Engelmann spruce regeneration following natural disturbances and forest management: A literature and expert-knowledge review focused on southwestern Colorado

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1. Introduction

Bark beetle outbreaks in Engelmann spruce (*Picea engelmannii*; hereafter referred to as ‘spruce’) forests in southwestern Colorado and nearby have resulted in widespread, high-severity forest mortality, prompting public concern and plans to harvest beetle-killed timber. However, much of our understanding of spruce regeneration and management is derived from forests further north in colder, wetter, climates which may not be applicable to spruce-dominated forests at the southern portion of the species range, particularly as climate change impacts become larger and more certain. This review attempts to fill this knowledge gap by synthesizing research and reports about Engelmann spruce regeneration following natural fire, bark beetle outbreaks, and management activity in southwestern Colorado, southern Utah and northern Arizona/New Mexico (hereafter referred to as the ‘southwestern’ portion of Engelmann spruce’s range). This report, to the best of my knowledge, include all relevant published reports and studies on Engelmann spruce from this immediate area. It also includes information from elsewhere in Colorado and Utah, and also Wyoming but is not comprehensive outside the southwestern focus. Finally, this report incorporates expert knowledge from foresters and scientists with decades of experience in spruce-dominated forests in southwestern Colorado and southern Utah (Table 1). Due to the relative remoteness of this area from research centers, relatively little peer-reviewed research is focused on spruce forest in this immediate area so information from these people provides invaluable region-specific insights which can help guide local management decisions. Finally, this report is intended to be a “living document” and should be updated with relevant new information.

Table 1. List of experts interviewed for this work.

Name	Employer	Geography of expertise
Dave Crawford	USDA Forest Service (Retired), San Juan National Forest	Southwest Colorado
Gretchen Fitzgerald	USDA Forest Service, San Juan National Forest	Southwest Colorado
Tim Garvey	USDA Forest Service (Retired); Grand Mesa, Uncompahgre, and Gunnison National Forests	Southwest Colorado
Art Haines	USDA Forest Service; Grand Mesa, Uncompahgre, and Gunnison National Forests	Southwest Colorado
Diana McGinn	USDA Forest Service; Rio Grande National Forest	Southwest Colorado
Kirby Self	USDA Forest Service; Rio Grande National Forest	Southwest Colorado
Sarah Pearson	USDA Forest Service; White River National Forest	Northwest Colorado
Dr. Wayne Shepperd	USDA Forest Service (Retired), Rocky Mountain Research Station, Fort Collins	Forest Service Region 2
Jim Thinnes	USDA Forest Service (Retired), Rocky Mountain Region	Forest Service Region 2
Dr. Marcella Windmuller-Campione	University of Minnesota, Formerly at Utah State University	Utah

2. Engelmann spruce forests distribution and associates

Throughout much of its range, Engelmann spruce is commonly associated with fir (subalpine fir [*Abies lasiocarpa* var. *latifolia*] in central Colorado and north or corkbark fir [*Abies lasiocarpa* var. *arizonica*] in southern Colorado and further south), which Sudworth (1900) called spruce's "inseparable associate". Engelmann spruce and subalpine or corkbark fir are commonly lumped together into one forest type and called "spruce/fir". For example, the widely used, if dated, SAF forest cover type guide (Society of American Foresters 1980) lists only Engelmann spruce and fir as dominant species in the "spruce/fir" cover type, though aspen (*Populus tremuloides*) and lodgepole pine (*Pinus contorta* var. *latifolia*) and Douglas-fir (*Pseudotsuga menziesii*) are common associates in various parts of its range, particularly at lower elevations. More rare associates may include limber pine (*Pinus flexilis*) particularly in northern Colorado, bristlecone pine (*Pinus aristata*) in south-central Colorado, and even southwestern white pine (*Pinus strobiformis*) in southwestern Colorado and northern New Mexico. Blue spruce (*Picea pungens*) also mixes (and hybridizes) with Engelmann spruce but is more typical of riparian areas and lower elevations. Scattered ponderosa pine (*Pinus ponderosa*) may also be present in some spruce-dominated forests.

Though Engelmann spruce and fir commonly coexist, this is not always the case, particularly in more southern portions of its range. On the Gunnison, Uncompahgre, and Grand Mesa National Forests (GMUG), there are areas where spruce occurs nearly absent of subalpine or corkbark fir (A. Haines, J. Thinnes, personal communication). Northeast of Gunnison there are areas dominated by spruce and lodgepole pine, but lodgepole is virtually absent from the remainder of southwestern Colorado (except where it was planted, such as on Molas Pass [D. Crawford, personal communication]). Extensive areas in and near the La Garita Wilderness on the Gunnison Ranger District of the GMUG have little to no fir and are either nearly pure spruce or a spruce and aspen mix (A. Haines, personal communication). Similarly, much of the spruce in the western portion of the Rio Grande National Forest is in a 'rain shadow' and has little fir present (K. Self, D. McGinn, personal communication; Alexander 1987).There are also areas of pure spruce in southern Utah (Long 1995, Schmid and Hinds 1974, Mielke 1950).

Romme et al. (1994) describe the spruce and fir forest on the San Juan National Forest. In this area, Engelmann spruce commonly occurs with a closely-related sub-species of subalpine fir, corkbark fir (*Abies lasiocarpa* var. *arizonica*). This sub-species is defined by a thicker, spongier bark than subalpine fir (Alexander et al. 1990) but there is not substantial evidence that it is different from subalpine fir in its life history traits so this review will not attempt to separate them. Douglas-fir, white fir (*Abies concolor*), and aspen are the most common associates at lower elevations. Limited amounts of limber pine and southwestern white pine exist on mostly steep, southern slopes, and bristlecone pine is rare but present at high elevations. The majority of the 5-needle pines in the area are reported to be southwestern white pine (O'Hara 1986, cited in Romme et al. 1994).

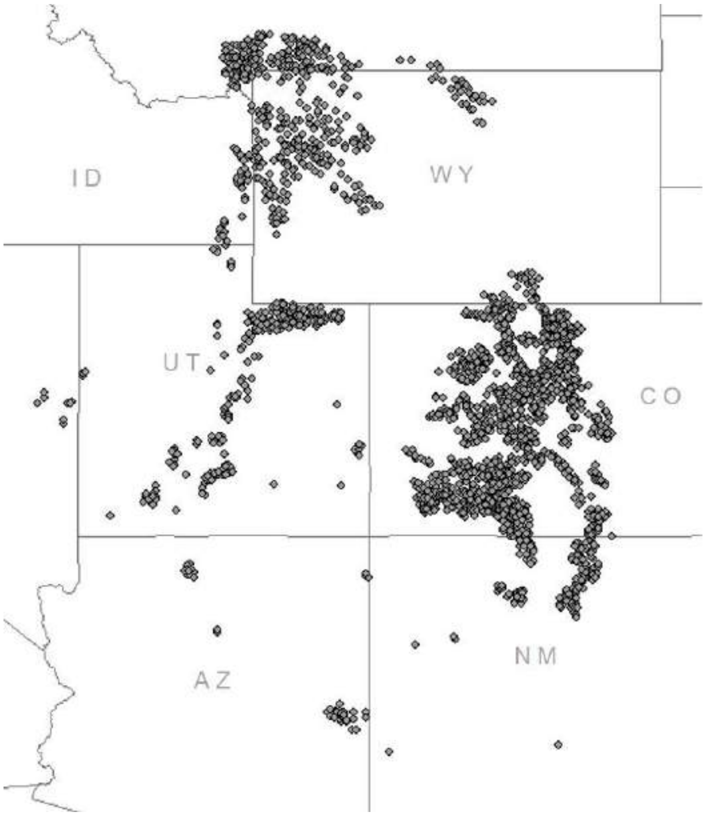


Figure 1. Occurrence of Engelmann spruce (*Picea engelmannii*) from the Interior West Forest Inventory and Analysis database. Map from R. Justin DeRose, Inventory and Monitoring Program, Rocky Mountain Research Station.

3. General climate conditions of spruce forests

Spruce and subalpine fir both exist in cold environments at high elevation in the southern parts of their ranges. The USDA Conifers of North America states that Engelmann spruce exists in areas with very low mean annual temperatures in New Mexico, Arizona, Utah, Wyoming and Colorado (Alexander and Shepperd 1990). Alexander et al. (1990) provide climate values for where fir occurs in Colorado, Wyoming, and northern Utah that are the same as for Engelmann spruce (Table 2), but subalpine fir exists at temperatures and precipitation amounts that are higher than for spruce in New Mexico, Arizona, and the southern Utah Plateaus.

Table 2. Climate where Engelmann spruce (*Picea engelmannii*) and fir (subalpine and corkbark are lumped together; *Abies lasiocarpa* [var. *latifolia* and var. *arizonica*]) are located, according to Alexander et al. (1990) and Alexander and Shepperd (1990). Spruce and fir in southern Colorado could arguably be grouped with the "southern Rockies" group rather than the "central Rockies" group, which are defined by the states listed in this table.

Species	Location	Mean annual temperature	Mean annual precipitation	Mean annual snowfall
Engelmann spruce	'Southern Rockies' (NM, AZ, South UT)	36◦F (2◦C)	24 – 35+ in (610 – 890+ mm)	200 in (5080 mm)
	'Central Rockies' (CO, WY, North UT)	30 – 36◦F (-1 – 2◦C)	24 – 55 in (610 – 1400 mm)	150 – 350+ in (3810 – 8890+ mm)
Subalpine and corkbark fir	'Southern Rockies' (NM, AZ, South UT)	30 – 39◦F (-1 – 4◦C)	24 – 40+ in (610 – 1020+ mm)	200 in (5080 mm)
	'Central Rockies' (CO, WY, North UT)	30 – 36◦F (-1 – 2◦C)	24 – 55 in (610 – 1400 mm)	150 – 350+ in (3810 – 8890+ mm)

Data from the Forest Inventory and Analysis Program show spruce-dominated forests occur where temperature, and especially precipitation, is lower than subalpine fir-dominated forests (Table 3; Garbarino et al. 2015). The mean annual precipitation (MAP) for spruce-dominated forests is 789 mm yr^{-1} and mean annual temperature (MAT) is 2.0°C. Subalpine fir-dominated forests are nearly 40% wetter and warmer, with MAP at 1080 mm yr^{-1} and mean temperature at 2.9°C. Conditions in mixed-dominance spruce-fir forests are, predictably, intermediate between the two, but are closer to conditions observed in fir-dominated than spruce-dominated forests, especially because precipitation is much higher than in spruce-dominated forests.

Table 3. Mean climate variables for forests dominated by Engelmann spruce, subalpine fir, and co-dominated by spruce-fir from Forest Inventory and Analysis data (Garbarino et al. 2015). Climate data taken from PRISM (Oregon State University).

Forest type	Mean annual temperature	Mean annual precipitation
Engelmann spruce	35.6◦F (2.0◦C)	31.1 in (789 mm)
Subalpine fir	37.2◦F (2.9◦C)	42.5 in (1080 mm)
Spruce/fir	36.5◦F (2.5◦C)	40.2 in (1022 mm)

4. Regeneration of Engelmann spruce without management

Engelmann spruce regeneration is sensitive to multiple environmental conditions: viable seed production, dispersal, germination, and seedling survival. Inability to meet minimum requirements associated with any of these will potentially result in regeneration failure. The science suggests that Engelmann spruce regeneration is most limited by the survival phase -- its sensitivity to desiccation and, perhaps relatedly, intense sun, results in the majority of seedling mortality (Ronco and Noble 1971, Noble and Alexander 1977), though seedcrops and germination can also be fickle.

4.1 Seed availability

We know spruce seed production can vary substantially from year to year and place to place. There is likely a connection between seed production and weather conditions, but interannual variation in seed production is not predictable (see Long 1995). Production is generally highest on the largest, oldest spruce trees and is positively related to basal area (Alexander et al. 1982, Stromberg and Patton 1993). There is evidence that seedcrop may vary from north to south in Colorado, which could influence forest regeneration differences between the regions. Ronco (1970) studied seedcrops across Colorado between 1961 and 1967 and found that they were most prevalent on two of the three northern forests (the Arapaho and White River but not the Routt), which had 'good' (100,000+ sound seeds per acre) or moderate (50,000 – 100,000 seeds per acre) seedcrops in 3 of 6 years. More southern forests (Rio Grande, San Juan) and the Routt had only one good crop in 6 years, and all other years they produced little or no sound seed. Only 1 of 4 years produced a substantial seedcrop in the Pinaleño Mountains of Arizona (Stromerg and Patton 1993). Seedcrops have been shown to vary between locations at much smaller scales as well. At the Fraser Experimental Forest in the 1970s, some drainages had good or better seedcrops while others within 10 miles had poor seed production in the same year (Alexander et al. 1982). Continued data collection on spruce seed production at FEF has shown huge interdecadal variability during the last 40 years, with very little seed production during all but one year of the 1980s. Seed production was highly synchronous among sites and seed numbers were greater after warmer, drier years than after cooler, moister years (Buechling et al. 2016).

Differences in seed availability could be driving patterns of relative dominance of fir and spruce. Like spruce, subalpine fir and corkbark fir seed production is also temporally inconsistent, but seems more consistently related to moisture than spruce seed production (Alexander et al. 1990). And, though fir seed production is variable, seed production does not seem to be a limiting factor in the species' seedling recruitment. In a 42-year study in Colorado, fir only produced good seed 8 years and all other years were near complete failures (Noble and Ronco 1978). Subalpine fir (var. l*asiocarpa*) begins producing seeds when it is approximately 5 feet tall (often an age of 50+ years), and corkbark fir (var. *arizonica*) also does not produce until it is roughly 50 years old. Seed production is not maximized until both subspecies are 100 to 200 years (Alexander et al. 1990). The relationship between fir (both varieties of *A. lasiocarpa*) seed production and moisture could drive lower fir abundance in southern Colorado mountains which have greater insolation than northern Colorado mountains. Spruce seed production was also greater, and more consistent, across the Pinaleño mountains of Arizona than that of corkbark fir during the 4 years study in the late 1980s/early 1990s (Stromberg and Patton 1993). They also found corkbark fir produced seeds only in the wettest sites while spruce seed was produced equally across a gradient of productivity.

Though *A. lasiocarpa* seed production may be more limiting in its southern range, successful Engelmann spruce regeneration seems far more limited by seed productions than that of fir.

4.2 Germination

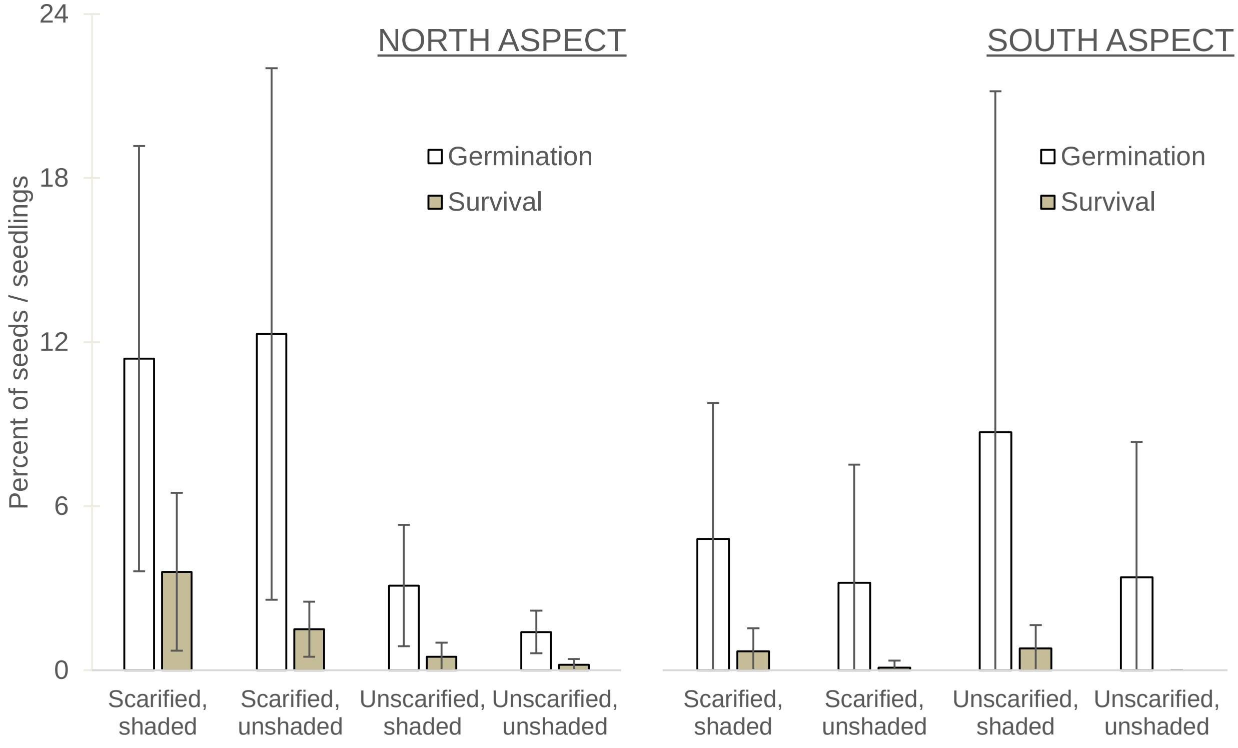
Alexander and Shepperd (1990) report that spruce germination usually occurs ‘when seedbeds are moist and air temperature is at least 7˚C (45˚F)’. Under consistently moist conditions, average germination capacity per 100 filled seeds is nearly 69% for Engelmann spruce, twice the rate of subalpine fir and white fir and roughly equal to lodgepole pine (Schopmeyer 1974). This germination advantage over fir (subalpine fir, but perhaps corkbark as well) appears to hold across different substrates when conditions are favorable. Anderson and Winterton (1996) showed that spruce germinated more reliably than subalpine fir on all logs, bare soil, and litter substrates under high moisture levels in a greenhouse study (seeds were watered daily; daytime temperatures were 25˚C).

4.3 Seedling survival

Survival of germinated seeds is likely to be the factor that limits Engelmann spruce regeneration most (e.g., Ronco 1970, Noble and Alexander 1977, Roberts and Long 1991). The classic study of Engelmann spruce regeneration requirements, done in northern Colorado at Fraser Experimental Forest, showed that shade was absolutely necessary for spruce seedling survival on south slopes, and doubled seed survival on north slopes (Noble and Alexander 1997). Therefore, some degree of shading is nearly universal in environments that produce spruce regeneration. Physiologically, the operative effect of shade is that it reduces the vapor pressure deficit experienced by seedlings (Roberts and Long 1991). For example, successful regeneration methods for spruce consistently prescribe some amount of ‘dead shade’ (Alexander 1987). (‘Dead shade’ is provided by a relatively permanent unmoving structure, such as a rock or down woody debris.) Spruce often recruits in protected locations under the edge of mature tree canopies (Sudworth 1900) and low-lying shrubs like *Vaccinium* spp. (Pelz 2014). Small-scale canopy openings provide good opportunities for spruce recruitment (Aplet 1987, Aplet et al. 1988, Veblen 1991). Once seedlings are 2-3 years old, they are much more tolerant of drier environmental conditions (Noble and Alexander 1977).

The Noble and Alexander (1977) study, along with others, is often cited as supporting the need for bare mineral soil for spruce regeneration. However, they found overall survival was very low and that seedbed scarification was important to survival on north slopes but it made no difference on south slopes (Figure 2). Organic matter was <5 cm thick on south slopes but was 7+ cm thick on north slopes in their study, which is typical for forests of the region (Noble and Alexander 1977). This suggests that scarification may not be important where needle and duff layers are shallow and where exposed soil is more likely to dry than soil covered with thin organic matter, such as at lower elevations and high solar radiation sites like south slopes. In fact, Noble and Alexander (1977) made this observation, though Alexander’s works in the years following consistently state that scarification and mineral soil are needed for spruce regeneration. On the Gunnison Ranger District in southwestern Colorado, spruce regeneration is common on undisturbed seedbeds (A. Haines, personal communication). Mineral soil may be more favorable for spruce than deep duff, but in warmer, drier, environments, mineral soil is likely to dry more quickly than soil with a thin layer of litter matter and may therefore not be favorable for spruce recruitment in lower elevations, southern slopes, particularly in warmer and drier conditions expected with climate change.

Figure 2. Results from Noble and Alexander (1977) study of spruce germination and one-year survival at Fraser Experimental Forest. Graphs show data presented in tables in the original article. The right graph shows results from north aspects, the bottom from south aspects. Bars are the average across years (1968-1972 for north aspect, 1969-1972 for south aspect); error bars show the standard deviation. Shade treatments had a huge positive effect on survival on north slopes, and both germination and survival on south slopes. Scarification significantly increased germination and survival on north but not south slopes.



In areas with deep duff and litter layers, rotting logs may be an important substrate for spruce seedlings. In more moist locations (such as at higher elevations) spruce seedlings seem to show a preference for regeneration on rotting coarse woody debris (e.g., Daubenmire 1943, Whipple and Dix, 1979, Knapp and Smith 1982, Alexander 1987). The phenomenon of conifers regenerating on 'nurse logs' is common to cool, wet forests such as those in the Pacific Northwest and northern New England. However, in lower, drier locations, spruce is rarely found on rotten wood substrates (Pelz, 2014; K. Pelz, personal observation). This may be because the thinner organic layers typical of drier sites do not inhibit spruce regeneration, and because wood does not retain wetness at dry sites like it does in more mesic settings.

Differences in the survival stage of regeneration are likely one reason that fir seedlings often outnumber spruce seedlings. Knapp and Smith (1982) showed that subalpine fir root growth is faster than spruce root growth, allowing fir germinants to better survive drier conditions in the critical early years. However, once spruce is established, it can grow more quickly than fir and in high light conditions. Fir is a poor competitor with spruce once shade levels are below 50% (Alexander et al. 1984).

5. Major disturbances affecting Engelmann spruce and impacts on regeneration

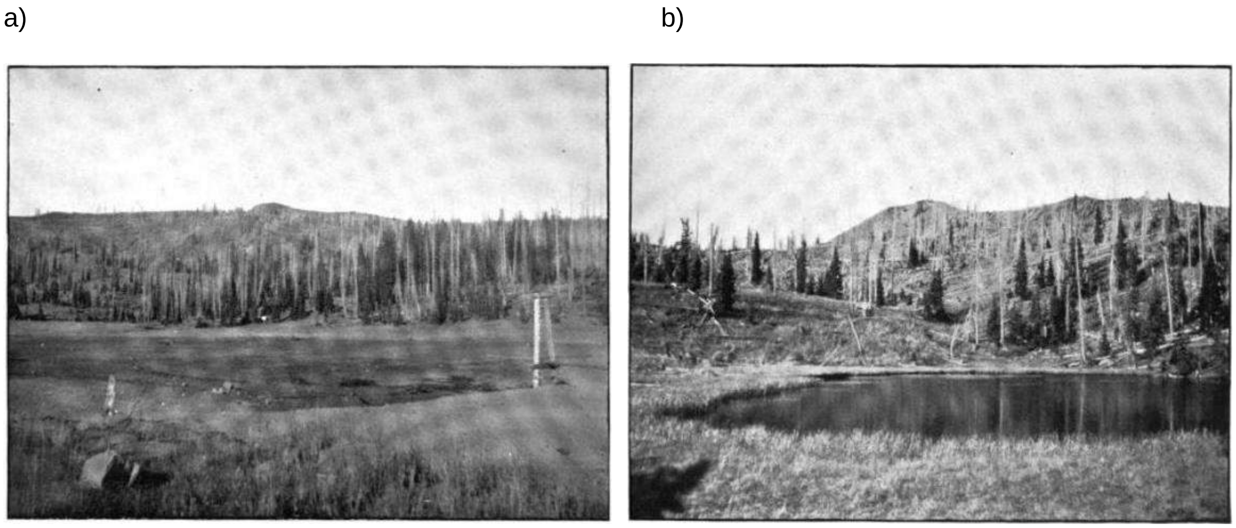
The major natural disturbances affecting Engelmann spruce forests are fire, bark beetles, both of which tend to be tied to drought (DeRose and Long 2012), blowdown from windstorms (e.g., Kulakowski and Veblen 2002, Bigler et al. 2005), and snow avalanches (e.g., Veblen et al. 1994). There is evidence of a half-dozen widespread spruce beetle outbreaks since Euro-American settlement and before 1990 in the western Colorado (Baker and Veblen 1990), and there have been three in Colorado and one in Utah in the 30 years since.

5.1 Disturbance by fire in spruce forests

Engelmann spruce-dominated forests typically have a long fire rotation (one hundred to several hundred years) (e.g., Kipfmueller and Baker 2000; Veblen et al. 1994; Howe and Baker 2003), with high-severity fires occurring over large landscapes. However, southwestern Colorado is on the boundary between the areas usually defined as the southern Rockies and Southwest (Grissino-Mayer et al. 2004) and may have a different fire history than forests further north. Fire regimes in the lower-elevation mixed-conifer and ponderosa pine forests of the San Juans have been shown to be less frequent and more severe than would be expected compared to forest with similar composition, elevation, and aspects located on less dissected topography (Bigio et al. 2016, see also Korb et al. 2013). Romme et al. (1994) suggest that spruce and spruce/fir forests in the San Juans are likely to have unique fire and disturbance regimes due to “the unique climatic and biogeographic location of the San Juan Mountains”. Although most large fires in spruce cause high mortality where they burn, many historical fires were patchy. For example, on the White River Plateau in Colorado, a large fire that burned at high severity in 1879 left patches of unburned forest in many places within its boundary (Bebi et al. 2003), particularly when forested islands are interspersed with unforested areas, as is common in Southwestern Colorado (personal communication, A. Haines) and throughout spruce and spruce fir forest in the West.

There is evidence of extensive burning across much of Colorado's spruce forests in the late 1800s. While surveying the Grand Mesa, Sudworth (1900) reported that "all of the interior valleys and canyons of the reserve are more or less marked with old and new fires". Sudworth observed that the older fires, thought to have occurred in the 1870s, appear to have affected the landscape at roughly the same time. Sudworth also reported that, despite the widespread mortality, "patches of coniferous timber were also left in the burned regions" in many places (Figure 3).

Figure 3. Photos of headwaters of Lereaux Creek in 1897, taken from Sudworth (1900). Contemporary place names include both "East" and "West" Lerueax Creeks, it is unclear which one is represented here. Sudworth states that this forest was partly destroyed by fire. However, the fire did not result in complete forest mortality over the area pictured. Historical photo captions: Both: "Head of Lereaux Creek." Top photo: "Shows Engelmann spruce and alpine fire forest party destroyed by fire. Head gate of dry reservoir." Bottom: "Partly burnt forest of Engelmann spruce and alpine fire, showing slow reproduction."



More recent studies also suggest that fires in spruce forests had a patchy mosaic of burned and unburned areas (Baker and Veblen 1990, Howe and Baker 2003; Figures 4 and 5). It is possible this patchy fire regime may be more dominant outside of the archetypal, high-elevation spruce/fir forests of the central and northern Rockies (Margolis et al. 2011; O'Connor et al. 2015). Fire ecology work in the high-elevation spruce forest near the Grand Canyon and the San Francisco Peaks and Pinaleño Mountains has shown spruce fires occurred in patches of burned and unburned areas (Fulé et al. 2003, Margolis et al. 2011).

Figure 4. From Howe and Baker (2003). Despite the watershed being dominated by spruce and fir forest throughout, there was variation within this forest in past frequency of stand-replacing fire. Disturbances were determined from combined evidence from tree ages, fire scars, and aerial imagery. Higher elevations burned 0 – 3 times, while lower elevations burned 1-4 times. North facing slopes had burned less frequently than south facing slopes. (n = 14 points for north-facing low elevations, n = 20 for south-facing, low-elevations, n = 11 for north-facing, high-elevation; n = 17 for south-facing, high-elevation.)

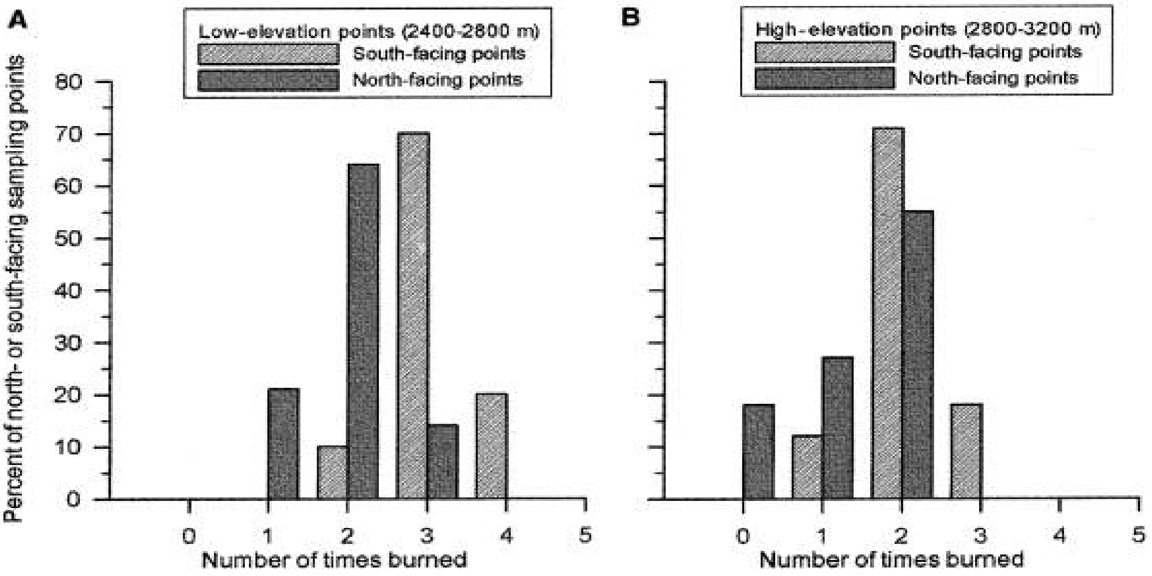
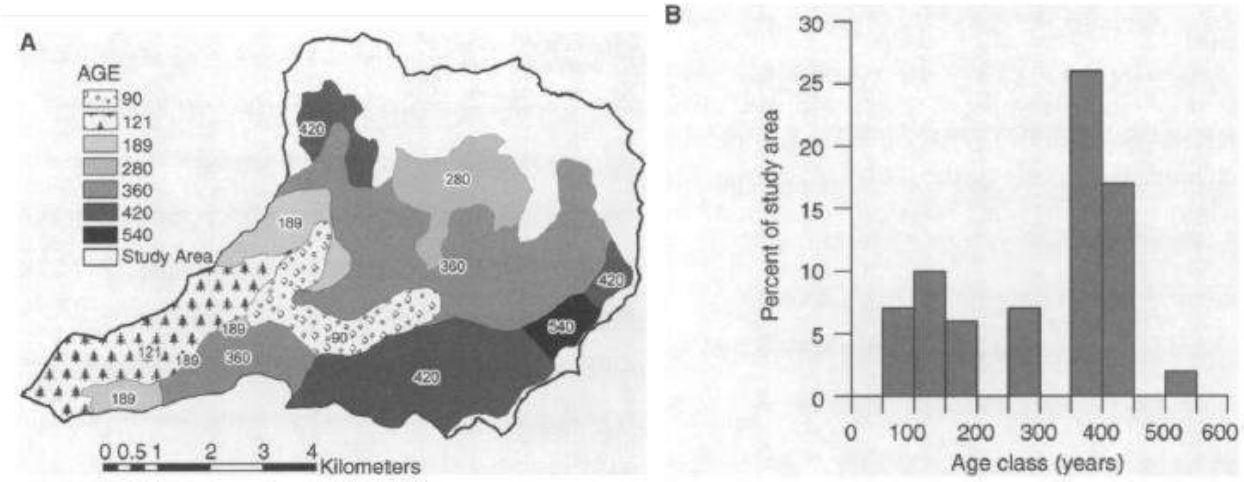


Figure 5. From Howe and Baker (2003). Despite the general consensus that spruce-fir forests burned under high-severity fires over large landscapes, continuous areas of forest killed in a single fire event probably rarely covered whole watersheds in complex mountainous terrain. For example, the map below shows estimated forest patch ages in the Middle Fork of the Elk River watershed near Steamboat, Colorado (A). The graph (B) shows the percent of the landscape in each estimated age class. The unshaded (white) area in the watershed was not aged because it was above treeline.



5.2 Regeneration after fire

Post-fire regeneration of spruce is a slow process (e.g. Fielder et al. 1985). There is typically a slow expansion around living seed trees that survive the fire, with gradual infill (Sudworth 1900, D. Crawford, personal communication, Figure 6). Areas that burn with high-severity and have little seed source may remain void of trees for centuries (Stahelin 1943; Billings 1969). For example, spruce exhibited chronic (but low-density) regeneration for nearly two centuries in Utah following stand-replacing fire (DeRose and Long 2012). Accumulation of snow around surviving overstory trees, dead snags, and fallen trees may also be an important mechanism allowing regeneration. The snowdrifts protect seedlings and provide snowmelt longer into the summer, and therefore can provide 'safe sites' for spruce regeneration (Billings 1969).

Figure 6. Google imagery (from 2015) of area likely burned in 1800s fires northwest of Hermosa, Colorado, just southwest of Purgatory ski area. Spruce have been gradually filling in these areas since the fire, with the greatest tree density on northern and western slopes, and the lowest tree dnesity on southern/southeastern slopes. Aerial imagery from early 1900s shows very few scattered trees on western slopes only, with pockets of continuous canopy by the 1980s (insert scanned images from D. Crawford). Today, western slopes are mostly forested in an open-canopy condition. Area in foreground of tilted perspective image (bottom) is generally within dotted green circle in aerial image (left). Area direcly above dotted line was harvested (shelterwood regeneration cut) in the 1980s. Information from Dave Crawford, San Juan National Forest, Retired.

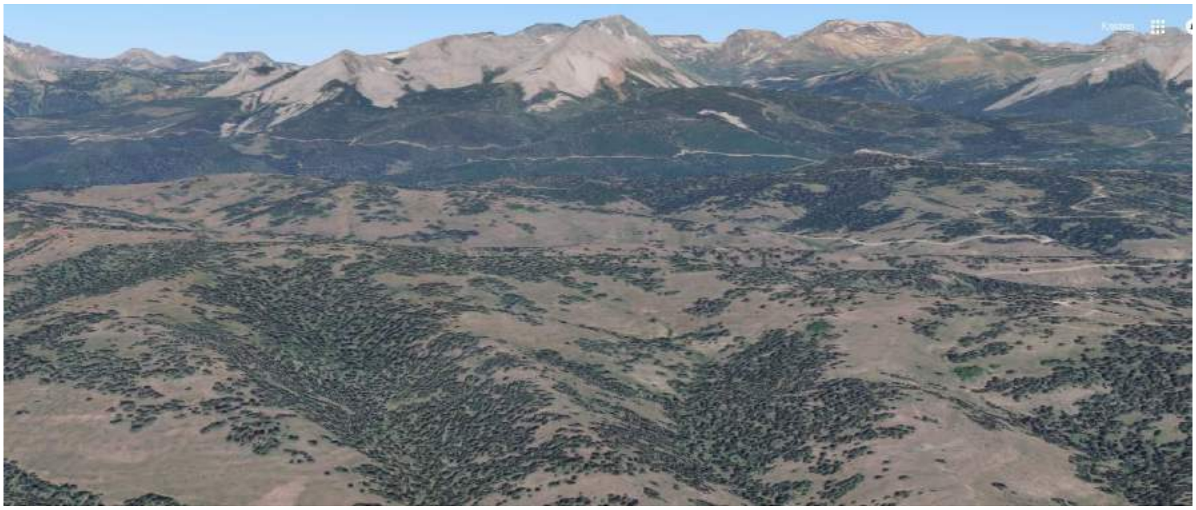


Figure 7. Figure taken from Billings (1969) showing conversion of formerly dense spruce forest to meadow-like conditions by approximately 150 years after fire. Forest will likely re-colonize the area as the live trees clump in the background slowly expands. Original caption reads: “Site of 1809 fire on South Libby Flats, Medicine Bow Mts., showing trees killed by fire and replacement of forest by mesic tundra. Elevation: 3,200 m. 1 August 1967.”

Sudworth (1900) reported on the open nature of spruce forests on the White River Plateau and the Battlement and Grand Mesas in the late 1800s (Figures 8-10). Sudworth noted that regeneration was scarce in burned areas (Figure 7), but seedlings from 2 to 4 feet high were plentiful around the edges of groups though new germinants were scarce. He hypothesized the following mechanisms for the creation of their spatial pattern, which is not inconsistent with our understanding of these forests today:

> “The spruce and fir are spread over the high plateaus, but are nowhere found in great bodies. They occur as single trees or in isolated groves varying in size up to 50 acres. The stand is dense, not uncommonly 10 or 12 trees occurring in a plat 10 to 15 feet square … followed by intervals of up to 8 to 10 feet to the next similar group. At a distance the timber appears to be of uniform density. The advance of the species in the gradual formation of larger groups by the coalition of neighboring small groups is very apparent, and doubtless is the explanation of this peculiar density of growth of spruce and fir observable everywhere on the plateaus. A single individual, seeded from a mother group or tree and established many yards away, in favorable seasons and good seed years soon gathers about it a cordon of young plants from its own falling seed. The establishment of another outpost several yards distant, less difficult now under the fostering protection of the original group, soon takes place… many seeds fail to germinate, but the proper timely moisture conditions for starting the seed do occur… and another part has been added … to the original group.
>
> “The distribution of spruce and fir … at the heads of streams which cut the plateau region, and about isolated mountain peaks, is sometimes quite similar to this peculiar group growth, but as a rule is much less interrupted, continuous, stands of timber often being seen. Here the timber appears in much more homogenous stands. The explanation seems apparent from the greater protection afforded the advancing growth from high winds in shut-in, deep valleys … and on the constantly shaded, moist northern mountain slopes.”

Figure 8. Photo showing open forest conditions “characteristic” of Grand Mesa spruce forests described by Sudworth in (1900). Original caption reads: “Engelmann spruce and alpine fire on summit of southwest prong of Grand Mesa. Shows characteristic open stand of timber; tress stunted by high winds.”

Figure 9. 1897 photo (left) showing area burned by high-severity fire near North Mam[m] on Grand Mesa. Sudworth (1900) reported that the burned forests appear to have been spruce dominated prior to burning. The right image taken from Google in 2015. Although the image quality in this perspective is poor, the image shows only scattered trees today. The historical photo was likely taken in area in foreground of the Google photo, as this is the only side of North Mamm Peak where the rocky overhang in the historical photo is visible. Closer views of Google imagery show trees are conifers (from crown shadow shape). Original historical photo caption reads: “North Mam Peak, Battlement Mesa. Shows almost complete destruction of Engelmann spruce and alpine fire by old deep-burning ground fire.”

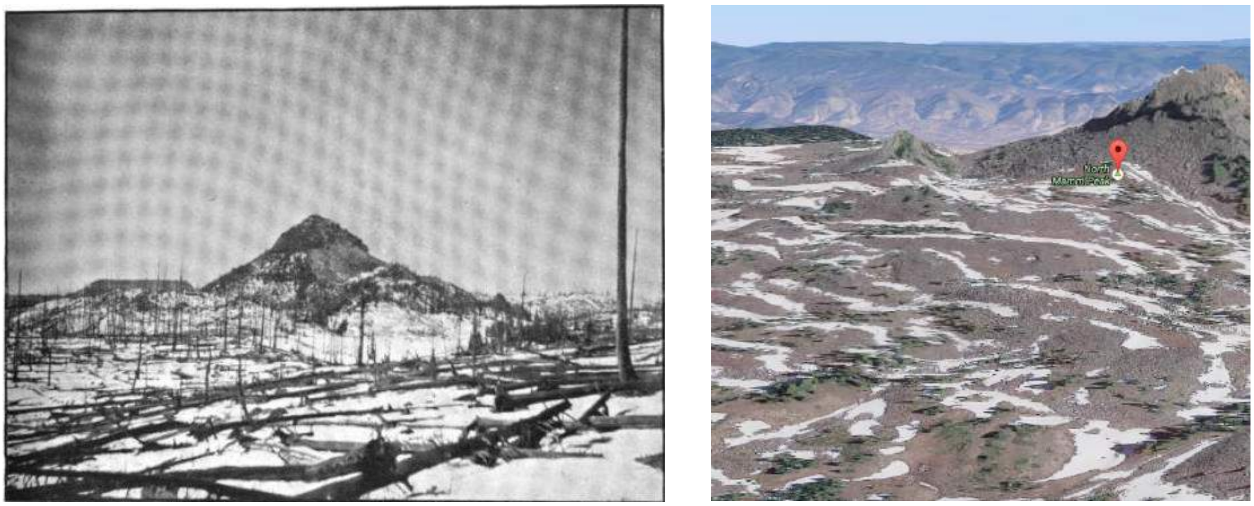


Figure 10. Headwaters of Fourmile Creek in aerial imagery from 2015. Snow is on the ground in this photo, with brown areas showing bare dirt. Dark trees are conifers and brushy areas without leaves are deciduous shrubs or trees, likely aspen. About this area, Sudworth (1900) reported: "the once generally wooded north slopes of Fourmile Creek are denuded, excepting a narrow strip of timber lying along the top of the divide. The lower part of Fourmile Creek is entirely stripped of its original stand of red fir [Douglas-fir] on the lower slopes, and of Engelmann spruce and [sub] alpine fir on the higher ridges."

5.3 Bark beetles as disturbance agents in spruce forests

Bark beetles are today and have historically been a major disturbance in spruce forests. Some have argued that their impact is as important or exceeds the importance of fire in structuring subalpine forests in Colorado (Baker and Veblen 1990, Eisenhart and Veblen 2000). For example, spruce beetle killed much of the mature spruce on the White River Plateau, Grand Mesa, and future Pike National Forest in the late 1800s (Sudworth 1898a,b, Sudworth 1900, Hopkins 1909), and across much of western Colorado in the 1940s (Schmid and Frye 1977, Schmid and Hinds 1974, Miller 1970). Photos taken by Sudworth in 1897 of Grand Mesa show that there was substantial mortality in both the dense closed-canopy stands he observed on steeper slopes and valley bottoms, but also in the more open park-like spruce forests characteristic of the plateau top (Figure 11).

Figure 11. Imagery from 1897 showing likely beetle-killed spruce forest on Grand Mesa. Sudworth (1900) noted that many of the Grand Mesa spruce forests that had not been burned had substantial mortality in the larger trees, which was later attributed to spruce beetles. Mortality was present in the more dense stands he observed on steeper slopes and valley bottoms, but also in the more open park-like spruce forests characteristic of the plateau top. Pictured is the "head waters of Hubbard Creek."

Spruce beetles typically kill larger spruce (Massey and Wygant 1954, Cahill 1977), leaving non-host trees that occur in the stand (such as aspen, subalpine fir, or others, if present). Spruce, typically smaller, usually survive the outbreak, though there have been reports of complete mortality in the outbreak affecting southwestern Colorado (K. Self, D. McGinn, A. Haines, J. Sibold, personal communication). Stands with complete mortality of spruce have typically been in areas where spruce < 10 inches diameter at breast height were rare (Kirby Self, Diane McGinn, Art Haines, personal communication). Dead trees eventually fall, but can remain standing for several decades following mortality. In Utah, 84% of trees were still standing with branches and twigs retained 25 years after a beetle outbreak (Mielke 1950). On the White River Plateau in Colorado, 60-70% of trees were still standing 20 years after spruce beetle outbreak (Hinds 1965, Cahill 1977).

There is a vast literature addressing the factors influencing bark beetle outbreak inception, spread, and severity, and the potential for management of spruce beetle (see DeRose and Long 2012, Hansen et al. 2010, Fettig et al. 2007, Bentz and Munson 2000, Massey and Wygant 1954, Temperli et al. 2014). Taken as a whole, the research supports the idea that there is little forest management activities can do to reduce final outbreak severity once an outbreak has begun (DeRose and Long 2014).

5.4 Forest regeneration after spruce beetle

We have learned much about the development of forests following spruce beetle in the last 50 years. Spruce beetle-affected forests develop from the trees that were not killed by beetles and the trees that regenerate following the disturbance. Trees that remain alive include any spruce that escape mortality and the non-host species that happen to be present, such as subalpine fir, corkbark fir, aspen, or even lodgepole pine. The mortality of overstory trees also provides an increase in light and other resources that can facilitate a pulse of successful establishment. The release of smaller trees and advance regeneration is generally thought to be more important to post-beetle forest composition than post-disturbance regeneration (Schmid and Frye 1977, Veblen et al. 1991). However, recruitment of spruce following opening of the canopy, has been hypothesized to be important to long-term stand dynamics in mixed spruce/fir forests (Schmid and Frye 1977, Aplet et al. 1988, DeRose and Long 2007). In contrast to stands with abundant advance regeneration or non-host tree species (like subalpine fir) recruitment following an outbreak may be the most important determinant of future stand conditions where little forest is left alive following spruce beetle outbreak (i.e. where advance regeneration is scarce and where overstory mortality is very high). This may be the case in some pure (or nearly pure) spruce forests with very high mortality in southwestern Colorado.

Figure 12. From Cahill (1977). A 1970s picture showing regeneration in an area with high mortality in the 1940s-50s outbreak on the White River Plateau. Because of their relatively large size, it is fair to assume these trees were present before the outbreak (they were 'advance regeneration').

Where subalpine fir is a substantial component of forests before outbreak, it is likely to become dominant in forests following spruce beetle outbreak. This is because dense subalpine fir advance regeneration is usually present in the understory of mixed spruce-fir forests, and these small trees will release following bark beetle outbreak (Figure 12). Schmid and Hinds (1974) looked at areas across Colorado and Utah following bark beetle outbreak (Table 3, Figures 14 and 15). They found that before the 1940s spruce beetle outbreak on the White River plateau, stand composition was 90% spruce (by basal area) and approximately 10% fir. By 25 years the outbreak, spruce was about 10-50% of the total live basal area, a finding corroborated by Veblen et al. (1991) 40 years after the outbreak in northern Colorado. Stands that were dominated by spruce prior to the beetle outbreak in the 1940s were dominated by small-diameter fir in the 1980s. The shift towards subalpine fir was greatest in the stands with the highest 1940s mortality on the White River plateau where 90+% of larger spruce were killed. The stands present in the 1980s was largely made up of releases of advance regeneration and small-diameter trees present but not killed during the 1940s outbreak. Both spruce and fir showed a pulse of growth release (defined as an increase in growth of >250%) in the 10 years following beetle-caused mortality. DeRose and Long (2010) also found that subalpine fir dominated the smaller tree size classes by 20 years after a spruce beetle outbreak in southern Utah -- 62% of trees <5 in diameter at breast height were subalpine fir, 32% were aspen, and only 6% were Engelmann spruce. These studies illustrate the classic shift in composition of spruce / fir forests to being dominated by fir following beetle outbreak which is often repeated. These studies have also shown no marked increase in conifer establishment following bark beetle activity.

Table 3. Characteristics of post-beetle sites studied by Schmid and Hinds (1974). See article for map of study locations. All sites except Rocky Mountain National Park included areas that were logged following spruce beetle outbreak along with areas unlogged after outbreak. Sites had variable times since spruce beetle outbreak (from 50 to 15 years), and some sites had evidence of repeated outbreaks (100 and 25 years before sampling on both the Grand Mesa and the White River sites; see Figure 14). Approximate elevations for each site were as follows: Grand Mesa: 10,000 ft; Boulder Top: 11,000 ft; White River Plateau: 10,000-10,500 ft; Lone Cone: 8,500 ft; Rocky Mountain National Park: 10,300 ft.

Location	Approx. years since outbreak	Elevation	Beetle activity notes	Logging information	Other notes
Grand Mesa (southwest Colorado)	100, 25	10,000 ft	Sudworth reported that the 1870s outbreak killed 25 – 40% of mature spruce and the 1940s outbreak killed approximately 50% of spruce basal area. “Numerous” 5-9 inch spruce remained alive.	Salvaging after 1940s outbreak; Scales Lake area logged after ‘light’ beetle activity and Flowing Park and Big Creek areas were heavily impacted.	Small meadows mixed with forest are characteristic of the area.
Aquarius Plateau (southwest Utah)	50	11,000 ft	Outbreak from around 1916 to 1929 that killed “nearly all of the large spruce”.	Post-beetle cutting included commercial cutting (1930s thru 1970s) using horses (early) and mechanical equipment (1970s). Cutting was also done by locals for products-other-than-logs. Boulder Top cut areas were mechanically logged; off Boulder Top areas were cut using horses.	Boulder Top area is grasslands mixed with nearly pure spruce. Characterized by poor, rocky soils. Area off Boulder top is a mix of spruce, fir, and aspen.
White River Plateau (northeast Colorado)	100, 25	10,000 – 10,500 ft	Spruce beetle outbreak in the 1870s and in 1940s. Nearly all spruce >8 inches were killed in 1940s outbreak.	Salvage logging began in late 1940s and was variable in intensity. One logged site was very wet.	Forest stands are mixed with meadows and open areas. Spruce and fir are usually

					present together, along with lodgepole and aspen at lower elevations.
Lone Cone (southwest Colorado)	15	8,500 ft	When beetle outbreak was first detected, sanitization cutting done and trees were treated with pesticides. Outbreak became extensive after this action.	Logged areas were clearcut with mechanized equipment. Trees skidded	In valley, area had very few meadows.
Rocky Mtn Nat'l Park (north-central Colorado)	n/a (endemic beetles)	10,300 ft	Area had endemic spruce beetle activity but no outbreak during previous 100 years.	No cutting done.	On north facing slope.

Figure 14. Seedlings and sapling densities in the early 1970s following spruce beetle-caused mortality, and post-beetle logging, in Colorado and Wyoming. Taken from Schmid and Hinds (1974).

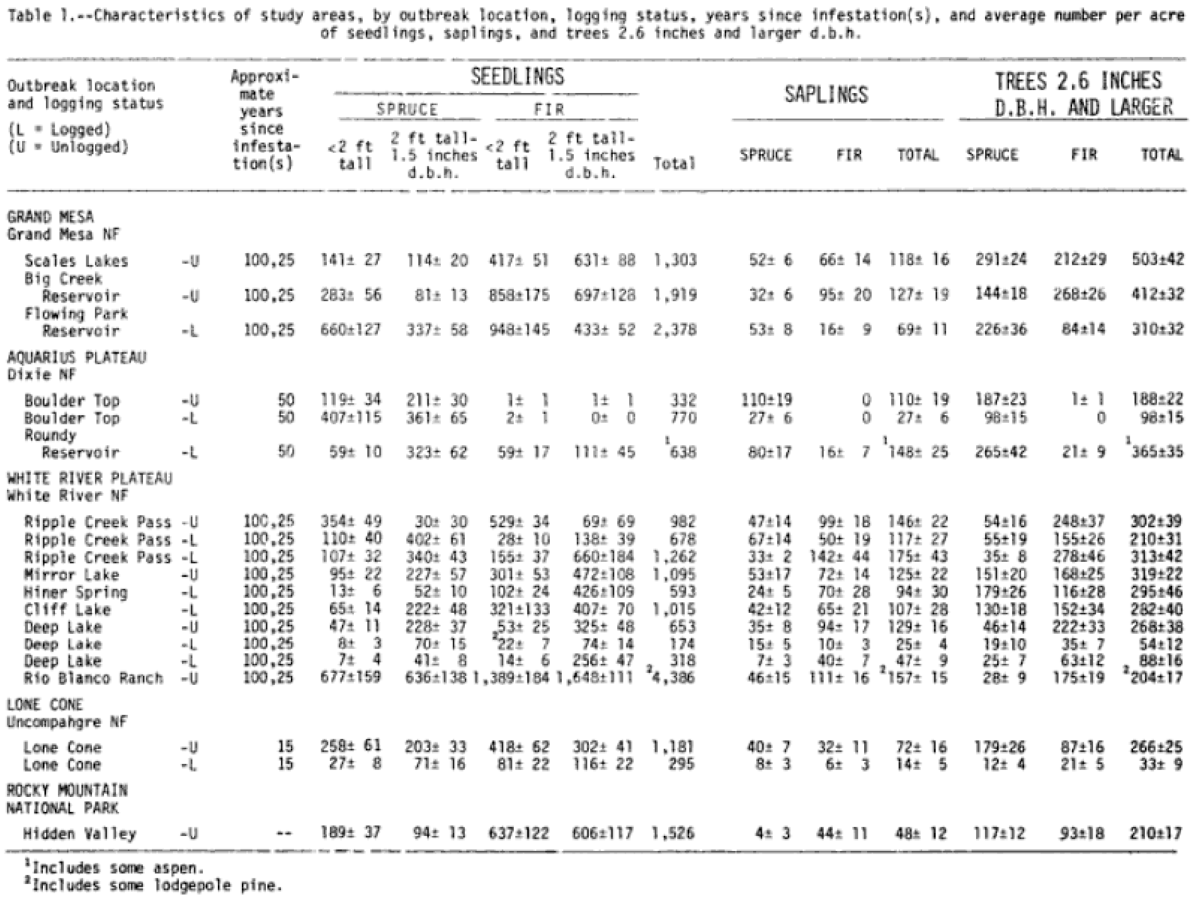


Table 1.--Characteristics of study areas, by outbreak location, logging status, years since infestation(s), and average number per acre of seedlings, saplings, and trees 2.6 inches and larger d.b.h.

Outbreak location and logging status (L = Logged) (U = Unlogged)		Approximate years since infestation(s)	SEEDLINGS					SAPLINGS			TREES 2.6 INCHES D.B.H. AND LARGER		
			SPRUCE		FIR								
			<2 ft tall	2 ft tall-1.5 inches d.b.h.	<2 ft tall	2 ft tall-1.5 inches d.b.h.	Total	SPRUCE	FIR	TOTAL	SPRUCE	FIR	TOTAL
GRAND MESA Grand Mesa NF													
Scales Lakes	-U	100,25	141± 27	114± 20	417± 51	631± 88	1,303	52± 6	66± 14	118± 16	291±24	212±29	503±42
Big Creek Reservoir	-U	100,25	283± 56	81± 13	858±175	697±128	1,919	32± 6	95± 20	127± 19	144±18	268±26	412±32
Flowing Park Reservoir	-L	100,25	660±127	337± 58	948±145	433± 52	2,378	53± 8	16± 9	69± 11	226±36	84±14	310±32
AQUARIUS PLATEAU Dixie NF													
Boulder Top	-U	50	119± 34	211± 30	1± 1	1± 1	332	110±19	0	110± 19	187±23	1± 1	188±22
Boulder Top	-L	50	407±115	361± 65	2± 1	0± 0	770	27± 6	0	27± 6	98±15	0	98±15
Roundy Reservoir	-L	50	59± 10	323± 62	59± 17	111± 45	[1]638	80±17	16± 7	[1]148± 25	265±42	21± 9	[1]365±35
WHITE RIVER PLATEAU White River NF													
Ripple Creek Pass	-U	100,25	354± 49	30± 30	529± 34	69± 69	982	47±14	99± 18	146± 22	54±16	248±37	302±39
Ripple Creek Pass	-L	100,25	110± 40	402± 61	28± 10	138± 39	678	67±14	50± 19	117± 27	55±19	155±26	210±31
Ripple Creek Pass	-L	100,25	107± 32	340± 43	155± 37	660±184	1,262	33± 2	142± 44	175± 43	35± 8	278±46	313±42
Mirror Lake	-U	100,25	95± 22	227± 57	301± 53	472±108	1,095	53±17	72± 14	125± 22	151±20	168±25	319±22
Hiner Spring	-L	100,25	13± 6	52± 10	102± 24	426±109	593	24± 5	70± 28	94± 30	179±26	116±28	295±46
Cliff Lake	-L	100,25	65± 14	222± 48	321±133	407± 70	1,015	42±12	65± 21	107± 28	130±18	152±34	282±40
Deep Lake	-U	100,25	47± 11	228± 37	53± 25	325± 48	653	35± 8	94± 17	129± 16	46±14	222±33	268±38
Deep Lake	-L	100,25	8± 3	70± 15	[2]22± 7	74± 14	174	15± 5	10± 3	25± 4	19±10	35± 7	54±12
Deep Lake	-L	100,25	7± 4	41± 8	14± 6	256± 47	318	7± 3	40± 7	47± 9	25± 7	63±12	88±16
Rio Blanco Ranch	-U	100,25	677±159	636±138	1,389±184	1,648±111	[2]4,386	46±15	111± 16	[2]157± 15	28± 9	175±19	[2]204±17
LONE CONE Uncompahgre NF													
Lone Cone	-U	15	258± 61	203± 33	418± 62	302± 41	1,181	40± 7	32± 11	72± 16	179±26	87±16	266±25
Lone Cone	-L	15	27± 8	71± 16	81± 22	116± 22	295	8± 3	6± 3	14± 5	12± 4	21± 5	33± 9
ROCKY MOUNTAIN NATIONAL PARK													
Hidden Valley	-U	--	189± 37	94± 13	637±122	606±117	1,526	4± 3	44± 11	48± 12	117±12	93±18	210±17

[1] Includes some aspen.
[2] Includes some lodgepole pine.

Figure 15. Average basal area (in ft^2 acre^{-1}) in logged and unlogged post-beetle forests in Colorado and Utah. See Figure X-1 for time since beetle. Data were collected in early 1970s (exact date not given). Taken from Schmid and Hinds (1974).

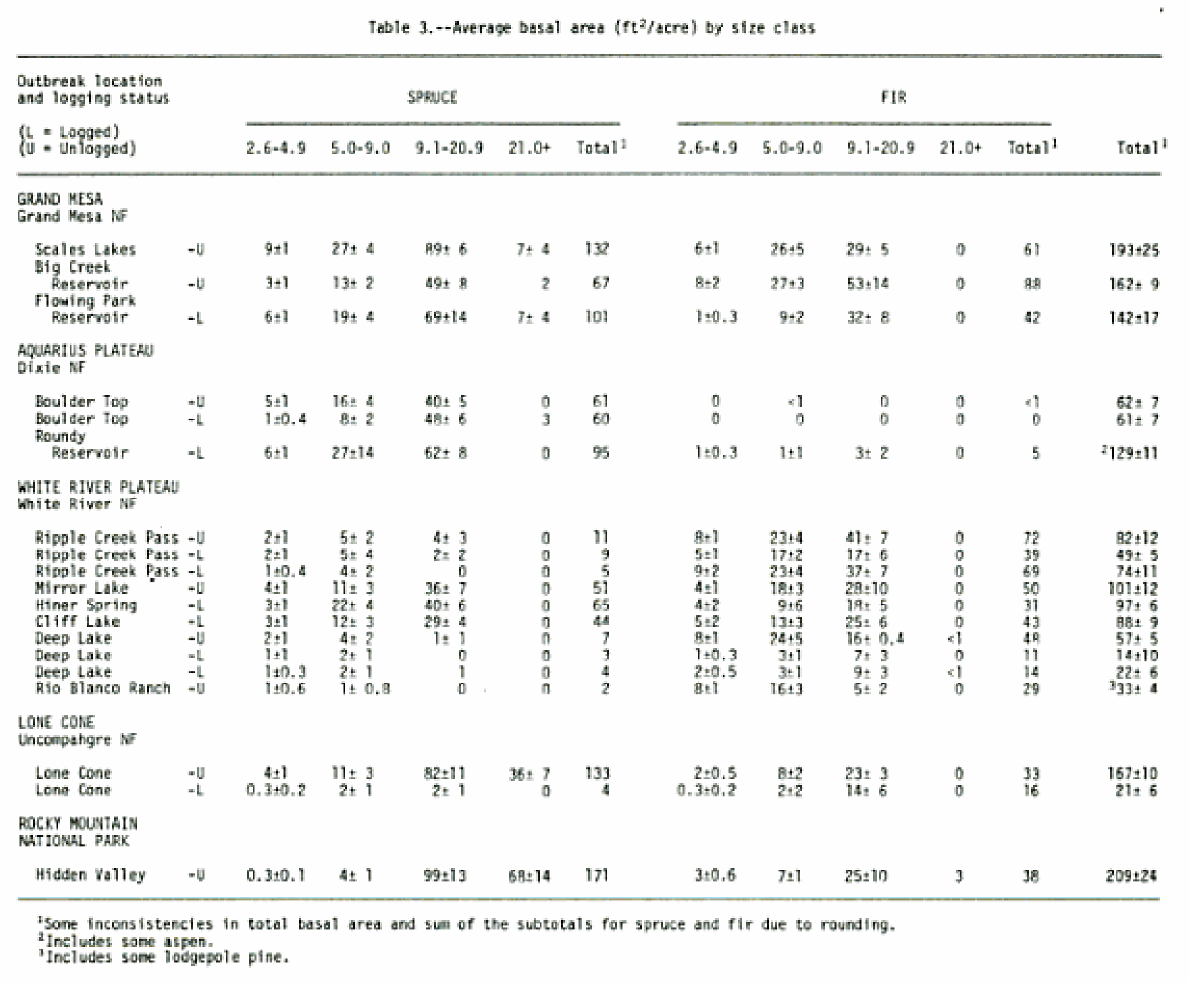


Table 3.--Average basal area (ft^2/acre) by size class

Outbreak location and logging status (L = Logged) (U = Unlogged)		SPRUCE					FIR					
		2.6-4.9	5.0-9.0	9.1-20.9	21.0+	Total[1]	2.6-4.9	5.0-9.0	9.1-20.9	21.0+	Total[1]	Total[1]
GRAND MESA Grand Mesa NF												
Scales Lakes	-U	9±1	27± 4	89± 6	7± 4	132	6±1	26±5	29± 5	0	61	193±25
Big Creek Reservoir	-U	3±1	13± 2	49± 8	2	67	8±2	27±3	53±14	0	88	162± 9
Flowing Park Reservoir	-L	6±1	19± 4	69±14	7± 4	101	1±0.3	9±2	32± 8	0	42	142±17
AQUARIUS PLATEAU Dixie NF												
Boulder Top	-U	5±1	16± 4	40± 5	0	61	0	<1	0	0	<1	62± 7
Boulder Top	-L	1±0.4	8± 2	48± 6	3	60	0	0	0	0	0	61± 7
Roundy Reservoir	-L	6±1	27±14	62± 8	0	95	1±0.3	1±1	3± 2	0	5	[2]129±11
WHITE RIVER PLATEAU White River NF												
Ripple Creek Pass	-U	2±1	5± 2	4± 3	0	11	8±1	23±4	41± 7	0	72	82±12
Ripple Creek Pass	-L	2±1	5± 4	2± 2	0	9	5±1	17±2	17± 6	0	39	49± 5
Ripple Creek Pass	-L	1±0.4	4± 2	0	0	5	9±2	23±4	37± 7	0	69	74±11
Mirror Lake	-U	4±1	11± 3	36± 7	0	51	4±1	18±3	28±10	0	50	101±12
Hiner Spring	-L	3±1	22± 4	40± 6	0	65	4±2	9±6	18± 5	0	31	97± 6
Cliff Lake	-L	3±1	12± 3	29± 4	0	44	5±2	13±3	25± 6	0	43	88± 9
Deep Lake	-U	2±1	4± 2	1± 1	0	7	8±1	24±5	16± 0.4	<1	49	57± 5
Deep Lake	-L	1±1	2± 1	0	0	3	1±0.3	3±1	7± 3	0	11	14±10
Deep Lake	-L	1±0.3	2± 1	1	0	4	2±0.5	3±1	9± 3	<1	14	22± 6
Rio Blanco Ranch	-U	1±0.6	1± 0.8	0	0	2	8±1	16±3	5± 2	0	29	[3]33± 4
LONE CONE Uncompahgre NF												
Lone Cone	-U	4±1	11± 3	82±11	36± 7	133	2±0.5	8±2	23± 3	0	33	167±10
Lone Cone	-L	0.3±0.2	2± 1	2± 1	0	4	0.3±0.2	2±2	14± 6	0	16	21± 6
ROCKY MOUNTAIN NATIONAL PARK												
Hidden Valley	-U	0.3±0.1	4± 1	99±13	68±14	171	3±0.6	7±1	25±10	3	38	209±24

[1] Some inconsistencies in total basal area and sum of the subtotals for spruce and fir due to rounding.
[2] Includes some aspen.
[3] Includes some lodgepole pine.

Seedling recruitment following spruce beetle may be more likely where there is not an established understory of advance regeneration. This is most likely in spruce forests which lack subalpine or corkbark fir. It has been hypothesized that lack of Engelmann spruce seed and mineral soil inhibit spruce regeneration following spruce beetle outbreak, but these have yet to be tested. Anecdotally, new spruce regeneration is not uncommon in pure spruce forests following the ongoing outbreak on the Gunnison Ranger District of the GMUG National Forests (A. Haines, personal communication) and ongoing observations and monitoring will only improve our understanding of post-beetle regeneration.

In contrast to locations where significant amounts of subalpine fir were present, it is reasonable to hypothesize that species composition may not shift significantly in areas of nearly pure spruce. The results of Schmid and Hinds (1974) highlight the importance of local conditions in future stand trajectories. Overall, Schmid and Hinds report that fir seedlings and saplings “generally outnumbered spruce”. However, there was marked variation in the ratio of spruce to fir across their study sites. Fir was most dominant (10 fir to 1 spruce seedling) on the White River Plateau and in Rocky Mountain National Park, while fir and spruce were nearly equal at sites farther south (Grand Mesa, Lone Cone) and spruce outnumbered fir on the Aquarius Plateau on the Dixie NF in southern Utah. Their studies showed forest composition was not affected by beetle outbreak at the Boulder Top site on the Aquarius Plateau. The forest was nearly pure spruce before the outbreak, though subalpine fir was present as a small component of the understory. Unlogged stands remained nearly pure spruce after the outbreak. Despite fir being present in these stands, seedling composition was still dominated by spruce by 50 years after the outbreak (Figures 14 and 15). The difference may in part be due to the more southern location of the Boulder Top (its latitude is roughly equal to that of Telluride, CO), which may be less suitable for fir than sites in north-central Colorado.

Where aspen is present, it will likely do well following bark beetles, provided shading from residual conifers is not high, and if it is not browsed heavily by animals (domestic or wild) (see DeRose and Long 2010). A review focused on how aspen will respond to mountain pine beetle details factors that influence aspen recruitment and growth, and is relevant to forests affected by spruce beetle in Colorado (Pelz and Smith 2013). In forests of mixed aspen, spruce, and fir, residual fir may prevent much aspen regeneration response, though aspen may still be present on the site and could respond vigorously following fire (see Kulakowski et al. 2013, Kulakowski and Veblen 2003). In forests of mixed aspen and spruce, where there is high spruce mortality, aspen will be able to regenerate prolifically, unless heavy animal browsing is occurring. Spruce mixed with aspen but without fir is rare in much of Colorado and the Rocky Mountains but is common on the GMUG, particularly near the La Garita Wilderness. This area is thought to be too dry for fir but cold enough for spruce (Jim Thinnes, personal communication; Art Haines, personal communication). The response of aspen following bark beetles may “contribute to a negative feedback that may diminish the probability and/or severity of future disturbances and thus increase overall forest ecosystem resiliency” (Kulakowski et al. 2013).

5.6 Disturbance due to avalanches and windthrow

Disturbance by wind and avalanche is also an important factor structuring spruce forests. In locations susceptible to avalanches, frequent snow slides kill larger trees while allowing smaller trees to survive, creating somewhat-permanent patches of younger fir and spruce and also encourage shade-intolerant and or vegetative regeneration (such as aspen) (e.g. Veblen et al. 1994; Bebi et al. 2009). In northwestern Colorado, a 1938 blowdown affected stands in what would become the Mount Zirkel Wilderness area. Forests in blowdown areas were dominated by subalpine fir when resampled in the 2000s, while forests unaffected by blowdown were dominated by spruce (Kulakowski and Veblen 2003, Figure 16). Smaller trees were dominated by subalpine fir in blowdown areas as expected, but, importantly, spruce establishment of 300-400 stems per hectare occurred in the 4 decades following the blowdown, while nearly none established in previous years (Figure 17). If aspen is present, however, blowdown may provide an opportunity for aspen to become dominant because of its ability to sucker and take advantage of disturbance (Kulakowski et al. 2013).

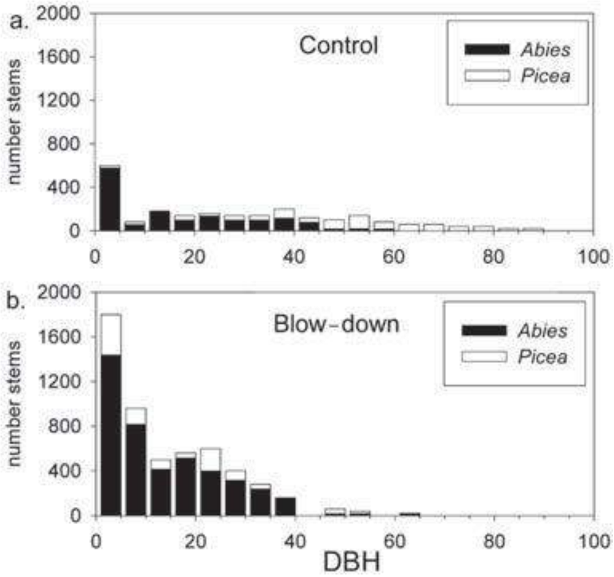


Figure 16. Comparison of fir (*Abies*) and spruce (*Picea*) density in stands with (b) and without (Control; a) blowdown. Blowdown stand had much greater density of fir and spruce in the small size classes, likely as a result of regeneration release and some post-blowdown establishment. Basal area was dominated by spruce in the control plots, as most of the largest trees were spruce.

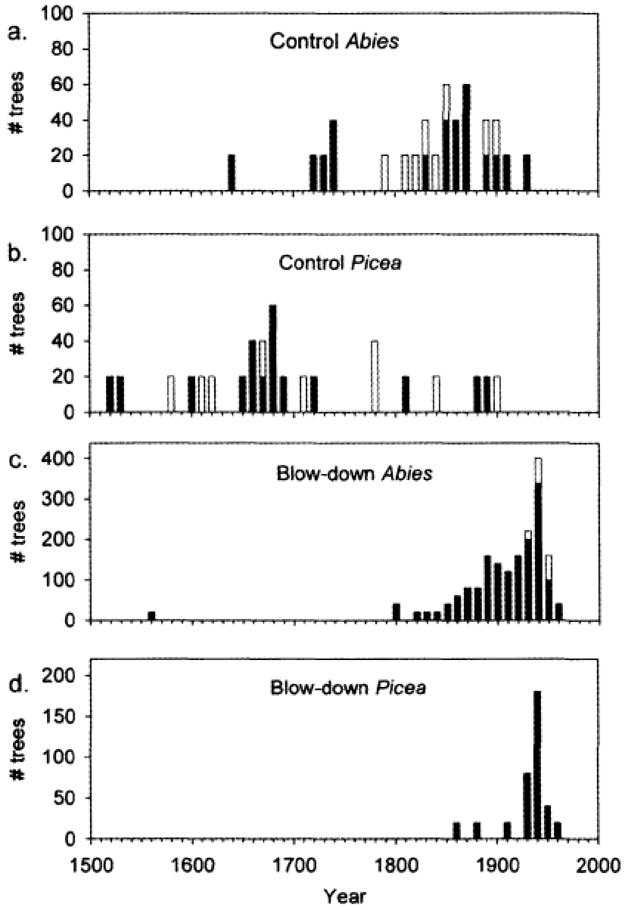


Figure 17. From Kulakowski and Veblen (2003). Dates of establishment for trees (stems per hectare) in blow-down and control areas by species. Empty bars indicate actual ages and white bars indicate minimum ages. Smaller trees were dominated by subalpine fir in blowdown areas as expected, but, importantly, spruce establishment of 300-400 stems per hectare occurred in the 4 decades following the blowdown, while nearly none established in previous years.

6. Spruce regeneration following mechanical harvest

Commercial clearcutting of Engelmann spruce was common between the 1940s and 1980s in Colorado, but was largely abandoned as a regeneration method due to the unpredictable nature of regeneration in these stands (e.g., Alexander 1987). Regeneration failures following clearcuts were common, and many stands that were clearcut in the past have been unsuccessfully planted repeatedly (A. Haines, D. Crawford, G. Fitzgerald, W. Shepperd, D. McGinn, K. Self, T. Garvey, personal communication). One of the major factors contributing to regeneration failure was that slash and other logging debris was cleared from sites after clearcutting reducing favorable microsites for spruce regeneration. In some cases, slash was burned following cutting, and these sites often had the worst regeneration failures (A. Haines, D. Crawford, G. Fitzgerald, W. Shepperd, K. Self, personal communication). According to practitioners, successful spruce regeneration in southwestern Colorado is best achieved with two-step shelterwood (preference of W. Shepperd, K. Self, D. Crawford, J. Thinnes, personal communication) or group selection techniques (preference of A. Haines, W. Shepperd, personal communication).

Much of our understanding of the effects of clearcutting on spruce regeneration comes from work done in the 1960s and 1970s. Alexander (1966) looked at 99 clearcuts on the Arapaho, Roosevelt, Routt, San Isabel, San Juan, and White River National Forests (Figures 18-20). The clearcuts were 200 to 400 feet wide, and either at right angles or parallel to the contour. Ninety percent or more of the advance regeneration was subalpine fir, but post-cutting regeneration was roughly evenly spruce and fir. Spruce regeneration was more likely where seedbeds were scarified while fir did well on undisturbed and disturbed areas. Overall, areas cut at right angles to the contour had better spruce reproduction than those cut parallel to the contour. Spruce stocking was greatest on north, north-west, and west aspects (~58%, ~50%, and ~42%, respectively) and had lowest stocking on south and south-western slopes (~10-12% on both). However, results were summarized by each factor separately and do not take into account the likely interaction of seedbed, aspect, slash, or slope. For example, Noble and Alexander (1977) showed that scarification was not important on south slopes but was important on north slopes. Also, this study showed that there was greatest stocking on plots with zero slash, though slash is widely considered necessary for creating micro-sites for spruce regeneration and successful planting (T. Garvey, A. Haines, W. Shepperd, D. Crawford, M. Windmueller-Campione, personal communication, Ronco 1970). Further, this study did not examine differences among treatment units or locations, which may have yielded important results. Therefore, the results of the original studies are full of uncertainty. Re-analysis of archived data with modern statistics may yield more definitive results.

Figure 18. Percent of plots (n = 1,748) stocked following clearcutting on different seedbeds (a), aspects (b), slopes (c) and slash cover (d) in survey of clearcut stands on the Arapaho, Roosevelt, Routt, San Isabel, and White River National Forests. Areas were logged between 1952 and 1956, and log skidding was done largely by horse but also 'tractors and jammers at some' sites. Results shown here are summarized by each factor separately and do not take into account the likely interaction of seedbed, aspect, slash, or slope. For example, Noble and Alexander (1977) showed that scarification was not important on south slopes but was important on north slopes. Interestingly, results show greatest stocking on plots with zero slash, which has been contradicted by observations and research since.

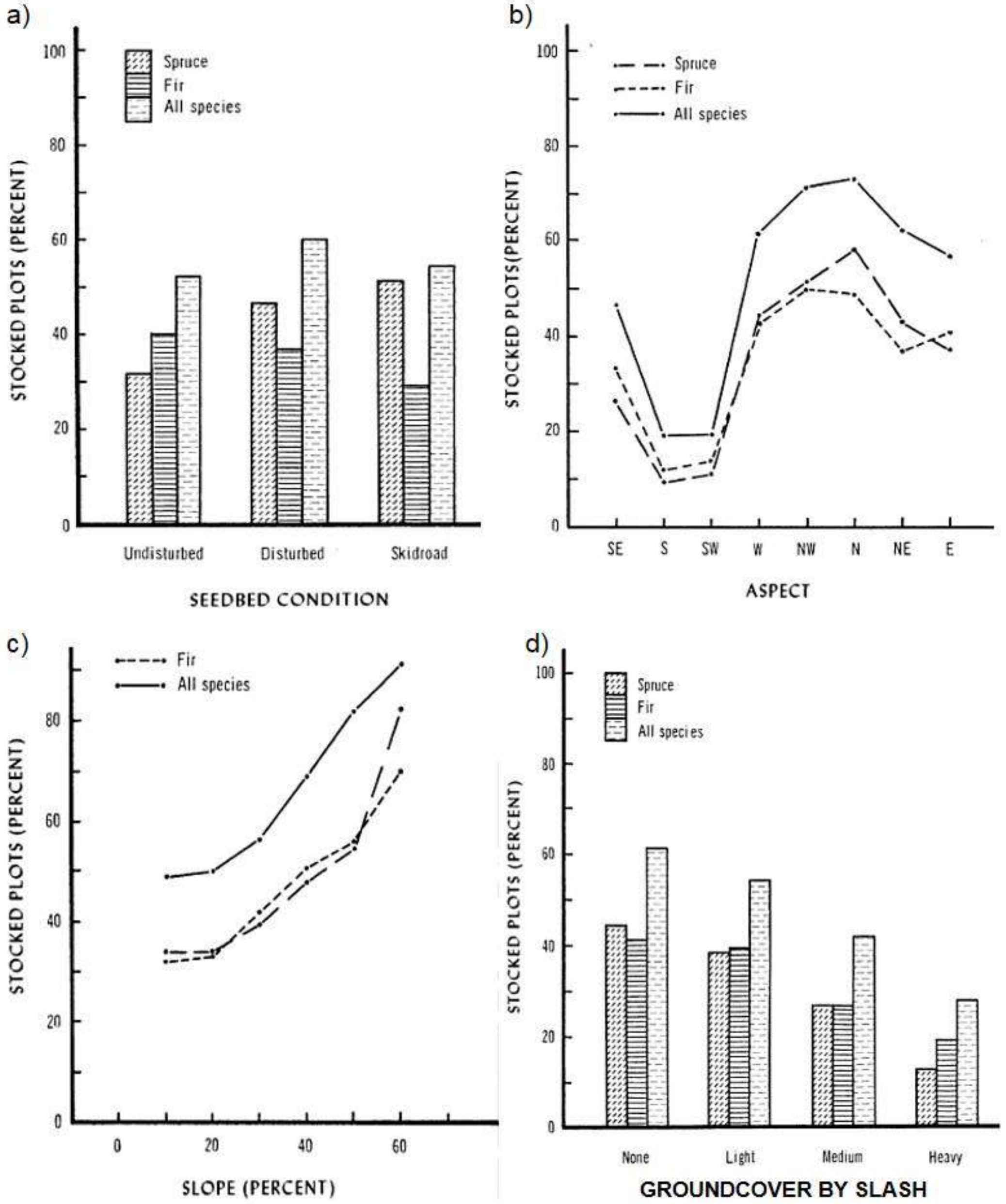


Figure 19. Engelmann spruce seedling density decreased with distance from edge in clearcuts across five forests of Colorado. Seedling density was much higher on the Routt NF than other Forests. X-axis values are in chains, or 66 ft (22.1 m). Logging slash was removed from cut area following harvest in all locations. Taken from Ronco (1970). See full article for more details on this study. Original caption reads, “Number of seedlings by age classes and percentage of stocked 1/300-acre plots (figures in parentheses) at different distances from the windward edge of clearcut openings on five National Forests. (Maximum possible age of seedlings: 5 years, Arapaho, Rio Grande, White River; 4 years, San Juan; 3 years, Routt.)”

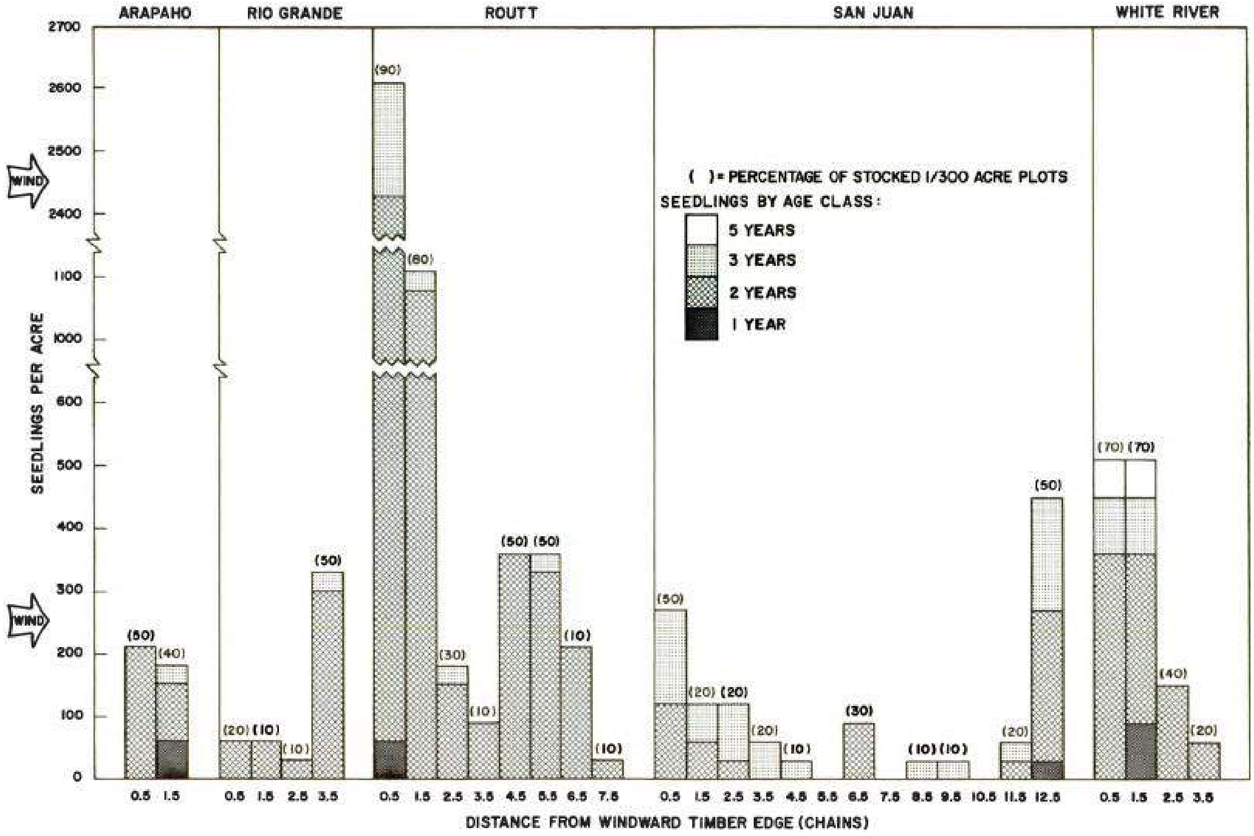
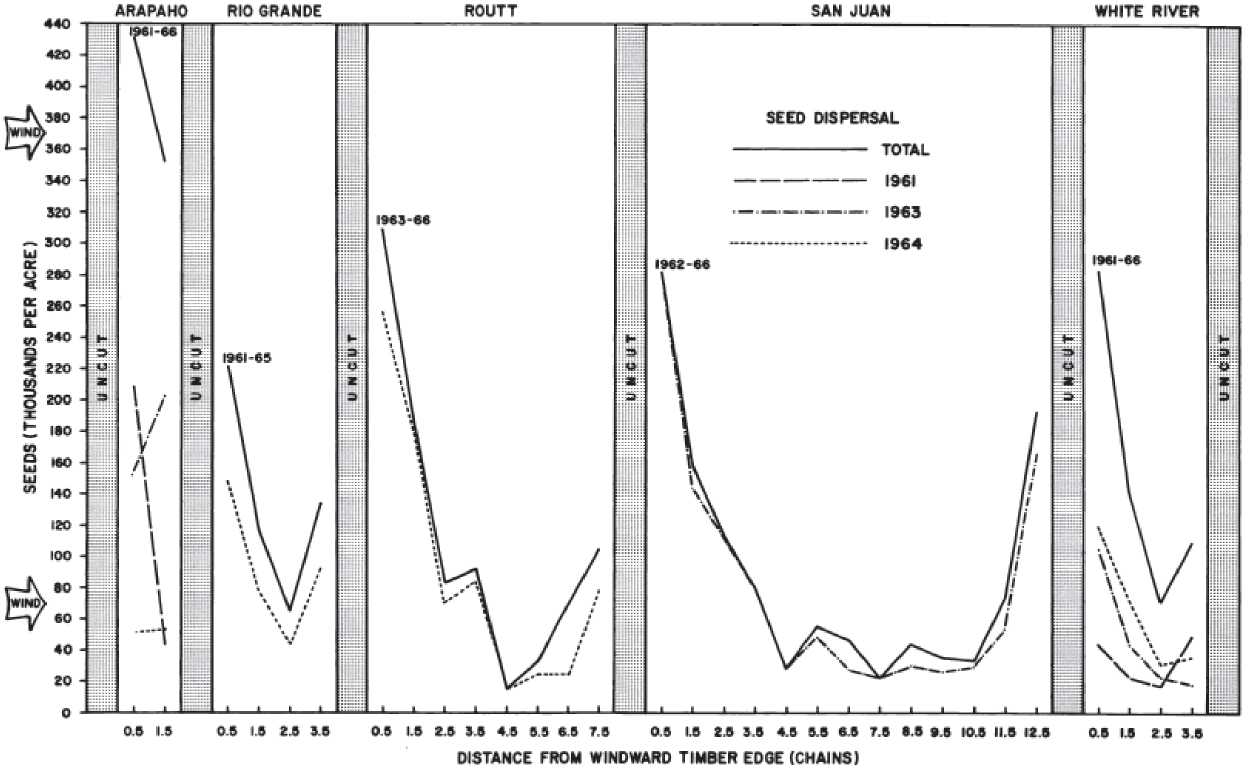


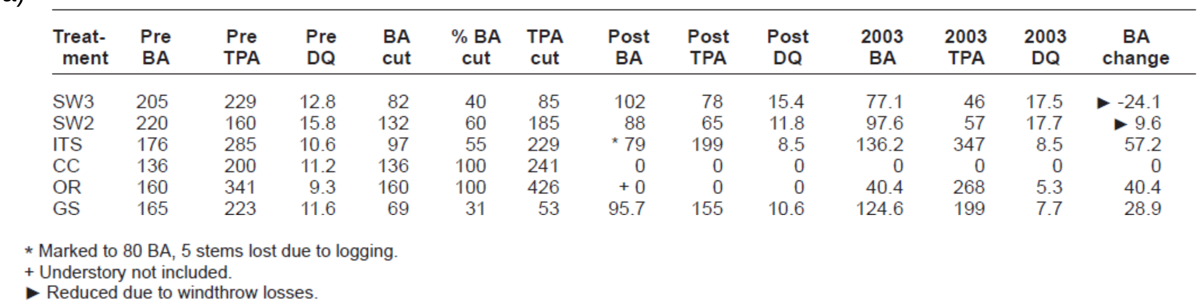
Figure 20. Seed availability with increasing distances from clearcut edges in five Colorado forests. Taken from Ronco (1970). Ronco concluded that low survival due to harsh environmental conditions, not lack of seed, was the primary factor limiting regeneration in clearcuts. However, seed dispersal appears to mirror the establishment pattern so seed availability likely contributed to regeneration density. One chain is equal to 66 ft, or 22.1 m. Original caption reads, “Seed dispersal by distance from windward edge of clearcut openings on five national forests for moderate to good seed years (1961, 1963, 1964), and total for all years measured on each Forest.”



One study has tracked the long-term effect of various cutting methods in spruce and fir forests in north-central Colorado. At Frasier Experimental Forest, stocking of fir and Engelmann spruce was ‘satisfactory’ 20 years after cutting with all methods (Shepperd et al. 2004). Cutting methods included: first cut of a three-step shelterwood; the first cut of a two-step shelterwood; individual tree selection; a clear cut; overstory removal; and group selection (see Shepperd et al. 2004 for prescription details). However, because of lack of replication and pre-cut forest structure and composition differences among stands, it is difficult to draw any statistically rigorous conclusions from this study. Each method was implemented on a one-acre site and forest composition and structure were not identical among sites. The ratio of spruce to fir seedlings/saplings by 20 years after cutting was greatest in the two-step shelterwood (1230:720 stems per acre) and lowest in the group selection (429:2210 stems per acre) (Table 4).

Table 4. Tables taken From Shepperd et al. (2004) showing 20 year results of silviculture trial in an Engelmann Spruce / Subalpine Fir forest at Frasier Experimental Forest. (A minor component of lodgepole pine was also present.) Top table (a) shows total (all species lumped) pre-cut ("pre", 1983) post-cut conditions ("post", 1984) and 2003 overstory (tress > 5 inches diameter at breast height) basal area (BA), trees per acre (TPA), and quadratic mean diameter (DQ) for stands with various treatments: SW3 = three-step shelterwood, SW2 = two-step shelterwood, ITS = individual tree selection, CC = clearcut, OR = overstory removal. Bottom table (b) shows seedlings and saplings present in this forest in 2003.

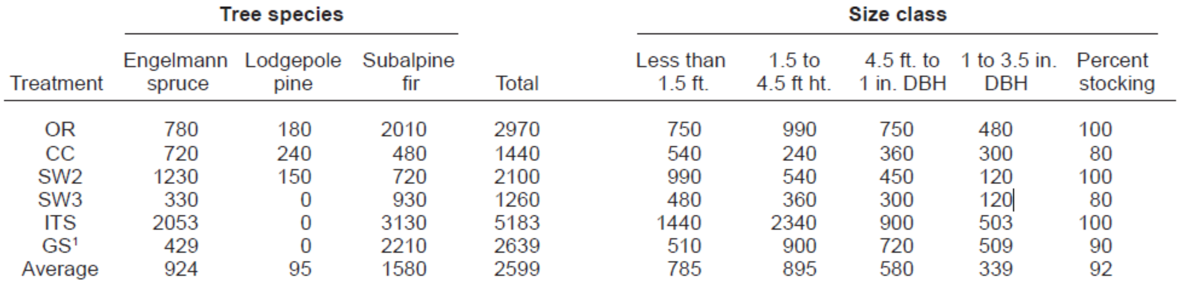
a)



Treat-ment	Pre BA	Pre TPA	Pre DQ	BA cut	% BA cut	TPA cut	Post BA	Post TPA	Post DQ	2003 BA	2003 TPA	2003 DQ	BA change
SW3	205	229	12.8	82	40	85	102	78	15.4	77.1	46	17.5	► -24.1
SW2	220	160	15.8	132	60	185	88	65	11.8	97.6	57	17.7	► 9.6
ITS	176	285	10.6	97	55	229	* 79	199	8.5	136.2	347	8.5	57.2
CC	136	200	11.2	136	100	241	0	0	0	0	0	0	0
OR	160	341	9.3	160	100	426	+ 0	0	0	40.4	268	5.3	40.4
GS	165	223	11.6	69	31	53	95.7	155	10.6	124.6	199	7.7	28.9

* Marked to 80 BA, 5 stems lost due to logging.
+ Understory not included.
► Reduced due to windthrow losses.

b)



	Tree species				Size class				
Treatment	Engelmann spruce	Lodgepole pine	Subalpine fir	Total	Less than 1.5 ft.	1.5 to 4.5 ft ht.	4.5 ft. to 1 in. DBH	1 to 3.5 in. DBH	Percent stocking
OR	780	180	2010	2970	750	990	750	480	100
CC	720	240	480	1440	540	240	360	300	80
SW2	1230	150	720	2100	990	540	450	120	100
SW3	330	0	930	1260	480	360	300	120	80
ITS	2053	0	3130	5183	1440	2340	900	503	100
GS[1]	429	0	2210	2639	510	900	720	509	90
Average	924	95	1580	2599	785	895	580	339	92

Regardless of regeneration methods, silviculture practitioners and researchers have emphasized the importance of protecting advance regeneration. Advance regeneration can be damaged by machinery. Over-snow harvesting is effective at reducing this damage (W. Shepperd, personal communication). Advance regeneration may also be damaged indirectly by harvesting by the change in environment. For example, at Fraser Experimental Forest around 10,000 ft elevation, spruce advance regeneration survival varied between aspects following clearcutting. On northern slopes, spruce advance regeneration was well represented, along with subalpine fir, but on west slopes, spruce did not survive as well as subalpine fir post-harvest (Alexander 1957). Ronco (1970b) found that loss of spruce seedlings due to solarization was likely above 10,000 feet in Colorado.

A major concern in Engelmann spruce management is loss of residual trees and trees along harvest edges to windthrow (Alexander 1963, 1964, 1986, 1987). Engelmann spruce is shallow rooted, and when neighboring trees are removed, trees which originally grew as part of a group are easily blown down (Alexander 1986). Placing cutting edges strategically can reduce windthrow, as discussed in Alexander (1964). Trees which were relatively open grown have a lower risk of windthrow than trees that have developed in dense, closed canopy stands. The loss of residual trees due to windthrow has been one of the major problems when doing individual tree selection (Alexander 1987, Long 1995, W.D. Shepperd, personal communication). Gradual reduction of stand density has been hypothesized to allow residual stems to build 'windfirmness'. Following this rationale, it is possible that the progressive nature of beetle-caused mortality could increase windfirmness of surviving trees. This is because the surviving trees would have several years to grow roots into areas formerly occupied by beetle-killed trees. However, we are not aware of studies that have shown this effect.

7. Effects of forest management following spruce beetle on regeneration

There is little published work specifically about the effects of forest management on forest regeneration following spruce beetle outbreaks in the Rockies. What does exist are retrospective studies of cutting from previous bark beetle outbreaks which lack good control of cutting methods, information about pre-treatment conditions and tree densities (e.g. Schmid and Hinds 1974). Studies show effects of cutting following spruce beetle in Alaska, but these forests are primarily white spruce (*Picea glauca*) and in locations with much different climate than the interior West. We can also look to recent work on the effects of harvesting following mountain pine beetle in the Rockies for insight into effects of harvesting following spruce beetle on future forest conditions.

Schmid and Hinds (1974) visited sites that had experienced spruce beetle and post-beetle harvesting ~15-50 years earlier in Colorado and Utah. Seedlings and sapling densities were highly variable across sites and between logged and unlogged areas. When averaged across logging units, harvesting had little measurable effect on seedling / sapling densities species composition. This may be because of the wide variety of logging intensities and techniques used, the variation in time since beetle and harvest, and the variation among sites. However, they did observe a few areas that had nearly complete regeneration failure. There sites were noted to have been "intensively logged" and the ground cover was not dominated by herbaceous vegetation. These failure sites included some sites that were clearcut at Lone Cone on the Uncompahgre National Forest.

There are studies showing the effects of management on regeneration following spruce beetle elsewhere, but the results are not likely to transfer from areas of different moisture and temperature regimes, or different latitudes, to Colorado. Spruce beetle affected thousands of hectares of white spruce (*Picea glauca*) forests in Alaska in the late 1990s and early 2000s. In these forests, studies showed that prescribed burning following forest salvage significantly increased post-beetle white spruce regeneration because it killed a competing grass, bluejoint (*Calmagrostis canadensisis*), and allowed spruce to establish at higher densities (Boucher and Mead 2006). However, areas that were burned following harvest in Colorado have, without exception that we are aware of, led to nearly complete regeneration failure (W. Shepperd, J. Thinnes, A. Haines, K. Self, D. Crawford, personal communications).

Salvage harvest has occurred following mountain pine beetle-caused mortality in lodgepole pine-dominated forests where Engelmann spruce, aspen, and subalpine fir were also present (as minor components, <10% of total pre-outbreak live basal area) in northern Colorado. These harvests increased lodgepole pine and aspen regeneration and reduced the shade-tolerant component of regeneration (composed primarily of subalpine fir but also Engelmann spruce) relative to that of uncut forests (e.g., Collins et al. 2011). Mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins), a close relative of spruce beetle, kills lodgepole pine trees and, like spruce beetle, the vast majority of trees killed are larger than 7 inches in diameter. Part of the relative reduction in subalpine fir following harvest was due to the post-harvest establishment of lodgepole pine and suckering of aspen. These shade-intolerant species are prolific regenerators in post-disturbance unshaded environments. Lodgepole pine and aspen recruitment was about 5 times greater in cut than uncut stands, with lodgepole densities of about 4500 ha^{-1} and aspen densities of about 2500 ha^{-1} in cut areas. Fir and spruce recruitment following cutting in beetle affected forests was not different between cut and uncut areas. Salvage in spruce-beetle-affected stands is therefore likely to increase establishment of lodgepole and aspen, if these species are present, at the expense of spruce and fir. However, an objective of many post MPB salvage operations was to establish lodgepole and aspen (if present) and protecting advance regeneration was not an objective of management in the situation studied, and harvested areas had half the spruce and fir advance regeneration of unharvested areas (Collins et al. 2011). Presumably, salvage efforts following spruce beetle will be designed to protect advance spruce and fir regeneration so harvest may not reduce their density as substantially as harvesting following mountain pine beetle.

Salvage following MPB in lodgepole pine forests of Colorado had effects on groundcover which may be similar to salvage following spruce beetle. Harvested areas were nearly ½ covered by woody debris, while uncut areas had only 2% woody debris cover. In cut areas, shrubs, graminoids, and forbs covered about half of the area they covered in uncut areas, likely due to the increase in woody cover. Interestingly, bare soil cover, often thought to increase following harvest, was not different between cut and uncut areas (about 3% cover in cut and uncut plots) (Collins et al. 2011). However, harvest following spruce beetle may have different effects particularly if protection of advance regeneration is a primary objective and forest floor disturbance is minimized through over-snow logging or other techniques.

8. Climate change and spruce regeneration

Although there is uncertainty in how climate change will affect specific locations, with some areas projected to receive increased total precipitation moisture, there is nearly unanimous consensus that climate change will lead to drier conditions due to the nearly universal increases in temperature (see Rocca et al. 2014 and Lukas et al. 2014 for relevant synthesis). Models generally estimate increases in total and winter precipitation in northern Colorado, and total annual precipitation decreasing in southern Colorado. Even if total precipitation increased, warmer air temperatures will almost certainly lead to drying -- for example, projected warming alone is likely to reduce Colorado River flow by 40-70% (Vano et al. 2014). Drier soils and fuels are a near certainty due to earlier snowmelt date and increased evaporative demand. This is likely to affect spruce forests by decreasing the incidence of the favorable conditions for successful Engelmann spruce establishment and is likely to increase fire season length and fire weather severity. Projected increases in season length and likely fire severity are likely to be the greatest climate-related threat to spruce forests (Rocca et al. 2014).

Engelmann spruce is sensitive to environmental conditions, particularly as a juvenile, and it is reasonable to expect climate change to have a substantial impact on the species. However, continental climates are known for extreme intra- and inter-annual variability to which native species are adapted. Spruce, like other conifers in the intermountain West, successfully regenerates only sporadically in much of its range when favorable climate and good seedcrop years coincide. Once established, mature spruce are long-lived and able to survive in many conditions that preclude successful regeneration. The different requirements of juvenile and established trees is one reason that studies which project loss due to climate change of tree species from specific areas using bioclimatic niche models should be interpreted cautiously (see Loehle and LeBlac 1996 for a good discussion of these concerns).

9. Conclusions

From this work, three major themes emerged:

1. **The importance of local climate.** Spruce, particularly when young, is highly sensitive to moisture and temperature. Thus, climate will have a direct impact on spruce regeneration and an indirect impact on its regeneration through climatic effects on disturbance regimes. The majority of what we know about spruce regeneration in Colorado comes from work done in/near Fraser Experimental Forest in the north central part of the state. This area has different growing season precipitation patterns than southwestern Colorado. Southwestern Colorado's climate is more similar to that of New Mexico and Arizona than that of northern Colorado. Within southwestern Colorado spruce forests, there are also important local differences: for example, the La Garita area on the Gunnison NF is in a 'rain shadow' and is much drier than the San Juan Mountains directly to the south.

2. **The importance of local species composition in future forest development and management planning.** Research and management guidelines related to spruce often assume all Engelmann spruce forests also have a large component of fir (usually subalpine

fir), calling the type 'spruce/fir'. Many forests are indeed a mix of both, especially in northern Colorado, but in southwestern Colorado there are significant areas dominated by spruce with little fir (either subalpine or corkbark) present. For example, on the Gunnison Ranger District, spruce occurs in nearly pure stands, stands of spruce mixed with aspen, and also spruce mixed with lodgepole pine. Species composition has major implications for post-beetle ecology and management. Subalpine fir is extremely shade tolerant and many 'spruce/fir' management guidelines have been developed with the objective of reducing fir to spruce ratios, though this difficult-to-achieve objective may be irrelevant in areas with little fir present.

3. **The slow pace of natural spruce regeneration.** Research throughout the range of Engelmann spruce consistently shows that the species naturally takes many years to regenerate 'fully-stocked' stands (that become forest with a closed canopy). Substantial recruitment occurs for 50 - 100 years (or more) after natural disturbances such as fire or beetle outbreaks. This creates age-class diversity and the open mosaic of forest and openings (often gramminoid and sagebrush-dominated) that are characteristic of high-elevation spruce forests. The slow recruitment is in part because seedlings are more sensitive to sun than mature spruce and often successfully establish in partially-shaded micro-sites, such as near the shade of a surviving tree or a dead standing or fallen tree trunk. (Therefore, if a seed source is present [e.g., mortality is not complete], bark-beetle outbreaks can provide good micro-site conditions for spruce forest regeneration.) The slow pace of regeneration naturally conflicts with National Forest Management Act requirements that areas within a Forest’s ‘suitable timber base’ be regenerated at a fully stocked level within five years of harvest.

Though we have considerable knowledge on Engelmann spruce in the southwest, we still have a limited understanding of the factors that control regeneration across different environmental gradients. Broad questions include: One of the broadest questions is “How will climate change influence regeneration niches for Engelmann spruce in southwestern Colorado, and how will fire, bark beetles and management interact with climate change effects?” Future studies that help answer this question in southwestern Colorado and beyond will improve the certainty of management decisions. Ongoing monitoring activities associated with the SBEADMR project will help address several of these issues. Yet, no matter how complete our understanding, science alone will not provide the answers for natural resource management. Management goals and objectives are designed based on values, and each of us has a different set of values. As forest researchers working on bark beetle management issues over 40 years ago stated, “factors such as values saved or lost, desires of the public, objectives of the land manager, and finances create a complex situation for which there is no answer agreeable to all” (Schmid and Hinds 1974).

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Appendix.

List of interview questions.

Questions:

1. In what geographic areas have you worked with Engelmann spruce?
2. Are there any specific conditions under which you've observed reliable natural regeneration of Engelmann spruce following harvest/salvage? Any conditions under which you've observed reliably poor regeneration? (Think about slope, aspect, elevation, forest floor cover, herbaceous vegetation cover, precipitation, soil type/condition, etc.)
3. Which silvicultural systems have produced the best regeneration of spruce? Any locations (aspects, elevations) where certain systems work better than others?
4. Have you observed effects of coarse woody debris on spruce regeneration (natural or planted) survival or growth?
5. When / where have you managed forest affected by spruce beetle? Any observations about regeneration / stand development in spruce or spruce / fir stands *without salvage* following spruce beetle? Following beetle, how does regeneration in un-salvaged areas compare to salvaged areas following spruce beetle? Any observations about how this has differed in different locations/aspects/elevations?
6. In your opinion, how do different silvicultural systems/prescriptions affect the ratio of Engelmann spruce to subalpine fir in mixed stands?
7. How have harvesting techniques and machines changed during your career, and how have any changes affected spruce / fir stand development following management activities?
8. What are your experiences/observations with spruce regeneration following prescribed fire or wildfire?
9. What triggers planting of spruce seedlings for you? What are your stocking guidelines in spruce / fir forests?
10. What kind of site preparation, if any, do you do following harvest in spruce/fir stands?
11. What conditions improve planted spruce seedling survival? What conditions result in the most planted spruce seedling mortality?
12. How has the Southern Rockies Lynx Amendment changed the way you manage spruce and spruce / fir forests?
13. How are you considering future climate predictions in your management of spruce / fir forests?
14. Do you have records about natural regeneration that you'd be willing to share? Any information on treatment location, prescriptions, seedling counts and stand exams from managed, unmanaged, green-tree harvest or spruce-beetle salvage, or post-fire forests is welcome.

About the Colorado Forest Restoration Institute

The Colorado Forest Restoration Institute (CFRI) was established in 2005 as an application-oriented program of the Department of Forest & Rangeland Stewardship in the Warner College of Natural Resources at Colorado State University. CFRI's purpose is to develop, synthesize, and apply locally-relevant science-based knowledge to achieve forest restoration and wildfire hazard reduction goals in Colorado and the Interior West. We do this through collaborative partnerships involving researchers, forest land managers, interested and affected stakeholders, and communities. Authorized by Congress through the Southwest Forest Health and Wildfire Prevention Act of 2004, CFRI is one of three Institutes comprising the Southwest Ecological Restoration Institutes, along with centers at Northern Arizona University and New Mexico Highlands University.

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