ± 5.7	(all PIPO)	5.0 ± 1.4	2005	2006, 2013
L Rx	36.9 ± 3.9	434 ± 22	566 ± 14	12.7 ± 3.7	16.0 ± 1.2	8.8 ± 5.6		2008
L 2Rx	41.4 ± 1.9	160 ± 36	(all PIPO)	28 ± 8	(all PIPO)	6.8 ± 2.7		2006, 2013

Metrics for intensively studied stands in south central Oregon, measured in summer of 2016. Means (± 1 S.D.) of trees per hectare (TPH) and basal area (BA, cm^2/ha) for ponderosa pine (PIPO) and all tree species (SPP), and average competitive zone density of four neighboring PIPO trees (4CZDPP, cm^2m^{-1}) in each unmanaged (uplands, U NM; lowlands, L NM) and managed stands: even or patchy harvests (L HE; L HP; U HP1; U HP2), even harvest and prescribed burn (L HE 2xRx), and lowlands prescribed burn (one or two prescribed burns, L Rx and L 2xRx). Months and years are given for recent treatments relevant to data presented here.

harvest (2005) and two prescribed fires (2006, 2013; L HE 2Rx); one prescribed fire (2008; L Rx); and two prescribed fires (2006, 2013; L 2Rx) (Table 1).

Treatments included: relatively even-spacing harvest of co-dominant trees for stand density reduction with piled and scattered litter (HE); patchy harvests with a range of spatial and tree-age patterns are retained (HP, Churchill et al., 2013; North et al., 2009); 'light' prescribed burns (single or repeated ground fires, Rx) with occasional consumption of single or patches of trees; combined harvest and prescribed burn (single or repeated); and prescribed burn alone. Recent harvests (L HP, U HP1, U HP2) had both patchy overstory thinning, as well as thinning from below (sapling and pole-sized tree removal). The elevation of lowland stands is 1500 m, and trees in these stands are acclimated to a high, persistent water table. Recent multi-year droughts have affected depth to water table. Trees in the upland stands rely on underground springs or water trapped in interstices of weathered bedrock in late summer (see McLaughlin et al., 2020), and were roughly 50 m higher in elevation than lowland stands.

2.2. Stand density and tree-tree competition

In each unmanaged and treated stands, tree density (TPH) and basal area (BA, $\text{m}^2 \text{ha}^{-1}$) were determined in three 30 m diameter circle plots, recording species and bole diameter at DBH for trees > 10 cm at DBH. The location of each plot was determined by selecting areas of representative density in each stand using aerial imagery. Tree to tree competition was quantified using competitive zone density (DBH in $\text{cm}^2/\text{distance}$ in m; CZD) defined in Shaw (2017). Four metrics were tested for both conspecific and interspecific trees: distance to the nearest single tree, average distance to the nearest tree in each of four quadrats to 20 m, CZD of the nearest tree, and average CZD of the four nearest trees > 10 cm DBH. A quadrat with no neighbor within 20 m was averaged in as 0.

2.3. Level of drought stress experienced turgor

Establishing the level of drought experienced was critical for assessing resiliency of forest treatments. Hydrologic drought is best described as site water deficit, but insufficient on-site data for its calculation or modeling was available. Regionally, several longer-term records (Klamath Falls, Chiloquin, and Lakeview, OR) exist, but none of the precipitation patterns were in sync with that of the Sycan River Watershed. Over the course of this study (2014–2018), precipitation was 77%, 83%, 104%, 93%, 112%, 122%, respectively, of the 22-year site average (C Bienz, unpublished data). The three years prior to this study (2011–2013) were considered 'pre-drought' (118%, 100%, 98%, respectively). Three indicators of tree physiological drought were used: total needle water potential (ψ_T) and turgor potential (ψ_p); average NDVI and within-growing season change in NDVI; and average BAI

(basal area increment, $\text{cm}^2 \text{yr}^{-1}$).

Needle total water potential and cell turgor was measured in a subset of trees (5–6 of the 30 intensively studied trees) in each stand in midday in mid-August to early September in 2014, 2015, and 2016. Total needle water potential was measured using a pressure chamber (PMS, Corvallis, OR), and cell turgor was determined after flash freezing needle tissue in liquid nitrogen using the psychrometric method (Wescor 33 T³³; Pallardy et al., 1991).

$$\psi_T = \psi_{(o+m)} + \psi_{(p)} \quad (2)$$

where ψ_T is total water potential, $\psi_{(o+m)}$ is osmotic plus matric potential (solutes and chemically bound water), and $\psi_{(p)}$ is cell turgor of needles.

Carbon allocation to bole diameter growth and tree ring growth is responsive to drought (Stokes and Smiley, 1996). Cores were taken ± 10 cm of DBH (to avoid irregular bark or bole imperfections) to tree center, mounted, sanded to 400 grit, measured (± 0.001 mm; Velmex Inc., 2009; using program J2x, Voor Tech Consulting, 2008), and checked for missing rings (Yamaguchi, 1991) based on cross-correlation with annual ring width patterns from Dr. Andrew Mershel's (Oregon State University) chronology (Holmes, 1983; Swetnam et al., 1995). Cross dating accuracy was evaluated statistically using the software program COFECHA, Version 6.06P (Holmes, 1983; Grissino-Mayer, 2001). Potential dating errors were identified by COFECHA were visually checked, re-dated, re-measured, or re-collected as necessary. For cores that did not intersect the pith, we estimated the number of rings to pith geometrically (Applequist, 1958).

Basal area increment (BAI), bole growth on a per year basis, was calculated from radial growth expressed on bole area in year $(t + 1)$ – bole area in year (t) :

$$BAI = \pi r_{(t+1)}^2 - \pi r_t^2 \quad (1)$$

where r is bole radius at time t .

Normalized difference vegetation index (NDVI) as detected by MODIS satellite imagery^[4] was used as a proxy of stand productivity, and an integration of carbon- and water-based attributes of tree vigor investigated here. NDVI of one MODIS pixel in each stand was used in this analysis (0.0625 km^2); the unmanaged stands and treatments were this size or larger. Average NDVI of the 3-yr pre-drought (2011–2013) and 3-yr drought (2014–2016, as determined by low needle water potential and low turgor, see Section 3), as well as the % change in NDVI from early to late summer (sampled June 25 and August 28) in pre-drought vs. droughted- years suggested and quantified late season drought.

2.4. Metrics for crown and whole tree vigor

Mature black bark trees were selected along a 20 m wide transect, with length determined by accumulating 30 trees in each of the

unmanaged and treated stands. If the forest stand was expected to be treated (harvested) in the next 5 years (U HP1, U HP2, L HP), the length of the transect was increased to select 60 trees for intensive measures. The initial choice of whole tree and crown health attributes in this study was selected from previous studies of ponderosa and Jeffrey pine (Grulke and Lee, 1997; Grulke, 2003; Grulke et al., 2003; Staszak et al., 2007; Miller et al., 1996).

The whole tree and crown morphological attributes selected, measured, and tested were related to carbon-based acquisition (eg, those related to the capacity of a tree to gain and/or retain biomass or carbon); tree water balance (those related to the level of physiological tree drought stress); insect and disease frequency, and abiotic needle damage. Some carbon balance-related attributes were confounded with water balance attributes. An example is leaf chlorosis, which is a proxy for needle chlorophyll content (Grulke and Lee, 1997) and thus photosynthetic capacity. However, chlorosis is also indicative of tree drought stress from chlorophyll oxidation (occurs when stomata are partially or wholly closed). All canopy and whole tree measurements were made by one observer (K. Hrinkevich) from mid-August to late September 2016, and by N. Grulke and or C. Bienz in all other years.

For crown measurements, three to five branchlets per tree were pruned from the third or fourth secondary branch from the distal end of primary branches within the upper part of the lower crown, or the lower part of the mid crown (approximately 11 – 13 m). In some trees, the lower crown had self-pruned due to high stand density, and previously 'mid-crown' branches inadvertently became lower crown. In these trees, only the lower primary branches were accessible with the pole pruner. Branchlets were pruned on the southern or most exposed (if crowded) crown aspect.

The full list and description of attributes considered is given in Appendix A; only attributes selected statistically (see Section 3) are described in the next several paragraphs. Carbon-based attributes included branchlet diameter at the base of the prior year growth (± 0.1 mm; BRDIA2; correlated with current year BAI; Grulke and Lee, 1997), years of needle retention (count, WHL; Fig. 2a); the proportion of the current year branchlet with needles (length of foliated portion in mm divided by the length of same year's branchlet growth in percent (%FOLLN; Fig. 2a), and the level of needle chlorosis relative to fully green, healthy needles in percent (ocular estimate according to Miller et al. (1996); %CHL2, %CHL4 for prior year and four year old needles; Fig. 2b; see also Grulke and Lee, 1997; Miller et al., 1996).

As the number of foliar cells are produced in the prior year, elongation growth is particularly sensitive to water availability in the current year. Water balance related attributes included measurements of needle (elongation) growth as % of maximum needle length (± 0.5 cm, %MxNL; Fig. 2a), branchlet elongation growth (± 2 mm, BRLN), occurrence of needle tip dieback or whole needle dieback (without insect damage; Fig. 2d; indicative of oxidative stress; Miller et al., 1996), and early needle senescence (ES) in the crown (not attributable to a pathogen or insect; in August vs. October; Fig. 2c). Needle dieback is a response associated with oxidative stress (at this site due to drought, but also can be due to O_3 exposure; Miller et al., 1996). The average frequency of needle tip dieback, whole needle dieback (tan or dark brown), and early needle senescence for the three to five branchlets per tree were collated into a single index per tree: leaf abiotic damage (LF A D).

Insect and disease frequency was reported as the occurrence (presence/absence) of any of the following agents observed per branchlet, regardless of whether it may be a primary or secondary agent of damage, averaged over all branchlets sampled per tree (eg, 1, 0, 0 = 0.33 frequency reported for the tree). The insects included: pine needle weevils (*Scythropus*, spp.), unidentified needle phloem feeder, needle scale (*Chionaspis pinifoliae* Fitch; see Fig. 2d), black pineleaf scale (*Dynaspidiotus californica* (Coleman)); western pine beetle (*Dendroctonus brevicornis* LeConte), pine engraver (*Ips pini* Say); red turpentine beetle (*Dendroctonus valens* LeConte); and flat-headed wood borer (*Buprestis*,



Fig. 2. Examples of insect, disease, and abiotic (drought) damage on ponderosa pine needles. A) reduced needle elongation in years of low water availability; (B) needle chlorosis, an oxidative response to high radiation and/or low water availability; (C) early senescence of needles due to drought stress; (D) high frequency of phloem feeder, scale, needle tip dieback, and weevil damage.

spp.). The pathogens included: needle blight (*Lophodermium* spp.; and dwarf mistletoe (*Arceuthobium campylopodum* Engelman (DMR, Hawksworth, 1977; Furniss and Carolyn, 1992). Except for DMR, the insects and diseases were collated into functional guilds (approach influenced by FIA¹, Bezemer and Jones, 1998; Coleman et al., 2018). Foliar insects included weevils, phloem feeders, and scales (LF BI); leaf biotic fungi included needle blight and dead needles (LF BF); bole insects included all bark beetles and wood borers (B I).

2.5. Approach to statistical analyses

Significance of statistical analyses is reported at the $p \leq 0.050$ level throughout unless otherwise described. The significance of correlation among all pairs of carbon-, water-, and functional index and guild attributes were evaluated using Pearson's correlation coefficient for the entire data set of 266 trees. The PCA was conducted to identify the most significant attributes for use in assessing tree vigor. Multiple iterations of Principle Component Analysis (PCA, McCune and Medford, 2011) were performed on combinations of whole tree and crown attributes with the objective of explaining the greatest amount of variation with the fewest attributes. Attributes that did not substantially contribute to the multivariate data structure were eliminated, and in the case of redundant PCA loadings, the attribute which explained less variance was eliminated. The robustness of the PCA was then tested via leave-one-out tests, which performed PCA on subsets of attributes. These analyses all produced substantially similar multivariate data structures, indicating that the overall multivariate structure was not strongly influenced by any single attribute.

Based on the PCA results, a Hierarchical Cluster Analysis (HCA, Boehmke and Greenwell, 2019) was performed using attributes most

significant identified in the PCA to cluster trees with similar characteristics to determine whether groups of trees with similar levels of vigor resulted from similar forest treatments. Within the HCA, multivariate distance was determined using Ward's method (Ward, 1963) to generate clusters with minimal within-cluster variability. A scree plot was used to select the smallest number of clusters that explained 75% of the variation in whole tree and crown health attributes.

2.6. Rapid, qualitative tree and stand health assessment

In anticipation of the need to quickly determine and compare the effects of forest treatments on stand health before treatment, and after treatments through time, the quantitative attributes were used to support the development of a rapid, qualitative classification of three levels of tree vigor: low [LOW], average [AVE], and above-average vigor [AA]. These ranks were assigned for each tree during quantitative whole tree and crown measurements. The proportion of the trees in the three ranks of each unmanaged and treated stands was used as a point-in-time assessment of stand health. Qualitative vigor ranks were assigned in 2016 by N. Grulke and K. Hrinkevich, and otherwise (2014, 2105, 2017 – 2019) were assigned by N. Grulke and or C. Bienz, with cross-calibration between observers. Each intensively studied tree in this study was also assigned a Keen's rank in August 2017 (Keen, 1943).

3. Results

3.1. Stand characteristics

Ponderosa pine density ranged from 137 to 434 TPH in forest treatments and 559–605 TPH in unmanaged stands (Table 1). Additional tree species (lodgepole, juniper) were encountered within only two lowland transects: the unmanaged (U NM), and the prescribed fire only stand (L Rx). The standard deviation of TPH among treated stands was high and averaged 23% (18–35%); variability among plots in the unmanaged stand was approximately 43%. Basal area of black bark mature trees was within the same order of magnitude across the sub-sampled plots in unmanaged stands and forest treatments. The relationship between stand basal area and DBH was not significant, whether only ponderosa or both ponderosa and lodgepole pine were considered ($r = 0.20$, $p = 0.29$; $r = 0.21$, $p = 0.26$; respectively). Tree size (DBH) was also not significantly correlated to stand density ($r = 0.17$, $p = 0.37$; $r = 0.15$, $p = 0.44$, respectively). Within the transects, black bark mature tree age varied by 58 yrs at DBH; tree age averaged 91 ± 13 (1 S.D.) and barkless DBH averaged 30.2 ± 8.4 cm (1 S.D.) across the 224 trees among the 10 stands sampled (Table 3). The relationship between tree age and (barkless) DBH was not significant ($r = 0.20$; $p = 0.29$). Of the four tree to tree competition attributes, the four-aspect, conspecific, average competitive zone density (4CZDPP; Shaw, 2017) had the highest correlation with crown morphological attributes (Table 4), and so was used exclusively. The unmanaged stands and the L Rx stand had the highest 4CZDPP. In L Rx, TPH was not only higher, but trees commonly occurred in dense patches, with smaller open spaces between patches. Tree to tree competition did not increase appreciably at stand densities in excess of 400 TPH.

3.2. Level of drought stress experienced

Across the 22 years of Syman Marsh precipitation data, 2001, 2002, 2014, 2015, and 2018 had below-average annual precipitation (65%, 80%, 77%, 84%, and 82%, respectively; C. Bienz, unpubl. data), each sufficient as single years of drought to induce moderately severe physiological drought stress in ponderosa pine (Grulke et al., 2009). Over 2014–2016, total needle water potential was low at noon in August (-2.0 to -2.3 MPa; Table 2), with the lowest turgor in 2014 (0.3 ± 0.06 MPa, approximately one third of full turgor in this

species), and the highest needle cell turgor occurred in 2015 (0.6 ± 0.02 MPa). Sufficient needle loss may have occurred in 2014 to improve tree water status in 2015, despite a second year of moderately low precipitation. Because needle turgor in August 2016 was generally lower than, or as low as that in known drought years, environmental conditions in 2014, 2015 and 2016 were sufficient to induce moderately severe physiological tree drought stress as defined by Levitt (1980). Although annual precipitation in 2016 was greater than that of 2014 and 2015, 25% of the annual precipitation was received in a single month, and some may have been lost to run-off due to still-moist soils.

BAI was negligibly affected by drought in two of the stands (U HP1, L NM; Table 3). U NM, U HP2, L HE, L HE 2Rx, and L 2Rx ranged from -4 to -7% change in BAI in drought years. L Rx and L HP had significant increases in BAI from pre- to droughted periods (9% and 42%, respectively), likely due to landscape-level hydrologic processes. Greater transpiration of trees in uphill trees may have increased downhill transfer of water, increasing the water availability in these lowland stands at the base of hills.

Pre-drought (2011–2013), early summer NDVI ranged from 0.25 to 0.53 (bars referenced to primary y-axis, Fig. 3), and was highly correlated with both stand TPH ($r = 0.76$) and BA ($r = 0.62$). The upland stand with high DMR (U HP1, see Table 5) had half the NDVI relative to other stands. Trees in this stand exhibited low turgor (Table 2), no difference in BAI between pre-drought and the droughted period (Table 3), intermediate TPH, and relatively high BA and 4CZDPP (Table 1). A patchy harvest was imposed prior to the 2016 field season, but there was no change detected in the NDVI: 2016 NDVI was intermediate between that in 2014 and 2015.

Relative to the pre-drought years, U HP2, L NM, and L HP had lower early summer NDVI in droughted years. Based on NDVI data observed in the spring^[4], NDVI was already depressed (8%) by late June in these stands. There was no consistent change in BAI with drought in these stands (Table 3). L NM had high TPH, moderately high BA, and high 4CZDPP, but the other stands had intermediate metrics (Table 1). In the other five stands, there was little difference in late June NDVI between pre-drought and droughted periods, and no consistency in TPH, BA, CZD, or needle turgor among those stands.

UNM, U HP1, U HP2, and L HE had small differences in within-growing season NDVI between pre-drought and droughted years (late June to late August NDVI; circles referenced to secondary y-axis, Fig. 3). U HP1 had little change in BAI from pre- to drought years, and the others had 4% to 6% decreases in BAI in drought years (Table 3). In the adjacent stands (L HE 2Rx and L 2Rx), within-growing season NDVI exhibited ca. 5% decrease in pre-drought years. In drought years, L 2Rx had a slight decrease in within-growing season NDVI, but L HE 2Rx had a large decrease (7% and 11%, respectively).

L NM, L HP, and L Rx had little within-growing season change in pre-drought NDVI (-1% , 2% , 3% , respectively), and all had greater within-growing season productivity in droughted years (ca. 4% to 5%; Fig. 3). There was a negligible change in BAI from pre- to droughted years in L NM, but L HP and L Rx both had large increases in BAI in the droughted years (9% and 42%, respectively; Table 3).

3.3. Selection of whole tree and crown attributes for field assessments of tree vigor

All intensively studied trees in the unmanaged and treated stands were included in the statistical selection of whole tree and crown attributes for tree vigor assessment. Approximately 60 attributes were measured per tree and tested for correlation with other attributes (see Appendix A), including responsiveness of different ages of each attribute (eg, needle length and chlorosis; retention by needle age; branchlet elongation and diameter growth; individual components of abiotic damage and foliar biotic insects and fungi). Of these, ten non-ordinal attributes were significantly correlated to other carbon-, water-, or biotic

Table 2
Midday, late summer total needle water potential (Ψ_T) and needle cell turgor (Ψ_P).

	2014		2015		2016	
	SN Ψ_T	Ψ_P	SN Ψ_T	Ψ_P	SN Ψ_T	Ψ_P
U NM	-2.44 (0.03)	0.34 (0.03)	-2.09 (0.05)	0.65 (0.07)	-2.13 (0.10)	0.43 (0.10)
U HP1	-2.32 (0.03)	0.17 (0.07)	nd	nd	-2.26 (0.06)	0.30 (0.10)
U HP2	nd	nd	nd	nd	-2.11 (0.06)	0.28 (0.08)
L NM	-2.21 (0.04)	0.18 (0.11)	-1.95 (0.04)	0.56 (0.09)	-2.25 (0.07)	0.15 (0.07)
L HE	-2.35 (0.09)	0.52 (0.13)	-2.00 (0.02)	0.64 (0.06)	-2.16 (0.08)	0.41 (0.07)
L HP	-2.21 (0.04)	0.18 (0.11)	-1.98 (0.03)	0.65 (0.04)	-2.14 (0.08)	0.49 (0.08)
L HE 2Rx	-2.33 (0.05)	0.38 (0.13)	-1.89 (0.04)	0.60 (0.06)	-2.30 (0.09)	0.40 (0.14)
L Rx	nd	nd	nd	nd	-2.13 (0.06)	0.20 (0.08)
L 2Rx	-1.85 (0.06)	0.30 (nd)	-1.86 (0.06)	0.48 (0.08)	-2.12 (0.07)	0.50 (0.10)
ALL SITES	-2.31 (0.10)	0.28 (0.15)	-2.01 (0.06)	0.63 (0.04)	-2.18 (0.06)	0.34 (0.12)

Midday, late summer noon total needle water potential (Ψ_T) and needle cell turgor (Ψ_P) in MPa for unmanaged stands and forest treatments. Site name acronyms as in Table 1. Values given are means ($\pm$ 1 S.E.). There were no significant differences in midday needle water or turgor potential among sites in 2016.

or abiotic defoliators (DMR and ES were excluded; Table 4). Insufficient numbers of trees had evidence of bark beetles and or wood borers (B I), or foliar fungi (LF BF) occurred to present significant correlations. Because of the interest in the effect of tree to tree competition on crown vigor, TPH, BA, and CZD attributes were also tested for correlation with tree attributes of vigor.

The selected carbon acquisition-related attributes included years of needle retention (WHL), prior year branchlet diameter (BRDIA2), the proportion of needles on current year branchlets (%FOLLN1), and chlorosis of 2- and 4-year old needles (CHL2, CHL4). The numbers following the attribute names indicate year of measurement, with 1 indicating current year, and 2 indicating prior year). Carbon-related attributes were correlated to other carbon-related attributes as well as to water-, foliar insects (LF BI), and tree-tree competition (4CZDPP). The statistically selected water-related attributes included branchlet elongation (BRLN1), current year percent of maximum needle length (%MxNL1), and foliar biotic damage (LF A D). Water-related attributes were correlated to other water- as well as LF BI. Of the four competitive zone density attributes tested, the average CZD of the four nearest conspecific neighbors (4CZDPP) was significantly correlated to both carbon- and biotic defoliator-related attributes. LF A D and LF BI were also significantly correlated.

Attributes with statistically significant correlations were further assessed with Principal Component Analysis (PCA, McCune and Medford, 2011) (Fig. 4) to identify redundancies in attribute loading, and to provide a statistical basis for minimizing the number of attributes to be measured in the field to quantitatively assess tree vigor. Using this approach, %FOLLN1 and CHL2 were eliminated from further analyses, but the nominal attribute DMR was included and improved explanation of the variance within the data. The first two and five components explained 39% and 75% of the variance, respectively,

across tree attributes in all unmanaged and treated, lowland and upland stands sampled.

3.4. Assessing effects of forest treatments

Hierarchical Cluster Analysis (HCA) was conducted using the quantitative measures of whole tree and crown attributes selected with multivariate analysis to determine whether trees with similar tree and crown attributes occurred in similar or disparate forest treatments. The HCA clustered trees into six groups (Table 5). When the carbon-, water-, defoliator-, and tree-tree competition attributes were averaged for each HCA-sorted group, trees were coarsely sorted into groups with similar values, suggesting similar levels of tree vigor, but different groups were cued to different attributes. Group 1 trees were drawn from all stands, had the greatest frequency of foliar abiotic damage, and high branch diameter and branchlet length. Group 2 trees were drawn from seven stands of which six were in lowlands, with both low branchlet diameters and lengths. Group 3 trees were drawn from five stands, both uplands and lowlands, had low needle retention and high needle chlorosis. Group 4 trees were from six stands, in both uplands and lowlands, and had relatively high tree-tree competition, high current year needle elongation growth, with high frequency of foliar insects. Group 5 consisted of both low- and upland stands, moderate DMR, high frequency of foliar insects, and all with high tree to tree competition. Group 6 was comprised of only upland stands (U NM and U HP1) with high DMR, high frequency of foliar insects, and low foliar abiotic damage. Each group was comprised of trees from more than one forest treatment: trees responded, or persisted, or were selected through treatment independently.

Table 3
Pre-drought and droughted BAI.

	AGE	BARKLESS DBH, cm	PRE-DRT BAI, cm ²	DRT BAI, cm ²	% Δ TO DRT	COUNT
U NM	87 $\pm$ 2	27.6 $\pm$ 1.0	11.9 $\pm$ 0.9	11.7 $\pm$ 0.8	-3.7 $\pm$ 4.3c	46
U HP1	80 $\pm$ 4	25.4 $\pm$ 1.6	9.0 $\pm$ 0.8	9.0 $\pm$ 0.9	-0.2 $\pm$ 6.0d	19
U HP2	101 $\pm$ 4	39.6 $\pm$ 2.7	26.6 $\pm$ 3.7	25.7 $\pm$ 3.7	-4.3 $\pm$ 2.6c	33
L NM	91 $\pm$ 3	28.9 $\pm$ 1.3	11.5 $\pm$ 1.1	11.7 $\pm$ 1.2	0.1 $\pm$ 2.9d	29
L HP	100 $\pm$ 2	33.2 $\pm$ 1.5	13.6 $\pm$ 1.8	15.0 $\pm$ 2.4	9.1 $\pm$ 2.8b	23
L HE	83 $\pm$ 3	31.2 $\pm$ 1.1	27.9 $\pm$ 1.3	25.6 $\pm$ 1.0	-5.7 $\pm$ 3.1c	30
L HE 2Rx	83 $\pm$ 4	32.4 $\pm$ 1.6	26.1 $\pm$ 2.4	24.0 $\pm$ 2.4	-7.3 $\pm$ 4.0c	26
L Rx	82 $\pm$ 4	24.1 $\pm$ 1.4	11.3 $\pm$ 1.3	14.6 $\pm$ 1.6	41.5 $\pm$ 8.9a	32
L 2Rx	81 $\pm$ 3	62.2 $\pm$ 4.0	50.3 $\pm$ 6.8	48.1 $\pm$ 6.6	-4.9 $\pm$ 3.5c	28

Basal Area Increment (BAI, in cm² y⁻¹) averaged ($\pm$ 1 S.D.) for 2011–2013 (pre-drought) and 2014–2016 (droughted), and the percent (%) change in BAI from pre-drought to droughted period calculated for each tree, then averaged over the trees in each stand. Different letters indicate significant differences in percent change in response to drought.

Table 4
Correlation coefficients among whole tree and crown attributes.

	WHL	BRDIA2	BRLN1	%FOLLN1	%MxNL1	CHL2	CHL4	LF BI
WHL	1							
BRDIA2		1						
BRLN1		0.484	1					
%FOLLN1				1				
%MxNL1				0.274	1			
CHL2			0.227		-0.275	1		
CHL4	-0.345		0.211		-0.196	0.567	1	
LF BI					0.231	-0.368	-0.196	1
LF A D								-0.222
4CZDPP						-0.188	-0.267	0.264

Correlation coefficients for attributes with $r^2 > 0.1$ among whole tree and crown attributes, where WHL is the number of years of retained needles; BRDIA2 is prior year branchlet diameter; BRLN1 is the length of current year branchlet growth; % FOLLN1 is the percent of the length of retained needles on the current year branchlet; %MxNL1 is current year needle elongation growth relative to the longest needles produced on the branchlet, in percent; CHL2, CHL4 is the percent chlorosis of 2 and 4 year old needles; LF BI is the average frequency of foliar insect per tree; LF A D is the average frequency of needle damage due to drought; and 4CZDPP is the average competitive zone density of the four nearest neighboring conspecific trees in 4 quadrats to 20 m.

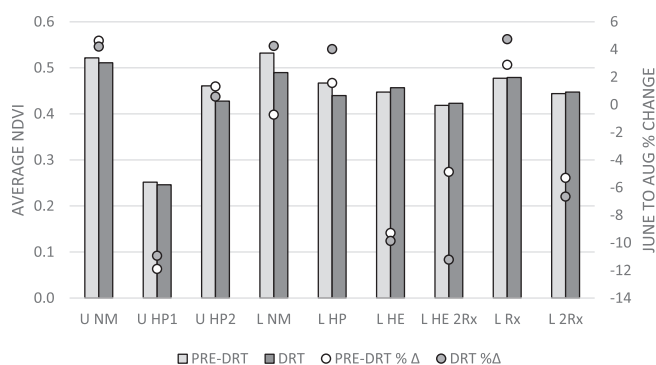


Fig. 3. Bars represent mean early season (June 28) NDVI in pre-drought years (2011 – 2013; light grey) and in drought years (2014 – 2016; dark grey). Circles referenced on the secondary y-axis represent the mean % change in within-year NDVI, as detected on June 28 and August 28th for pre-drought (open), and drought years (closed). Acronyms for stand names are as given in Table 1.

3.5. Rapid, qualitative tree and treatment health assessments

Each tree was qualitatively ranked into low- (L), average- (AVE), and above-average (AA) tree vigor (Fig. 5) at the time of whole tree and crown measurements. Whole tree and crown measurements for the statistically selected attributes are summarized by qualitative rank (Table 6). Not all attributes chosen through correlation and multivariate analysis significantly differed when summarized by rank.

Table 5
Hierarchical Cluster Analysis of trees using whole tree and crown attributes.

	U/ L	WHL	BRDIA2	BRLN1	%MxNL1	CHL4	LF BI	LF A D	DMR
1	1.1 (0.0)	6.5 (0.1)	6.6 (0.1)	19.5 (0.5)	86 (1)	14 (1)	2.2 (0.1)	1.0 (0.1)	0.0 (0.0)
2	1.1 (0.1)	6.0 (0.1)	5.0 (0.2)	11.5 (0.5)	81 (2)	15 (2)	2.1 (0.1)	0.8 (0.1)	0.0 (0.0)
3	1.3 (0.1)	5.1 (0.2)	5.9 (0.3)	19.0 (1.5)	89 (2)	54 (3)	2.3 (0.1)	0.8 (0.1)	0.2 (0.2)
4	1.6 (0.1)	6.6 (0.1)	5.7 (0.1)	12.0 (0.5)	97 (1)	7 (1)	2.8 (0.0)	0.8 (0.1)	0.0 (0.0)
5	1.6 (0.1)	6.9 (0.2)	6.3 (0.2)	15.0 (1.5)	85 (3)	8 (1)	3.3 (0.2)	0.8 (0.1)	0.7 (0.3)
6	2.0 (0.0)	6.3 (0.2)	6.5 (0.2)	16.5 (1.0)	93 (1)	8 (1)	2.7 (0.1)	0.5 (0.1)	3.1 (0.2)
1	U NM	U HP1	U HP2	L NM	L HP	L HE	L HE 2Rx	L 2xRx	L 1Rx
2		U HP1		L NM	L HP	L HE	L HE 2Rx	L 2xRx	L 1Rx
3	U NM		U HP2	L NM		L HE			L 1Rx
4	U NM	U HP1	U HP2		L HP		L HE 2Rx		L 1Rx
5		U HP1		U NM				L 2xRx	L 1Rx
6	U NM	U HP1							

Hierarchical Cluster Analysis of trees in all unmanaged and forest treatments. Upper portion gives means (± 1 S.E.) of whole tree and crown attributes in each cluster (acronyms as in Table 4). Stand membership in each cluster is given below (acronyms as in Table 1).

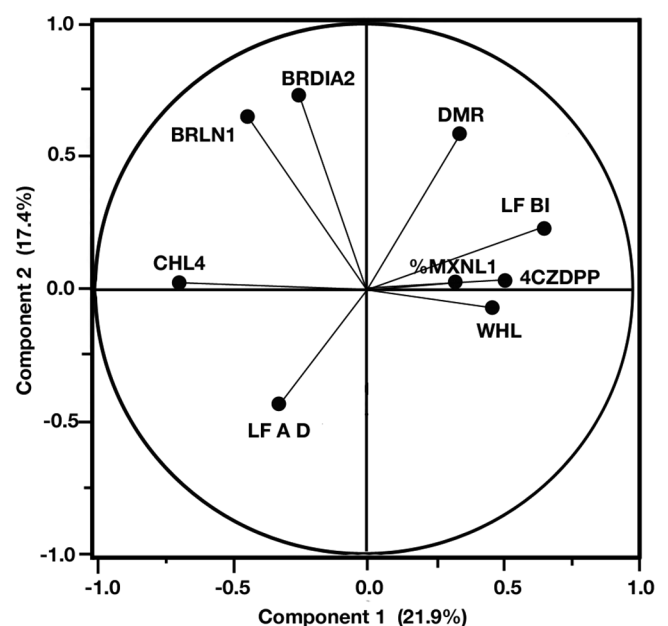


Fig. 4. Principal components analysis (PCA) portrays statistically selected whole tree and crown attributes in multivariate space. CHL2 was considered redundant (with CHL4), as was %FOLLN (with BRLN1); both were eliminated from further analysis.

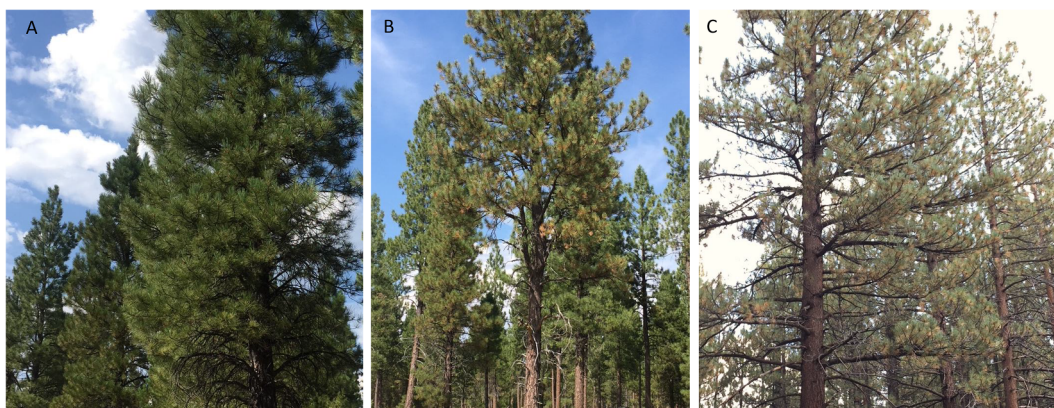


Fig. 5. Examples of above-average (A), average (B), and low vigor trees (C) described in Table 6.

Above-average vigor trees had low needle chlorosis, and a high needle retention (WHL) that visibly translated into canopies with bright green color, high needle mass, and low canopy transparency. Average health trees had intermediate needle chlorosis and needle retention, and greater branchlet diameter. Four attributes contributed to a low tree vigor rank: high needle chlorosis suggesting lower photosynthetic capacity (Nowak et al., 1991); low needle retention, suggesting lower photosynthetic surface area and lower tree capacity for photosynthetic gain; high frequency of early needle senescence (a component of LF A D in Table 6), suggesting too-high early season leaf area to carry for late summer tree drought stress; and greater BRDIA2, suggesting greater allocation to structure. Mistletoe frequency was high in low vigor trees.

The intensively studied mature, black bark trees in this study were primarily in Keen's (1943) age classes 1 and 2. Combining the inferred tree ages, the (Keen) letters assigned to crown degradation were assigned numerical ranks (the increasingly degraded canopies, A through D, were assigned 1 through 4) and tested for correlation with the tree vigor ranks assigned to individual trees in this study (LOW, AVE, and AA). There was a moderate relationship between the modified Keen degradation rank and this study's rank ($r = 0.388$; $p < 0.0001$). Our rank described lower tree vigor than would have been expected using Keen's approach using primarily crown structural attributes.

4. Assessing stand health using qualitative ranks

As a point-in-time demonstration of using qualitative ranks to assess stand health, the proportion of LOW, AVE, and AA tree ranks were presented for adjacent lowland, unmanaged (L NM) and a treated stand (L HE) (Fig. 6, upper box). In the first year of drought, the even harvest stand had a much greater proportion of AA trees than the unmanaged stand. As the drought progressed, the proportion of AA trees decreased in L HE, but the proportions of the three tree vigor ranks was relatively

stable for L NM until 2018, another drought year. Stand health of L HE continued to decline in 2017, but recovered in 2018.

This approach was also applied to show how a prescription was modified to meet management objectives, and to evaluate post-harvest stand health (Fig. 6, lower box). Pre-harvest, the population-at-large ($n = 48$) was mostly comprised of AVE vigor trees, with the same proportion of LOW and AA vigor trees (26% each). Trees were marked in late fall, 2016 for retention, evaluated, then re-marked to eliminate LOW vigor trees in the retained-tree population. Pie diagrams show the high proportion of AA and AVE trees as implemented, and in the first and second year post-harvest ($n = 30$; Fig. 6, lower box, upper row). The time series of only the same, retained trees (2014 to 2018, pre- to post-harvest) is shown in the lower box, lower row (Fig. 6). There was no change in the proportion of LOW : AVE : AA trees until the 2nd post-harvest year with greater water availability.

5. Discussion

A statistical approach was developed to identify whole tree and crown metrics to assess tree vigor in ponderosa pine. The quantitative approach presented here is codified, and conducive to repeat measures by the same or another observer. The attributes chosen were related to tree carbon balance, water balance, and susceptibility to foliar insects, fungi, and abiotic damage. Many of the attributes chosen have been suggested by others (reviewed in the Introduction), and are included in parameterizations of single tree physiological growth models (reviewed in Twery and Weiskittel, 2013), and vegetation models (Weiskittel et al., 2011). Most of these attributes have also been used to assess ponderosa pine response to O_3 (Staszak et al., 2004; 2007), and Jeffrey pine response to drought stress, another oxidative stress (Grulke, 2003; Grulke et al., 2003).

In order to apply the term 'resilient' to trees, stands, and forests,

Table 6

Translation from quantitative whole tree and crown attributes to qualitative ranking.

RANK	WHL	BRDIA2	BRLN1	%MxNLI	CHL4	LF BI	LF A D	DMR
AA	6.7 (0.1)a	5.9 (0.1)b	15 (1)	90 (1)	8 (1)a	2.6 (0.1)a	0.8 (0.0)	0.3 (0.1)a
AVE	6.3 (0.1)b	6.3 (0.1)a	16 (1)	90 (1)	14 (1)b	2.4 (0.1)b	0.8 (0.1)	0.6 (0.1)b
LOW	6.0 (0.2)b	5.8 (0.2)b	15 (1)	89 (1)	19 (3)c	2.5 (0.1)a	1.0 (0.1)	0.8 (0.2)b
LOW VIGOR			AVERAGE VIGOR			ABOVE-AVERAGE VIGOR		
CHLOROTIC NEEDLES			INTERMEDIATE			BRIGHT GREEN NEEDLES		
LOW NEEDLE MASS			INTERMEDIATE			HIGH NEEDLE MASS		
THINNER BRANCHLETS			GREATER BRANCHLET LENGTH			LITTLE BRANCH WOOD VISIBLE		
EARLY NEEDLE SENESCENCE			INTERMEDIATE LEAF DEFOLIATORS			LOW DMR		

Mean (± 1 S.E.) quantitative values for whole tree and crown attributes (top) related to the qualitative ranking of tree vigor (bottom). Significant differences are indicated with different letters within an attribute. Differing letters within a column indicate significant differences among vigor ranks. Acronyms for attributes as in Table 4. Examples of trees of above average (AA), average (AVE), and low (LOW) vigor are given in Fig. 5.

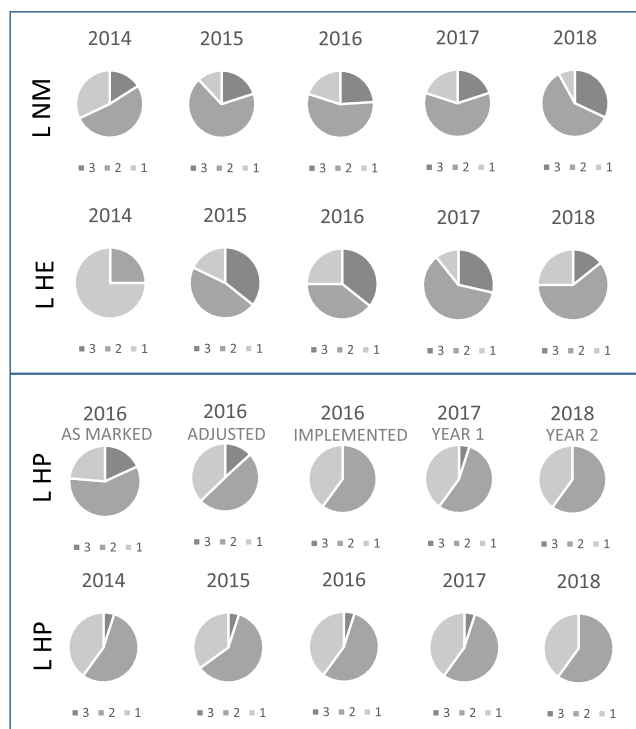


Fig. 6. Proportion of trees in the three vigor ranks (1 = AA, light grey; 2 = AVE, medium grey; 3 = LOW vigor trees, dark grey). Upper box: comparison of adjacent, lowland stands, one unmanaged (L NM) and one treated (even harvest, L HE) in 2014–2018. Lower box, top row: changes in proportion of mature, black bark tree vigor in late 2016 as marked, as adjusted to meet management objectives, as implement, and in year 1 and 2 post-harvest. Lower box, bottom row: changes in proportion of tree ranks from 2014 to 2018 for the same 30 trees.

assessments are best conducted under quantified levels of environmental stress. In this study, an effort was made to describe the level of drought stress experienced during assessments. Acute and chronic droughts accompanied by higher than average temperatures have been linked to forest die-backs (Allen et al., 2015; Adams et al., 2017). Water deficits were noted in 2014 and 2015, but extremely low measured cell turgor (0.2 to 0.5 MPa, Table 2) indicated that ‘adequate’ precipitation received in 2016 was insufficient to replenish water availability. Cell turgor loss point (0 MPa turgor), an indication of severe drought stress, was reported at a total needle water potential of -2.3 MPa for both montane and desert populations of ponderosa pine (Maherali and DeLucia, 2000). In another study, a single year of 60% and 80% of long-term average precipitation, each preceded by an average precipitation year, induced severe and moderate physiological drought stress (respectively, as defined by Levitt, 1980) also in ponderosa pine (Grulke et al., 2009).

Known water deficits did not affect all stands uniformly. Two tree (BAI, NDVI) and one stand level (NDVI) responses to water deficits were evaluated in this study, but the responses were not in sync. BAI response to the 3-yr drought relative to pre-drought ranged from no response (U HP1, L NM), to decrease (4% to 9%; U NM, U HP2, L 2Rx, L HE, L HE 2Rx), and increase (9% and 42%, respectively, L HP, L Rx; Table 3). Although midday cell turgor was highest in the stands with increased BAI during the drought, it was not appreciably greater than in other stands with decreases in BAI. Also, L NM, L HP, and L Rx had greater late than early summer NDVI during the three year drought (Fig. 3). Landscape-level processes may have played a role in continued access to water during the drought: uphill trees may have had reduced leaf area and transpiration during the drought, resulting in greater underground water transport to these stands on toeslopes (see also

McLaughlin et al., 2020). As new patterns and extremities of environmental conditions develop, it may be increasingly important to verify the level of physiological tree drought experienced and its duration (perhaps with remote sensing tools), in reporting that a stand, treatment, or forest is ‘resilient’ to an environmental stressor. Identifying components and conditions of imminent ecological drought (Crausbay et al., 2017; Slette et al., 2019) is critical.

There were two locations where unmanaged and treated stands were adjacent and more likely to have similar properties. In comparison to an adjacent unmanaged upland stand, a stand with a patchy harvest (U HP1) resulted in lower stand density, basal area, and tree-to-tree competition (Table 1), but trees were slightly more drought stressed in the treated stand (Table 2). A lowland area with an even harvest (L HE) in 2005 still had lower stand density, basal area, and tree-to-tree competition than an adjacent unmanaged stand. Although water balance was slightly improved during the drought in L HE, this improvement was not reflected in an increase in BAI (Table 3). Denser patches of trees or even tree adjacency may improve tree water status through reduced windspeeds, increased relative humidity and reduced evaporation in clusters of crowns, as demonstrated among different silvicultural treatments (Kovács et al., 2019). Lowland stands on toeslopes unresponsive to moderately severe drought may not persist without risk in extreme and or prolonged droughts (see Van Gunst et al., 2016).

Early summer NDVI, and early to late season changes in NDVI in pre- and droughted years identified stands affected by moderate severity drought. The differences in responses could be interpreted with field knowledge of the stands. However, MODIS NDVI at a resolution to be representative of a single forest stand, sometimes did, but sometimes did not reflect impacts of drought or harvests on vigor of component trees and stands. The additional lines of evidence (level of tree drought stress, BAI response) aided interpreting stand response to water deficits.

The whole tree and crown attributes statistically selected were relevant, robust, morphological attributes known to be responsive to environmental and biotic stressors. We expected these tree attributes to respond similarly within a stand with consistent topographic position, soil type, and inferred availability of belowground water resources (Weiskittel et al., 2011), as well as implemented treatment. However, all six of the hierarchical clusters were comprised of trees from multiple treatments: trees responded, persisted, or were selected independently within a treatment (Table 5). The clusters of trees were sorted on the basis of different combinations of attributes supporting a particular level of vigor.

A reason for multiple traits to be clustered into a single group may be that ponderosa pine is a ‘plastic’ species (Grulke, 2010; Grulke and Lee, 1997). Ponderosa pine has dimorphic responses to oxidative stress (high light exposure, drought stress and or ozone exposure): many needle ages are retained but all are chlorotic, or few needle ages retained, but all are bright green (Grulke and Lee, 1997). With oxidative stress, photosynthetic pigments are oxidized and rendered inoperative, nutrients are translocated from older to younger needles to produce new pigments, increasing chlorosis in older needles, then older needles are excised (‘early senescence,’ Grulke, 2003; and here Fig. 2c; 5b, c). With drought stress, some oxidative stress as described above occurs, but the primary response is that older needles are abscised to balance transpirational requirements of retained leaf area with fine root mortality under conditions of low soil water content (Margolis et al., 1995). Early needle senescence can occur in mid growing season with either drought- or oxidative stress (Grulke, 2003). Despite this plasticity, ten whole tree and crown attributes were sufficient to characterize tree vigor, and when qualitatively applied, could be used to differentiate point-in-time ponderosa pine response to forest treatments.

Quantitative measures of whole tree and crown vigor provided data-based support for human perception of tree vigor and stand health. The quantitative metrics were translated into three qualitative tree vigor classes: low, average, and above-average. In applying the qualitative field ranking, 1) foliar color was prioritized (the presence and level of

needle chlorosis or yellowing, fading, and/or early needle senescence [brown or tan]); then 2) crown transparency (foliar retention both on the branch and within a needle age class, needle mass/length; 3) occurrence and location of excising foliage, growing points, and primary branches (the latter also included in Keen, 1943 and FIA Phase 3 assessments⁵); and 4) the high frequency of foliar insects, fungi, and abiotic damage, and high DMR, suggesting trees already ‘at risk’ (Fig. 2d).

The differences in whole tree and crown attributes were subtle (Table 6) but effective in assigning tree vigor and in assessing stand health. Above-average vigor trees had low needle chlorosis (e.g., greater needle chlorophyll retained; Grulke and Lee, 1997), which translates to greater photosynthetic capacity (Nowak et al., 1991). Above-average vigor trees also had a low frequency of early needle senescence (incorporated into the LF A DF attribute), suggesting that these trees were well-acclimated to their location in the landscape, had greater access to or less competition for resources (Van Mantgem et al., 2018), and or did not overshoot water resource availability by producing more leaf area than could be supported through mid- to late summer drought. Average vigor trees had intermediate values of crown vigor relative to above-average and low vigor trees. The exception was branchlet length, which was higher, possibly reflecting different allocation patterns. Fewer needle age classes in average vigor trees, and more within-needle age class needle senescence (Fig. 2c) may have reduced leaf area and permitted more water availability per leaf surface area during growth, and thus greater leaf cell elongation with less chlorophyll concentration per surface area (Duan et al., 2019).

Low vigor trees had the lowest needle retention and branchlet diameter growth, the highest level of needle chlorosis, the fewest number of needle age classes, and frequently exhibited early needle senescence. Low vigor trees allocated more resources to elongation growth (branchlets and needles), but the high frequency of early senescence suggested poorer acclimation to its location in the landscape, that the tree was in a marginal site, and or did not have the capacity to respond with adaptive resource acquisition and allocation strategies to thrive in that location. Chronically stressed trees may be better suited to surviving unfavorable environmental conditions (McNulty et al., 2014). Low vigor trees may be the most vulnerable to changes in environmental-, biotic-, or management-induced stresses, several years prior to the stress (Sanguessa-Barreda et al., 2015). Low vigor trees could be identified and removed prior to an above-ground based spatial pattern to reduce risk of loss in extreme or prolonged unfavorable conditions.

The lack of a common tree response to forest treatments supports the importance of evaluating and understanding individual tree response (see Grote et al., 2016) to management activities and natural stressors, whether the understanding is obtained with quantitative measures or qualitative ranking. Stand health could be assessed by evaluating the proportion of low, average, and above-average vigor trees. Tracked through time, stand response to both drought and drought alleviation, as well as forest treatment could be observed (Fig. 6). In this study, significant physiological tree drought stress developed despite the treatments implemented. Average and above-average vigor trees were resilient to a three-year, moderately severe drought, followed by variable water availability in two subsequent years. Following the same trees pre- and post-treatment, without (2017) and with drought (2018), tree rank was unaffected by thinning, suggesting that the selection of trees to be retained is critical (Fig. 6, lower box, lower row).

Quantitative or qualitative assessments of tree vigor could be used as a pre-treatment tool to remove trees ‘at risk’ or already in decline, which are likely to be more susceptible to environmental stressors and or successful insect and disease attack, and if not considered pre-treatment, could alter desired spatial distribution of trees on the landscape. These assessments could also be used to evaluate the potential stand health as marked using the proportion of above-average, average, and low tree vigor of trees to be retained. Applying these qualitative

principles to evaluate an already-marked stand reduced the proportion of low vigor trees and improved the proportion of average vigor trees in the stand after harvest, and through time (Fig. 6, top row). The choices of trees to be left on the landscape are the most important as they have the acquired resources, expressed attributes, and the potential to be resilient to disturbance and environmental extremes. Assessed periodically, either approach could be used to permit mid-course changes to achieve desired outcomes. The quantitative measures may also be used to understand the mechanism of tree response to environment, biotic, or management activity.

In dense forests developed over the last century, ranks based on tree size and form (crown structure; Keen, 1943) may not be sufficient to assess tree vigor and stand health. Tree crowding can cause tree form to be uneven, and the height of the first live branch may be high due to excised, shaded, lower branches, but not necessarily indicative of low tree vigor. Although trained and experienced marking crews ‘know tree vigor when they see it,’ whole tree and crown metrics proposed here for assessing tree vigor are quantitative, repeatable, and based on attributes that are representative of whole tree carbon (biomass), water balance, and susceptibility to insects, diseases, and abiotic damages. The approaches presented could be used to document expected stand health as-marked, as well as monitor post-treatment health through time.

- [1] www.fia.fs.fed.us/library/fact-sheets/data-collections/Phase2_3.pdf
- [2] <https://data.fs.usda.gov/geodata/edw/datasets.php>
- [3] commercial names are given for the convenience of the reader only, and do not constitute endorsement by the U.S. government
- [4] <https://usda-drought.appspot.com/>

CRediT authorship contribution statement

Nancy Grulke: Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation. **Craig Bienz:** Conceptualization, Data curation, Investigation, Project administration. **Kate Hrinkevich:** Data curation, Investigation. **Jason Maxfield:** Data curation, Methodology, Validation, Visualization. **Kellie Uyeda:** Data curation, Data curation.

Acknowledgements

Thanks to Charlie Schrader who supported field efforts and discussed approaches to correlate spectral attributes to the morphological attributes presented here. Much thanks to four anonymous reviewers, and Dr. Paul Anderson who provided suggestions on this manuscript. Internal funding of the U.S. Department of Agriculture, Forest Service, supported this research.

Appendix A

List and description of whole tree, crown, bole, insects, diseases, and abiotic damage observed on ponderosa pine.

Carbon acquisition attributes:

Branchlet diameter (BRDIAx), measured to 0.01 mm at the base of each year's growth with retained needles ('x' up to 8 years);

Number of whorls (WHL), years of needle retention (count);

Proportion of the branchlet with retained needles (%FOLLNx), measured in mm length of foliated branchlet/mm length of branchlet, expressed as % ('x' up to 8 years);

Needle chlorosis (CHLx), ocular estimate, in % of discoloration (yellowing, loss of chlorophyll) relative to fully green, healthy needles ('x' up to 8 years); see Fig. 2b;

Water acquisition attributes:

Needle elongation growth (%MxNLx), current year needle length to the nearest 0.5 cm/longest retained needle lengths, expressed as % ('x'

up to 8 years); See Fig. 2a;

Branchlet elongation growth (BRLNx), measured to the nearest 2 mm ('x' up to 8 years);

Needle tip dieback (TDB) without insect damage, recorded when dark brown needle tip, marked by a necrotic line on the needle, is greater than 2 mm and when more than two occurrences on whole branchlets (presence/absence, averaged across sampled branchlets for each tree, eg, 0, 1, 1 would be recorded as 0.67 for frequency occurrence for needle tip dieback on the tree); See Fig. 2d;

Whole needle die back (WNDB) without insect damage, light to medium brown hue, recorded when greater than two occurrences on whole branchlets (presence/absence, averaged across sampled branchlets for each tree as for TDB above);

Early needle senescence (ES), premature whole fascicle needle death, light medium brown hue, of older needles on branchlets (presence/absence, averaged across sampled branchlets for each tree as for TDB above; See Fig. 2c;

Leaf, abiotic damage (LF A D), the sum of tree frequencies of TDB, WNDB, and ES (above);

Leaf, biotic insect (LF BI), the sum of frequencies of LC, PF, SC, BSC, and BSC for each tree;

Scythropus, spp.; pine needle weevil (LC), margins of needles nipped at .5 mm intervals; recorded when observed on at least two needles per branchlet;

Unidentified needle phloem feeder (PF), single point of insertion of proboscis into needle phloem, slight necrosis around insertion point, with or without chlorotic 'halo' around insertion point; recorded when observed on at least two needles per branchlet;

Chionaspis pinifoliae Fitch; armored scale (SC) approximately 0.5 mm in diameter or its waxy white encasement of eggs on the surface of needle; see Fig. 2d), recorded when observed on at least two needles per branchlet;

Dynaspidiotus californica (Coleman); black pineleaf scale (BSC), black scale approximately 0.1 mm in length; recorded when observed on at least two needles per branchlet;

Bole Insects (B I), the sum of frequencies of WPB, IPS, RTB, FHWB (below) for each tree;

Dendroctonus brevicomis LeConte, western pine beetle (WPB), evidence of one exit hole, rusty brown resin with frass;

Ips pini Say (IPS); pine engraver, evidence of powdery appearance of rusty brown resin appressed against the bark with frass, not associated with mechanical damage to the bole; evidence of one attack;

red turpentine beetle *Dendroctonus valens* LeConte (RTB); copious dark red/brown resin with frass, generally lower on the bole; evidence of one attack;

Buprestis, spp. (FHWB); many long clear streams of resin from the top of the tree, not originating from broken branches, cracks in the bark, or other damage;

Leaf Biotic Fungi (LF BF), the sum of frequency of LOPH (below) for each tree;

Lophodermium spp. (LOPH); needle blight, small black reproductive structures on the needles and or hanging, grey, dead needles on branchlets; any definitive observation reported as presence;

Arceuthobium campylopodum Engelm (DMR, [Hawksworth, 1977](#); [Furniss and Carolyn, 1992](#)); dwarf mistletoe, reported as rank, from 1 to 6.

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