WHITE PAPER

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Stand Density Thresholds Related to Crown Fire Susceptibility[1]

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[1] White papers are internal reports; they receive only limited review. Viewpoints expressed in this paper are those of the author – they may not represent positions of USDA Forest Service.

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INTRODUCTION

This white paper describes how to use common measures of forest stand density to derive estimates of crown fire susceptibility. An abbreviated version of this material is presented in a journal article from Fire Management Today, volume 70, issue 3: "Estimating Crown Fire Susceptibility for Project Planning" (Powell 2010).

For at least the last several thousand years, wildfire has been a primary initiator of plant succession for the interior Pacific Northwest (Habeck 1976). At least three types of wildfire are recognized (Scott and Reinhardt 2001):

- Ground fires burning in organic substrates such as peat;
- Surface fires burning in herbs and other materials lying on or near the ground surface; and
- Crown fires burning in elevated canopy fuels.

Crown fire, one of the most severe disturbance events that a forest ecosystem experiences (Pyne et al. 1996, Rothermel 1991), spreads quickly through the forest canopy, releasing tremendous amounts of heat and energy in a relatively short time period (Van Wagner 1977).

Crown fire spread rates exceeding 7 miles per hour and flame lengths of more than 150 feet have been recorded (Pyne et al. 1996). A crown fire may spread for several hours, burning out entire drainages and crossing mountain ridges that might otherwise serve as topographic barriers to fire spread (Rothermel 1991), at least for ground or surface fires.

Crown fires cause profound and enduring changes to forest composition and structure (fig. 1), and to other ecosystem components as well (Rothermel 1991). In the Blue Mountains, crown fires historically occurred in areas with predisposing damage from insect or disease outbreaks:

- Early in the 20th century, Kan Smith (1912) described a conflagration (crown) fire on the Whitman National Forest in an extensive area of lodgepole pine killed by mountain pine beetle (this was the 1910 Ladd Canyon fire). Crown fire is typically a characteristic feature of the disturbance regime for lodgepole pine ecosystems (Agee 1993).
- On August 16, 1973, a fast-moving crown fire covered 6,000 acres near Perry, Oregon and eventually threatened the city of La Grande, destroying several homes near its edge. Most of this Rooster Peak fire occurred in areas defoliated by Douglas-fir tussock moth in 1971-73 (Powell 2016). Crown fire under these circumstances is an uncharacteristic event and probably indicative of compositional changes following fire suppression (Williams 1978).

"Crown fires result from certain combinations of fuels, weather and topography" (Scott and Reinhardt 2001). Obviously, weather and topography cannot be controlled, but land managers can manipulate fuels and thereby influence fire behavior (Bilgili 2003, Graham et al. 2004).

Canopy bulk density (CBD), a measure of foliage biomass available as crown fire fuel, is "the primary controlling factor of crown fire behavior" (Graham et al. 1999). CBD is strongly influenced by species composition and stand density (Agee 1996, Keyes and O'Hara 2002).

A high-intensity crown fire in the Blue Mountains of northeastern Oregon (from Powell 1994). In dense forests with large amounts of canopy fuel, fires are very intense and travel rapidly from one tree crown to another. Crown fires were an important process for perpetuating lodgepole pine, moist grand fir, and subalpine fir forests, although any particular area seldom experienced a stand-initiating crown fire more than once every 80 to 110 years. Historically, dry-forest sites seldom experienced crown fire; that is no longer true following widespread changes in species composition and forest structure over the last 100 years (Arno and Allison-Bunnell 2002).

Effects of the 1996 Tower Fire, North Fork John Day Ranger District, Umatilla National Forest (from Powell 1997). Dry forests and other areas exposed to a century or more of over-protection from fire can be especially susceptible to soil damage when a fire eventually occurs (Grier 1975). Occasionally, an intense fire consumes the forest floor, adversely affecting nutrient cycling (DeBell and Ralston 1970, Tiedemann and Klock 1973), soil wettability (Dyrness 1976), and other ecosystem processes influencing site productivity. [This image shows a lodgepole pine site, not a dry-forest area.]

Figure 1 – Crown fire in Blue Mountains. This figure illustrates long flame lengths and high fireline intensity typically associated with crown fire (and upper image shows high severity in terms of first order fire effects on vegetation); it also portrays impact of crown fire on soils, coarse woody debris and down wood, and other site-level resources (lower image).

Canopy bulk density is usually expressed in kilograms per cubic meter; it is dry weight of available canopy fuel per unit of canopy volume, including spaces within and between tree crowns. CBD ranges from zero, where there is no canopy, to about 0.4 kg/m^3 in very dense forests[2] (Scott and Reinhardt 2002).

This paper describes how to use five forestry metrics to estimate canopy fuel load, categorized as three ranges of CBD, when assessing crown fire susceptibility.

[2] According to personal communication with Jim Agee, professor of forest ecology in the College of Forest Resources at the University of Washington in Seattle, forests east of the Cascade Mountains in eastern Oregon and Washington probably never reach CBD levels above .15-.18 kg/m^3 (Agee 2000).

DEVELOPING AN ANALYSIS PROTOCOL

A protocol is valuable for producing long-term data sets of known quality; protocols help provide information to meet business requirements and program objectives. An analysis protocol establishes standards, procedures and expectations relating to data content, consistency and accuracy.

To be confident that trends in resource condition are real, and that changes are not being masked by inconsistent methods, a protocol should demonstrate that data was collected and analyzed by using repeatable and documented methods.

PROTOCOL OBJECTIVES

An objective of this protocol is to quantify three crown fire susceptibility categories (low, moderate, high) by using five traditional forestry metrics: stand density index, trees per acre, basal area per acre, canopy cover percentage, and equilateral tree spacing.

Expressing crown fire susceptibility in traditional forestry metrics is useful because a direct determination of canopy bulk density is not practical in the field due to the involved calculations required (it is probably impossible to measure CBD directly except in a research context).

This protocol was designed to take a continuous variable (CBD ranging from 0 to 4.0 kg/m^3) and transform it to three categorical values (low, moderate, high), and then to present queries (rule sets) for calculating these values by using conventional or typical attributes from vegetation databases. The database queries are also ideal for developing crosswalk or lookup tables to populate analysis with polygon-based estimates of CBD.

TERMINOLOGY CONSIDERATIONS

"Foresters and ecologists use the term crown in reference to the branches and foliage of individual trees, and the term canopy when referring to the aggregation of crowns at the stand or forest level. Technically, a crown fire is one that consumes the crowns of individual trees (torching or a passive crown fire), while a canopy fire would be one that burns the whole canopy stratum as a unit (active crowning)" (Scott and Reinhardt 2001).

Both fire types, however, are commonly referred to as crown fires (whether passive or active), and that convention will also be used in this white paper.

A similar naming convention exists for foliage biomass, which has traditionally been referred to as "crown bulk density." In this white paper, the term "canopy bulk density" is used, and it refers to foliage biomass – an aggregation of crowns at the stand or forest level.

RISK ASSESSMENT TERMINOLOGY

Risk assessment refers to a process for evaluating wildfires and other natural hazards by assessing probability of a hazardous event occurring, and resulting consequences or potential losses if an event does occur.

This protocol provides fire analysts with a process to assess crown fire susceptibility or hazard. Since risk assessment terminology is often used inconsistently, definitions for common terms are provided below.

Hazard: a potential disturbance event (such as wildfire) and conditions causing it (GAO 2004). Hazard-rating systems are used to determine occurrence potential (of a wildfire with a particular fireline intensity or vegetation severity, for example), and where the most substantial impact is expected when considering certain biotic and abiotic conditions (Dodds et al. 2004). Hazard and susceptibility are often used interchangeably.

Risk: likelihood or probability that a hazard event (such as wildfire) will actually occur (GAO 2004). In a context of wildfire risk assessment, for example, risk depends on both hazard potential (fuel conditions, etc.) and fire ignition sources (Dodds et al. 2004, Wulder et al. 2004). Risk and vulnerability are often used interchangeably.

Susceptibility: potential for a disturbance event (wildfire) as based on inherent or intrinsic fuel characteristics (species composition, stem density, coarse woody debris size and configuration, etc.). Susceptibility and hazard are often used interchangeably.

Vulnerability: probability of tree or stand damage resulting from a wildfire. Note that susceptibility reflects influence of forest or stand conditions on hazard: Is canopy bulk density high enough to sustain crown fire spread (e.g., is it greater than 0.1 kg/m^3)? Vulnerability refers to probability that damage will actually occur: Is a highly susceptible stand located near an active fire or in an area with abundant ignition sources?

Values: things that might be lost or damaged because of a hazard (GAO 2004). In a human context, social or economic values might be lost or compromised as a result of wildfire. In an environmental context, wildlife habitat and other values could either deteriorate or improve as a result of wildfire occurrence.

CANOPY BULK DENSITY THRESHOLDS

Forest cover type groups and stand density thresholds presented in this paper are based on an article in a journal, the Western Journal of Applied Forestry (Keyes and O'Hara 2002), and it was based on a paper by Jim Agee (Agee 1996) and a research note by Pat Cochran and others (Cochran et al. 1994).

Three categories of crown fire susceptibility are established for analysis purposes: low, moderate and high. Foliage biomass thresholds for separating one crown fire susceptibility category from another are based on canopy bulk density (CBD).

CBD thresholds, expressed as kilograms of canopy fuel (foliage and small branches) per cubic meter of canopy volume (kg/m^3), are derived from research (Agee 1996, Alexander 1988, Keyes and O'Hara 2002, Scott and Reinhardt 2001).

Agee (1996) analyzed seven stands that had been thinned and subsequently exposed to crown fire during the 1994 Tyee Fire on the Wenatchee National Forest; he found that crown fire was not sustained in stands where recent thinning had reduced CBD below about 0.10 kg/m^3.

Anecdotal evidence from the southwestern United States also indicates that stands with canopy bulk densities exceeding 0.10 kg/m^3 are susceptible to crown fires (Cram et al. 2003).

Van Wagner (1977) and Alexander (1988) showed that crown fire is nearly impossible below a CBD of 0.05 kg/m^3, although research in the Lake States suggests that a CBD as low as 0.037 kg/m^3 might be marginally capable of sustaining crown fire under certain circumstances (Sando and Wick 1972).

Analysis of two stands on Bitterroot National Forest in western Montana concluded that a Sando and Wick (1972) threshold value (0.037 kg/m^3) might also be relevant to forests of the interior Pacific Northwest (Scott and Reinhardt 2001).

Nonetheless, a CBD value of 0.05 kg/m^3 was selected as the lower threshold for this analysis methodology.

After quantifying these two thresholds – CBD above which active crown fire is easily sustained (0.10 kg/m^3) and CBD below which crown fire is impossible or unlikely (0.05 kg/m^3) – boundaries of high and low categories have been established. By default, a moderate category then includes all CBD values lying between these upper and lower boundaries.

RELATING CBD THRESHOLDS TO STAND DENSITY INDEX

Once CBD was used to quantify three categories of crown fire susceptibility, it was then necessary to translate CBD thresholds into traditional forestry metrics such as stand density index (SDI). Keyes and O'Hara (2002) started this task by taking Agee's (1996) upper threshold value (a CBD of 0.10 kg/m^3) and relating it to relative density for three tree species: grand fir, interior Douglas-fir, and ponderosa pine.

Keyes and O'Hara (2002) used the relative density concept by calculating SDI values for Agee's (1996) upper-threshold CBD value and then relating them to published values of maximum "normal" density for Blue Mountains (e.g., maximum normal density values were used as relative density reference levels).

Normal density reference values were reported by Cochran et al. (1994) and are referred to as "full stocking" in their Research Note (table 1).

Based on mathematical relationships developed by Keyes and O'Hara (2002), the following relative density percentages were calculated for a lower threshold CBD of 0.05 kg/m^3:

- Grand fir is about **12%** of its maximum full stocking SDI (an SDI of 70);
- Interior Douglas-fir is about **26%** of its maximum full stocking SDI (an SDI of 100); and
- Ponderosa pine is about **38%** of its maximum full stocking SDI (an SDI of 140).

Based on the mathematical relationships developed by Keyes and O'Hara (2002), the following relative density percentages pertain to an upper threshold CBD of 0.10 kg/m^3:

- Grand fir is about **35%** of its maximum full stocking SDI (an SDI of 200);
- Interior Douglas-fir is about **66%** of its maximum full stocking SDI (an SDI of 250), and
- Ponderosa pine remains below the upper CBD threshold even at its maximum full stocking SDI (an SDI of 365).

Table 1: Maximum values of full stocking (normal density) for the Blue Mountains.

TREE SPECIES	MAXIMUM VALUES OF FULL STOCKING
	Stand Density Index
Engelmann spruce	469
Grand fir	560
Interior Douglas-fir	380
Lodgepole pine	277

TREE SPECIES	MAXIMUM VALUES OF FULL STOCKING
Ponderosa pine	365
Subalpine fir	416
Western larch	410

Source: Cochran et al. 1994 (see their table 1). Scientific names and codes for these tree species are provided in a list of common and scientific names later in this paper.

FOREST DENSITY: STAND DENSITY INDEX

Stand density index (SDI) expresses a relationship between a number of trees per acre and a quadratic mean diameter (QMD); SDI is indexed to a QMD of 10 inches (Daniel et al. 1979, Reineke 1933).

This relationship means that an SDI of 140 can be the same as 140 trees per acre, but only when a stand's QMD is 10 inches; at any other QMD, tree density (stocking) associated with an SDI of 140 would be something other than 140 trees per acre.

Table 2 shows the stand density index (SDI) ranges associated with low, moderate, and high categories of crown fire susceptibility.

Table 2: Stand density index ranges associated with three categories of crown fire susceptibility.

COVER TYPE GROUPS[1]	CROWN FIRE SUSCEPTIBILITY CATEGORIES LOW (L) (<.05 kg/m^3 CBD)	MODERATE (M) (.05−.10 kg/m^3 CBD)	HIGH (H) (>.10 kg/m^3 CBD)
	----------- *Stand Density Index* -----------		
Ponderosa pine	≤ 140	141-364	≥ 365
Interior Douglas-fir	≤ 100	101-249	≥ 250
Grand fir	≤ 70	71-199	≥ 200

Sources/Notes: Stand density index ranges are based on relative density relationships developed by Keyes and O'Hara (2002); CBD refers to canopy bulk density.

[1] Cover type groups include these forest cover type codes – ponderosa pine: LAOC, mix-LAOC, PIAL, mix-PIAL, PICO, mix-PICO, PIPO, and mix-PIPO; interior Douglas-fir: PSME, mix-PSME, OTHER, and mix-OTHER; and grand fir: ABGR, mix-ABGR, ABLA, mix-ABLA, PIEN, and mix-PIEN (Powell 2013 describes how cover types are derived).

FOREST DENSITY: TREES PER ACRE

This metric is an absolute measure of tree density per unit area. Tree density is generally more useful than canopy cover for estimating species abundance because two tree species could have an identical canopy cover percentage, even though one occurs as many small individuals (high density) whereas the other has relatively few large individuals (low density).

Stem density is often considered to be the most efficient metric when comparing individuals in the same lifeform (trees with trees, tall shrubs with tall shrubs, etc.). Conversely, stem density is not considered an appropriate metric when comparing divergent lifeforms (e.g., comparing density of trees and forbs, for example) (Floyd and Anderson 1987).

To evaluate crown fire susceptibility by using a "trees per acre" density metric, it was necessary to translate "stand density index" values (table 2) into their corresponding trees per acre density values. This was accomplished in one step (Powell 1999):

1. Stand density indexes (table 2) were converted into their equivalent trees per acre (TPA) values (table 3). TPA calculations were completed by using this equation:
$TPA = SDI \div (QMD/10)^{slope}$ where slope exponent values vary by tree species: ponderosa pine = 1.77; Douglas-fir = 1.51; grand fir = 1.73. Resulting calculated values (three TPA columns in table 3) pertain to an even-aged stand structure.

Table 3 shows "trees per acre" (TPA) ranges associated with low, moderate, and high categories of crown fire susceptibility.

Table 3: Database queries utilizing "trees per acre" information to calculate a canopy fuel load rating for forest polygons.

Cover Type Groups[1]	Diameter Class Categories[2]	Size Class Codes[3]	CROWN FIRE SUSCEPTIBILITY: TPA[4]		
			Low (L)	Moderate (M)	High (H)
Ponderosa pine	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 1,173	1,174-3,057	≥ 3,058
	Poles (7" QMD)	5 or 6	≤ 262	263-682	≥ 683
	Small+ (12" QMD)	> 6	≤ 101	102-262	≥ 263
Interior Douglas-fir	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 563	564-1,406	≥ 1,407
	Poles (7" QMD)	5 or 6	≤ 157	158-390	≥ 391
	Small+ (12" QMD)	> 6	≤ 69	70-172	≥ 173
Grand fir	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 592	593-1,692	≥ 1,693
	Poles (7" QMD)	5 or 6	≤ 137	138-390	≥ 391
	Small+ (12" QMD)	> 6	≤ 54	55-153	≥ 154

[1] Cover type groups are described in footnote 1 to table 2.

[2] Average size class pertaining to an entire forest polygon (see Powell 2013); "QMD" refers to quadratic mean diameter – diameter associated with a tree of average basal area in a stand (Helms 1998) – and it is also referred to as "average stand diameter" (ASD).

[3] Size class codes are described in Powell (2013). Vegetation databases typically contain an average size class code representing an entire polygon, and these queries are designed to use a polygon-based size class code.

[4] TPA refers to trees per acre, and these TPA values pertain to an even-aged stand structure.

FOREST DENSITY: BASAL AREA PER ACRE

Basal area refers to cross-sectional area of a tree (in square inches) above a specified diameter (a break-point diameter); a "basal area per acre" metric takes individual-tree basal area values and sums them for all trees occurring on an acre.

Foresters often use basal area when prescribing stand stocking targets, and it is sometimes used in ecological studies as a measure of species predominance.

To evaluate crown fire susceptibility by using a "basal area per acre" metric, it was necessary to translate "stand density index" values (table 2) into their corresponding basal area per acre values. This was accomplished in two steps (Powell 1999):

1. Stand density indexes (table 2) were converted into their equivalent trees per acre values (table 3); and
2. Trees per acre values (table 3) were converted into their equivalent basal area per acre (BAA) values (table 4). BAA calculations were completed by using this equation: $BAA = TPA \times 0.005454154 \times QMD^2$. Resulting calculated values (three BAA columns in table 4) pertain to an even-aged stand structure.

Table 4 shows “basal area per acre” (BAA) ranges associated with low, moderate, and high categories of crown fire susceptibility.

Table 4: Database queries utilizing “basal area per acre” information to calculate a canopy fuel load rating for forest polygons.

Cover Type Groups[1]	Diameter Class Categories[2]	Size Class Codes[3]	CROWN FIRE SUSCEPTIBILITY: BAA[4]		
			Low (L)	Moderate (M)	High (H)
Ponderosa pine	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 58	59-149	≥ 150
	Poles (7" QMD)	5 or 6	≤ 70	71-181	≥ 182
	Small+ (12" QMD)	> 6	≤ 79	80-206	≥ 207
Interior Douglas-fir	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 28	29-68	≥ 69
	Poles (7" QMD)	5 or 6	≤ 42	43-104	≥ 105
	Small+ (12" QMD)	> 6	≤ 54	55-135	≥ 136
Grand fir	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 29	30-82	≥ 83
	Poles (7" QMD)	5 or 6	≤ 37	38-103	≥ 104
	Small+ (12" QMD)	> 6	≤ 42	43-120	≥ 121

Footnotes 1-3 are the same as for table 3.

[4] BAA refers to basal area per acre (expressed in square feet per acre), and these BAA values pertain to an even-aged stand structure.

FOREST DENSITY: CANOPY COVER

Canopy cover is a forest density metric used extensively in ecological studies. It is defined as vertical projection of vegetation foliage onto the ground surface when viewed from above. Canopy cover provides a quantitative and rapid characterization of vegetation abundance, but it has limitations when compared with other forest density metrics (for example, see a discussion above about “trees per acre”).

When vegetation conditions are characterized during database compilation (as described in Powell 2013), some polygons are described by using low-resolution data sources such as remote sensing information (e.g., interpretation of aerial photography) whereas others are characterized by using high-resolution sources such as stand examinations or field-sampled surveys.

For polygons characterized by using remote-sensing information, canopy cover (also known as canopy closure, crown cover, or crown closure, depending on context) is typically the only data item that can reasonably represent foliage biomass because tree density indicators such as stand density index, trees per acre, or basal area per acre are not provided directly by a low-resolution data source (Powell 1999).

Efforts to measure canopy cover during a field survey (by using instruments such as a spherical densiometer or moosehorn) have often been unsatisfactory (Cook et al. 1995), so it is common to calculate canopy cover by using equations requiring basal area or another field-surveyed metric as an input variable (Dealy 1985, Gill et al. 2000, Mitchell and Popovich 1997).

To evaluate crown fire susceptibility by using a "canopy cover" metric, it was necessary to translate "stand density index" values (table 2) into their corresponding canopy cover percentages. This was accomplished in three steps (Powell 1999):

1. Stand density indexes (table 2) were converted into their equivalent trees per acre values (table 3);
2. Trees per acre values (table 3) were converted into their equivalent basal area per acre values (table 4); and
3. Basal area per acre values (table 4) were converted into their equivalent canopy cover percentage (CC%) values (table 5) by using equations from a Blue Mountains elk cover study (Dealy 1985). CC% calculations were completed by using these equations:
   Ponderosa pine CC% = $-28.5 + 43.2(\mathrm{LOG}_{10}(\mathrm{BAA}+1))$
   Douglas-fir CC% = $-1.27 + 37.33(\mathrm{LOG}_{10}(\mathrm{BAA}+1))$
   Grand fir CC% = $-5.55 + 41.59(\mathrm{LOG}_{10}(\mathrm{BAA}+1))$
   Resulting calculated values (three CC% columns in table 5) pertain to an even-aged stand structure.

Table 5 shows "canopy cover" (CC%) ranges associated with low, moderate, and high categories of crown fire susceptibility.

Table 5: Database queries utilizing "canopy cover" information to calculate a canopy fuel load rating for forest polygons.

Cover Type Groups[1]	Diameter Class Categories[2]	Size Class Codes[3]	CROWN FIRE SUSCEPTIBILITY: CC%[4]		
			Low (L)	Moderate (M)	High (H)
Ponderosa pine	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 45%	46-60	≥ 61%
	Poles (7" QMD)	5 or 6	≤ 48%	49-63	≥ 64%
	Small+ (12" QMD)	> 6	≤ 50%	51-66	≥ 67%
Interior Douglas-fir	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 49%	50-62	≥ 63%
	Poles (7" QMD)	5 or 6	≤ 55%	56-68	≥ 69%
	Small+ (12" QMD)	> 6	≤ 59%	60-72	≥ 73%
Grand fir	Seed-Sap (3" QMD)	≥ 1, < 5	≤ 52%	53-68	≥ 69%
	Poles (7" QMD)	5 or 6	≤ 56%	57-72	≥ 73%
	Small+ (12" QMD)	> 6	≤ 58%	59-75	≥ 76%

Footnotes 1-3 are the same as for table 3.

[4] CC% refers to canopy cover percentage (for trees only), and these canopy cover percentages pertain to an even-aged stand structure.

FOREST DENSITY: EQUILATERAL TREE SPACING

Tree spacing is often used with another forest density metric such as "trees per acre." It offers advantages when it is important to be able to characterize spatial relationships between adjacent individuals (trees) in a population (characterizing intertree spacing for a marking guide).

In a fire and fuels context, equilateral spacing can be an essential tenet because it relates to **space** – how much space is present around a tree, and how will a management practice (thinning, etc.) change the amount of space around residual (post-treatment) trees?

In simple terms, *space is a key factor when altering fuel loads and reducing fire hazard*. Treatments that adjust space between neighboring trees in a stand are referred to as 'disrupting canopy fuel continuity.' Equilateral tree spacing can be a good metric for estimating the extent to which a proposed treatment is expected to disrupt canopy fuel continuity.

Treatments that increase the amount of space between tree crowns and activity fuels (slash) or smaller live fuels (shrubs and tree seedlings or saplings) are referred to as ladder fuel reductions. Ladder-fuel treatments are effective at reducing wildfire hazard, but changes in ladder-fuel characteristics are generally assessed by using metrics other than equilateral tree spacing.

Note: equilateral tree spacing is generally not an effective way to characterize total density for an entire population.

To evaluate crown fire susceptibility by using equilateral tree spacing information, it was necessary to translate "stand density index" values (table 2) into their corresponding equilateral tree spacing values. This was accomplished in two steps (Powell 1999):

1. Stand density indexes (table 2) were converted into their equivalent trees per acre (TPA) values (table 3); and
2. Trees per acre values (table 3) were converted into their equivalent equilateral tree spacing (ES) values (table 6). ES calculations were completed by using this equation:

   ES = $\sqrt{50300.23/\mathrm{TPA}}$

   Resulting calculated values (three ES columns in table 6) pertain to an even-aged stand structure.

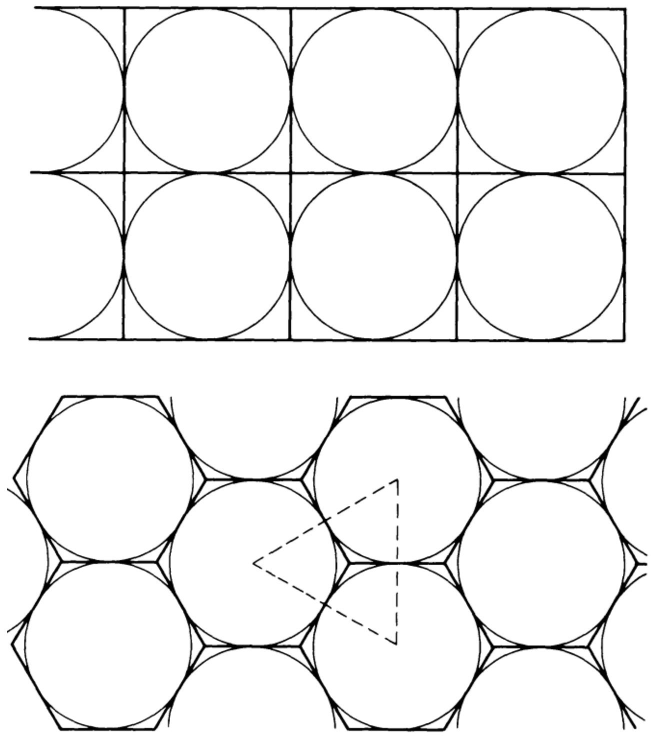
Table 6 shows "equilateral tree spacing" (ES) ranges associated with low, moderate, and high categories of crown fire susceptibility.

Table 6: Database queries utilizing "equilateral tree spacing" information to calculate a canopy fuel load rating for forest polygons.

Cover Type Groups[1]	Diameter Class Categories[2]	Size Class Codes[3]	CROWN FIRE SUSCEPTIBILITY: ES[4] Low (L)	Moderate (M)	High (H)
Ponderosa pine	Seed-Sap (3" QMD)	≥ 1, < 5	≥ 6.5	4.2-6.4	≤ 4.1
	Poles (7" QMD)	5 or 6	≥ 13.9	8.7-13.8	≤ 8.6
	Small+ (12" QMD)	> 6	≥ 22.3	13.9-22.2	≤ 13.8
Interior Douglas-fir	Seed-Sap (3" QMD)	≥ 1, < 5	≥ 9.5	6.1-9.4	≤ 6.0
	Poles (7" QMD)	5 or 6	≥ 17.9	11.4-17.8	≤ 11.3
	Small+ (12" QMD)	> 6	≥ 26.9	17.1-26.8	≤ 17.0
Grand fir	Seed-Sap (3" QMD)	≥ 1, < 5	≥ 9.2	5.6-9.1	≤ 5.5
	Poles (7" QMD)	5 or 6	≥ 19.2	11.4-19.1	≤ 11.3
	Small+ (12" QMD)	> 6	≥ 30.6	18.2-30.5	≤ 18.1

Footnotes 1-3 are the same as for table 3.

[4] ES refers to the equilateral spacing distance between adjacent trees, expressed in feet. Figure 2 explains equilateral spacing in more detail. ES values in this table pertain to an even-aged stand structure.



Square Spacing: each tree crown (circles) occupies the center of an adjacent square.

Equilateral Spacing: each tree crown (circles) occupies the center of an adjacent hexagon. Also called triangular spacing.

Figure 2 – Two measures of tree spacing (from Powell 1999). Square spacing assumes that tree crowns occupy centers of adjacent squares (top half); this model is most compatible with young, seedling-sapling stands (especially plantations where seedlings were planted on a square-spacing pattern). Equilateral spacing assumes that trees occupy adjacent hexagons (bottom half); this model best represents mature stands where trees are pole-sized or larger. Under a hexagonal spacing arrangement, imaginary lines connecting the centers of three adjacent trees (dashed lines in figure) form an equilateral triangle, so equilateral spacing is also known as triangular spacing.

CAUTIONS AND CAVEATS

No protocol can address every contingency or analysis scenario. Please consider these assumptions and potential limitations when using the protocol described in this document.

1. This protocol was based solely on canopy bulk density (CBD). Although CBD is considered to be the most important factor affecting crown fire susceptibility (Graham et al. 1999, 2004), this process does not predict potential crown fire behavior because it does not explicitly consider weather, topography, or non-CBD vegetation factors such as canopy base height or foliar moisture content (Scott and Reinhardt 2001), or the presence and density of ladder fuels influencing crown fire initiation.

2. Agee's (1996) original study included three tree species: ponderosa pine, interior Douglas-fir, and grand fir. Since vegetation databases almost always include more tree species (cover types) than these three, it was necessary to assign additional species to one of Agee's original forest types. These assignments were influenced primarily by crown characteristics (e.g., Engelmann spruce tends to have a similar crown shape and canopy density as grand fir, so Engelmann spruce was assigned to the grand fir cover type group).

3. Weather and physical site factors greatly influence fire behavior, particularly at a local (site level) scale: a 60% slope gradient, for example, results in about a 7-fold increase in fire spread rate when compared with the same fuel and weather conditions on level terrain (Alexander 1988). Once again, this protocol does not account for slope steepness, wind speed, and other local site factors influencing fire behavior.

4. This protocol was designed to determine a crown fire susceptibility rating for individual polygons (stands) in a vegetation database. It is not appropriate for a landscape-level analysis where canopy continuity and other interactions between polygons might be influential factors (including "neighborhood" spatial characteristics such as juxtaposition). In fact, an important limitation of this classification strategy is that it does not account for contagion (spatial, inter-polygon relationships) across a landscape.

   Note that FARSITE and NEXUS (in combination) provide a modeling framework for simulating crown fire spread and behavior in a landscape context (Finney 1998, Scott 1999).

5. This protocol evaluates canopy fuel load only. Surface fuel loading, including activity fuel produced by thinnings and other mechanical treatments designed to address crown fire susceptibility by disrupting overstory canopy continuity, is often an important factor affecting fire behavior and risk.

   A lop-and-scatter technique for treating thinning slash, for example, is ineffective for moderating post-thinning fireline intensity unless the combination of pre- and post-treatment fuel load is no more than 9 tons per acre (Kalabokidis and Omi 1998).

6. This protocol differs from traditional assessments that produce a chart expressing crown fire susceptibility in terms of open wind speeds needed to sustain a crown fire at varying levels of CBD.

   Other crown fire assessment processes express results as wind speed, such as torching index (passive crown fire) and crowning index (active crown fire) (Reinhardt and Crookston 2003, Scott and Reinhardt 2001). For wind-speed indices, the higher the CBD and the steeper the slope, the less wind speed is needed to sustain a crown fire.

7. Some protocol users believe ponderosa pine stocking levels are too high, particularly for stand density index (table 2), trees per acre (table 3), basal area per acre (table 4), and equilateral spacing (table 6) metrics. This belief reflects the fact that ponderosa pine values for those four metrics are higher than comparable values for grand fir and interior Douglas-fir. Why are ponderosa pine values higher than for the other two cover types?

   A counterintuitive result for ponderosa pine reflects differences in canopy characteristics (particularly crown density and length), and *it suggests that higher stocking levels of ponderosa pine are required for a specific amount of CBD than for either grand fir or interior Douglas-fir* (e.g., ponderosa pine crowns generally have lower foliage density, and less foliage-covered length (extent), than Douglas-fir and grand fir crowns).

8. This protocol is compatible with "forest polygons" as an analysis unit. If polygons are quite large or include substantial variation in forest (tree) density and its associated canopy fuel load, then protocol results may be inconsistent with an area's actual crown fire susceptibility.

   Crown fires tend to function at a landscape scale (i.e., in a multi-polygon setting), so a rating for an individual polygon might be irrelevant if crown fire arrives from an adjacent polygon (although this consideration often pertains more to crown fire initiation than to crown fire spread).

9. Except for possibly the ponderosa pine cover type group, stocking levels associated with a low crown fire susceptibility category are generally lower than historical stocking guidelines developed for timber production purposes.

This result means that if future wildfire resilience and an ecosystem structure amenable to low crown fire susceptibility is an important objective, then *land managers need to prescribe residual stocking levels by using the low category in tables 2-6*.

10. "Crown fire spread rate is more a function of the overstory trees than the total number of trees in the stand" (Wilson and Baker 1998). Database queries in this protocol are based on total tree stocking for a polygon: for multi-layered polygons, total tree stocking includes combined canopy cover of all overstory and understory layers.

For polygons where a high proportion of total tree stocking occurs in understory trees, and where understory tree height deviates substantially from overstory tree height, results of this protocol may overestimate potential for sustained crown fire spread (*although understory trees might function well as ladder fuel, and thereby contribute to crown fire initiation*).

11. This protocol has not been validated in the field, primarily because it is virtually impossible to measure CBD directly in a field setting. Users are encouraged to validate protocol results by using models or tools such as Scott and Reinhardt (2005) or Fire Management Analyst Plus (Fire Program Solutions 2005).

12. 'Answers' from a classification protocol are only as good as parent information they are based on. Errors in crown-fire susceptibility estimation can be compounded and propagated by errors in vegetation databases supplying base-level data for cover type, diameter-class, size-class, and stand density.

COMMON AND SCIENTIFIC NAMES

COMMON NAME	SCIENTIFIC NAME
Douglas-fir tussock moth	*Orgyia pseudotsugata*
Engelmann spruce	*Picea engelmannii*
Grand fir	*Abies grandis*
Interior Douglas-fir	*Pseudotsuga menziesii*
Lodgepole pine	*Pinus contorta*
Mountain pine beetle	*Dendroctonus ponderosae*
Ponderosa pine	*Pinus ponderosa*
Subalpine fir	*Abies lasiocarpa*
Western larch	*Larix occidentalis*
Whitebark pine	*Pinus albicaulis*

GLOSSARY

Basal area. Cross-sectional area of a single tree stem, including bark, measured at breast height (a point 4½ feet above ground surface on upper side of a tree); also, cross-sectional area of all stems in a stand and expressed per unit of land area (basal area per acre) (Helms 1998).

Canopy. Continuous cover of branches and foliage formed by crowns of trees (Hoffman et al. 1999).

Canopy base height. Lowest height above ground surface at which there is sufficient amount of canopy fuel to propagate fire vertically into a canopy. Canopy base height incorporates ladder fuels such as shrubs and understory trees (Scott and Reinhardt 2001).

Canopy bulk density. Mass of available canopy fuel per unit of canopy volume. It is a bulk property of a stand, not of an individual tree (Scott and Reinhardt 2001).

Canopy cover. Proportion of ground or water surface covered by a vertical projection of outermost perimeter of natural spread of foliage or plants, including small openings within a canopy. In some applications of this concept, total canopy cover can exceed 100 percent because layering of different vegetative strata results in canopy covering the ground more than once. In other applications, a ground surface can only be obscured by foliage once and canopy cover can never exceed 100 percent (Helms 1998).

Canopy fuels. Live and dead foliage, live and dead branches, and lichen complement of trees and tall shrubs that lie above surface fuels (Scott and Reinhardt 2001).

Condition class (also known as fire regime condition class). An assessment of a vegetation polygon's degree of departure from an historical fire regime, possibly resulting in alterations of key ecosystem components (Schmidt et al. 2002).

Cover type. Plant species forming a plurality of composition across a given land area, e.g., Engelmann spruce-subalpine fir, ponderosa pine-Douglas-fir or lodgepole pine forest cover types (Helms 1998). Forest cover types of United States and Canada are described in Eyre (1980). Rangeland cover types of United States are described in Shiflet (1994).

Crown. Crown refers to leaves and branches of a tree (Helms 1998).

Crown bulk density. See: canopy bulk density.

Crown fire. An intense fire that burns primarily in leaves and needles of live trees, spreading from one tree crown to another above the ground (Brenner 1998); three primary crown fire types are recognized (Scott and Reinhardt 2001):

> **Active** – a crown fire in which an entire fuel complex becomes involved, but crowning phase remains dependent upon heat released from surface fuels for continued spread. Also called running and continuous crown fire.
>
> **Independent** – a crown fire that spreads without aid of a supporting surface fire.
>
> **Passive** – a crown fire in which individual or small groups of trees torch out, but solid flaming in an upper canopy layer cannot be maintained except for short periods.

Crowning index. Open windspeed (6.1-meter or 20-foot) at which active crown fire is possible for a specified fire environment (Scott and Reinhardt 2001).

Disturbance. A relatively discrete event that disrupts structure of an ecosystem, community or population, and changes resource availability or the physical environment. Disturbances include processes such as fires, floods, insect outbreaks, disease epidemics, and windstorms (Dodson et al. 1998).

Equilateral spacing. An expression of intertree distance assuming that tree crowns occupy adjoining hexagons. Calculated as square root of 50,300.23 divided by number of trees per acre (Helms 1998).

Fire behavior. Manner in which a fire reacts to fuel, weather, and topography; common terms used to describe fire behavior include smoldering, creeping, running, spotting, and torching (Brenner 1998).

Fire frequency. Return interval between fires. Fire frequency has been categorized by using three classes: very frequent, 0-25 years; frequent, 26-75 years; and infrequent, 76-150 years (Rapp 2002).

Fire intensity (fireline intensity). Amount of heat released per unit length of fireline. Fire intensity has been categorized by using three classes: low intensity, average flame length of less than 3 feet; intermediate intensity, average flame lengths between 3 and 9 feet; high intensity, average flame lengths above 9 feet, or flames enter tree crowns extensively, or both (Rapp 2002).

Fire regime. Role fire plays in an ecosystem; a function of frequency of fire occurrence, fire intensity, seasonal timing, and fire size (Brenner 1998). Four fire regimes are currently recognized (Brown and Smith 2000):

> **Understory (low severity)** – fires are generally nonlethal to dominant vegetation and do not substantially change its structure. Approximately 80 percent or more of aboveground dominant vegetation survives fires.
>
> **Mixed severity** – fire severity either causes selective mortality in dominant vegetation, depending on fire susceptibility of individual species, or varies between understory and stand replacement.
>
> **Stand replacement (high severity)** – fires kill aboveground parts of dominant vegetation, changing its structure substantially. Approximately 80 percent or more of aboveground dominant vegetation is either consumed by fire, or dies as a result of fire.
>
> **Nonfire** – little or no occurrence of natural fire.

Fire regime condition class. See: condition class.

Fire severity. A characterization of fire effects based on damage to ecosystem components. Fire severity is assessed by using a variety of factors, such as percentage of trees killed or soil char. A high-severity forest fire, for example, would result in a high proportion of trees being killed (Rapp 2002). Also see: fire regime. Compare with: fire intensity.

Foliar moisture content. Moisture content (dry weight basis) of live foliage, expressed as a percent. Effective foliar moisture content incorporates moisture content of other canopy fuels such as lichen, dead foliage, and live and dead branchwood (Scott and Reinhardt 2001).

Fuel. All dead and living material in an ecosystem that will burn; fuel includes grasses, dead branches, and pine needles on the ground, as well as standing live and dead trees (Brenner 1998).

Fuel load. Amount of combustible material (living and dead organic matter) found in an area (Brenner 1998).

Full stocking. A point in development of even-aged stands in which differentiation has resulted in crown classes (Cochran et al. 1994); at full stocking, high stand density levels are causing intertree competition and resultant mortality of weaker, less-vigorous trees (e.g., self-thinning is occurring). Also see: normal density; reference level; self-thinning.

Ground fire. A slow-burning, smoldering fire in ground fuels such as organic soils, duff, decomposing litter, buried logs, roots, and below-surface portion of roots (Scott and Reinhardt 2001).

Normal density. Stand density level assumed to represent full site occupancy but which allows room for development of crop trees; assumed to represent "average-maximum" competition or average density of natural, undisturbed, fully-stocked stands. Normal density is assumed to be about 80% of maximum density (Powell 1999).

Overstocked. Forestland stocked with more trees than is normal or typical when evaluated by using a stocking standard (Dunster and Dunster 1996). In an overstocked stand, forest (tree) density is generally high enough that intertree competition is occurring and large trees are killing small trees in a process called self-thinning. Also see: self-thinning; stocking.

Overstory. In a forest with more than one story (layer), overstory includes trees forming an uppermost canopy layer; in a two-storied forest (stands with two clearly defined canopy layers), tallest trees form an overstory and shortest trees form an understory (Helms 1998).

Polygon. A series of line segments defined by x,y geographical coordinates (vectors) and completely enclosing an area (line segments close and thereby enclose a definite area).

Prescribed fire. Deliberate burning of wildland fuels in either a natural or modified state, and under specified environmental conditions, in order to confine fire to a predetermined area and produce a fireline intensity and rate of spread that meets land management objectives (Helms 1998).

Quadratic mean diameter. Diameter corresponding to mean basal area; diameter of a tree of average basal area in a stand (Helms 1998).

Reference level. Absolute stand density normally expected in a stand of given characteristics under some standard condition such as average maximum competition (Ernst and Knapp 1985). For canopy fuel load categories described in this document, full stocking (normal density or an "average-maximum" level of competition) was used as a reference level (Powell 1999).

Relative density. Ratio, proportion, or percent of absolute stand density to a reference level defined by some standard level of competition (Helms 1998).

Self-thinning. Plant mortality caused by intraspecific (interplant) competition in crowded, even-aged stands. For self-thinning populations, increasing average size is associated with a progressive diminution in tree density (Long and Smith 1984). Self-thinning is also known as $-^{3}/_{2}$ power rule, since self-thinning zones for many plant species have a slope of $-^{3}/_{2}$ when plotted with a logarithmic scale (Westoby 1984).

Size class. Characterization of a vegetation polygon's predominant tree size when using tree diameter at breast height; a layer with a pole size class, for example, has a predominance of trees whose diameter ranges between 5 and 8.9 inches at breast height (breast height is defined as a point 4½ feet above the ground surface on upper side of a tree).

Slash. Woody residue, e.g., treetops or branches left on ground surface after tree harvest or resulting from a storm, fire, or other disturbance event (Helms 1998).

Square spacing. An expression of intertree distance assuming that tree crowns occupy the center of adjacent squares. Calculated as square root of 43,560 divided by number of trees per acre (Helms 1998).

Stand density. A quantitative measure of tree stocking expressed absolutely in terms of number of trees, basal area, or volume per unit area (Helms 1998).

Stand density index (SDI). A widely used tree density measure developed by Reineke (1933); it quantifies tree density as a relationship between number of trees per acre and a stand's quadratic mean diameter (SDI indexes tree density to a quadratic mean diameter of 10 inches).

Stocking. Amount of anything present on a given land area, particularly in relation to what is considered optimum; in silviculture, stocking provides an indication of growing-space occupancy relative to a pre-established standard (Helms 1998).

Surface fire. A fire burning primarily along the ground surface, consuming leaf litter (needles), grass, forbs, shrubs, short trees, fallen branches and other fuels located on, or directly adjacent to, a forest floor (Brenner 1998, Scott and Reinhardt 2001). Surface fires tend to cause minimal damage to large trees; historically, surface fire was a prevailing fire type for ponderosa pine ecosystems throughout western United States (Agee 1993).

Thinning. A silvicultural treatment in immature forests designed to reduce tree density and thereby improve growth of residual trees, enhance forest health, or recover potential mortality resulting from intertree competition (Helms 1998). Two types of thinning are recognized (Powell et al. 2001):

> **Commercial thinning:** a thinning treatment where trees being removed have characteristics imparting economic value (sufficiently large size, etc.), thereby allowing them to be sold to a business enterprise.
>
> **Noncommercial (precommercial) thinning:** a thinning treatment where trees being cut (but generally not removed from a site) are too small to be sold for conventional wood products such as lumber; excess trees are often left on site after being cut (e.g., lopped and scattered, or aggregated into piles for later burning).

Torching index. Open windspeed (6.1-meter or 20-foot) at which crown fire activity can initiate for a specified fire environment (Scott and Reinhardt 2001).

Understory. All vegetation growing under a forest overstory. In some applications, understory is only considered to be small trees (e.g., in a forest comprised of multiple canopy layers, taller trees form an overstory and shorter trees form an understory); in other instances, understory is assumed to include herbaceous and shrubby plants in addition to trees.

When understory is assumed to refer to trees only, other low-growing plants (herbs and shrubs) are often called an undergrowth to differentiate between these two components (Helms 1998).

Wildfire. Any wildland fire that is not meeting management objectives and thus merits a suppression response (Brenner 1998).

Wildland-urban interface. Areas where human communities are built in proximity to flammable fuels found in wildlands (Brenner 1998).

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APPENDIX: SILVICULTURE WHITE PAPERS

White papers are internal reports, and they are produced with a consistent formatting and numbering scheme – all papers dealing with Silviculture, for example, are placed in a silviculture series (Silv) and numbered sequentially. Generally, white papers receive only limited review and, in some instances pertaining to highly technical or narrowly focused topics, the papers may receive no technical peer review at all. For papers that receive no review, the viewpoints and perspectives expressed in the paper are those of the author only, and do not necessarily represent agency positions of the Umatilla National Forest or the USDA Forest Service.

Large or important papers, such as two papers discussing active management considerations for dry and moist forests (white papers Silv-4 and Silv-7, respectively), receive extensive review comparable to what would occur for a research station general technical report (but they don't receive blind peer review, a process often used for journal articles).

White papers are designed to address a variety of objectives:

(1) They guide how a methodology, model, or procedure is used by practitioners on the Umatilla National Forest (to ensure consistency from one unit, or project, to another).
(2) Papers are often prepared to address ongoing and recurring needs; some papers have existed for more than 20 years and still receive high use, indicating that the need (or issue) has long standing – an example is white paper #1 describing the Forest's big-tree program, which has operated continuously for 25 years.
(3) Papers are sometimes prepared to address emerging or controversial issues, such as management of moist forests, elk thermal cover, or aspen forest in the Blue Mountains. These papers help establish a foundation of relevant literature, concepts, and principles that continuously evolve as an issue matures, and hence they may experience many iterations through time. [But also note that some papers have not changed since their initial development, in which case they reflect historical concepts or procedures.]
(4) Papers synthesize science viewed as particularly relevant to geographical and management contexts for the Umatilla National Forest. This is considered to be the Forest's self-selected 'best available science' (BAS), realizing that non-agency commenters would generally have a different conception of what constitutes BAS – like beauty, BAS is in the eye of the beholder.
(5) The objective of some papers is to locate and summarize the science germane to a particular topic or issue, including obscure sources such as master's theses or Ph.D. dissertations. In other instances, a paper may be designed to wade through an overwhelming amount of published science (dry-forest management), and then synthesize sources viewed as being most relevant to a local context.
(6) White papers function as a citable literature source for methodologies, models, and procedures used during environmental analysis – by citing a white paper, specialist reports can include less verbiage describing analytical databases, techniques, and so forth, some of which change little (if at all) from one planning effort to another.
(7) White papers are often used to describe how a map, database, or other product was developed. In this situation, the white paper functions as a 'user's guide' for the new product. Examples include papers dealing with historical products: (a) historical fire extents for the Tucannon watershed (WP Silv-21); (b) an 1880s map developed from General Land Office survey notes (WP Silv-41); and (c) a

description of historical mapping sources (24 separate items) available from the Forest's history website (WP Silv-23).

The following papers are available from the Forest's website: Silviculture White Papers

Paper #	Title
1	Big tree program
2	Description of composite vegetation database
3	Range of variation recommendations for dry, moist, and cold forests
4	Active management of Blue Mountains dry forests: Silvicultural considerations
5	Site productivity estimates for upland forest plant associations of Blue and Ochoco Mountains
6	Blue Mountains fire regimes
7	Active management of Blue Mountains moist forests: Silvicultural considerations
8	Keys for identifying forest series and plant associations of Blue and Ochoco Mountains
9	Is elk thermal cover ecologically sustainable?
10	A stage is a stage is a stage…or is it? Successional stages, structural stages, seral stages
11	Blue Mountains vegetation chronology
12	Calculated values of basal area and board-foot timber volume for existing (known) values of canopy cover
13	Created opening, minimum stocking, and reforestation standards from Umatilla National Forest Land and Resource Management Plan
14	Description of EVG-PI database
15	Determining green-tree replacements for snags: A process paper
16	Douglas-fir tussock moth: A briefing paper
17	Fact sheet: Forest Service trust funds
18	Fire regime condition class queries
19	Forest health notes for an Interior Columbia Basin Ecosystem Management Project field trip on July 30, 1998 (handout)
20	Height-diameter equations for tree species of Blue and Wallowa Mountains
21	Historical fires in headwaters portion of Tucannon River watershed
22	Range of variation recommendations for insect and disease susceptibility
23	Historical vegetation mapping
24	How to measure a big tree
25	Important Blue Mountains insects and diseases
26	Is this stand overstocked? An environmental education activity
27	Mechanized timber harvest: Some ecosystem management considerations
28	Common plants of south-central Blue Mountains (Malheur National Forest)
29	Potential natural vegetation of Umatilla National Forest
30	Potential vegetation mapping chronology
31	Probability of tree mortality as related to fire-caused crown scorch
32	Review of "Integrated scientific assessment for ecosystem management in the interior Columbia basin, and portions of the Klamath and Great basins" – Forest vegetation
33	Silviculture facts
34	Silvicultural activities: Description and terminology

Paper #	Title
35	Site potential tree height estimates for Pomeroy and Walla Walla Ranger Districts
36	Stand density protocol for mid-scale assessments
37	Stand density thresholds related to crown-fire susceptibility
38	Umatilla National Forest Land and Resource Management Plan: Forestry direction
39	Updates of maximum stand density index and site index for Blue Mountains variant of Forest Vegetation Simulator
40	Competing vegetation analysis for southern portion of Tower Fire area
41	Using General Land Office survey notes to characterize historical vegetation conditions for Umatilla National Forest
42	Life history traits for common Blue Mountains conifer trees
43	Timber volume reductions associated with green-tree snag replacements
44	Density management field exercise
45	Climate change and carbon sequestration: Vegetation management considerations
46	Knutson-Vandenberg (K-V) program
47	Active management of quaking aspen plant communities in northern Blue Mountains: Regeneration ecology and silvicultural considerations
48	Tower Fire…then and now. Using camera points to monitor postfire recovery
49	How to prepare a silvicultural prescription for uneven-aged management
50	Stand density conditions for Umatilla National Forest: A range of variation analysis
51	Restoration opportunities for upland forest environments of Umatilla National Forest
52	New perspectives in riparian management: Why might we want to consider active management for certain portions of riparian habitat conservation areas?
53	Eastside Screens chronology
54	Using mathematics in forestry: An environmental education activity
55	Silviculture certification: Tips, tools, and trip-ups
56	Vegetation polygon mapping and classification standards: Malheur, Umatilla, and Wallowa-Whitman National Forests
57	State of vegetation databases for Malheur, Umatilla, and Wallowa-Whitman National Forests
58	Seral status for tree species of Blue and Ochoco Mountains

REVISION HISTORY

October 2005: First version of this report was prepared in March 2004 as a single-page table (actually an Excel worksheet) showing EVG database queries and associated stocking levels for two categories of crown-fire risk (low and high), three stand size classes (QMDs of 3, 7, and 12 inches), and five stand density metrics (SDI, trees per acre, basal area per acre, canopy cover, and equilateral tree spacing).

An October 2005 revision was a major overhaul designed to provide much more background information about how database queries had been developed, including conceptual information about crown fires and how conifer stand susceptibility to crown fire could be assessed.

This October 2005 revision expanded a 1-page table/worksheet to a 20-page white paper that included 4 pages of literature citations.

February 2017: Minor formatting and editing changes were made during this revision, including adding a white-paper header and assigning a white-paper number. An appendix was added describing the white paper system, including a list of available white papers. A Contents section was also added.