Section 2—Forest Ecology

This section builds upon recent synthesis reports by focusing on four topics: (1) how to regenerate shade-intolerant pine trees; (2) strategies for managing red fir forests, which are likely to be greatly affected by climate change; (3) how to design forest treatments to facilitate heterogeneous fire outcomes; and (4) strategies to promote long-term carbon storage in fire-prone forests. All these topics are important in designing strategies to promote forests that will be resilient to climate change, wildfires, and other stressors.

Malcom North

Regeneration underneath large sugar pines is shifting to shade-tolerant white fir as a result of fire suppression and closing of the forest canopy.

Chapter 2.1—Forest Ecology

Malcolm North[1]

Summary

Building on information summaries in two previous general technical reports (PSW-GTR-220 and PSW-GTR-237), this chapter focuses on four topics raised by forest managers and stakeholders as relevant to current forest management issues. Recent studies suggest that the gap size in lower and mid-elevation historical forests with active fire regimes was often about 0.12 to 0.32 ha (0.3 to 0.8 ac). This small size was sufficient to facilitate shade-intolerant pine regeneration, probably because the surrounding forest canopy was more open than is common in modern fire-suppressed forests. Treatments that create these regeneration gaps may not significantly reduce canopy cover (a stand-level average), but they will create greater variability in canopy closure (a point-level measure), which may also increase habitat heterogeneity. A review of red fir forest literature suggests that these forests historically had a highly variable fire regime. Red fir in drier conditions and in locations well connected to forests with more frequent fire regimes probably had a shorter fire return interval. These forests may need treatment with managed fire or mechanical thinning to help restore their resilience to fire and potential climate change. In another section, this chapter examines how current constraints on prescribed fire use may decrease the variable burn conditions that increase heterogeneity in postburn forests. Fire management officers may consider intentionally varying fuel loads within a stand in an effort to increase burn effect variability. The next section examines the role of fire-dependent forests as potential carbon sinks to offset anthropogenic emissions of carbon dioxide (CO_2). Forest treatments may reduce wildfire emissions if a treated forest burns. However, many fuels treatments are likely to be a net carbon loss, as the probability of any particular treated stand burning is low, and treatments require continuing maintenance. Where treatments may have a net carbon gain is if they can change the current equilibrium between growth and mortality. Treatments that shift tree composition toward pine may accomplish this. A final section discusses how longer timeframes and larger spatial scales may help inform and explain how management decisions are made in the context of the larger landscape and long-term objectives.

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Introduction

Two U.S. Department of Agriculture Forest Service general technical reports, PSW-GTR-220 (North et al. 2009b) and PSW-GTR-237 (North 2012a), summarize some of the recent research in forest ecology relevant to a synthesis of science for the Sierra Nevada region. GTR-237 builds on concepts in GTR-220, providing new, more indepth information on topics of "Forest Health and Bark Beetles" (Fettig 2012), "Climate Change and the Relevance of Historical Forest Conditions" (Safford et al. 2012a), "Marking and Assessing Stand Heterogeneity" (North and Sherlock 2012), "GIS Landscape Analysis Using GTR 220 Concepts" (North et al. 2012a), and "Clarifying [GTR 220] Concepts" (North and Stine 2012). The final chapter in GTR-237, "A Desired Future Condition for Sierra Nevada Forests" (North 2012b), highlights three topics (the limitations of stand-level averages, economics and treatment scale, and monitoring) where ecological research suggests a need for fundamental changes in how the Forest Service approaches ecosystem management.

Building on these GTRs, this "Forest Ecology" chapter has a different structure than the other chapters. It is focused on four subjects for which stakeholders and managers have suggested that a summary of existing information would be relevant to a regional science synthesis: tree regeneration and canopy cover, red fir (*Abies magnifica*) forests, forest treatments to facilitate fire heterogeneity, and carbon management in fire-prone forests. These four sections do not attempt to summarize and cite all literature relevant to each section. Rather, each section begins with one or two questions that motivated the subject's inclusion in this synthesis. These questions provide the framework for how the relevant literature is selected and summarized. The chapter ends with a sidebar that gives an example of how larger scales may be incorporated into meeting forest management objectives.

To increase resilience in frequent-fire forests to a warming climate and wildfire, and to restore ecosystem functions, conifer regeneration across much of the Sierra Nevada needs to favor fire-tolerant pines.

Tree Regeneration and Canopy Cover

Within the last decade, there has been substantial new research on the light requirements and gap conditions associated with favoring shade-intolerant, fire-tolerant pines. Although forest managers have long known that high-light environments are needed to favor pines, creating these gaps has sometimes been seen as conflicting with canopy cover targets suggested in the current standards and guides.

- What gap size and light conditions are needed to favor pine establishment and growth over shade-tolerant firs and incense cedar?
- Do open conditions created in these gaps reduce canopy cover below threshold guidelines?

To increase resilience in frequent-fire forests to a warming climate and wildfire, and to restore ecosystem functions, conifer regeneration across much of the Sierra Nevada needs to favor fire-tolerant pines. Sugar (*Pinus lambertiana*), Jeffrey (*P. jeffreyi*), and ponderosa (*P. ponderosa*) pine are all shade intolerant and require high-light environments to survive, and they grow more rapidly than fire-sensitive, shade-tolerant species such as white fir (*Abies concolor*) and red fir. Two species, incense cedar (*Calocedrus decurrens*) and Douglas-fir (*Pseudotsuga menziesii*), are considered shade tolerant in the central and southern Sierra Nevada, but in the northern Sierra Nevada, southern Cascade Range, and Klamath Mountains, they are sometimes able to survive and thrive in high-light environments if there is sufficient precipitation. Studies have shown that firs and incense cedars can produce 20 to 30 times the amount of seed per unit basal area as many pine species (Gray et al. 2005, Zald et al. 2008). Even fuels reduction and forest restoration treatments that favor pine retention in mixed-conifer forests often retain enough large fir and incense cedar seed trees to perpetuate pretreatment composition (Zald et al. 2008). Fire suppression, which has increased canopy cover and reduced understory light, has been in effect long enough that many shade-tolerant species are now large enough to survive low-intensity fire (Collins et al. 2011, Lydersen and North 2012, Miller and Urban 2000). Moderate-severity fire or mechanical thinning may be needed to sufficiently open the canopy. Repeated applications of low-intensity fire may also eventually shift tree regeneration and sapling composition toward pine, but at present, few forests burn with sufficient frequency to affect this compositional shift. In the absence of frequent fire, reducing canopy cover and planting pine seedlings may be the most effective means of overcoming the entrenched effects of fire suppression, which favor shade-tolerant, fire-sensitive regeneration.

Recent work has examined what understory light level is needed to favor pine regeneration over fir and incense cedar (Bigelow et al. 2011; York et al. 2003, 2004). These studies suggest that in many forests, a minimum opening of 0.10 ha (0.25 ac) is needed to provide enough light (40 percent of full sunlight) to support pine regeneration within part of the opening. As gap size increases, so does the area with a high-light environment favoring pine, and the growth rate of the gap's pine seedlings (McDonald and Phillips 1999, York et al. 2004, Zald et al. 2008). A similar response occurs in smaller gaps when canopy cover is reduced on the southern side of a gap ("feathering the edge"). This may explain why pre-fire-suppression gap sizes appear to have been relatively small (0.12 to 0.32 ha [0.3 to 0.8 ac]) (Knapp et al. 2012), yet most of these stands likely supported robust pine regeneration, because reconstruction studies and old data suggest pine often contributed >40 percent of mixed-conifer basal area (McKelvey and Johnson 1992). A

Figure 1—White fir regenerating under an overstory dominated by pines owing to high levels of canopy cover from fire suppression at the Teakettle Experimental Forest.

recent study found that small gaps (0.04 ha [0.1 ac]) created in pile and burn treatments significantly increased stand-level light heterogeneity; that study also found greater ponderosa pine germination on ash substrates produced by the pile burns compared with bare soil (York et al. 2012). At the Beaver Creek Pinery, a ponderosa pine forest with a modern history of low-intensity burns, Taylor (2010) found a small average gap size of 0.06 ha (0.14 ac) with high variability (range 0.008 to 0.24 ha [0.02 to 0.6 ac]), suggesting that small gaps may be sufficient for shade-intolerant regeneration if the forest matrix surrounding the gap has a low density and low canopy cover.

Outside of gaps, Bigelow et al. (2011) found that thinning the forest matrix to a canopy cover of 40 percent provided sufficient light to support pine regeneration in about 20 percent of the treated area. In a recent study of old-growth mixed-conifer stands with restored fire regimes (Lydersen and North 2012), canopy cover averaged 44 percent, which supported a regeneration composition consistent with overstory composition (about 50 percent pine). These low estimates of canopy cover may seem at odds with the goal of providing habitat sufficient for some species designated as sensitive by the Forest Service, such as fisher (*Pekania pennanti*) and California spotted owl (*Strix occidentalis occidentalis*). However, canopy cover is a stand-level average of canopy conditions. In heterogeneous forests composed of tree groups, gaps, and a low-density matrix (Larson and Churchill 2012, North et al. 2009b), most of the gaps and some of the matrix will likely have low canopy closure (i.e., the percentage of the sky hemisphere covered with foliage when viewed from a single point [Jennings et al. 1999]). In contrast, canopy closure in tree clusters often exceeds 65 percent. Distinguishing between stand-level average measures of vertical porosity (canopy cover) and point-level measures of how much of the sky hemisphere is blocked by foliage (canopy closure) can improve assessments of canopy conditions (North and Stine 2012).

Point measures of canopy closure are probably best for assessing how much “protection” and foliage cover there is over a patch or microsite. Spherical densiometers are often used to assess canopy conditions in the field. Practitioners should understand that densiometers do not measure canopy cover. Instead, they are designed to measure canopy closure (a large viewing angle represented by an inverted cone) over the point from which the readings are taken (Nuttle 1997). Of several methods available, closure is probably most effectively measured with a digitized hemispherical photograph that is analyzed with computer software. In contrast, canopy cover is probably most effectively measured with a siting tube or densitometer, which records whether, within a narrow view window approaching a point, the observer can or cannot see the sky. Multiple readings (often 100 or more) are taken throughout the stand of interest and the percentage of readings where the sky is obscured is recorded as canopy cover. Canopy cover, however, is often indirectly estimated from plot data using the Forest Vegetation Simulator (FVS). Managers should be aware that these estimates are based on an assumption about how trees are distributed that does not account for actual conditions in the stand that is being modeled. If managers want to increase fine-scale heterogeneity, variability in canopy closure may provide a better assessment of conditions than canopy cover, which is a stand-level average. North and Sherlock (2012) suggest using both to provide estimates of stand-level conditions and within-stand or patch conditions.

With high within-stand variability in canopy closure, openings can be produced that favor pine regeneration and still attain a stand-level average of canopy cover high enough to meet canopy cover targets.

Distinguishing between canopy cover and closure may help resolve one problem often faced by foresters: how to provide high-light environments that favor pine regeneration and also meet canopy cover targets for Forest Service sensitive species. With high within-stand variability in canopy closure, openings can be produced that favor pine regeneration and still attain a stand-level average of canopy cover high enough to meet canopy cover targets. Further discussion of this distinction and a figure illustrating the differences can be found in North and Stine (2012).

Red Fir Forests

Forest management in the Sierra Nevada has often focused more of its attention on forest types that historically had a frequent, low-intensity fire regime. With fire regimes now having been altered for over a century, some managers and stakeholders have asked whether red fir, generally the next higher forest type in elevation above mixed conifer, should receive more active management. In particular, there is interest in understanding whether these forests need fire or mechanical treatment to help restore ecosystem conditions and increase resilience to a changing climate.

- What was red fir's historical fire regime and how did it vary with site conditions?
- Is gap creation needed to facilitate red fir regeneration and development of younger tree cohorts?

According to a Gap Analysis Program (GAP) of forest types and ownerships in the Sierra Nevada, red fir forests are the fourth most extensive forest type. These forests cover 339 493 ha (838 905 ac) in the Sierra Nevada (or about 11 percent of the region's 3.2 million ha), of which 207 091 ha (511 732 ac) are on Forest Service land (Davis and Stoms 1996) (table 1). It is the largest forest type in the upper montane zone (above 1830 to 2286 m [6,000 to 7,500 ft] in elevation from the northern to southern Sierra Nevada, respectively), and it is often "passively" managed (i.e., rarely receives active management treatments, such as mechanical thinning, planting, or prescribed fire), because it is remote, in wilderness designation, or less of a fire danger to structures and humans. These forests are important habitat for many species, including the Pacific marten (*Martes caurina*) (see discussion in chapter 7.1, "The Forest Carnivores: Marten and Fisher"), and they occupy the elevation zone with greatest snowpack depth (Laacke 1990). As

Table 1—Forest type, total area, fractional Forest Service ownership, historical fire return interval (HFRI), and estimated historical amount of area burned each year in the Sierra Nevada before fire suppression on Forest Service lands

Forest type	Total area	Forest Service ownership	Forest Service area	HFRI mean	Historical burn
	Hectares (acres)	*Percent*	*Hectares (acres)*	*Years*	*Hectares/year (acres/year)*
Mixed-conifer	593 (1,467)	62	368 (909)	12	31 (76)
West-side ponderosa pine	440 (1,087)	53	233 (576)	5	47 (115)
Lower cismontane mixed conifer–oak	423 (1,046)	46	195 (481)	10	19 (48)
Jeffrey pine–fir	296 (730)	80	236 (584)	8	30 (73)
Jeffrey pine	196 (484)	75	147 (363)	6	25 (61)
East-side ponderosa pine	161 (399)	76	123 (303)	5	25 (61)
Black oak	109 (269)	60	65 (161)	10	7 (16)
White fir	54 (133)	70	38 (93)	25	2 (4)
Aspen	10 (24)	89	9 (22)	30	0.3 (0.7)
Sequoia–mixed conifer	7 (18)	31	2 (5)	15	0.1 (0.4)
Active management total	2290 (5,658)		1416 (3,499)		184 (454)
Red fir	339 (839)	61	207 (512)	40	5 (13)
Lodgepole pine	216 (533)	60	129 (320)	30	4 (11)
Red fir-western white pine	159 (394)	75	120 (295)	50	2 (6)
White bark pine–mountain hemlock	38 (93)	62	23 (58)	85	0.3 (0.7)
White bark pine–lodgepole pine	37 (92)	86	32 (79)	40	0.8 (2)
Upper cismontane mixed conifer–oak	26 (64)	48	13 (31)	15	(0.8) (2)
Foxtail pine	24 (59)	21	5 (12)	50	0.1 (0.25)
Whitebark pine	22 (54)	68	15 (37)	65	0.2 (0.6)
Passive management total	861 (2,128)		544 (1,344)		14 (35)
All lands total	3151 (7,786)		1960 (4,843)		198 (489)

Hectare and acre values are in thousands and rounded from the original source. Historical fire return interval was determined from three sources with extensive literature reviews of many fire history studies: Stephens et al. 2007, van de Water and Safford 2011, and the fire effects information database (http://www.fs.fed.us/database/feis/plants/tree/). The extent of the Sierra Nevada is the Jepson (Hickman 1993) definition, which generally corresponds to the Plumas National Forest south through the Sequoia National Forest including the Inyo National Forest. The table is adapted and updated from North et al. (2012b). Forest type, total area, and fractional ownership are from Davis and Stoms (1996).

a result, they may be significantly affected by climate change, as most models suggest that precipitation may often turn from snow to rain in much of this zone in the future (Safford et al. 2012a). It is unclear how this will affect red fir forests. Climate change may become a chronic stress in red fir forests in the lower parts of its present distribution, but the exact mechanisms of this stress and its potential influence on ecosystem processes are unknown. Historically, there was some timber harvested in red fir forests in the 1970s and 1980s (Laacke 1990), but with increased designation of roadless areas and public controversy, there has been much less active management in many red fir forests since the 1990s. The concern with red fir is what type of management would best maintain or restore its ecosystem processes given a century of altered fire frequency and uncertain but probable future climate warming.

Management concepts in GTR-220 are applicable to forests that historically had frequent, low-intensity fire regimes. The historical fire regime in red fir is not as well defined as it is in lower elevation forest types, such as ponderosa pine and mixed conifer, and it has often been classed as mixed severity (Parker 1984, Skinner 2003, Sugihara et al. 2006). A recent review paper of all fire history studies on dominant woody species in California for different forest types lists 29 studies with some information on red fir fire return intervals (van de Water and Safford 2011). The review paper reports mean, median, minimum mean, and maximum mean fire return intervals of 40, 33, 15, and 130 years, respectively. Using a 40-year historical fire return interval, approximately 5177 ha (12,793 ac) of red fir may have burned each year before fire suppression (about 2.3 percent of the historical annual burn acreage for all forest types) (table 1). Many of the red fir fire history studies, like those at lower elevations, found few if any fires in their sample area in recent decades, which suggests that some red fir forests have now missed more than one fire return interval (Stephens 2001).

A review of these studies suggests a wide range of fire regimes, possibly because many of the studies examine stands in which red fir is mixed with other species. Red fir is often found across a broad elevation band from mixed conifer (generally 1372 to 2286 m [4,500 to 7,500 ft]) to western white pine (*Pinus monticola*) (generally 2591 to 3200 m [8,500 to 10,500 ft]) forest types. Studies at lower elevations, where the tree species composition suggests drier site conditions, have generally found shorter historical fire return intervals and age structures that suggest frequent pulses of regeneration. In contrast, higher elevation and more mesic site studies often document a mixed-severity fire regime with distinct recruitment pulses following fire events (Scholl and Taylor 2006, Taylor 2004). One study documented a strong linear relationship between fire return interval and elevation, possibly driven by snowpack and its effect on fuel moistures (Bekker and Taylor 2001). Another factor may be landscape context. Red fir forests that are well connected with lower elevation forest may have shorter intervals because fire could easily carry up into higher elevations under suitable weather and fuel moisture conditions (Skinner 2003). In contrast, some red fir forests grow in shallow “flower pot” pockets surrounded by extensive exposed granite. These red fir forests likely had longer intervals because of their relative isolation.

Analysis of fire patterns in red fir indicates that high-severity patches often occur (Pitcher 1987, Stephens 2000). A recent paper analyzing fire-severity patterns between Yosemite National Park and adjacent national forest lands found that wildfires in red fir forests in Yosemite averaged 7.1 percent high severity and burned at significantly lower severity than wildfires on Forest Service lands on the east and west sides of the Sierra Nevada crest (16.3 and 12.1 percent, respectively) (Miller et al. 2012). Given Yosemite's more extensive use of fire for resource benefit, Miller et al. (2012) suggested that the park's levels of high-severity fire may more closely mimic the area's historical fire regime. Another study in upper montane mixed-conifer and red fir forests with a restored fire regime in Illilouette Basin (Collins and Stephens 2010) found higher levels (about 15 percent) of high severity. This paper also analyzed high-severity patch size, finding that most patches in that area were small (<4 ha [10 ac]), but about 5 percent of the total number of patches were large (61 to 93 ha [150 to 230 ac]). High-severity patches larger than the upper bounds of this range may be uncharacteristic of historical fire patterns. If fire burns at high intensity in red fir, larger patches can switch to montane shrub fields. This switch may persist for decades, as shrubs inhibit tree regeneration, slow their


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Figure 2—Red fir regenerating after a mixed-severity fire in the Illilouette Basin of Yosemite National Park.

Where feasible, fire restoration would benefit red fir ecosystems.

With a mixed-severity fire regime, higher fuel loads may still be acceptable under moderate weather conditions because some torching and large tree mortality may be a desired outcome.

growth, and facilitate postfire, small-tree mortality that favors shrub resprouting and dominance (Nagel and Taylor 2005).

Collectively, the research suggests two considerations for managing red fir forests. First, where feasible, fire restoration would benefit red fir ecosystems (Skinner 2003). For some remote areas, this may mean designation as managed wildfire areas or include the application of prescribed fire. Fire history studies suggest that many stands have "missed" one to three burn events and, consequently, are likely to have increased fuel loading, higher stem densities, and less light in the understory (Taylor 2000). These changes have also reduced shrub cover, and the habitat that shrubs provide, to the low levels noted in some red fir studies (North et al. 2002, Selter et al. 1986). Fuel loads will need to be evaluated on a site-by-site basis (McColl and Powers 2003). With a mixed-severity fire regime, however, higher fuel loads may still be acceptable under moderate weather conditions, because some torching and large tree mortality may be a desired outcome. Fire appears to be the most effective means of ensuring natural red fir regeneration.

Second, in drier, lower elevation red fir forests, and in productive stands connected to lower elevation forests with frequent fire regimes, some fuels reduction may be needed to reduce risks to structures and people (Zhang and Oliver 2006). Initial treatments in these areas could focus on surface fuels reduction and removal of some smaller trees. Canopy openings do not appear to be required for successful regeneration as long as canopy cover is low enough to allow sun flecking, which is associated with increased seedling survival (Ustin et al. 1984). Red fir is shade tolerant, so seedlings and saplings can persist in stands with high canopy cover (Barbour et al. 1998, Selter et al. 1986). Studies suggest, however, that recruitment and establishment are often linked to disturbance, particularly fire (Taylor 1993, Taylor and Halpern 1991, Taylor and Solem 2001).

Experimentation with mechanical treatments that create small openings (i.e., 0.04 to 0.2 ha [0.1 to 0.5 ac]) may be needed later as seedlings grow. Some evidence suggests that rates of sapling survival and growth are higher in areas where mixed-severity fire has killed overstory trees (Chappell and Agee 1996, Pitcher 1987). Long-term regeneration studies have found abundant natural seedling and successful red fir establishment in canopy openings created by mechanical thinning (Gordon 1970, 1973a, 1973b, 1979).

Forest Treatments to Facilitate Fire Affects Heterogeneity

Fire restoration in the Sierra Nevada is difficult owing to many constraints including enforcement of air quality regulations, liability and safety concerns, and increased rural home construction (North et al. 2012b). Some fire managers and scientists have questioned whether prescribed fire constraints limit their intended ecological benefits, and in particular whether there is sufficient heterogeneity in intensity and severity.

- Given current limitations, how can prescribed fire be applied with different intensities to create forest structural heterogeneity, a common goal in forest restoration?

Recent ecosystem management approaches that emphasize increasing forest structural heterogeneity largely focused on mechanical treatments while stressing the benefits of reintroducing fire where possible (North 2012a, North et al. 2009b). Prescribed fire, however, can often be used only under certain weather and fuel moisture conditions during a limited "burn window" allowed by air quality regulators. These constraints reduce fire effects variability because burns must often be quickly executed, which reduces the heterogeneity produced by slower moving burns that tend to be patchier. Furthermore, when fire has been absent for several decades, dense stands of young trees may not be killed by rapid, low-intensity prescribed fire, and structural homogeneity within the stand may be retained (Miller and Urban 2000). In contrast, accounts of historical fires and managed wildfires (often in wilderness) suggest that under less constrained conditions, fires burned for a long time and at different intensities, depending on changes in fuel and weather conditions (Nesmith et al. 2011). This variability likely created greater microclimate and habitat heterogeneity in the postburn forest, producing bare mineral soil areas where fire burned at high intensity and other areas missed by fire that could provide refugia for tree saplings and some fire-sensitive understory plant species (Wayman and North 2007). With prescribed fire, this variability is often markedly reduced owing to the constrained conditions of where and when fire can now be used.

In stands with constrained burn windows, forest managers might consider varying fuel conditions within treatment areas to help prescribed burning produce variable fire effects. In general, fuels treatments have been focused on removing ladder and surface fuels to facilitate fire containment, suppression, and reduced mortality of overstory trees (Reinhardt et al. 2008). When prescribed fire is allowed to burn for only a brief period, or when fuels have relatively similar moisture contents, creating surface and ladder fuel heterogeneity may help achieve some

In stands with constrained burn windows, forest managers might consider varying fuel conditions within treatment areas to help prescribed burning produce variable fire effects.

of the variable fire effects that would have been produced under less constrained conditions. Studies suggest that surface fuel input rates and higher stem density associated with ladder fuels vary with site productivity (Taylor and Skinner 2003, van Wagtendonk and Moore 2010, van Wagtendonk et al. 1998). To create variable fuel conditions, managers might use small changes in productivity to guide spatial variation. In many mixed-conifer forests, productivity is often associated with available moisture. Higher surface fuel loads and some ladder fuels might be left in more mesic microsites and more extensively removed in more xeric conditions, such as ridge tops and areas with shallow soils. Metrics for evaluating prescribed fire effectiveness may also need to be adjusted. Desirable outcomes when creating variable fire effects will include limited areas of torching and some ground that has not been blackened. Safford et al. (2012b) recommend that prescribed burn projects plan for 5- to 15-percent overstory mortality. In mixed conifers, topography will naturally increase variability in fire effects, but given the time, weather, and fuel conditions, and the constraints associated with current prescribed fire policy, manipulations of fuel heterogeneity may be needed in some areas to produce the variable postburn conditions likely created by historical fire regimes.

Carbon Management in Fire-Prone Forests

Forests store large amounts of carbon and through growth can become carbon sinks to offset anthropogenic emissions of CO_2. Wildfires release carbon back to the atmosphere, and the amount of release increases with fire severity. Fuels treatments can, in the event of a wildfire, reduce fire severity and consequent carbon release, but they come at a "cost," because in the near-term they also reduce forest carbon stores.

- Do young, fast-growing trees that are harvested for wood products provide greater long-term carbon storage than growing and retaining large, old trees?
- What are the carbon costs and benefits of fuels reduction in fire-prone forests?

Through growth and the long-lived nature of many trees, forests sequester carbon from the atmosphere. Recent state policy and political attention has been focused on the potential to mitigate the effects of climate change through forest management. The most ready means of increasing forest carbon stores is through afforestation and reforestation of forest lands converted to other uses (i.e., agriculture, pasture, etc.) (IPCC 2005). Although developing countries often reduce their carbon stores as forest land is converted to other uses, forests in the United States have been a net carbon sink in the last century because of forest regrowth (particularly in the upper Midwest and New England) and, in some cases (see discussion below), fire suppression (Hurtt et al. 2002). For much of the United States, where forest land cover is now relatively stable, the question has been whether different management practices could stabilize or increase the amount of carbon storage that forests presently contain.

In the past, some groups have suggested that converting old forests to young, fast-growing plantations, where harvested wood products could store carbon for several decades, would create a net increase in long-term carbon stocks. This approach was based on the idea that old forests are slow growing and carbon neutral because respiration costs nearly balance carbon uptake (Odum 1969). More recent research generally does not support this idea, as a global survey of old forests found that many continue to sequester carbon and have stocks that far exceed young, managed forests (Luyssaert et al. 2008). In addition, there is some evidence (Sillett et al. 2010) that large trees may contain even more carbon than our current estimates predict. This is because a tree's carbon storage is estimated from its diameter, and, unlike younger trees upon which most carbon allometric equations are based, old trees may be allocating most of their growth to the upper bole (Sillett et al. 2010).

If young forest stocks could be efficiently harvested and their carbon sequestered in wood products for centuries, after several rotations they might match carbon stores in old forests dominated by large trees. However, this would be difficult with current wood use practices. The problem is not with the immediate carbon expense from machinery, because generally the amount of carbon loss from fossil fuel used in the forest operations (i.e., diesel and gasoline) is quite small (often <5 percent) compared with the carbon captured in the harvested forest biomass (Finkral and Evans 2008, North et al. 2009a). The problem is that the carbon is not stored for long and often ends up, through decomposition, back in the atmosphere. A recent global analysis of the longevity of harvested forest carbon found that after 30 years, in most countries (90 of 169), less than 5 percent of the carbon still remained in longer storage, such as wood products and landfills (Earles et al. 2012). Most temperate forest countries with longer-lived products, such as wood panels and lumber, had higher carbon storage rates, with Europe, Canada, and the United States averaging 36 percent of the forest carbon still stored after 30 years (Earles et al. 2012). This higher rate, however, is still far short of what large long-lived trees would continue to accumulate and store over several decades to centuries.

In fire-prone forests, there has been substantial debate about whether carbon loss through fuels treatment (mechanical thinning or prescribed fire) is offset by lower carbon emissions if the treated stand is later burned by wildfire (Campbell et al. 2012, Hurteau and North 2009, Hurteau et al. 2008, Mitchell et al. 2009, North and Hurteau 2011). Different results from these studies and others are in part due

Box 2.1-1

Forest Management at Landscape Scales

Most forest ecology research has been concentrated on small spatial and temporal scales that are not always relevant to managing forest landscapes over the long term. What research has occurred at broader scales is often context-specific, providing case studies of particular landscapes and species. Although there are many relevant modeling studies, it is difficult to find empirical landscape-scale, long-term ecological research that is directly relevant to current management issues in the Sierra Nevada. In practice, it is often local managers who must make these decisions and must balance where and when to maintain current conditions versus treating forests to move toward a desired condition decades in the future. An example may help illustrate how different scales are often considered and how a stand's context might affect management decisions.

A manager might be faced with the choice of whether to thin around a large black oak (*Quercus kelloggii*) that is being overtopped by surrounding conifers. If thinning sufficiently opens up the canopy, the oak will likely survive and may produce acorns that could thrive in the high-light environment. If left alone, the oak will likely die within a few years, but even so, the tree can provide valuable resting and nesting habitat for sensitive species in the near future (as both a near-dead tree and, later, as a snag). Any manager faced with this decision will have to weigh current and future needs for habitat and oak regeneration, both locally and across the landscape in which the stand is embedded. The context of the forest's current condition forces consideration of landscape scales. For example, how rare are sensitive species habitats and large oaks within the broader landscape, and how rare will they be in the future? How resilient will a large oak be to prolonged drought under different levels of stem density? There is no clear resolution to this situation. Communicating what the tradeoffs are and how decisions will be made may help stakeholders understand the effort to incorporate broader spatial and temporal scales into current, stand-level management decisions.

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Figure 3—Large legacy black oak used by a fisher for a rest site. The tree is surrounded and overtopped by ingrowth resulting from fire suppression.

to the spatial and temporal scale over which the carbon accounting is assessed, the "fate" of the carbon removed in the fuels treatment, and whether long-term carbon emissions from dead trees are included (Hurteau and Brooks 2011). In general, treating forests often results in a net carbon loss owing to the low probability of wildfire actually burning the treated area, the modest reduction in wildfire combustion and carbon emissions, and the need to maintain fuels reduction through periodic additional carbon removal (Campbell et al. 2012). Over the long term (i.e., centuries), Campbell et al. (2012) suggest that carbon stores in unthinned forests and those that experience infrequent high-severity fire will exceed those exposed to frequent low-severity fire. Forest location, however, is an important consideration, as some areas (e.g., road corridors, ridge tops) have much higher risk of ignition and carbon loss from wildfire than other areas. For most policy and economic analyses, the temporal scale identified by Campbell et al. (2012) may not be as relevant as carbon dynamics over the next few decades (Hurteau et al. 2013).

Recent research has proposed the idea of carbon carrying capacity (Keith et al. 2009). This concept may be particularly relevant to forest managers because it emphasizes carbon stability and the level of storage that forests can maintain. In the absence of disturbance, a forest may "pack" on more carbon as the density and size of trees increase. This additional biomass, however, makes the forest prone to disturbances, such as drought stress, pests, pathogens, and higher severity wildfire, which increase tree mortality. This mortality reduces carbon stocks as dead trees decompose, and through efflux much of the carbon returns to the atmosphere. Carbon carrying capacity, therefore, is lower than the maximum storage potential of a forest, but represents the biomass that can be maintained given disturbance and mortality agents endogenous to the ecosystem. In frequent-fire forests such as Sierra Nevada mixed conifer, the carbon carrying capacity is the amount that a forest can store and still be resilient (i.e., have low levels of mortality) to fire, drought, and bark beetle disturbances (Earles et al. 2014).

One factor that would change this long-term balance is if management activities led to increased carbon storage by altering the amount and longevity of sequestered carbon. In Sierra Nevada mixed-conifer forests, two studies that examined historical forest conditions have suggested that this might be possible. Although historical forests were less dense as a result of frequent fire, they may have stored more carbon because the number and size of large trees was greater than in current forests that have fewer large trees (Fellows and Golden 2008, North et al. 2009a), possibly owing to increased mortality rates from increased stand density (Smith et al. 2005). Carbon stores are calculated from total tree biomass (a three-dimensional measure) and will be much higher in a stand with a few large trees compared with

In general, forests managed so that growth and carbon accumulation are concentrated in large trees will have longer, more secure carbon storage than stands where growth is concentrated in a high density of small trees prone to pest, pathogen, and fire mortality.

a stand with many small trees, even if both stands have similar basal area (a two-dimensional measure). Other studies (Hurteau et al. 2010, Scholl and Taylor 2010), however, have found higher carbon storage in modern fire-suppressed forests than in historical active-fire forests, suggesting that there may be considerable variability between different locations and levels of productivity. In general, forests managed so that growth and carbon accumulation are concentrated in large trees will also have longer, more secure carbon storage than stands where growth is concentrated in a high density of small trees prone to pest, pathogen, and fire mortality.

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