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Climate Change and Carbon Sequestration: Vegetation Management Considerations[1]

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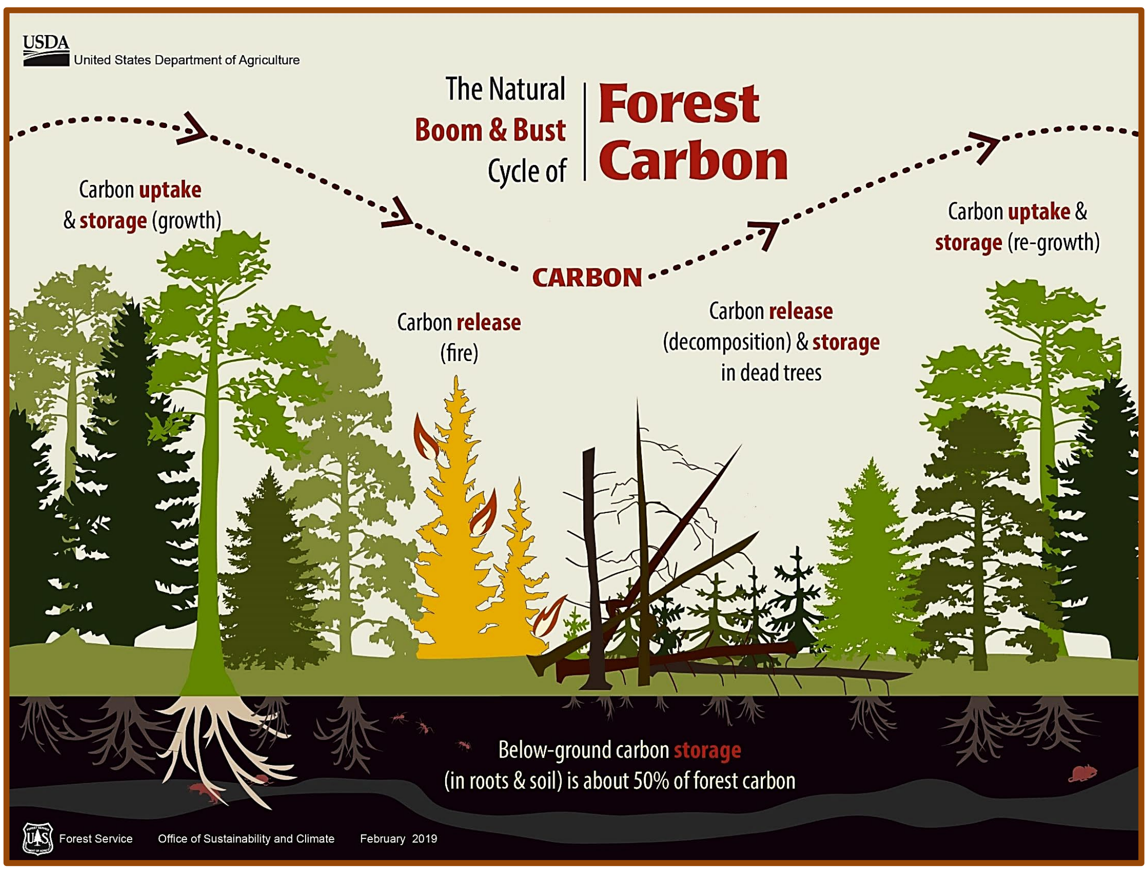

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[1] White papers are internal reports; they receive only limited review. Viewpoints expressed in this paper are those of the author – they may not represent official positions of USDA Forest Service.

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BACKGROUND AND CONTEXT

The Intergovernmental Panel on Climate Change (IPCC) (IPCC 2014), a third National Climate Assessment (Melillo et al. 2014), and other sources (Halofsky and Peterson 2017) suggest that the magnitude and pace of climate change in forest ecosystems will be unprecedented. Under some circumstances, climate change is capable of changing forests to meadows or shrublands, and changes of this extent will trigger a cascade of associated impacts on plants, wildlife, and other ecosystem services.

For the Blue Mountains ecoregion, monthly average temperature during the 21st century is projected to increase by ~3.3°C in winter (December-February) and 5.0°C in summer (June-August). Projected changes in precipitation vary substantially among models, but a central tendency is for increased precipitation (~15%) in winter (November-February) and decreased precipitation (~17%) in summer (June-September) (Mauger and Mantua 2011).

Changes in temperature and precipitation will have important implications on soil moisture, water availability, and streamflow timing for the Blue Mountains. Projections for the end of this century show a 69-72% decrease in April 1st snowpack, with snowmelt occurring at least 3 weeks earlier than now. Projected changes in soil moisture, which have important implications on tree growth and stand vigor (Grant et al. 2013), show increases in average winter amounts (12-13% for January-April) and decreases in average summer storage (4-7% for June to September) (Mauger and Mantua 2011).

IPCC concluded with high confidence (8 out of 10 chance) that "disturbances such as wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons, and to interact with changing land use and development affecting the future of wildland ecosystems" (Parry et al. 2007, page 56).

Since about 1990, it has become increasingly obvious that changing climatic conditions are causing ripple effects, many of which are expressed as variations in disturbance regimes. As wildfires become larger and as wildfire season lengthens (fig. 1), land managers are now recognizing that climate change is more than just a 'continental-scale' problem – its effects are also occurring at geographical scales commensurate with their management activities (fig. 2).

Because climatic changes are broad-scale phenomena, and because natural resource management activities occur at fine scales, there is uncertainty about whether it is even appropriate to address climate change in environmental analysis documents for local management projects. Some managers believe that project-scale work has little or no potential to influence climate change one way or another, so including it in environmental analyses is either irrelevant (at best) or misleading (at worst), because including it could suggest to readers that project-scale work has potential to affect climate change.

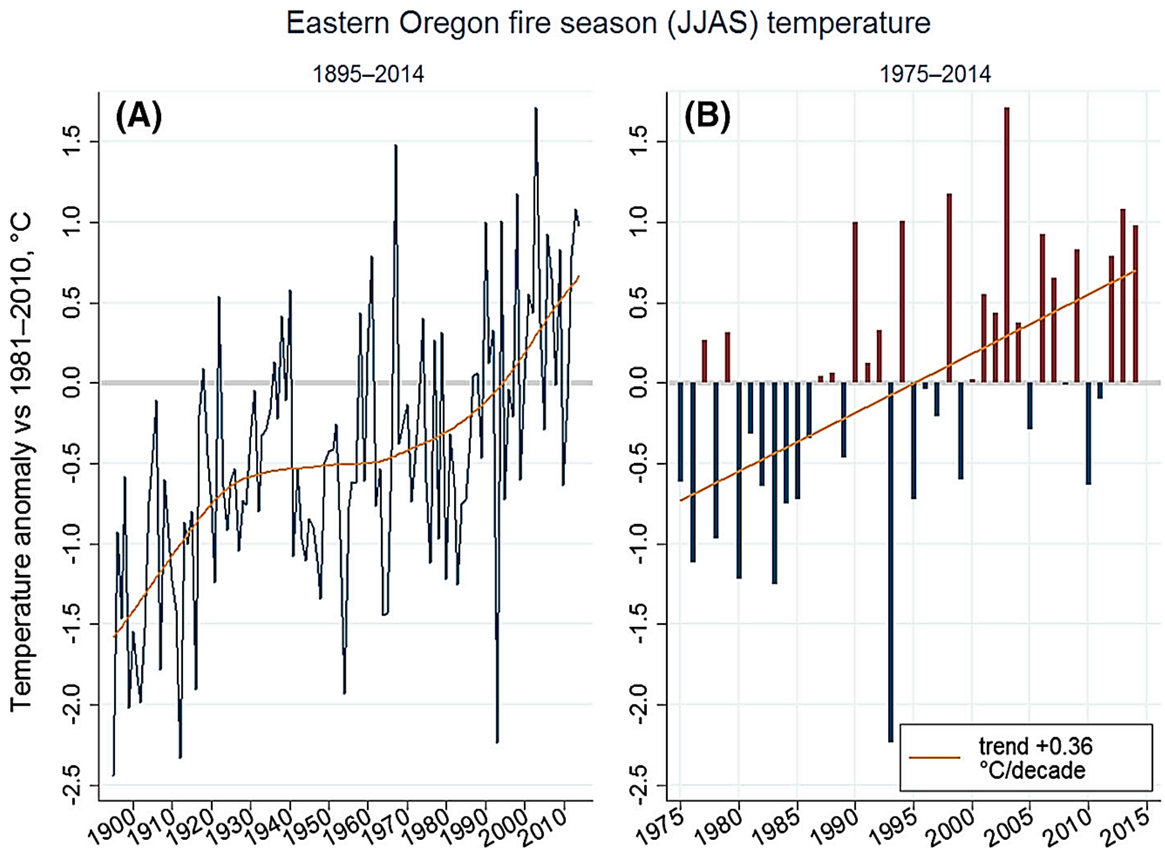

Figure 1 – Empirical trends in fire season temperatures for eastern Oregon, expressed as temperature anomalies (source: Hamilton et al. 2016, p. 1824). Part A (left side) shows June through September temperature anomaly for eastern Oregon, 1895-2014, with a lowess regression curve; Part B (right side) shows June through September temperature anomaly for eastern Oregon, 1974-2014, as a linear trend. Note that the baseline for this analysis (the 0.0 point on each vertical axis, signified by a heavy gray line) represents 1981-2010 climatic normals (means); anomalies were calculated by subtracting annual values from their 1981-2010 means. Negative values, those located below the 0.0 baseline, represent years with temperatures cooler than the 1981-2010 means; positive values, those located above the 0.0 baseline, represent years with temperatures warmer than the 1981-2010 means. This figure, and its associated analysis, demonstrates that: (A) Eastern Oregon has experienced a significant trend of increasing temperatures during the summer months representing 'fire season' (and this temperature trend has been accompanied by decreasing soil moisture and more fire activity); (B) "Average monthly June-September temperatures in eastern Oregon have risen over the past century, from a median around 60.1 °F during 1895-1914 to 63.4 °F during 1995-2014, the coolest and warmest 20-year periods on record;" (C) "Recent warming, since 1970, has been accompanied by more frequent wildfires: a statistically significant upward trend averaging 2.3 additional fires per decade;" (D) "The past 20 years include 6 of the 10 warmest in this 120-year record;" and (E) "The June through September warming in eastern Oregon over these 120 years has been steeper than global trends" (Hamilton et al. 2016). Eastern Oregon springs now tend to come earlier, and autumns stretch out longer. The trends shown here contribute to a documented increase in fire season length, fires that are hotter and more difficult to suppress, and increased moisture stress on trees. In fact, these trends have caused many fire managers to recently change their language – they now talk about a 'fire year' instead of a 'fire season.'

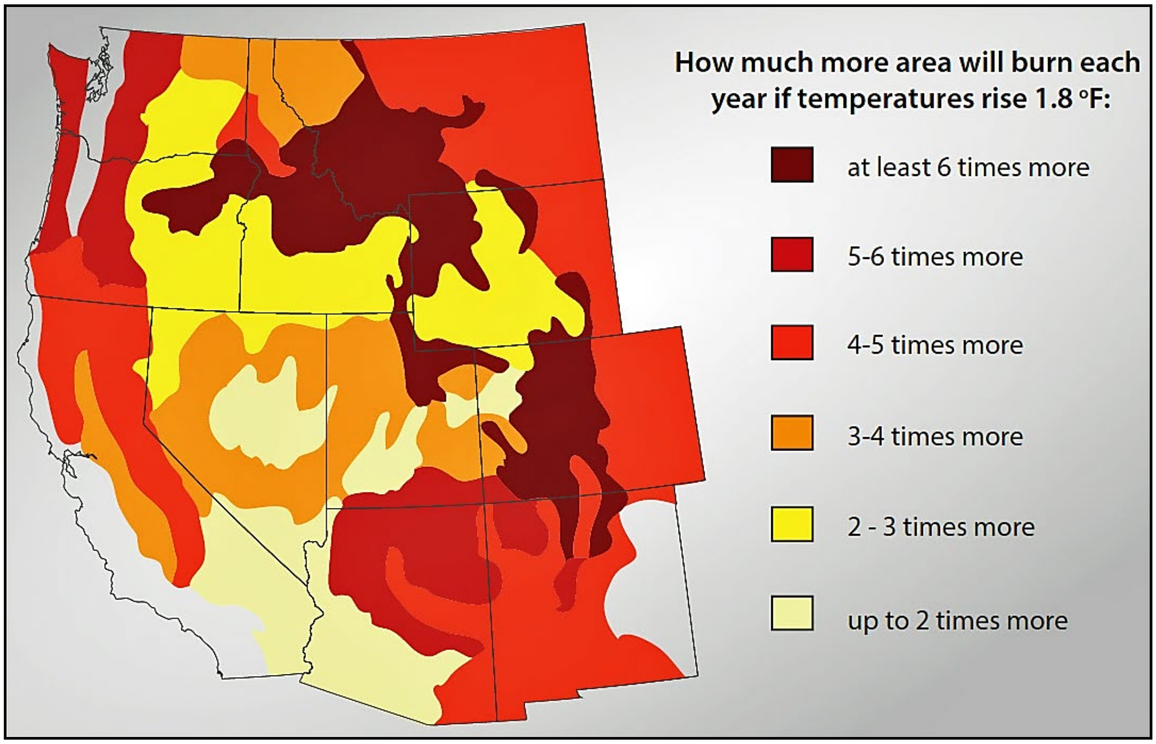

Figure 2 – Projected increase in wildfire area burned with a mean annual temperature increase of only 1° C (1.8° F), shown as a percentage change relative to median annual area burned during 1950-2003 (source: Climate Central 2012, as adapted from fig. 5.8 in National Research Council 2011; also see Vose et al. 2012b, page 250). Results are aggregated to eco-provinces (Bailey 1995) of the western United States; Blue Mountains occur in a large brown zone (upper central portion) with projected burn-area increases of at least six times. Climate-fire models were derived from National Climatic Data Center climate division records; observed burn-area data follows methods described in Littell et al. (2009). This map is alarming because when comparing the 1970-99 and 2070-99 time periods, an increase in average temperature of 3.3 to 9.7°C is projected, and increases will be greatest in summer during fire season. This figure suggests that future wildfire effects could continue to be problematic unless thinnings and other density-management treatments are implemented to reduce stand density levels and thereby provide fire-safe forest conditions (figs. 3, 4).

As noted in many other assessments, "the most extensive and serious problem related to health of national forests in the interior West is the overaccumulation of vegetation, which has caused an increasing number of large, intense, uncontrollable and catastrophically destructive wildfires" (GAO 1999). In the climate change context shown here, "lower stand densities may be necessary in a warmer climate to achieve the same level of reduced intertree competition as was achieved in the past" (Peterson et al. 2011). Or, to put it another way, residual-tree density after thinning must be lower now to confer the same level of stand protection provided by higher densities in the past (retaining 60 square feet of basal area now, for example, provides a comparable level of protection as was obtained from 80 square feet historically). In a climate change context, existing stand densities should be reduced all the way down to the lower limit of the management zone, as specified in Cochran et al. (1994) and Powell (1999). After thinning, prescribed fire should be used periodically to preclude establishment of additional tree regeneration ('ingrowth'), and thereby maintain stand densities at the lower levels most congruent with a warmer and dryer future.

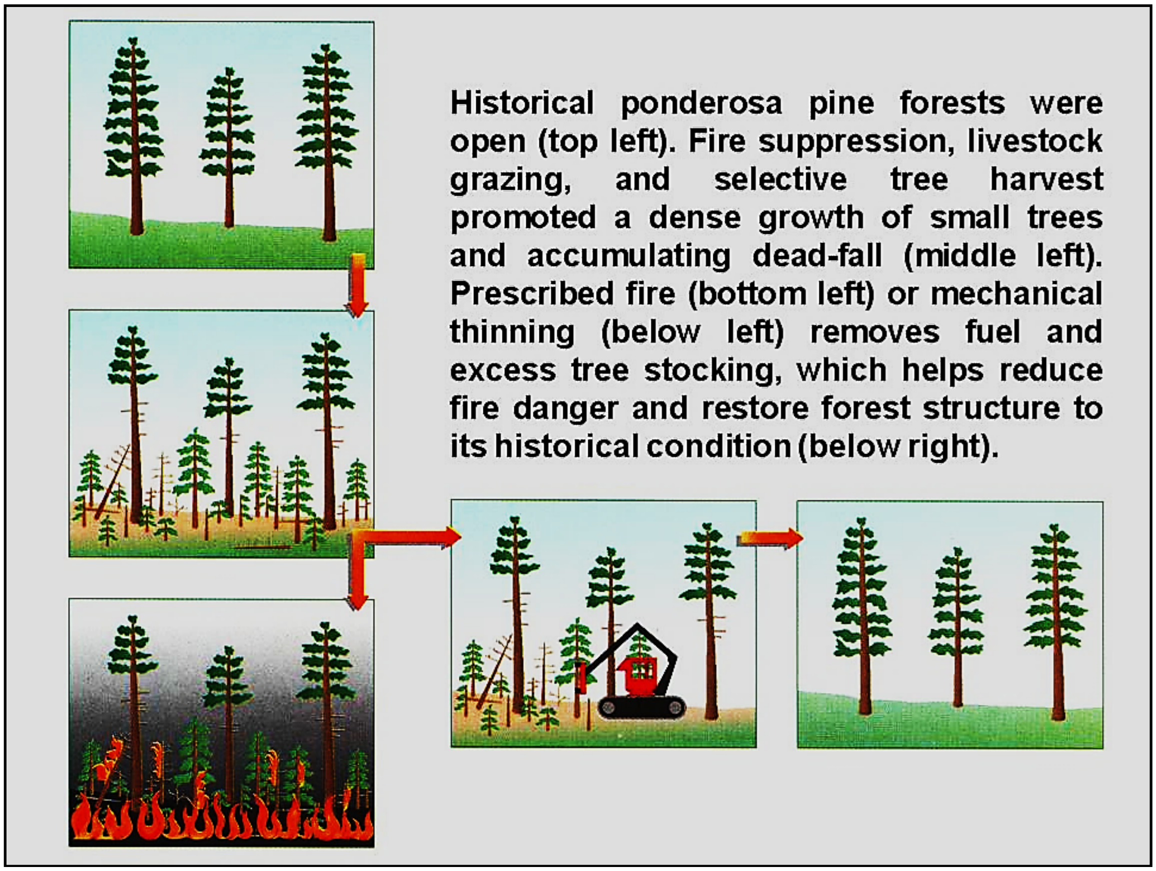

Figure 3 – Restoration objectives for dry forests (from Powell 2014a). Mechanical thinning and prescribed fire are effective treatments for increasing climate-change resilience for dry-forest ecosystems (Johnson et al. 2011; McIver et al. 2013; Stephens et al. 2009, 2018; Youngblood 2010). It is becoming increasingly evident that if dry forests are to be made resilient to climate change, their restoration is needed on a scale unprecedented in recent history (Franklin and Johnson 2012, Nagel et al. 2017, USDA Forest Service 2012). What might qualify as dry-forest restoration? I believe a successful restoration outcome for dry forests includes the following six elements, taken primarily from Agee and Skinner (2005), Covington (2003), and Powell (2014a).

1) Species composition, forest structure, and stand density occur within their historical ranges of variation.
2) Both trees and forests express indicators of high vigor, such as high sap flow, increased radial growth, good seedling height growth, and high foliar nitrogen levels.
3) Stands and landscapes have high fire resistance, high capacity to accept and absorb fire, and high competency to exhibit positive ecosystem responses to fire's ecological benefits.
4) Forests exhibit high resilience to insects and diseases at a landscape scale – individual tree stands in a landscape do experience insect and disease activity, but it occurs at characteristic levels when evaluated in a landscape context.
5) Landscapes are effectively buffered for future climate change, exhibiting appropriate near-term (resistance) and long-term (resilience) adaptation to effects caused by warmer temperatures and reduced precipitation. Vulnerable ecosystems have received appropriate mitigation treatments to increase their survivability and persistence in a climate change context.
6) Sustainable wood product outputs are both possible and realized, contributing to socioeconomic resilience and community stability (including wood-processing infrastructure).

Figure 4 – Thinning and low-severity fire reduce the risk of stand-replacing fire (from Hurteau et al. 2008). <u>Above</u>: forest management can sequester more carbon (lower right) than allowing it to burn as a stand-replacing fire (lower left). <u>Below</u>: Not all fire is created equal: low-severity fire (bottom) maintains high climate-change and conservation benefits, whereas high-severity fire (top) releases high amounts of greenhouse gases and results in reduced conservation value.

Other land managers realize that climate change must be addressed in environmental analyses because climate change continues to affect their project proposals, whether they like it or not. As climate change modifies environmental settings, resource conditions also change, and project proposals should be responsive to these changes.

Climate change is complex, and options for addressing it are also complex. This white paper describes one approach for addressing climate change for a moist-forest project (South George area, Pomeroy Ranger District). It provides an example of a climate change and carbon analysis. *It is only provided as an example*. It is not offered as a template or standard for how climate change should be addressed.

When South George project was analyzed, carbon sequestration was a national policy issue (Heath and Joyce 1997), leading the Regional Office to commission carbon assessments for Region-6 national forests (USDA Forest Service 2013). Since then, carbon sequestration has retreated somewhat as an issue, demonstrating that a NEPA analysis must account for circumstances as they exist when it is conducted. If South George was analyzed today, carbon would not be emphasized to the same extent described here.

INTRODUCTION

A primary assumption for this climate change analysis is that a project planning area is too small for a direct evaluation of potential climate change effects. Our current understanding of climate science suggests that at a project scale, it is difficult to establish a cause-and-effect relationship between management activities and climate change. Therefore, no attempt was made to use climate change as an issue during the National Environmental Policy Act (NEPA) process for South George, and no indicators were established for comparing potential climate change effects between NEPA alternatives.

However, certain principles and concepts of climate change can be used to assess whether silvicultural activities might help mitigate potential future effects of climate change, or perhaps exacerbate their effects. To help with this evaluation, a Nature Conservancy web-based tool called the Climate Wizard (www.climatewizard.org) was used to estimate future mid-summer temperature and precipitation conditions at a regional scale (Washington State in this instance); the selected regional scale includes the South George planning area (fig. 5).

The geographical distribution of precipitation is likely to shift, with high latitudes generally becoming wetter. Precipitation form shifts as well, with less occurring as snow and more as rain for many areas. Reduced snowpack levels and earlier runoff dates have already been observed for the western US (Adam et al. 2009, Mote et al. 2005). Figure 5 shows projected temperature and precipitation changes for year 2100, as projected by Climate Wizard. The spatial extent of figure 5 is Washington State, although the South George planning area is also shown, at scale, for perspective.

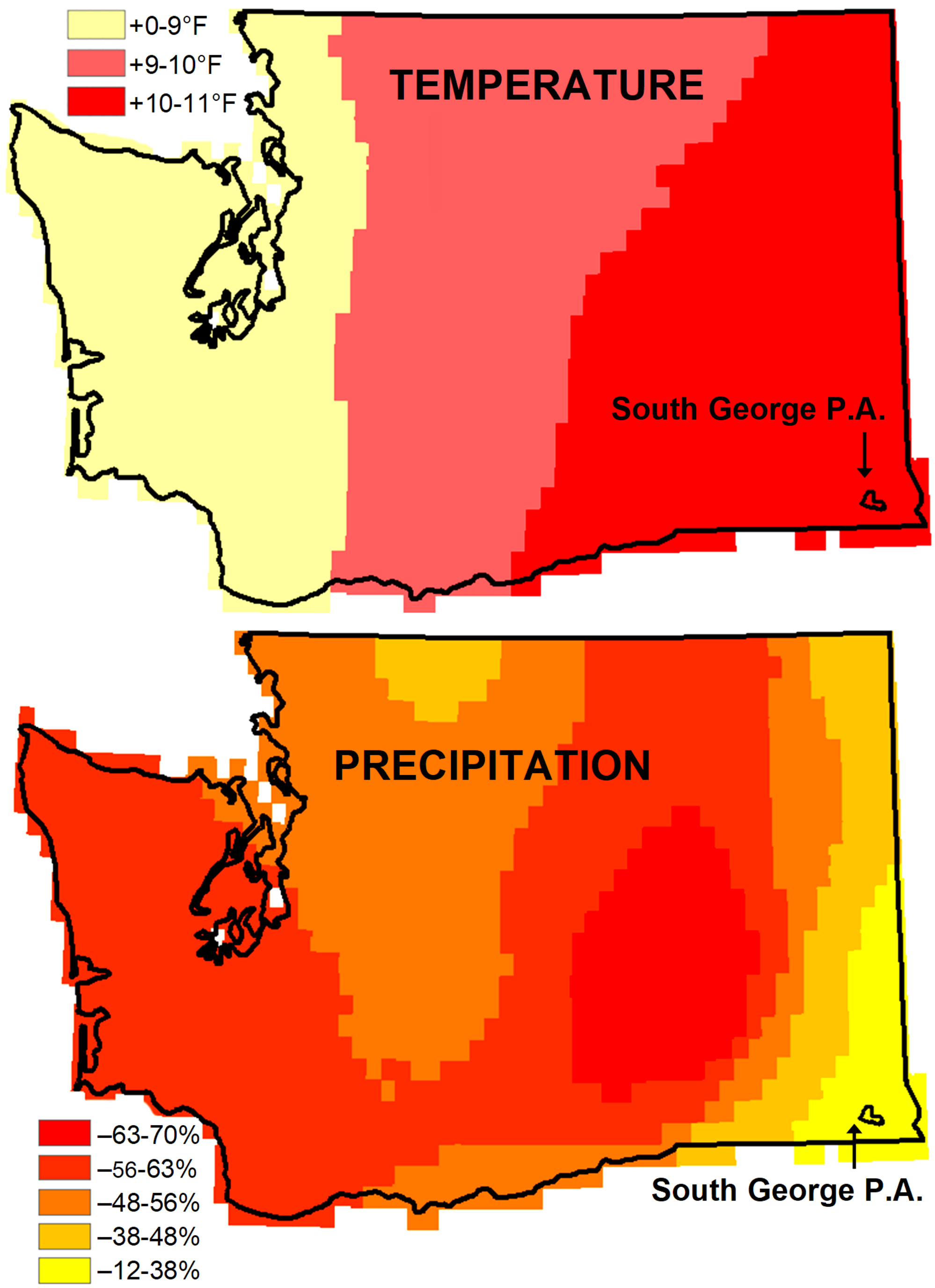

Figure 5 – Projected, worst-case scenario for temperature and precipitation change for Washington State in the year 2100 (outputs derived from Climate Wizard web-based application). South George area occurs in a zone where average July temperature could increase by 10-11° F (top), and average July precipitation could decrease by 12-38% (bottom), when compared with recent empirical temperature and precipitation trends (parameters: Ensemble Average, SRES emission scenario A2; SRES A2 scenario is worst-case because it reflects no societal restraints on carbon dioxide emissions). Modeled projections are based on a suite of international general circulation models used for 4th assessment of Intergovernmental Panel on Climate Change (IPCC 2007). Note that annual precipitation for Washington and Oregon is projected to increase slightly, but summers are expected to be drier. Drier summers will be exacerbated by average spring snowpack for Columbia River Basin declining 52% (projected) by 2080s (Hamlet et al. 2013).

Although temperature and precipitation trends depicted in figure 5 could be perceived as dire, it is important to acknowledge that modeled responses of species and ecosystems to climate change might be too narrow, leading to overestimates of climate change impacts (Hamann and Wang 2005).

Much concern about climate change relates to how it might affect baseline climate processes such as drought. Action of the environment on an individual plant or its overall community is neither uniform nor consistent because atypical events are quite normal: a severe frost episode every few years, or a protracted drought every few decades.

But it is important to consider the magnitude and frequency of atypical events that local ecosystems have evolved with – Would we expect climate change to be additive, subtractive, or neutral in terms of its effect on baseline temperature and moisture relationships, and would the magnitude of projected effects be great enough to exceed the environmental tolerances of existing plant and tree species?

Perhaps the most ecologically important climatic change will be an increase in precipitation variability, contributing to drought events. Dendrochronology studies indicate that droughts of varying magnitude were common in eastern Oregon during the last 500 years (Graumlich 1987, Keen 1937).

Recent reconstructions of the Palmer Drought Severity Index (Cook et al. 2004, Woodhouse and Overpeck 1998) show that droughts in a large area containing the South George planning area have been frequent, and several historical droughts were worse than two relatively recent droughts of note – a 1930s 'dust bowl' event and a late-1950s drought (fig. 6).

If climate change is expected to cause epic droughts like those occurring between AD 900 and 1300 in a 'Medieval Warm Period' (Fagan 2002), then we have every reason to be concerned about whether existing plant communities have enough resilience to handle such events without experiencing major changes in species composition or forest structure (Meehl and Tebaldi 2004).

Although climate change adaptation is not a Purpose and Need for South George Vegetation Management Project, and although the project's proposed actions were not designed specifically to address climate change effects, two South George silvicultural activities are compatible with 'climate-smart' mitigation strategies (Baron et al. 2008, Janowiak et al. 2014, Nabuurs et al. 2007, Reyer et al. 2009, Salinger et al. 2005).

Intermediate cutting contributes to a 'maintain forest area' mitigation objective (D'Amato et al. 2013, Sohn et al. 2016), and tree planting contributes to an 'increase forest area' mitigation objective (Nabuurs et al. 2007, Nave et al. 2018). Narrative about predicted interactions between silvicultural activities and projected climate change effects is provided next, in a *Silvicultural Activities and Climate Change* section.

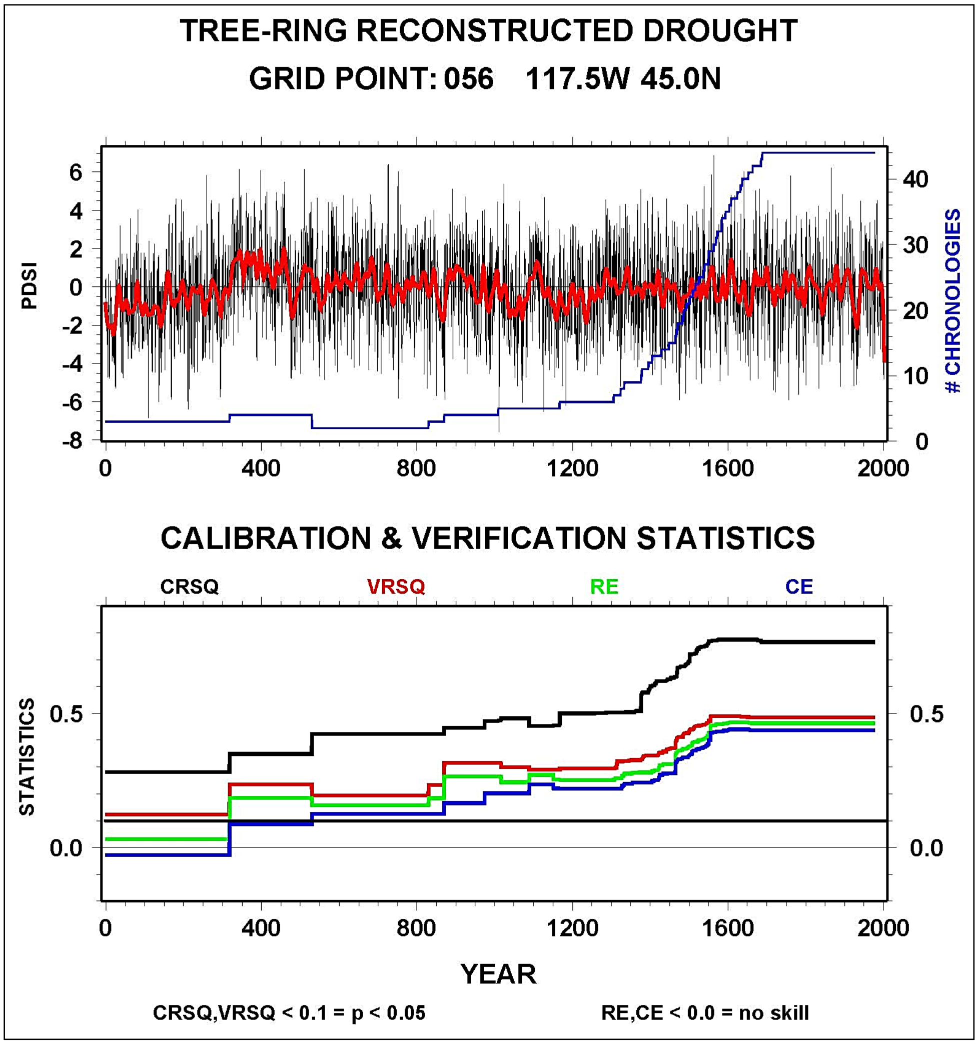

Figure 6 – Reconstructed, 2000-year chronology of Palmer Drought Severity Index (PDSI) for a grid cell of 2.5° latitude by 2.5° longitude (Cook et al. 1999, Dai et al. 1998, Woodhouse and Overpeck 1998), and containing the South George planning area in the northern Blue Mountains. Derived from North American Drought Atlas: Drought Atlas

North American instrumental PDSI grid is composed of 286 grid points covering most of the continent. Reconstructions were based on monthly PDSI records from US Historical Climatology Network and a network of North American tree-ring chronologies (835 in total), some of which are 1,000 years long. Top plot shows PDSI reconstruction with 20-year low-pass smoothing in red and changing number of chronologies used for reconstruction in blue. Bottom plot shows changing calibration and verification statistics (CRSQ = calibration R^2; VRSQ = verification R^2; RE = verification reduction of error; CE = verification coefficient of efficiency).

Palmer Drought Severity Index (PDSI), most commonly used drought index in the United States, was developed to measure intensity, duration, and spatial extent of drought. PDSI values are derived from measurements of precipitation, air temperature, and local soil moisture, along with prior values of these measures. Values range from -6.0 (extreme drought) to +6.0 (extreme wet conditions) and have been standardized to facilitate comparisons from region to region. Increasing drought is a climate change with high potential to impact forests (Bigler et al. 2007, Choat et al. 2012, Clark et al. 2016, D'Amato et al. 2013, Kolb et al. 2016, Sohn et al. 2016, Stephens et al. 2018).

SILVICULTURAL ACTIVITIES AND CLIMATE CHANGE

Three silvicultural activities are included in a South George proposed action: intermediate cutting (improvement cutting, low thinning), regeneration cutting (clearcutting with reserves, seed-tree cutting with reserves), and tree planting. Projected changes in temperature and precipitation for a large region containing the South George planning area, as presented in figure 5, are expected to have varying interactions with estimated effects from proposed silvicultural activities.

1. **Intermediate Methods (improvement cutting; low thinning).** Figure 5 suggests that drought will become more common as mid-summer temperatures increase, and as mid-summer precipitation declines. Dense tree stands experience chronic physiological drought because there is insufficient soil moisture to meet the needs of all trees; thinning alleviates moisture stress and allows residual trees to better handle chronic temperature increases (Bottero et al. 2017, D'Amato et al. 2013, McDowell et al. 2016, Sohn et al. 2016). Future climates (fig. 5) may have significantly more impact on dense stands than is caused by current climates (Choat et al. 2012, Clark et al. 2016, Kolb et al. 2016). Therefore, future need for thinning will be much greater than at present, especially to maintain physiological tree vigor (Stephens et al. 2018). Vigorous trees produce more resins for repelling insects and diseases, so thinned stands have lower susceptibility to biotic pests than unthinned stands (Kolb et al. 1998, Mitchell et al. 1983, Pitman et al. 1982, Safranyik et al. 1998).
2. **Regeneration Methods (clearcutting, seed-tree cutting).** These silvicultural activities are expected to cause the greatest difference between pre- and post-implementation environmental conditions by creating open, unshaded environments in the near-term. Because climate change is expected to cause warmer, dryer conditions in the mid-term, it would be useful to consider the life-history traits of native trees, and how they might influence the fitness of a species to thrive in post-regeneration conditions and to persist under future climates. Life-history traits are provided in table 1, and they suggest that ponderosa pine, western larch, and lodgepole pine are well-adapted to open conditions created by regeneration cutting. When considering projected impacts of climate change on temperature and precipitation, and when considering indirect effects of climate change on wildfire and insects (Canadell and Raupach 2008, Westerling et al. 2006), it is likely that the same three species, along with Douglas-fir, will be best adapted to future climates of the South George area.
3. **Reforestation/Tree Planting.** This silvicultural activity is used to reestablish tree cover in areas affected by regeneration cutting (clearcutting, seed-tree cutting), or to augment existing stocking levels in understocked stands resulting from historical insect or disease damage (understocked stands have tree density levels below minimum acceptable stocking levels). As demonstrated by a suite of life-history traits

provided in table 1, many of which have a direct bearing on reproductive capacity, species to be emphasized during tree planting are: ponderosa pine, western larch, lodgepole pine (if natural regeneration is inadequate for this species), and Douglas-fir. These four species are the same ones identified as being most adaptable to future climates. This means that species with optimal fitness for post-harvest environments will also be acceptable for warmer and dryer climates. Natural regeneration also occurs in areas receiving regeneration cuttings, so ultimate species diversity for these areas will likely be greater than just the four species being planted.

Certain life history traits in table 1 might seem unrelated to climate change – "tolerance to frost" is an example. But cold hardiness of forest trees is influenced significantly by climate change, with boreal forests experiencing loss of cold hardiness in response to early-spring warming (late April to early May) (Cayan et al. 2001), followed by severe frost damage during subsequent cold snaps in mid spring (mid to late May) (Man et al. 2009). Before onset of climate change, frost damage in mid-May was unusual because boreal trees had not lost cold hardiness (as dormancy waned) at that point in the spring.

Table 1: Life history traits for tree species of the Blue Mountains; traits were selected with relevance to climate-change adaptability.

	Pacific ponderosa pine (*Pinus ponderosa* var. *ponderosa*)	Western larch (*Larix occidentalis*)	Rocky Mtn. lodgepole pine (*Pinus contorta* var. *latifolia*)	Quaking aspen (*Populus tremuloides*)	Black cottonwood (*Populus balsamifera* ssp. *trichocarpa*)	Thinleaf alder (*Alnus incana* ssp. *tenuifolia*)	Water birch (*Betula occidentalis*)	Western white pine (*Pinus monticola*)	Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*)	Engelmann spruce (*Picea engelmannii*)	Grand fir (*Abies grandis*)	Subalpine fir (*Abies lasiocarpa*)
Tolerance to shading	L	L	L	L	L	M	M	M	M	H	H	H
Tolerance to full sunlight	H	H	H	H	H	H	M	H	M	L	L	L
Seral status	Early	Early	Early	Early	Early	Early	Mid	Mid	Mid	Late	Late	Late
Tolerance to frost	L	L	H	H	M	H	H	H	L	H	M	M
Tolerance to drought	H	M	M	L	L	L	L	M	M	L	M	L
Rooting habit (depth)	D	D	M	S	M	S	S	M	D	S	S	S
Average lifespan (years)	300	300	100	100[4]	100	50-75	50-75	400[1]	200	250	200	150
Fire resistance	H	H	L	L[2]	L[2]	L[2]	L[2]	M	M	L	L	L
Evolutionary mode	Inter	Inter	Spec	NR	NR	NR	NR	Gen	Spec	Inter	NR	NR
Regeneration on charred or ashy soil	IN	NE	NE	IN	IN	IN	IN	IN	IN	RE	IN	NR
Maximum seed dispersal distance (feet)	120	150	200	1600[3]	660[3]	NR	300[3]	400	330	120	200	100
Potential for regeneration in the open	H	H	H	H	H	H	M	H	H	M	L	L
Overall reproductive capacity	H	H	H	H	H	H	H	H	H	M	M	M

Sources/Notes: Ratings are derived from the Fire Effects Information System (USDA Forest Service 2013), the North America silvics manuals (Burns and Honkala 1990a, 1990b), autecological summaries such as Klinka et al. (2000) and Minore (1979), and a variety of other sources. Rating codes are: L, low; M, moderate; H, High; D, deep; S, shallow; IN, increased; NE, no effect; and RE, reduced. Average lifespan values are taken from Powell (2000) and a few other sources. Evolutionary mode refers to the amount of genetic differentiation; it is an indicator of how well a species could adapt to future climates (Gen is generalist; Inter is intermediate; Spec is specialist; NR is not reported; source is Rehfeldt 1994). Overall reproductive capacity considers minimum seed-bearing age, seed crop frequency and size, seed soundness, and related factors.

[1] This average lifespan value is based on historical western white pine populations unaffected by white pine blister rust, an introduced, nonnative disease with negative influence on the longevity of western white pine and other five-needled pines.

[2] Fire resistance ratings reflect ability of existing stems to survive exposure to fire. All these species have relatively thin bark that does not insulate a stem's cambium layer from fire damage, so fire generally top-kills them.

All species with this footnote have high reproductive capacity, however, because they possess many adaptations assisting with postfire recovery (e.g., root-crown sprouting, root-system suckering, rooting capacity of leafy stems that excise from the stem (cottonwood), etc.).

[3] These riparian trees have very small seeds, and some also have 'cotton' appendages on their seed to aid in long-distance dispersal. Due to their common proximity to perennial streams, water transport of their seeds (e.g., hydrochory) is also important.

A combination of light seed weight and water dispersal often results in a small proportion of seed for these species being dispersed for several miles or more from a parent tree.

[4] A commonly cited average age for aspen ramets (stems produced from an underground root system called a genet) is 100 years, with a maximum lifespan of 200 years claimed (Burns and Honkala 1990b).

However, genets (root systems) of some studied aspen clones have been found to be thousands of years old. This means that individual ramets of an aspen clone may be short-lived, but a genet (clone) may be thousands of years old, older than the oldest giant sequoia or Great Basin bristlecone pine (two conifers known for longevity exceeding a thousand or more years).

This also means that a single root system may have produced 50 to 100 generations of aspen ramets (stems) during its lifespan, each of which persisted for a hundred years or more. Genetic testing, for example, indicates that an ancient clone has existed for thousands of years in Morsay Creek drainage of North Fork John Day Ranger District (about 15 miles west of Ukiah, Oregon), Umatilla National Forest (Shirley and Erickson 2001).

WILDFIRE AND WILDLAND-URBAN INTERFACE CONSIDERATIONS

Silvicultural activities, even when designed specifically as fuels treatment, are not designed to 'stop' wildfires. A primary goal of fuels treatment is to use management activities (treatments) to modify fuel conditions and increase the likelihood of desirable post-fire outcomes by reducing adverse fire effects, protecting structures, maintaining soil quality and clean drinking water supplies, and restoring properly functioning forest processes (Halofsky et al. 2018, Janowiak et al. 2014, North et al. 2012).

An important objective of fuels treatment is to create post-treatment conditions contributing to improved firefighter safety (Withen 2015), since men and women working on firelines often experience significant risk to their personal safety, particularly when attempting to suppress wildfire in situations where structures and other infrastructure are threatened (Liu et al. 2015, Stephens et al. 2014).

In an impending future influenced by climate change, fuels treatment must become sharply focused on specific areas or situations because it is likely that fires will be more abundant and widespread (fig. 2) than can be suppressed with existing resources. For the Blue Mountains, wildfire in a climate-changed future will be up to six times more common than now (National Research Council 2011) (fig. 2).

Recent demographic data shows increasing levels of human development in forested wildlands qualifying as WUI (Stein et al. 2013). Two results of recent climate/WUI trends are: (1) structures are more plentiful in flammable wildland environments than previously, and (2) human infrastructure is projected to experience more exposure to future wildfire, due to climate change, than previously (figs. 1, 2). These trends also suggest that in a climate-changed future, fire suppression resources will likely be allocated more for WUIs than for general forest areas (Stephens et al. 2014, 2018).

Detailed analyses for most upland-forest project-planning areas identify a need to modify forest vegetation conditions to create a less hazardous fire environment (fig. 7), and to provide more options for suppressing a late-summer wildfire occurring in proximity to human values at risk. And when designed properly, proposed fuel treatments can also qualify as a 'climate-smart management' strategy in response to predicted climatic effects on wildfire occurrence (fig. 2) (Halofsky and Peterson 2017; Hartter et al. 2017, 2018; Kerns et al. 2017, 2018; Peterson and Halofsky 2018).

Why is fuels treatment proposed as a strategy for modifying fire behavior and creating less hazardous fire environments for a planning area? "Empirical studies from wildfires (Finney et al. 2005, Collins et al. 2009, Martinson and Omi 2013) and studies based on modeled fire (Finney et al. 2007, Collins et al. 2011, Chiono et al. 2012, Stephens et al. 2012a) suggest that treatments can be expected to reduce fire behavior and effects within individual stands and across landscapes for 10-20 years" (Collins et al. 2013).

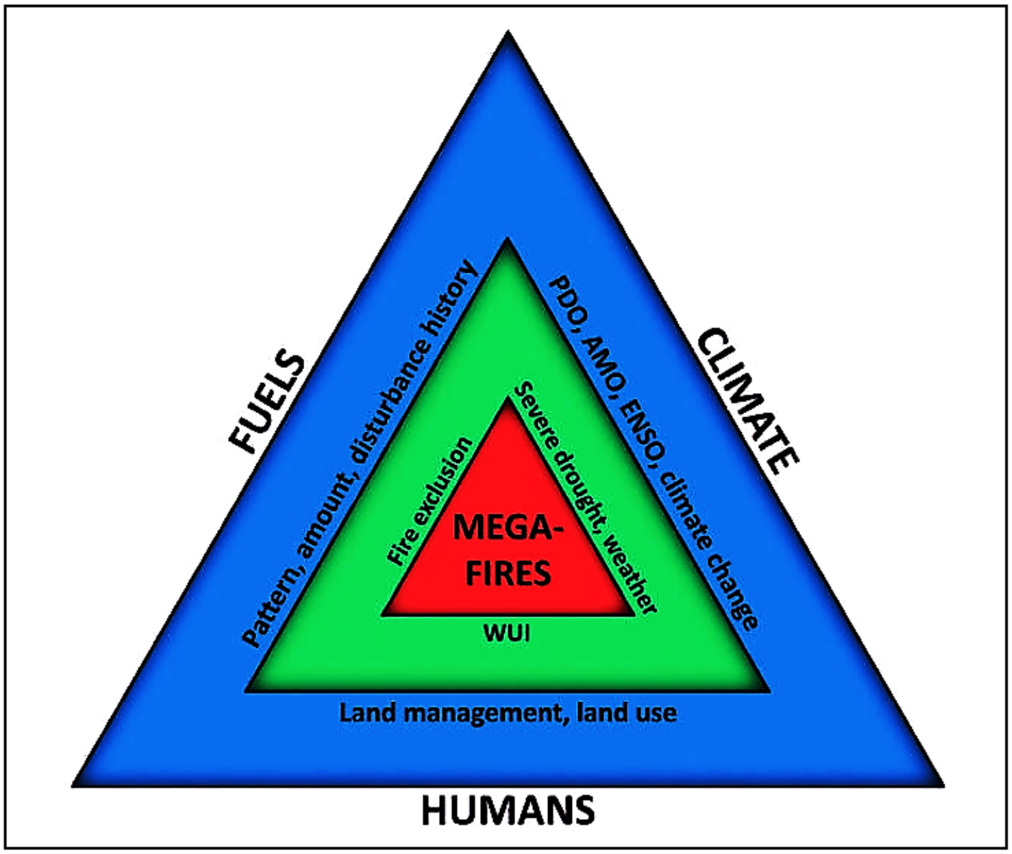

Figure 7 – The megafires triangle (from Stephens et al. 2014). Factors shown outside the blue triangle are those influencing contemporary fire regimes. Items outside the green triangle are key processes and conditions governing fire regimes. Items outside the red triangle identify causes, nested under the factors, that influence and predispose landscapes to megafires. PDO = Pacific Decadal Oscillation (a multi-decadal climate pattern); AMO = Atlantic Multi-decadal Oscillation; ENSO = El Nino-Southern Oscillation; WUI = wildland-urban interface.

Megafires are 100,000 acres or more in size (Stephens et al. 2014). Megafires are an issue because they have been increasing in frequency over the last several decades, a trend expected to continue due to climate change impacts. Fuels treatments can reduce potential for future megafire.

In addition to empirical studies from wildfires, research examining fuel treatment effectiveness demonstrated that treatments can effectively alter fire behavior and severity within treated forest areas (Cram et al. 2006, Pollet and Omi 2002, Raymond and Peterson 2005, Wimberly et al. 2009).

Research studies examining wildfire effects and fuel treatment efficacy, as reported in this section, suggest that beneficial effects of fuel treatments will likely be fading by 20 years after treatment. Local experience, in combination with research studies specifically designed to evaluate fuel treatment longevity, corroborate this conclusion – fuels treatment benefits will probably fade about 20 years after implementation (Battaglia et al. 2008, Bostwick et al. 2011, Crook et al. 2014, Hudak et al. 2011, Kennedy and Johnson 2014, Prichard et al. 2010, Raymond and Peterson 2005, Reiner et al. 2014, Schoennagel et al. 2017, Stephens et al. 2012a, Stevens-Rumann et al. 2018).

CLIMATE CHANGE AND HRV

Historical range of variability (HRV) is defined as a range of conditions and processes likely to have occurred prior to settlement by Euro-American emigrants (Landres et al. 1999). HRV is an analytical procedure for evaluating inherent variation in vegetation composition, structure, and density, reflecting recent evolutionary history and dynamic interplay of biotic and abiotic factors (Morgan et al. 1994).

In the context of forest vegetation analyses for South George planning area, HRV was used extensively – not only for a National Forest Management Act analysis (which compares existing and reference conditions), but also when evaluating environmental effects of implementing alternatives. HRV was used as a tool to help understand present forest conditions and why they respond as they do to silvicultural activities – it uses the past to help us understand the present, to understand forces affecting vegetation response, to gain insight into possible trajectories of future forests, and to integrate these insights when proposing management alternatives (Millar and Woolfenden 1999).

"Some feel that HRV may no longer be a viable concept for managing lands in the future because of expected climate warming and increasing human activities across the landscape. Today's climates might change so rapidly and dramatically that future climates will no longer be similar to those climates that created past conditions. Climate warming is expected to trigger major changes in disturbance processes, plant and animal species dynamics, and hydrological responses to create new plant communities and alter landscapes that may be quite different from historical analogs" (Keane et al. 2009, pages 1033-1034).

"At first glance, it may seem obvious that using historical references may no longer be reasonable in this rapidly changing world. However, a critical evaluation of possible alternatives may indicate that HRV, with all its faults and limitations, might be the most viable approach for the near-term because it has the least amount of uncertainty" (Keane et al. 2009, page 1034), particularly as compared to uncertainty associated with the magnitude, timing, scale, and spatial extent of climate change impacts.

"Given the uncertainties in predicting climatic responses to increasing CO_2 and the ecological effects of this response, we feel that HRV time series derived from the past may have significantly lower uncertainty than any simulated predictions for the future. We suggest it may be prudent to wait until simulation technology has improved to include credible pattern and process interactions with regional climate dynamics and there has been significant model validation before we throw out the concept and application of HRV" (Keane et al. 2009, page 1034).

"In the meantime, it is doubtful that the use of HRV to guide management efforts will result in inappropriate activities considering the large genetic variation in most species and the robustness inherent in regional landscapes that display the broad range of conditions inherent in HRV projections" (Keane et al. 2009, page 1034).

The concept of HRV and historical reference-condition information continuing to have relevance in a climate-change context is expressed well by Haugo et al. (2010: p. 2212): "To effectively manage the effects of climate change, natural resource managers must also explicitly incorporate environmental history in their management decisions. Understanding the processes that generated an ecosystem's current structure will lead to more informed management decisions to effectively respond to projected climate changes." A similar conceptual discussion is provided by Wiens et al. (2012).

CLIMATE CHANGE SUMMARY

The Intergovernmental Panel on Climate Change (IPCC) concluded with high confidence (8 out of 10 chance) that "disturbances such as wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons, and to interact with changing land use and development affecting the future of wildland ecosystems" (Parry et al. 2007, page 56).

This IPCC conclusion demonstrates that climate change involves more than just direct effects of warming temperatures and variable precipitation – it includes indirect effects of climate change on wildfire, insect outbreaks, and other biotic and abiotic disturbance processes (Jenkins et al. 2014, Luce et al. 2012, Williams et al. 2016).

"In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit" (IPCC, Fourth Assessment Report, 2007).

This analysis indicates that direct effects of climate change on temperature and precipitation (fig. 5), in combination with indirect effects related to wildfires, insect outbreaks, and other disturbance processes, could cause profound and enduring changes in forest vegetation if estimated effects occur as projected (Clark et al. 2016, Halofsky et al. 2018, Luce et al. 2012, McDowell et al. 2016).

If dire climate outcomes occur, including what is shown in fig. 5, modeling suggests that Engelmann spruce and western larch could be extirpated (Rehfeldt et al. 2006) from southeastern Washington and South George planning area (Justice 2009), along with possibly red alder, Pacific yew, and other tree species from a larger Washington state area (Bell et al. 2014, Davis and Shaw 2001, McKenney et al. 2007, Shafer et al. 2001). On the east side of the Cascades, where conditions are already dry, many drought-adapted species are near their tolerance limits and increased drought is expected to have more prominent effects than for the west side of the Cascades.

At a broad, bioregional scale (much broader than South George and Washington state areas), modeling indicates that many terrestrial animal and plant species are threatened with extinction due to impacts of climate change (Thomas et al. 2004).

Depending on the pace of climate change, the relatively long lifespans associated with forests and trees result in less opportunity for rapid changes in their adaptedness. Consider this example for western larch in the Priest River Experimental Forest portion of the northern Rocky Mountains:

"Compared to the first 15 years of records, climate in the last 15 years, for instance, has 30 more frost-free days. This change suggests that the climate in 1912 was similar to today's climate at elevations 300 m higher. Because much of the experimental forest burned during the early part of the 20th century, current forests are no longer optimally adapted to contemporary environments. This situation, described as an adaptational lag (Matyas, 1990), arises because natural selection is retrospective: current levels of adaptedness have developed from environmental selection in the past" (Rehfeldt 1995).

"Since genetic differences among western larch populations occur in association with temperature differentials of about 2.6°C, accommodating a climate change of 5°C will necessitate wholesale redistribution of genotypes across the landscape. An increase of 5°C [as is suggested by fig. 5] would produce a mean annual temperature exceeding that associated with the current ecological distribution of the species (Table 6, in Rehfeldt 1995). Ledig and Kitzmiller (1992) have reached similar conclusions for *Pinus ponderosa* in the Sierra Nevada" (Rehfeldt 1995).

When evaluating dry upland forests of the South George planning area, vegetation changes caused by fire suppression, livestock grazing, and selective timber harvest since the 19th century (Harrod et al. 1999, Mast et al. 1999, Powell 2014a, Sloan 1998, Turner and Krannitz 2001) will not be resilient to warm, fire-favoring climatic conditions expected in the 21st century (Brown et al. 2004, Flannigan et al. 2005, Gillett et al. 2004, Macias Fauria and Johnson 2006, Miller et al. 2009, Running 2006, Spracklen et al. 2007, Stephens et al. 2018, Westerling et al. 2006).

If dry upland forests of South George planning area are to have a reasonable opportunity for persistence under future climate regimes, restoring conditions more similar to historical characteristics of frequently-burned, open forests of the past is likely to serve as a useful startpoint (Fiedler 2000b, Harrod et al. 1999, Munger 1917).

For this reason, the HRV concept (see *Climate Change and HRV* section) is expected to remain particularly relevant for dry-forest biophysical environments, regardless of how much the climate changes (Keane et al. 2009).

For a climate-change context, dry-forest conditions approximating those found in the HRV (presettlement) era would almost always be more resilient, and sustainable, than existing conditions, because existing conditions reflect a long period of fire suppression, livestock grazing, and selective timber harvest (Powell 2014a).

The ultimate objectives of dry-forest treatments are to: (1) reduce tree density to eliminate surface and ladder fuels; (2) increase average tree size, because stands comprised of larger-diameter trees are more resilient to fire; and (3) shift forest (tree) composition toward more drought- and fire-tolerant species (Agee and Skinner 2005).

Accomplishing these objectives would restore conditions like those before a fire suppression policy was adopted, and safely support a more natural fire regime featuring frequent, low-severity (and low-intensity) fires. Both outcomes could be served well by returning dry forests to presettlement (HRV) conditions.

Here are dry-forest conditions with high value for climate-change resilience (Powell 2014a); they are compatible with recommendations from Agee and Skinner (2005):

- Forest density: A moderately open stand density (40 to 70 ft^2/ac of basal area).
- Forest structure: Large trees (up to 60 percent of the basal area occurs in trees with a diameter of 21 inches or more).
- Forest composition: A species mix featuring a predominance of ponderosa pine (up to 70 percent of the composition is ponderosa pine).

Sustainable, dry-forest conditions can be achieved in the future, even in a climate-change context, by reintroducing surface fire to reduce fire intervals from centuries to decades, consuming accumulated surface fuels, thinning dense canopy and ladder fuels, and counteracting a species composition trend toward reduced representation by fire-resistant ponderosa pines and western larches. The South George project includes silvicultural activities designed to begin moving dry-forest portions of the landscape toward a more sustainable, and a more historically appropriate, condition.

Note that dry-forest silvicultural activities are intended for implementation on the portion of the planning area that is currently classified as dry upland forest; no attempt was made to predict how this biophysical environment might expand, contract, or migrate in response to climate change. Although an attempt to predict how climate change might increase Dry UF PVG sites, at the expense of Moist UF or Cold UF PVG sites, would be speculative at this point, temperature and precipitation scenarios presented in figure 5, along with other information, suggests that transitions from one biophysical environment to another is a likely outcome (Schoennagel et al. 2017).

There is also no assurance that current acreage and spatial configuration of dry forest will remain the same under climate change. Research suggests that changes in fire regimes due to climate feedbacks led to expansion of savanna environments (open tree stands whose physiognomy is more reminiscent of grassland than forest) in response to hotter and drier conditions (Bond et al. 2005, Bowman et al. 2009). Based on how it occurred elsewhere, a savanna outcome is certainly plausible for some portion of the dry-forest biophysical environment in South George planning area.

Many policy proposals being considered to address climate change are based on mitigation – reducing greenhouse gas emissions from energy use and land-use changes to minimize the pace and extent of climate change. While mitigation is crucial, adaptation to climate change is increasingly viewed as a necessary and complementary strategy to mitigation (Halofsky et al. 2018, Joyce et al. 2009, Nagel et al. 2017).

Table 2 provides adaptation strategies proposed for National Forest System forest vegetation. It also describes whether proposed silvicultural activities for South George Vegetation Management Project would be compatible with adaptation strategies.

The information in table 2 indicates that active-management practices reducing stand vulnerabilities to uncharacteristically severe wildfire and similar climate-induced disturbance outcomes could meet multiple goals of near-term mitigation and mid-term adaptation if such practices also reflect goals for other ecosystem services such as late-old structure and water quality (Janowiak et al. 2014, Joyce et al. 2009).

Critics of active management may contend that climate change and other human impacts inevitably lead to forestland 'destruction.' They believe it's important to protect unmanaged areas for future generations. But this viewpoint fails to acknowledge that after more than a century of relatively effective fire suppression, the great majority of federal forestland is no longer 'natural' – even for areas that never experienced timber harvest. For these reasons, South George active management treatments are designed to address two primary issues and concerns: (1) changes caused by long-term fire suppression policies; and (2) expected future (predicted) climate-change impacts.

Proposed silvicultural activities are expected to improve 'adaptive capacity' (Janowiak et al. 2014, Olsson et al. 2004) of forest stands in South George planning area, particularly by alleviating chronic stress associated with high tree density levels. Improvements in adaptive capacity are important for helping forest vegetation deal with direct effects of warming temperatures and reduced precipitation (fig. 5), as well as indirect effects caused by climate-influenced disturbance processes such as wildfire.

Thinning and other mechanical treatments, alone or in combination with prescribed fire (figs. 3, 4), are not intended to exclude fire from the landscape because doing so perpetuates a counter-productive paradigm of fire exclusion. Fuel treatments are designed to slow the spread of fires and reduce their severity by reducing fuel loadings (Agee and Skinner 2005, Stephens et al. 2018); an ultimate objective is to allow reintroduction of fire with moderated fire severity (effects) (Syphard et al. 2011).

Table 2. Climate change adaptation strategies and South George silvicultural activities.

Climate Change Adaptation Strategies That Are Related to Forest Vegetation	Predicted Compatibility of Strategy with South George Proposed Silvicultural Activities
Improve the capability of ecosystems to withstand uncharacteristically severe drought, wildfires and insect outbreaks at landscape scales.	Rationale for the silvicultural activity proposals is based largely on insect and disease susceptibility, and the potential to reduce uncharacteristic fire hazard on dry-forest sites. Low thinning would be aggregated on blocks up to 1,000 acres in size to emulate the spatial extent produced historically by surface fire (Heyerdahl 1997).
Facilitate natural (evolutionary) adaptation through silvicultural treatments that shorten regeneration times and promote interspecific competition.	The South George proposed action includes regeneration cutting and tree planting, both of which are responsive to shortened regeneration times and promotion of interspecific competition. Planting emphasizes a mixed-species composition but based on recent climate change modeling for South George (Justice 2009), the amount of western larch in the species mix might be too high because larch is not expected to fare well under climate change.
Where ecosystems will very likely become more water limited, manage for drought- and heat-tolerant species.	Specifications for how silvicultural activities will be implemented will account for species-specific life history traits affecting drought and heat resistance (see table 1). Drought-tolerant species will be preferentially retained during intermediate cutting activities, and they will be emphasized in the species mix to be planted after regeneration cutting.
Reduce homogeneity of stand structure and synchrony of disturbance patterns across broad landscapes by promoting diverse age classes and species mixes, stand diversities, and genetic diversity.	Rationale for proposing certain silvicultural activities instead of others uses results from an HRV analysis, and several HRV components (composition and structure) account for age-class, species, and successional-stage diversity. Tree planting will promote a diverse species composition rather than single-species stands. Regeneration cutting will introduce or improve landscape heterogeneity by reducing homogeneity.
Reset ecological trajectories to take advantage of early successional stages that are adaptive to present rather than past climates.	Regeneration cutting will reset ecological trajectories for activity units in which it occurs; tree planting will use a mixed-species composition consisting primarily of early-seral (early successional) tree and shrub species.
Use historical ecological information to identify environments buffered against climate change and which would be good candidates for conservation.	Although climate change could potentially affect a full range of biophysical environments, the historical structure associated with dry-forests (a low-density cohort of large-diameter, fire-resistant trees comprised primarily of ponderosa pine) is likely to be resilient to projected climate change. Proposed silvicultural activities are directed toward conserving this structure when it currently exists or restoring it if important biological legacies (such as large trees) are still present. Using regeneration cutting and thinning will introduce heterogeneity on moist-forest sites and help create resilient tree density levels on all biophysical environments.

Climate Change Adaptation Strategies That Are Related to Forest Vegetation	**Predicted Compatibility of Strategy with South George Proposed Silvicultural Activities**
Encourage local industries that can adapt to or cope with variable types of forest products because of the uncertainty about which tree species will prosper in the future.	It is anticipated that some portion of silvicultural activities involving timber removal (intermediate cutting and regeneration cutting) would be accomplished by using stewardship authority or another alternative that would not involve a standard timber-sale contract. Local stewardship or biofuel/bioenergy industries are well positioned to deal with unconventional species or product types.
Reforestation after disturbance may require different species than were present before the disturbance to better match site-level changes associated with climate change.	Reforestation activities will use a mixed-species composition emphasizing early-seral, drought-tolerant species. All species to be used are presently found in the planning area; currently, there is no proposal to anticipate future effects of climate change by introducing non-native tree species.
After a disturbance event, use intensive site preparation activities to remove competing vegetation and replant with high-quality, genetically appropriate and diverse stock.	After implementation of regeneration cutting silvicultural activities, tree planting would be completed by using conventional removal of competing vegetation (scalps), and seedlings to be out-planted would be produced from genetically diverse (but local) seed sources.
To promote climate resilience for existing stands, use widely spaced thinnings or shelterwood cuttings and rapid response to forest mortality from fire or insects.	The intermediate cutting (thinning) and seed-tree cutting treatments would be implemented to the widest reasonable inter-tree spacing; rapid response to forest mortality is not included explicitly as a proposed action for the South George Vegetation Management Project.
Plan for higher-elevation insect outbreaks, species mortality events, and altered fire regimes.	Silvicultural activities proposed for moist, upland-forest sites anticipate accelerated mortality of subalpine fir (which is currently occurring at high levels due to infestations of balsam woolly adelgid, an introduced insect species), Engelmann spruce, and other species projected to not fare well under future climate scenarios (Rehfeldt et al. 2006).

Sources/Notes: the climate change adaptation strategies pertain to forest vegetation only and were derived from Joyce et al. (2008, 2009) and West et al. (2009). Predicted compatibility of each adaptation strategy with South George silvicultural proposed actions was provided by the author of this white paper.

Climate scientists have issued warnings about climate change effects for decades. Although it seems as if each warning is more ominous than the last ("the last time it was 4 degrees warmer there was no ice at either pole and sea level was 260 feet higher than it is today"), this climate-change analysis suggests that South George silvicultural treatments adequately anticipate future change, appropriately provide for future ecosystem resiliency and ecological integrity, and reasonably realign current conditions to be more sustainable (Abatzoglou and Kolden 2013; Barbero et al. 2015; Dale et al. 2001; Halofsky et al. 2016, 2017, 2018a, 2018b, 2018c; Janowiak et al. 2014; Kerns et al. 2018; McKenzie and Littell 2017; Nagel et al. 2017; Schoennagel et al. 2017; Stavros et al. 2014; Stephens et al. 2018; Trumbore et al. 2015).

FOREST CARBON ANALYSIS

Increased burning of fossil fuels (coal, oil and its refined products including gasoline, and natural gas) since the beginning of the Industrial Revolution has resulted in dramatic increases of carbon dioxide (CO2) and methane (CH4) in the atmosphere. As CO2, methane and other greenhouse gases accumulate, they contribute to a host of changes referred to as the greenhouse effect, global warming, or climate change (fig. 8).

Terrestrial carbon (C) sequestration involves processes through which CO2 from the atmosphere is absorbed by trees, plants, and crops through photosynthesis, and then stored as C in biomass (tree trunks, branches, foliage, and roots) and in soils. The term 'sink' is also used to refer to forests, croplands, and rangelands and their ability to sequester C. Because agriculture and forestry activities can also release CO2 to the atmosphere, a C sink occurs when carbon sequestration is greater than carbon release over a given time period. When more CO2 is being released than sequestered, an activity or condition is a C 'source' rather than a C sink (Fahey et al. 2009).

Primarily in response to concerns about climate change, land managers are being asked to consider the potential carbon consequences of forest management activities (Williams et al. 2016). Forest ecosystems have an important role in global C cycles because they are estimated to sequester ('fix') about 80% of the aboveground terrestrial C pool (Waring and Running 1998), and forests store more than 45% of the carbon found in terrestrial ecosystems (Bonan 2008).

Therefore, forests and their management are at the forefront of efforts and programs to address global climate change because they might provide one of the most efficient and effective options for offsetting CO2 emissions from fossil-fuel consumption (Bonan 2008, Canadell and Raupach 2008, Salinger et al. 2005, Winnett 1998).

The remainder of this relatively long section discusses issues associated with carbon accounting, carbon storage and sequestration, carbon stocks and fluxes, and possible interactions between management practices that would be expected to cause short-term reductions in carbon stocks (such as thinning and prescribed fire), but whose implementation could potentially avoid large carbon emissions from wildfire and other stand-replacing disturbance processes in the future. A wide range of scientific research is summarized in this section.

Wildfire and other disturbance processes (insect outbreaks, disease epidemics, windthrow episodes, avalanches and debris flows, etc.) can release a forest's stored C as CO2 emissions, either directly by combusting wood, or indirectly by killing trees that eventually decompose, with CO2 being emitted during microbial decomposition of standing or down dead wood.

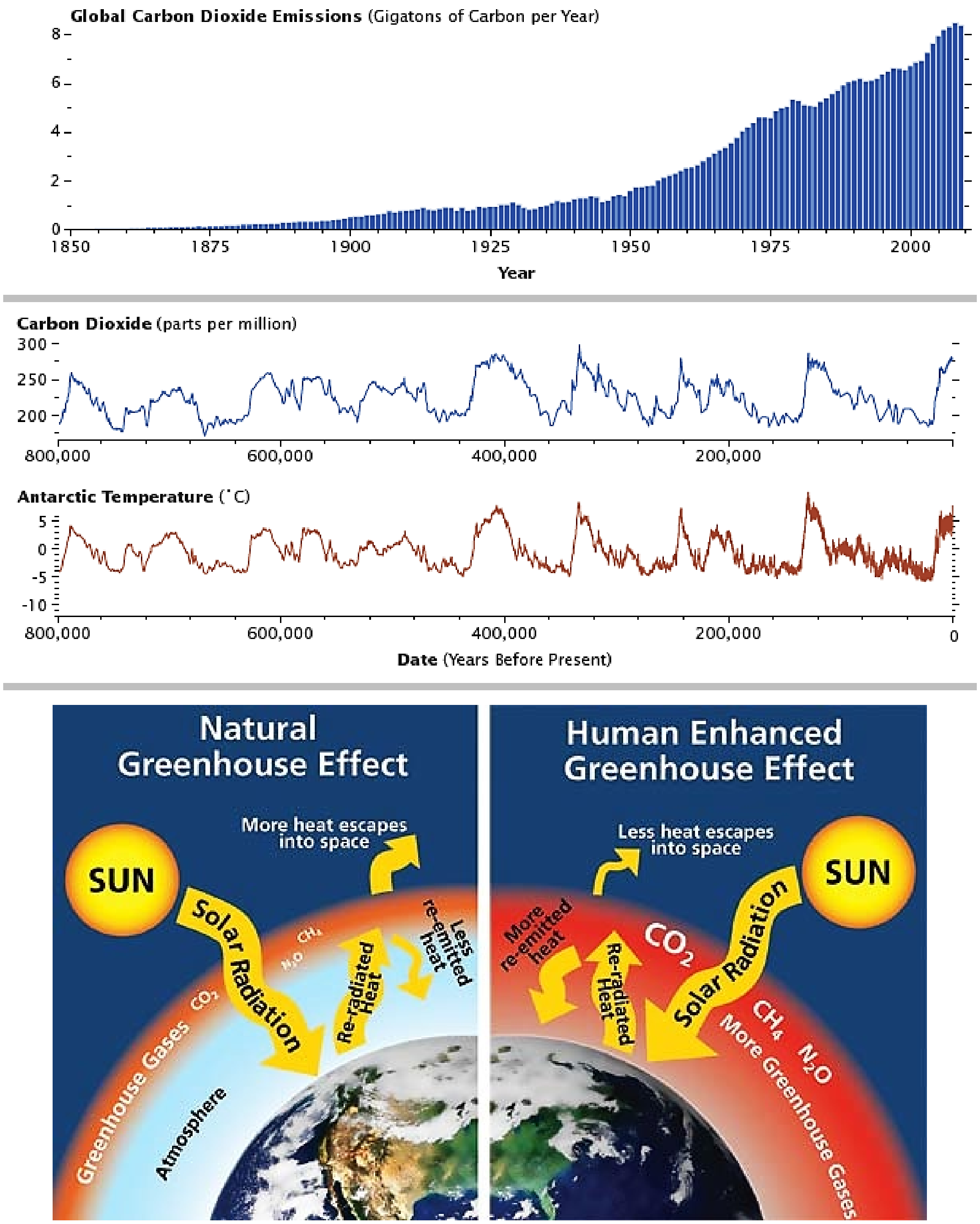

Figure 8 – Carbon dioxide emissions have increased steadily since the beginning of the Industrial Revolution era (top third; source: NASA Earth Observatory website).

Atmospheric carbon dioxide levels have corresponded closely with temperature over the past 800,000 years (middle third). Although pre-industrial-era temperature changes were touched off by variations in Earth's orbit, increased global temperatures released CO_2 into the atmosphere, which in turn warmed the Earth. Antarctic ice-core data show the long-term correlation until about 1900; after 1900, temperature trends are related primarily to greenhouse-gas increases due to emissions from fossil-fuel burning (source: NASA Earth Observatory website).

Earth has a natural greenhouse effect, allowing human life to exist (lower third, left side). Greenhouse gas emissions since about 1750 (Industrial Era) resulted in an amplified greenhouse effect (lower third, right side) and associated climate change.

Traditionally, it was believed that primary losses of C and other nutrients during a fire was in gaseous form (as CO_2, NO_2, and H_2O), but recent research shows that much loss occurs as particulate matter carried in the smoke plume (Bormann et al. 2008).

A surprisingly large loss of soil nutrients from fire can not only contribute to greenhouse gas emissions, but research suggests it can lower productivity and C sequestration rates for a substantial period after burning (Bormann et al. 2008).

Because old forests accumulate biomass for centuries, they contain large amounts of C and function as a C sink (Rhemtulla et al. 2009). But the cumulative probability of stand-replacing wildfire, or similarly intense disturbance processes, is greater for stands with high aboveground biomass, so old forests tend to be less common than young or mid-age stands, even in unmanaged landscapes (Lesica 1996, Luyssaert et al. 2008).

Disturbance effects are often indirect – fire can change the albedo of a soil surface (defined as the proportion of solar radiation reflected, rather than absorbed, by a land surface), allowing more solar energy to be absorbed rather than reflected, which in turn fosters increased decomposition rates for many decades (Running 2008). Forests are generally darker than bare or agricultural land and consequently absorb more solar radiation, but black soil surfaces created by fire have even lower albedo than forest.

Because a young forest generally gets established after fire and develops for 100-300 years, eventually recapturing an equivalent amount of C to what was released by fire, forests can be 'carbon-neutral' when evaluated across long timeframes. If climate change or other factors alter these post-fire successional relationships, however, it is possible that forests could disappear altogether following wildfire (Adams et al. 2009), in which case the system would obviously not be C neutral.

Other research indicates that fire causes accelerated decomposition rates after burning, likely related in part to soil warming from albedo changes described above. Auclair and Carter (1993), for example, calculated that post-wildfire C release after a high-intensity fire, presumably related to microbial decomposition rates, was approximately three times greater than direct release of CO_2 during the fire itself.

In a drier ponderosa pine ecosystem, direct C flux measurements found higher CO_2 emissions from a high-intensity burn area than an adjacent unburned area, even ten years after burning (Dore et al. 2008).

Fire and C relationships are complex because fire has an important influence on the vegetation baseline against which climate change and C effects are measured (see figure 12 later in this report). Climate plays an important role in determining fire patterns, particularly regarding temporal trends in the El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation climate patterns, and fire influences the climate system via the release of C. In the interior Pacific Northwest, for example, large fire years were correlated with years when the ENSO was in its negative phase (El Niño) for some portions of the Blue Mountains but not for others (Heyerdahl et al. 2002).

Fires influence the natural cycle of primary production and respiration, and if climate and fire regimes equilibrate, then fire-induced atmospheric CO_2 emissions are balanced by uptake from surviving vegetation and postfire regeneration (Bond et al. 2005, Bowman et al. 2009) (fig. 9).

Forests in the United States sequester about 10% of annual anthropogenic CO_2 emissions (Woodbury et al. 2007). Wildfires are increasing in size and severity (Barbero et al. 2015, Dennison et al. 2014, Miller et al. 2009, Stavros et al. 2014, Westerling et al. 2006), and they produce large direct CO_2 emissions on the order of 4-6% of annual U.S. anthropogenic CO_2 emissions (Spracklen et al. 2007, Wiedinmyer and Neff 2007).

As the amount of burned acreage increases, fire suppression costs routinely exceed $1 billion a year, and this is causing managers to consider a policy where some fires would be allowed to burn (such as a Wildland Fire Use program) when doing so would provide ecosystem benefits and reduce suppression costs (Donovan and Brown 2005, 2007, 2008).

Because wildfires represent a substantial potential source of future CO_2 emissions, recent forest management emphasis is often directed at either reducing fire susceptibility or improving fire resistance (Sohngen and Haynes 1997). One of the objectives of using mechanical thinning, prescribed fire, or a combination of both activities to reduce fuel loadings is to produce relatively small carbon releases now to preclude or minimize large CO_2 wildfire emissions in the future (Canadell and Raupach 2008).

And, because climate change research suggests that the area burned by wildfire could increase 78% by 2100 (and perhaps much more than this for the Blue Mountains – see fig. 2), with much of an increase attributable to a 44% increase in lightning ignitions (Price and Rind 1994), implementing active-management practices to increase forest resilience to wildfire (improvement cutting and low thinning, in particular) could provide important C sequestration benefits.

A recent study found that significant increases in fire resistance can be achieved by removing only small ladder fuels (vegetation providing vertical fuel continuity between the forest floor and overstory tree crowns) and fire-sensitive intermediate trees without reducing most of a live-tree C pool associated with intermediate pines and large trees of all species. It found that thinning and prescribed fire have a positive influence on forest development by redirecting tree growth and C storage into large-diameter trees, a more stable C stock, and large trees are generally more resistant to postfire mortality and other potentially detrimental fire effects (Hurteau and North 2009, North et al. 2009).

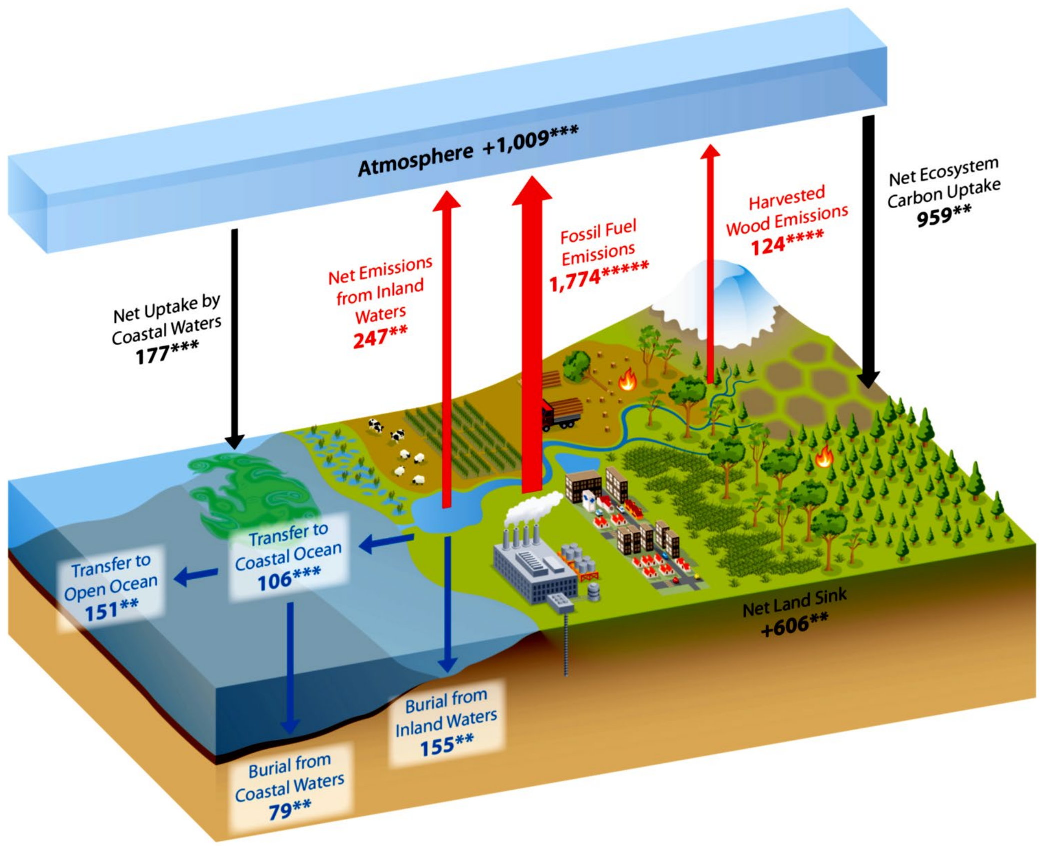

Figure 9 – Major carbon fluxes of North America (source: Cavallaro et al. 2018). Net fluxes and transfers of carbon among the atmosphere, land, and water are depicted in this simplified representation of a North American carbon cycle. The diagram includes fluxes of carbon dioxide but not methane or other carbon-containing greenhouse gases. These carbon flows include 1) emissions (red arrows); 2) uptake (black arrows); 3) lateral transfers (blue arrows); and 4) burial (blue arrows), involving transfers of carbon from water to sediments and soils (Cavallaro et al. 2018).

Other research suggests that historic stands with a low density of large trees supported more biomass (and C) than contemporary, fully-stocked, fire-suppressed old growth forest (DeLuca and Aplet 2008).

An explanation for this seemingly counterintuitive result is as follows: on a proportional basis, one large tree has a higher C content than many small trees – according to Fellows and Goulden (2008), a single large tree (> 90 cm; 35 in) contains the same amount of C as 60 small (10-30 cm; 4-12 in) trees.

Another contributing factor is that large trees mostly use deep soil water (≥ 70 cm; 28 in), whereas small trees and shrubs rely on shallow soil water (< 50 cm; 20 in), and shallow soil water is rapidly depleted during the growing season (Arkley 1981, North et al. 2009). A thick zone of weathered bedrock is particularly important for supplying the water needed by large trees on sites where the overlying soils are relatively thin (< 1 m; 3.3 ft), especially for summer-dry (Mediterranean) ecosystems (Witty et al. 2003).

Similar C emission concerns exist for disturbances other than wildfire – climate mitigation through forestry also carries the risk that C stocks may return to the atmosphere after events such as landscape-scale insect outbreaks (Breshears et al. 2005, Carroll et al. 2004, Fleming and Volney 1995, Ghimire et al. 2015, Logan et al. 2003, Macias Fauria and Johnson 2009, Morehouse et al. 2008, van Mantgem et al. 2009, Williams and Liebhold 1995) (fig. 10).

A recent increase in areas affected primarily by mountain pine beetle helped drive Canadian forests from functioning as a CO2 sink (before 2000) to a C source for at least two or three more decades (Kurz et al. 2008a, 2008b), and Canadian beetle-caused forest mortality is believed to be climate-related (Anderegg et al. 2013) (fig. 10).

Recent research could perhaps be interpreted as suggesting that an unintended benefit of successional changes spawned by fire suppression is an increase in forest biomass (Myneni et al. 1997), and biomass increases have sequestered C that might otherwise have contributed to climate change (Fellows and Goulden 2008, Houghton et al. 2000, Hurtt et al. 2002). In other words, if frequent, low-severity fire not been suppressed, allowing an understory tree cohort to develop, then our C sequestration levels would be lower than now.

This interpretation is problematic in several respects, not the least of which is that fuel-loaded forests are susceptible to large carbon emissions (see fig. 4) when they eventually and inevitably burn in a stand-replacing wildfire (Hurteau et al. 2009).

And in forests that historically burned with high frequency and low severity (fire regime 1), adding to the C baseline by increasing stocking levels to sequester more carbon (Myneni et al. 1997) may exacerbate a recent trend toward an increased amount of uncharacteristic, high-severity fire on dry-forest sites, attributed largely to fire suppression (creating more fuel) and climate change (creating a longer and more severe fire season) (Miller et al. 2009, Powell 2014a, Stephens et al. 2018, Westerling et al. 2006).

There are also synergistic effects between climate change, insect-caused tree mortality, and wildfire (Williams et al. 2016). Insect outbreaks may serve to pre-condition fuels for a future wildfire by killing trees, allowing them to dry out and eventually become fuel for fire ignition and spread. For example, Lynch et al. (2006) found the extent and severity of Yellowstone fires of 1988 to be closely correlated with prior mountain pine beetle outbreaks.

All fuels and vegetation treatments create C emissions to some extent, but overall C emissions can be reduced, and future C stocks increased, by modifying treatments to reduce surface fuels, small understory trees, and intermediate fire-sensitive trees (North et al. 2009). When fuels treatment activities appropriately consider C stocks and fluxes, it is possible to create favorable forest conditions for increasing large-tree growth.

Figure 10 – Mountain pine beetle outbreak in central British Columbia (photo by L. MacLauchlan; source: Woods et al. 2010). Very large, landscape-level outbreaks of forest-killing insects, particularly bark beetles such as mountain pine beetle, have caused much of western Canada to transition from a reliable carbon sink to a carbon source, and these landscapes are expected to function as sources for several more decades at least (Kurz et al. 2008a, 2008b).

This strategy is based on the concept that by accepting repeated but small reductions in C stocks (associated with treatments), it is possible to create or maintain a substantial future C sink by sequestering C in relatively stable, long-lived forest structure in the form of large-diameter trees (Hurteau et al. 2008, North et al. 2009).

The sequestration rationale for a fuels treatment strategy on dry sites is that forests where stocking levels have been reduced sufficiently to approach presettlement tree density and structure (as represented by HRV) contain substantially more C, after wildfire, than adjacent unthinned stands where presettlement conditions were not restored (Hurteau et al. 2008).

And, because the Umatilla National Forest has no explicit objective to manage forests for C sequestration purposes (USDA Forest Service 1990), perhaps the most important benefit of completing effective fuels treatment activities is restoration of late-old structure and associated ecosystem function (USDA Forest Service 1995), particularly for dry forests where historical composition, structure, and density were maintained by a short-interval, low-severity fire regime (Mutch et al. 1993).

A life-cycle analysis for a second-growth forest in the Pacific Northwest indicates that allowing a harvested stand to grow and sequester C resulted in less emission of CO2 than resulted from harvest and storage in wood products; however, when effects of substituting wood for concrete and steel was also considered, then harvest scenarios resulted in less CO2 emission than was produced from a no-harvest scenario (Perez-Garcia et al. 2005).

The option of using wood as a construction material in place of concrete or steel, or as an energy source to replace fossil fuels, has consistently been shown to offer significant C benefits (Eriksson et al. 2007, Gustavsson et al. 2006).

An accurate C budget for both durable products and wood-based energy accounts for fossil fuel use associated with harvest, transport, and processing. Houses constructed primarily of wood have 20-50% lower emissions of greenhouse gases over their entire life cycle (typically assumed to be 80-100 years) than comparable dwellings whose aboveground walls were framed with concrete or steel (Miner and Perez-Garcia 2007).

Using woody debris to produce energy could address two issues: (1) it reduces demand for coal, oil, natural gas, and other fossil-fuel derivatives; and (2) if wood comes from dense, overgrown forests, its removal reduces the threat of uncharacteristic wildfire and an associated emission of greenhouse gases (for example, wildfire typically emits more methane, a potent greenhouse gas, than is produced when generating bioenergy).

An expected outcome of the South George Vegetation Management Project is provision of timber and woody biomass that could then be converted into durable wood products for home construction, or for utilization as an energy source or specialty products such as biochar (fig. 11).

SILVICULTURAL ACTIVITIES AND CARBON SEQUESTRATION

An analysis of existing and historical forest vegetation conditions suggests that certain vegetation conditions in South George planning area (particularly species composition, forest canopy layering, tree density, and forest canopy biomass) reflect the impact of fire suppression. On dry-forest sites, fire suppression caused a multi-decade period of infilling (encroachment) by small trees beneath large overstory trees, and many of the infilled trees consist of shade-tolerant and fire-sensitive species.

Each of the project's action alternatives (B, C, D) would respond to fire suppression effects and other forest vegetation issues by using timber harvest and prescribed fire activities to remove varying amounts of woody biomass. Because about half the volume of woody biomass consists of C (Birdsey 1992, Jenkins et al. 2003, Smith et al. 2006), these activities are expected to reduce the amount of C stored in treated stands. For timber removals, however, a portion of the C removed by harvest will remain stored for a relatively long period in durable wood products, or in landfills.

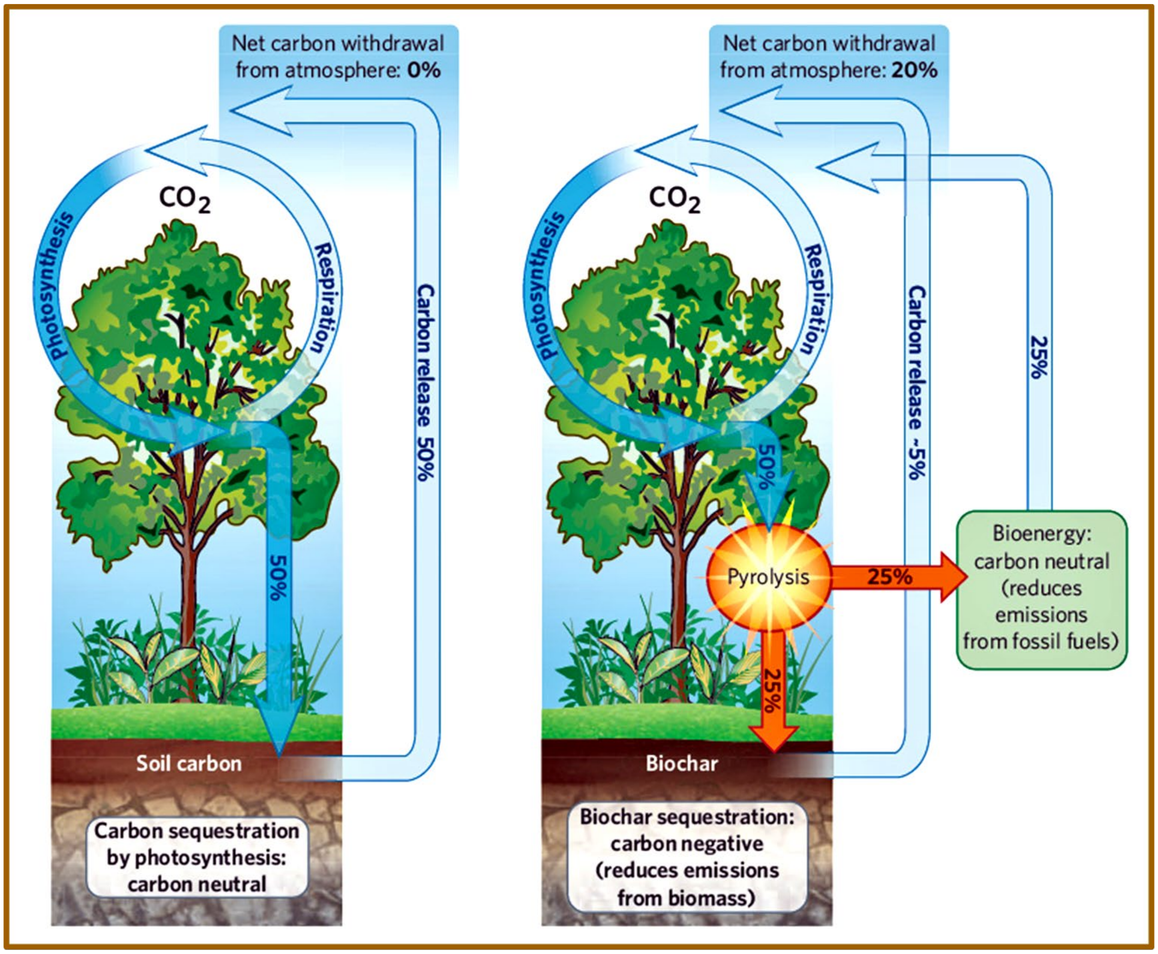

Figure 11 – Biochar can be carbon negative. A carbon analysis suggests that carbon sequestration by photosynthesis (e.g., a 'normal' forest carbon cycle) is carbon neutral – net carbon withdrawals from the atmosphere are balanced by carbon releases (figure and analyses from Lehmann 2007). Burning fossil fuels (coal, oil, gasoline, natural gas, etc.) to provide energy is a carbon positive activity – more carbon is released (emitted) to the atmosphere than is withdrawn or fixed. Lehmann's (2007) analysis found that using woody biomass to generate biochar through a process referred to as pyrolysis is carbon negative, which means that more carbon is retained (sequestered) than is emitted to the atmosphere.

Intermediate cutting practices (low thinning, improvement cutting) are expected to cause similar effects on C fluxes and storage. However, initial reductions in aboveground C storage from intermediate cutting will be less than reductions associated with regeneration cutting (clearcutting, seed-tree cutting). Intermediate cutting will initially reduce C storage in treated stands, but it is unclear whether reductions would be substantial enough to transform activity units from a net C sink to a net C source.

On dry-forest sites, future application of prescribed fire and intermediate cutting activities could continue to maintain aboveground C stocks and net ecosystem productivity (NEP) at a lower level than would occur if the stands were permitted to continue accumulating biomass indefinitely (which is basically until the next wildfire).

[Terminology note: Net ecosystem productivity, or NEP, is defined as gross primary productivity minus ecosystem respiration (Chapin et al. 2006). It reflects a balance between absorbing CO_2 from the atmosphere through photosynthesis, and release of C into the atmosphere from live-plant respiration and microbial decomposition of organic matter. When NEP is positive, C accumulates in biomass and the ecosystem is viewed as a carbon sink. When NEP is negative, more C is emitted than is absorbed and an ecosystem is a C source.]

Note that a Proposed Action for South George Vegetation Management Project includes silvicultural activities proposed for implementation in the near term, which is assumed to be the next 5-10 years.

Any reference to 'future' activities or treatments refers to what might occur in the mid-term, which is assumed to be more than 10 years in the future when considering conventional treatment regimes involving a sequence of coordinated activities, such as application of thinning and prescribed fire in the next 5 years or less (near-term), followed by thinning and prescribed fire on the same areas 20 years from now (mid-term).

As described earlier, intermediate cutting practices are designed to improve physiological tree vigor and stand resistance to a variety of insects and diseases, and these improvements will contribute to long-term persistence of large-diameter trees in the planning area. By using intermediate treatments to increase the probability that large trees will persist over time, silvicultural activities are expected to help sustain larger C stocks and a more positive NEP than would be obtained from stands with high vulnerability to uncharacteristic wildfire, insect outbreaks, disease epidemics, and other disturbance processes (Hurteau et al. 2008, Hurteau and North 2010, North et al. 2009).

Forests of the United States store approximately 66,600 Mt (million metric tons) of C (Birdsey et al. 2007). It is estimated that the Umatilla National Forest has approximately 60.4 million tons of biomass (consisting of standing live, standing dead, and down log components; see table 3 on page 15 in Christensen et al. 2007). This amount of biomass is equivalent to 54.8 million metric tons (by using a conversion factor of .907 metric tons per U.S. ton), which represents approximately 27.4 Mt of C (by assuming that biomass is app. 50% C – see Woodbury et al. 2007). This means that the Umatilla National Forest contains less than four one-thousandths of a percent (.0004) of total U.S. carbon stocks.

South George planning area contains 15,430 acres of forestland, which is approximately 1.2% of total forestland for Umatilla National Forest (comprising 1,254,000 acres; see table 2 on page 7 in Christensen et al. 2007). This means that South George planning area contains approximately 0.34 Mt of C (1.2% of 27.4 Mt). If alternative B or C are selected for implementation, then approximately 0.09 Mt of C would potentially be affected by silvicultural activities (intermediate and regeneration cutting methods). If alternative D is selected for implementation, then approximately 0.06 Mt of C would potentially be affected by silvicultural activities.

In either instance, implementing the South George project will affect only a tiny percentage of Umatilla National Forest C stocks, and an infinitesimal amount of total forest C stocks for the United States.

How much C is stored in proposed activity units for the South George Vegetation Management Project, and how would proposed treatments affect C stocks? These questions were examined by using the Forest Vegetation Simulator (FVS) modeling system (Dixon 2015). FVS has potential to serve as a quantitative, national platform for projecting near- to mid-term (<50 year) trends in C pools for forests of the United States, and their response to silvicultural manipulations. FVS was approved by CCX (Chicago Climate Exchange) and CCAR (California Climate Action Registry) to meet their criteria for providing verifiable estimates of C sequestration for forestry work (Fahey et al. 2009).

FVS was used to estimate C pools for forest vegetation activity units in South George planning area. Modeling accounted for near-term activities only, and it included both intermediate cutting (low thinning and improvement cutting) and regeneration cutting activities (seed-tree cutting and clearcutting). No attempt was made to estimate near-term C sequestration implications of tree planting, nor were non-silvicultural activities such as prescribed fire included in the analysis.

FVS tracks C by using a series of C pools: total aboveground live (live trees, including stems, branches, and foliage, but not including roots); merchantable aboveground (only merchantable portion of live trees); belowground live (roots of live trees); belowground dead (roots of dead and harvested trees); standing dead (dead trees, including stems and any branches or foliage still present, but not including roots); forest down dead wood (all woody surface material, regardless of size); forest floor (litter and duff); herbs and shrubs; and total stand carbon (total of all the above categories).

Table 3 summarizes C pools for South George alternatives, as stratified by potential vegetation group. It shows that C stocks are greater on moist-forest sites than on dry-forest sites, reflecting the higher inherent productivity of moist sites, and that post-treatment C stocks are expected to be reduced from pre-treatment levels.

Table 3 only shows differences between pre- and post-treatment C stocks for a 'live merchantable' pool because other C pools are not expected to change from implementing silvicultural activities (intermediate and regeneration cutting, and tree planting).

C-stock values included in table 3 are per-acre averages calculated using all activity units included in an alternative. Keith et al. (2009) suggest that the C carrying capacity of a forest, the maximum amount of C that can be stored with a natural disturbance regime, is an effective baseline for comparing current C stocks.

Table 3. Carbon accounting for near-term effects of implementing silvicultural activities only, by alternative and potential vegetation group (PVG); all table values are tons per acre.

CARBON POOLS		ALTERNATIVES B/C Dry UF PVG	Moist UF PVG	ALTERNATIVE D Dry UF PVG	Moist UF PVG
Live aboveground C		53.4	59.6	53.4	57.2
Live merchantable C	**Pre**	32.7	36.1	32.7	34.4
	Post	11.7	12.5	11.7	15.8
Live belowground C		11.5	12.9	11.5	12.4
Dead belowground C		1.1	1.5	1.1	1.5
Dead standing C		5.4	8.6	5.4	8.6
Dead down wood C		10.0	10.6	10.0	11.1
Forest floor C		7.8	10.0	7.8	9.6
Herb and shrub C		0.2	0.1	0.2	0.2
Total stand C	**Pre**	89.3	103.3	89.3	100.4
	Post	68.3	79.8	68.3	81.7

Sources/Notes: from Carbon Report output provided by FVS (Dixon 2015) for silvicultural units (intermediate cutting or regeneration cutting) included in alternative B, C, or D. All C pools except "live merchantable" are assumed to be unchanged because organic materials will remain on site (only C removed is live merchantable material).

Figure 12 shows how post-treatment C stocks, by individual activity unit, compare with C stocks produced by the natural disturbance regime (e.g., the C carrying capacity).

Figure 12 demonstrates that for some activity units, proposed silvicultural activities will reduce pre-treatment C stocks to a level below the historical equilibrium; it also shows that for other units, post-treatment C stocks will still be greater than the historical equilibrium (baseline) level.

This outcome portrayed in figure 12 (some post-treatment conditions above a baseline, and some below) illustrates the concept that using silvicultural practices to improve forest health and address wildfire risk may necessitate removing trees, but these choices can also involve trade-offs in terms of C sequestration.

And, as trade-offs are being evaluated in a contemporary, climate-changed era, land managers are reevaluating traditional approaches to forest management. What silviculture has written on the landscape, at a stand scale, is being steadily erased by stand-replacing wildfires and insect outbreaks (fig. 13).

As climate change continues, and unfolds further in coming decades, active management will undoubtedly become more reactionary – dealing with an existing 'crisis' such as megafire or mega-outbreaks of mountain pine beetle – rather than remaining focused on a long-term silvicultural strategy or plan. This will occur even if long-term plans include measures designed specifically for climate change mitigation and adaptation.

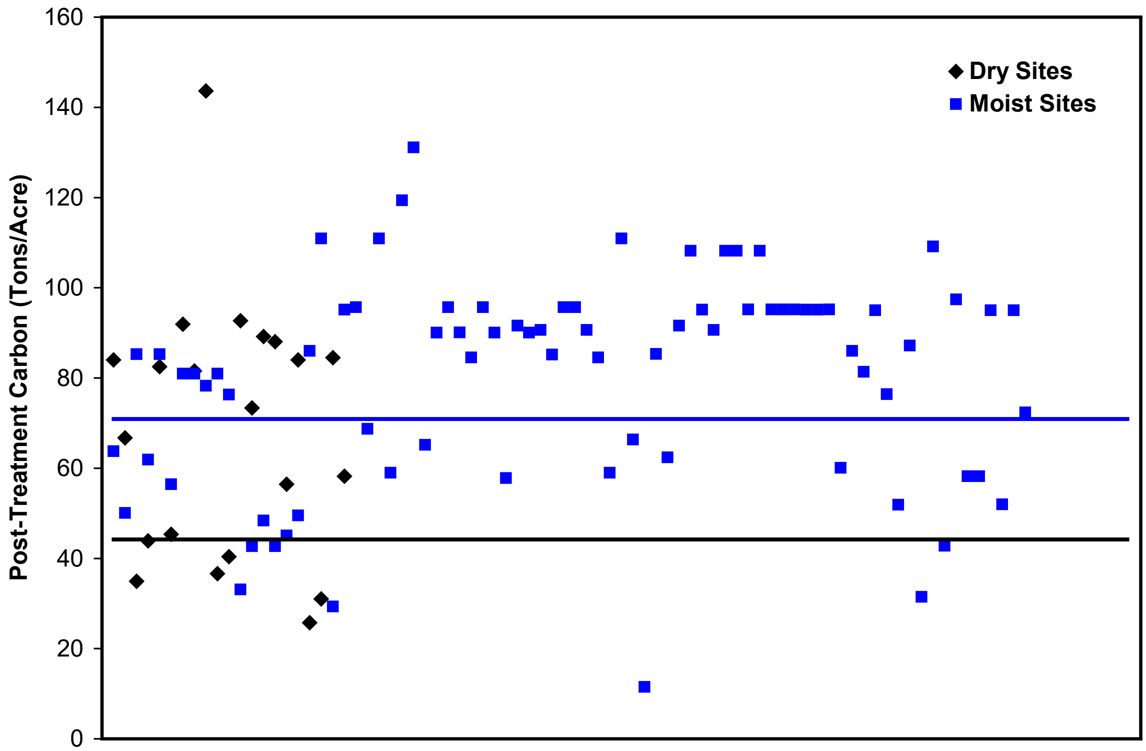

Figure 12 – Estimated post-treatment C stocks for individual activity units included in alternative B, C, or D. Solid lines, portraying C amounts corresponding to a natural disturbance regime (e.g., C carrying capacity for these environments), are based on bareground simulations completed by using FVS (Dixon 2015).

Or, another strategy for the future is that managers need to develop a mindset where they accept more disturbance-related change to natural resources, as predicted by figure 2, largely by becoming 'oblivious' to it (ignoring it), especially if a staying-the-course approach is more important than maintaining a reactionary approach to contemporary issues spawned from disturbance events and processes.

As is often the case, I suspect real life will unfold somewhere in the middle – we will be able to avoid a reactionary posture in some instances (no one likes to feel that they spend much of their time being buffeted by winds of change – seldom, if ever, a master of their own destiny), but for other circumstances, I'm sure we will be forced to set aside ongoing work and react to that year's megafire or insect outbreak.

But regardless of where we end up, it will always be important to keep our eyes up and focused on the future – plan for increased moisture deficits, more fire, more bark beetles, more change, and more 'disruption' to the status quo (depending on context).

And, we always need to remember that neither historical nor contemporary forests will be perfectly suited (sustainable) in the future – climate change is a game changer, and we need to treat it as such. Variability is key. Variability is our friend – we should count on it, and most importantly, any future project plans should account for it!

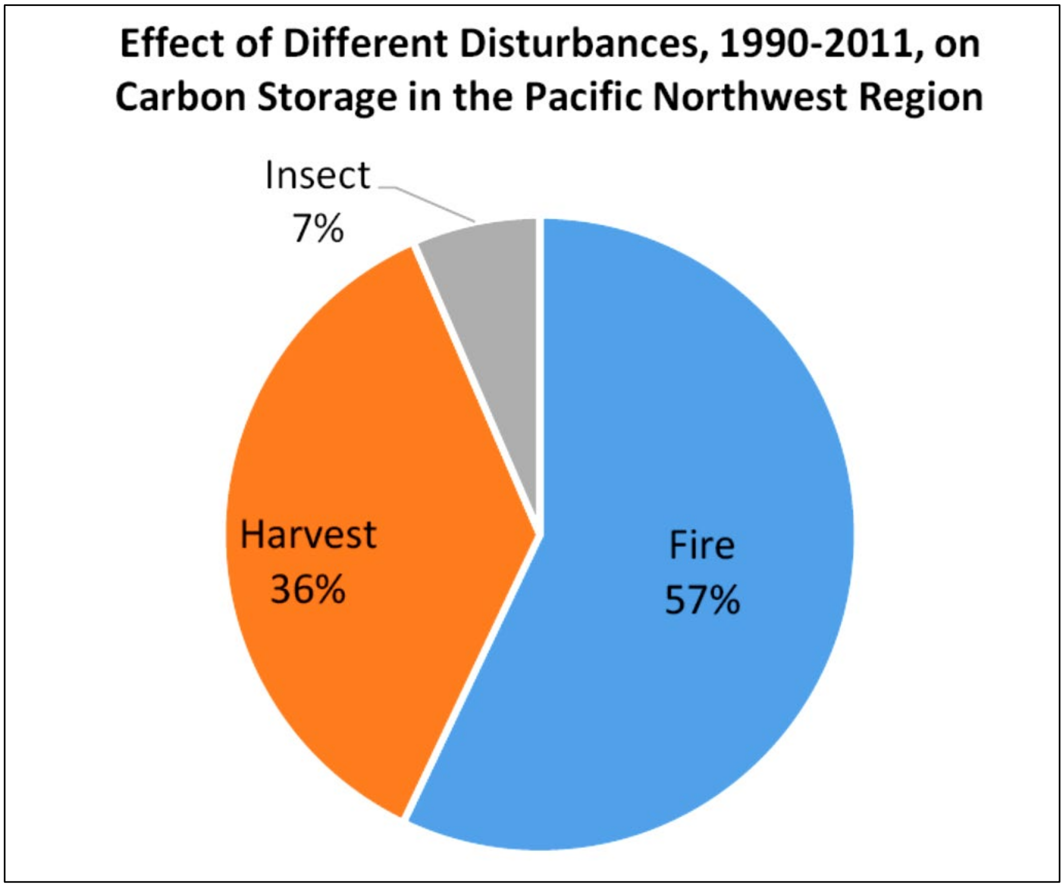

Figure 13 – Effect of three disturbance process categories on carbon storage for national forests of the Pacific Northwest Region (source: Birdsey et al. 2019, fig. 54 on p. 77 in that source). Some observers of public-land management still believe that timber harvest has the most effect on carbon storage for national forests of the Pacific Northwest Region, as it did in the late 1980s and early 1990s. But as this figure from a recent analysis shows, wildfire is now firmly established in the number 1 position (Birdsey et al. 2019).

APPENDIX 1: SITE SPECIFIC INFORMATION FOR CARBON ANALYSIS

Table 4 provides information related to a Forest Carbon Analysis for the South George planning area. It includes these items for each activity unit (all carbon values are in tons and expressed on a per-acre basis): (1) unit number; (2) live aboveground carbon (C) including live trees, stems, branches, and foliage; (3) live merchantable C pre-treatment, which includes the merchantable portion of live trees only; (4) live merchantable C post-treatment, showing C stocks remaining after treatment; (5) live belowground C including the roots of live trees; (6) dead belowground including the roots of dead and cut (harvested) trees; (7) dead standing including dead trees, stems, branches, and any foliage still present; (8) dead down including all woody surface material regardless of size; (9) forest floor including litter and duff; (10) herbs and shrubs; (11) total stand C pre-treatment, which includes the sum of these columns: 2, 5, 6, 7, 8, 9, 10; and (12) total stand C post-treatment, which was calculated this way: [col 2 – col 3] plus columns 4, 5, 6, 7, 8, 9, 10.

Table 4 – Site specific information pertaining to a Forest Carbon Analysis for silvicultural activities only (intermediate cutting, regeneration cutting); table values are in tons of carbon per acre by carbon pool (each column is a different C pool)

Unit	Live Above-ground	Live Mer-chantable: Pre	Live Mer-chantable: Post	Live Below-ground	Dead Below-ground	Dead Standing	Dead Down	Forest Floor	Herb Shrub	Total Stand Pre	Total Stand Post
1	71.2	45.0	15.3	15.2	1.2	4.7	10.7	10.6	0.1	113.7	84.0
4	33.7	21.2	15.2	7.2	0.3	0.8	4.6	4.1	0.4	51.2	45.1
6	53.5	32.9	14.6	11.5	1.3	5.1	8.4	5.1	0.2	85.1	66.7
9	62.8	36.4	5.4	13.5	2.9	22.9	12.8	10.9	0.1	126.0	95.0
10	24.8	14.2	9.5	5.3	0.4	2.5	4.5	2.0	0.2	39.7	34.9
11	24.8	14.2	5.5	5.3	0.4	2.5	4.5	2.0	0.2	39.7	31.0
12	59.5	37.2	4.5	12.8	1.0	3.5	9.5	10.1	0.1	96.4	63.8
13	26.1	12.3	7.5	5.7	0.7	2.8	8.8	10.0	0.1	54.3	49.5
14	60.0	37.1	14.1	12.9	2.9	11.8	10.7	10.6	0.1	109.0	86.0
15	72.0	41.5	19.1	15.5	2.0	19.9	12.7	11.1	0.1	133.4	110.9
16	73.4	45.9	7.0	15.7	1.6	5.6	8.5	10.4	0.1	115.3	76.4
17	19.5	11.7	8.8	4.2	0.2	0.7	3.7	3.3	0.5	32.2	29.4
18	41.3	26.7	6.3	8.9	0.7	2.0	9.1	10.1	0.1	72.2	51.9
19	31.9	17.6	9.0	7.0	0.8	2.7	7.1	2.9	0.2	52.5	43.9
20	73.2	44.4	21.3	15.7	1.5	6.3	10.6	10.8	0.1	118.2	95.1
21	70.3	43.7	15.2	15.1	1.9	14.5	11.6	10.7	0.1	124.2	95.7

Unit	Live Above-ground	Live Mer-chantable: Pre	Live Mer-chantable: Post	Live Below-ground	Dead Below-ground	Dead Standing	Dead Down	Forest Floor	Herb Shrub	Total Stand Pre	Total Stand Post
22	70.3	43.7	6.6	15.1	1.9	14.5	11.6	10.7	0.1	124.2	87.2
23	60.0	37.1	10.6	12.9	2.9	11.8	10.7	10.6	0.1	109.0	82.5
24	77.7	46.3	6.4	16.7	1.4	5.2	11.9	11.3	0.1	124.4	84.5
25	41.3	26.7	4.5	8.9	0.7	2.0	9.1	10.1	0.1	72.2	50.1
26	38.7	22.4	15.6	8.4	1.1	3.3	11.9	12.0	0.2	75.5	68.7
27	72.0	41.5	19.1	15.5	2.0	19.9	12.7	11.1	0.1	133.4	110.9
28	23.3	11.6	8.8	5.0	0.2	1.2	8.3	10.1	0.1	48.2	45.4
29	70.3	43.7	4.7	15.1	1.9	14.5	11.6	10.7	0.1	124.2	85.3
30	20.4	11.3	5.4	4.4	0.3	1.2	4.9	6.1	0.3	37.4	31.5
32	36.1	21.8	12.0	8.0	1.0	4.4	9.3	9.9	0.1	68.7	59.0
35	88.9	58.4	18.2	19.0	2.1	22.9	14.7	11.9	0.2	159.6	119.4
36	51.9	32.9	4.5	11.1	1.5	5.0	10.7	10.1	0.1	90.3	61.9
37	89.0	58.8	18.8	19.0	1.3	13.6	38.1	10.1	0.1	171.2	131.1
38	88.9	58.4	8.0	19.0	2.1	22.9	14.7	11.9	0.2	159.6	109.2
40	70.3	43.7	11.4	15.1	1.9	14.5	11.6	10.7	0.1	124.2	91.9
41	51.2	32.8	16.0	10.9	0.1	0.5	9.1	10.0	0.1	82.0	65.2
42	30.8	18.4	5.0	6.8	0.2	0.8	8.1	9.6	0.1	56.3	42.8
43	70.3	43.7	4.7	15.1	1.9	14.5	11.6	10.7	0.1	124.2	85.3
44	64.6	40.9	14.1	14.0	2.6	8.8	14.0	12.6	0.2	116.7	90.0
45	70.3	43.7	15.2	15.1	1.9	14.5	11.6	10.7	0.1	124.2	95.7
46	53.3	32.6	17.9	11.6	2.8	9.8	14.5	12.6	0.2	104.8	90.1
47	65.4	40.9	20.1	14.3	0.9	3.8	10.0	10.9	0.1	105.3	84.5
48	70.3	43.7	15.2	15.1	1.9	14.5	11.6	10.7	0.1	124.2	95.7
49	64.6	40.9	14.1	14.0	2.6	8.8	14.0	12.6	0.2	116.7	90.0
50	32.1	17.6	14.1	7.8	1.1	3.5	10.3	6.4	0.2	61.3	57.8
51	74.0	43.0	20.2	15.9	0.7	3.0	9.8	10.9	0.1	114.4	91.6
52	64.6	40.9	14.1	14.0	2.6	8.8	14.0	12.6	0.2	116.7	90.0

Unit	Live Above-ground	Live Mer-chantable: Pre	Live Mer-chantable: Post	Live Below-ground	Dead Below-ground	Dead Standing	Dead Down	Forest Floor	Herb Shrub	Total Stand Pre	Total Stand Post
53	67.4	42.3	10.9	14.5	2.2	7.3	10.7	10.7	0.1	113.0	81.6
54	82.3	51.5	16.2	17.6	1.0	4.3	10.0	10.6	0.1	125.9	90.6
55	67.4	42.3	14.5	14.5	2.2	7.3	10.7	10.7	0.1	113.0	85.2
58	70.3	43.7	15.2	15.1	1.9	14.5	11.6	10.7	0.1	124.2	95.7
59	70.3	43.7	15.2	15.1	1.9	14.5	11.6	10.7	0.1	124.2	95.7
60	82.3	51.5	16.2	17.6	1.0	4.3	10.0	10.6	0.1	125.9	90.6
61	72.0	41.5	5.6	15.5	2.0	19.9	12.7	11.1	0.1	133.4	97.4
62	51.4	32.8	4.5	11.0	0.8	3.6	8.1	9.7	0.1	84.7	56.4
63	65.4	40.9	20.1	14.3	0.9	3.8	10.0	10.9	0.1	105.3	84.5
64	36.1	21.8	12.0	8.0	1.0	4.4	9.3	9.9	0.1	68.7	59.0
65	72.0	41.5	19.1	15.5	2.0	19.9	12.7	11.1	0.1	133.4	110.9
68	51.4	32.8	14.5	11.0	0.8	3.6	8.1	9.7	0.1	84.7	66.4
69	89.0	58.8	31.2	19.0	1.3	13.6	38.1	10.1	0.1	171.2	143.6
71	7.3	1.4	0.8	1.6	0.0	0.0	1.7	1.3	0.2	12.1	11.5
72	73.4	45.9	15.9	15.7	1.6	5.6	8.5	10.4	0.1	115.3	85.3
73	32.1	19.9	10.6	6.9	0.3	1.1	2.9	2.2	0.4	45.9	36.6
74	51.4	32.8	6.3	11.0	0.8	3.6	8.1	9.7	0.1	84.7	58.2
75	51.4	32.8	6.3	11.0	0.8	3.6	8.1	9.7	0.1	84.7	58.2
76	35.3	21.7	12.6	8.2	1.1	5.9	11.2	9.6	0.2	71.5	62.4
77	62.8	36.4	5.4	13.5	2.9	22.9	12.8	10.9	0.1	126.0	95.0
78	74.0	43.0	20.2	15.9	0.7	3.0	9.8	10.9	0.1	114.4	91.6
79	62.8	36.4	18.6	13.5	2.9	22.9	12.8	10.9	0.1	126.0	108.2
81	73.2	44.4	21.3	15.7	1.5	6.3	10.6	10.8	0.1	118.2	95.1
82	82.3	51.5	16.2	17.6	1.0	4.3	10.0	10.6	0.1	125.9	90.6
84	38.3	24.2	5.5	8.7	1.2	4.6	7.8	9.8	0.1	70.6	52.0
85	38.1	25.1	11.0	8.2	0.4	1.5	3.8	2.3	0.2	54.5	40.4
87	62.8	36.4	18.6	13.5	2.9	22.9	12.8	10.9	0.1	126.0	108.2

Unit	Live Above-ground	Live Mer-chantable: Pre	Live Mer-chantable: Post	Live Below-ground	Dead Below-ground	Dead Standing	Dead Down	Forest Floor	Herb Shrub	Total Stand Pre	Total Stand Post
88	62.8	36.4	5.4	13.5	2.9	22.9	12.8	10.9	0.1	126.0	95.0
89	27.6	16.4	12.9	6.0	0.4	1.5	8.4	2.2	0.2	46.2	42.7
90	62.8	36.4	18.6	13.5	2.9	22.9	12.8	10.9	0.1	126.0	108.2
91	31.9	17.6	13.5	7.0	0.8	2.7	7.1	2.9	0.2	52.5	48.4
92	27.6	16.4	12.9	6.0	0.4	1.5	8.4	2.2	0.2	46.2	42.7
94	74.4	41.7	18.0	16.0	1.1	5.7	10.2	11.5	0.1	118.9	95.2
95	77.7	46.3	14.6	16.7	1.4	5.2	11.9	11.3	0.1	124.4	92.7
96	62.8	36.4	18.6	13.5	2.9	22.9	12.8	10.9	0.1	126.0	108.2
97	74.4	41.7	18.0	16.0	1.1	5.7	10.2	11.5	0.1	118.9	95.2
99	49.0	30.0	13.5	10.6	1.6	10.8	12.5	5.2	0.2	89.9	73.4
100	74.4	41.7	18.0	16.0	1.1	5.7	10.2	11.5	0.1	118.9	95.2
101	74.4	41.7	3.8	16.0	1.1	5.7	10.2	11.5	0.1	118.9	80.9
102	74.4	41.7	18.0	16.0	1.1	5.7	10.2	11.5	0.1	118.9	95.2
103	74.4	41.7	3.8	16.0	1.1	5.7	10.2	11.5	0.1	118.9	80.9
104	74.4	41.7	12.0	16.0	1.1	5.7	10.2	11.5	0.1	118.9	89.2
105	73.2	44.4	21.3	15.7	1.5	6.3	10.6	10.8	0.1	118.2	95.1
106	73.2	44.4	4.4	15.7	1.5	6.3	10.6	10.8	0.1	118.2	78.3
107	73.2	44.4	21.3	15.7	1.5	6.3	10.6	10.8	0.1	118.2	95.1
108	73.2	44.4	14.2	15.7	1.5	6.3	10.6	10.8	0.1	118.2	88.0
111	51.4	32.8	6.3	11.0	0.8	3.6	8.1	9.7	0.1	84.7	58.2
112	74.4	41.7	18.0	16.0	1.1	5.7	10.2	11.5	0.1	118.9	95.2
113	74.4	41.7	3.8	16.0	1.1	5.7	10.2	11.5	0.1	118.9	80.9
114	64.0	40.1	7.0	13.7	1.5	5.6	10.0	10.5	0.1	105.5	72.4
115	41.3	26.7	10.9	8.9	0.7	2.0	9.1	10.1	0.1	72.2	56.4
116	60.0	37.1	4.4	12.9	2.9	11.8	10.7	10.6	0.1	109.0	76.3
119	41.3	26.7	14.5	8.9	0.7	2.0	9.1	10.1	0.1	72.2	60.1
120	60.0	37.1	14.1	12.9	2.9	11.8	10.7	10.6	0.1	109.0	86.0

Unit	Live Above-ground	Live Mer-chantable: Pre	Live Mer-chantable: Post	Live Below-ground	Dead Below-ground	Dead Standing	Dead Down	Forest Floor	Herb Shrub	Total Stand Pre	Total Stand Post
121	64.0	40.1	16.0	13.7	1.5	5.6	10.0	10.5	0.1	105.5	81.3
122	22.6	13.4	3.7	4.9	0.3	1.0	6.2	7.7	0.2	42.8	33.1
123	71.2	45.0	15.3	15.2	1.2	4.7	10.7	10.6	0.1	113.7	84.0
124	19.7	11.6	5.1	4.2	0.2	0.7	3.6	3.3	0.5	32.2	25.7

Sources/Notes: Information in this table was derived from Carbon Report output provided by Forest Vegetation Simulator (Dixon 2015). Carbon accounting considered silvicultural activities only (regeneration cutting – two methods, and intermediate cutting – two methods); no attempt was made to account for carbon implications of activity-fuel treatments such as broadcast burning or hand piling and burning. Post-treatment C stocks from this table are portrayed visually in figure 8 and compared with a dynamic equilibrium (baseline) level approximating historical C loading.

CLIMATE CHANGE/CARBON REFERENCES AND LITERATURE CITED

This section provides more than 1,000 references, consisting of literature citations for the text, and additional references dealing with climate change and carbon management.

The number of published climate change research items is enormous and growing exponentially. Climate-change references provided here constitute just a small percentage of what is available; they were taken from the Umatilla National Forest silviculture library and are viewed as being somewhat relevant for northeastern Oregon and southeastern Washington.

With few exceptions, sources contained in this References section are available from the World Wide Web in digital form, and a digital object identifier (doi) is included for these items whenever possible. [Digital object identifier is an international system used to uniquely identify, and link to, electronic versions of scientific information, primarily journal articles.]

All doi links pertain to formally published sources only; local analysis protocols, monitoring reports, and similar items will not have a doi.

For recent USDA Forest Service research products (general technical reports, research papers, research notes, conference proceedings, etc.), a doi is also available (but it is not generally provided in this section). For FS research items, however, this References section provides a weblink source for the online Treesearch system, because most FS research reports are available for download there.

Because the US Forest Service emphasizes using Best Available Science (BAS), and because there is so much climate-change research available for both national and international settings, and because it is unreasonable to expect each resource specialist to review a vast body of climate-change work to identify BAS themselves, it would be helpful to have a work-group identify BAS specifically for the Blue Mountains or eastern Oregon geographical areas, and by resource area (e.g., forest vegetation, fire/fuels, terrestrial wildlife, fisheries, etc.).

Much of the locally relevant climate-change BAS for the Blue Mountains region is included in a vulnerability and adaptation assessment edited by Jessica Halofsky and David Peterson; it was published as a general technical report by the Pacific Northwest Research Station (Halofsky and Peterson 2017).

Chapters from the Blue Mountains vulnerability and adaptation assessment (Halofsky and Peterson 2017) were used as the basis for a series of journal papers published in the journal Climate Services (Clifton et al. 2018, Dwire et al. 2018, Halofsky et al. 2018, Hartter et al. 2018, Kerns et al. 2018, Kim et al. 2018, and Peterson and Halofsky 2018).

When preparing a white paper, one of my objectives is to help users locate any of its references or literature citations. For journal articles or books, I provide a doi or isbn number whenever one is available. For other reference materials, a weblink is generally provided, although I realize that weblinks have not been stable (USDA Forest Service Treesearch links, however, have been quite stable thus far).

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APPENDIX 2: 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. Ex-

amples 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

Paper #	Title
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
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

December 2011: this white paper began as appendix D in a silviculture specialist report (forest vegetation) for South George Vegetation Management Project, Pomeroy Ranger District, Umatilla National Forest.

May 2013: 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.

March 2017: formatting and editing changes were made throughout the document. Much additional literature was added, along with a background/context section.

December 2018: quite a bit of additional climate change and carbon literature was added, mostly derived from the 4th National Climate Assessment (volume I was released in 2017; volume II was released in November 2018).