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A Scenario-Based Assessment to Inform Sustainable Ponderosa Pine Timber Harvest on the Black Hills National Forest

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Abstract

Since 2000, the Black Hills National Forest (BHNF) has experienced several disturbances that have reduced standing live sawtimber volume which will affect future harvest levels. To evaluate options concerning the future timber management program, we conducted a quantitative analysis to determine how mortality from these disturbances and potential growth rates will impact short-, mid-, and long-term sustainable sawtimber harvest levels of ponderosa pine (*Pinus ponderosa* var. *scopulorum* Dougl. ex Laws.). In 2019, there was 5,995,428 CCF (hundreds of cubic feet) standing live ponderosa pine sawtimber within the suitable timberlands. The current harvest level in the BHNF Forest Plan of 181,000 CCF/yr is not a sustainable option. Over the next several decades, if mortality rates stay below 1.04%, harvest levels of 72,400 and 90,500 CCF/yr appear to be sustainable if all suitable timberlands are available for harvest. History shows that allowing the forest to recover after large disturbances provides opportunities to adjust future harvest levels. Also, tending of young forests can promote recovery and produce sawtimber volume more quickly.

Keywords: ponderosa pine growth and mortality, disturbance, growth and yield, scenario planning

Cover: Upper left: Ponderosa pine advanced regeneration beneath an overstory that was killed by mountain pine beetle. (Photo by Russell Graham, Rocky Mountain Research Station, USDA Forest Service)

Upper right: An even-aged ponderosa pine stand that was not impacted by mountain pine beetle. Stands with this density are still susceptible to mountain pine beetle and limit successful establishment of ponderosa pine seedlings. These dense stands provide opportunities for future harvests. (Photo by Mike Battaglia, Rocky Mountain Research Station, USDA Forest Service)

Middle: A landscape view of the Black Hills looking north from Flag Mountain Lookout, Mystic Ranger District in 2014 showing the widespread impact of mountain pine beetle mortality (orange/brown areas) in dense forests. Forested stands managed at lower densities demonstrated lower mountain pine beetle mortality (Taylor Timber Sale). (Photo by Blaine Cook, Black Hills National Forest, USDA Forest Service)

Bottom left: A harvest operation in a ponderosa pine stand on the Black Hills Experimental Forest. (Photo by Russell Graham, Rocky Mountain Research Station, USDA Forest Service)

Bottom right: Ponderosa pine timber being processed at the Spearfish Forest Products, Inc mill in Spearfish, SD. (Photo by Mike Battaglia, Rocky Mountain Research Station, USDA Forest Service)

Authors

Russell T. Graham (deceased) was a Research Forester (Silviculturist) with the USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho. He started his Forest Service career in 1966 as a high school student working on the Bear Lodge Ranger District, Black Hills National Forest. His research activities included studying the role that coarse woody debris plays in forests, addressing large-scale ecosystem assessment and planning, describing northern goshawk habitat, and evaluating the impacts of major wildfires. Russell Graham passed away on August 29, 2020. Russell was leading our team; in his stead we continued to prepare this report and carry forward his vision and subsequent legacy.

Mike A. Battaglia is a Research Forester (Silviculturist) with the USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. His research focuses on developing and implementing innovative management strategies to enhance forest resiliency to disturbances and evaluating the subsequent ecological impacts of these activities.

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Each of the authors has had a unique familiarity with the Black Hills. Russell Graham grew up in Sundance, Wyoming, and his first job for the Forest Service was on the Bear Lodge Ranger District. Russell also supported the Forest Service with his continued research on the Black Hills producing several notable publications on goshawks, long-term studies of thinning in ponderosa pine, and mountain pine beetle dynamics. Mike Battaglia's Ph.D. work was within the Black Hills; he is currently the Scientist-in-Charge of the Black Hills Experimental Forest and continues to have an active partnership with the Black Hills National Forest. During the bark beetle infestation, Theresa Jain implemented the free selection silvicultural system on the Black Hills Experimental Forest and worked with Northern Hills Ranger District staff during sale preparation. Because of this connection to the Black Hills, we were honored to be approached by the USFS Rocky Mountain Region and Black Hills National Forest to prepare this report.

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Executive Summary

Since 2000, the Black Hills National Forest (BHNF) has experienced several disturbances that have reduced standing live sawtimber volume which will affect future harvest levels. We conducted a quantitative analysis to determine how mortality from these disturbances and potential growth rates will impact short-, mid-, and long-term sustainable sawtimber harvest levels of ponderosa pine (*Pinus ponderosa* var. *scopulorum* Dougl. ex Laws.) on the BHNF. More specifically, we estimated: (1) a sustainable timber harvest now and into the future, (2) how current harvest levels compare to alternative future harvests, and (3) the standing live sawtimber inventory volume needed to sustain the current Forest Plan sawtimber allowable sale quantity (ASQ) of 181,000 CCF/yr (hundreds of cubic feet). To provide plausible volume growth and mortality estimates, we: (1) evaluated disturbance related mortality in ponderosa pine forests within the Black Hills and across the Interior West using past Forest Inventory and Analysis (FIA) resource bulletins and (2) considered potential future climate and its influence on disturbance and potential mortality. From these assessments, 60 scenarios were developed and used to inform future potential changes (5, 20, and 80 years) in standing live sawtimber volume by varying degrees of mortality rates, growth rates, and harvest levels.

In 2019, the USDA Forest Service Northern Research Station Forest Inventory and Analysis (NRS-FIA) estimated that there were 5,995,428 CCF standing live ponderosa pine sawtimber within the suitable timberlands of the BHNF. The current harvest level in the BHNF Forest Plan of 181,000 CCF/yr is not a sustainable option. Sustaining harvest levels of 181,000 CCF/yr with mortality rates of 0.26% would require standing live sawtimber volumes of 7,327,950 to 8,743,950 CCF, depending on growth rate evaluated. If mortality rates are 0.60% to 1.04%, standing live ponderosa pine sawtimber volumes would require 8,497,670 to 14,031,000 CCF, respectively. Over the next several decades, if mortality rates stay below 1.04%, harvest levels of 72,400 and 90,500 CCF/yr appear to be sustainable if all suitable timberlands are available for harvest. These estimates provide a range of outcomes on the potential to sustain ponderosa pine sawtimber harvests over 5, 20, and 80 years; however, monitoring is crucial to obtain realized mortality and growth rates so harvest levels can be adjusted over time. History shows that allowing the forest to recover after large disturbances provides opportunities to adjust future harvest levels. Also, tending of young forests can promote recovery and produce sawtimber volume more quickly. It is important to understand that the scenario estimates we reported assume that all the estimated standing live ponderosa pine sawtimber volume within the suitable timberlands is available for harvest and does not include other resources that are identified in the 2007 Black Hills National Forest Land and Resource Management Plan Phase II Amendment.

Introduction

The Setting

Located on the eastern edge of the Rocky Mountains, the Black Hills, Bear Lodge, and Elk Mountains make up the Black Hills region, which are isolated mountain ranges surrounded by the Great Plains of the United States. Over two-thirds of the Black Hills are in southwestern South Dakota, while the neighboring Bear Lodge Mountains and remaining areas are in northeastern Wyoming. These mountains, collectively referred to as the "Black Hills," have a total land base of about 6,000 square miles: about 125 miles from north to south and about 60 miles from east to west (fig. 1). Across this large area, elevations range from 3,800 feet to 7,244 feet with distinct geomorphologic features that influence soils, site productivity, and vegetation. Although nearly 1.5 million acres of the area are dominated by ponderosa pine (*Pinus ponderosa* var. *scopulorum* Dougl. ex Laws.) forests (fig. 2), white spruce (*Picea glauca* (Moench) Voss), quaking aspen (*Populus tremuloides* Michx.), along with isolated lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *latifolia* (Engelm.) and limber pine (*Pinus flexilis* James) (Shepperd and Battaglia 2002; Walters et al. 2013) are present.

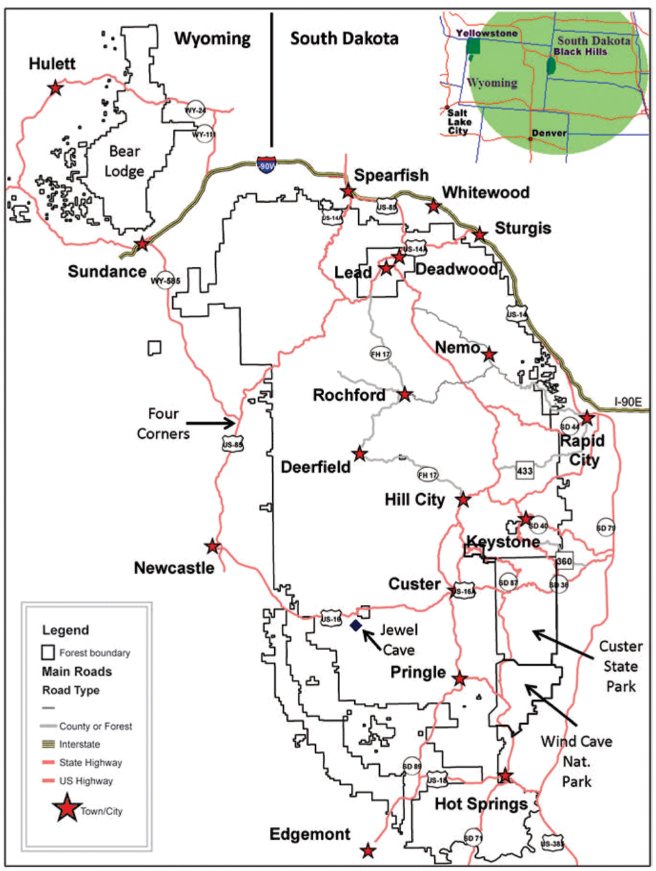

Figure 1—The Black Hills National Forest (BHNF) is approximately 1.2 million acres and is located in northeastern Wyoming and western South Dakota. This isolated mountain range is surrounded by the Great Plains and is dominated by ponderosa pine. The area is a popular destination for tourists due to the proximity of Custer State Park and several National Parks and Monuments.

Figure 2—A landscape dominated by dense ponderosa pine forests. USDA Forest Service photo by Mike Battaglia.

The Black Hills has a continental climate, with cold winters and hot summers. Although precipitation patterns differ along elevational and latitudinal gradients, in general, northern locations and higher elevations receive more precipitation than southern locations and lower elevations (Shepperd and Battaglia 2002). While precipitation falls year-round, most of the moisture occurs from March to August (Western Regional Climate Center 2020). Abundant ponderosa pine seed crops occur every 2 to 5 years that coincide with summer moisture leading to prolific seedling establishment (fig. 3).

Figure 3—Prolific ponderosa pine regeneration typically observed across the Black Hills. USDA Forest Service photo by Mike Battaglia.

This region has a well-developed road system and gentle topography that is well-suited for mechanized and efficient timber harvesting. Typical site index (base age 100) within the Black Hills ranges from 36 to 75 feet (Myers and Van Deusen 1960a). These forests produce high quality ponderosa pine lumber, geographically have access to midwestern U.S. lumber markets, and have sustained a viable timber industry for over 100 years (Boldt and Van Deusen 1974; Freeman 2015; Shepperd and Battaglia 2002).

This area is often referred to as the "Beautiful Black Hills" because of its geographic diversity, canyons, and unique rock formations that are interwoven within a scenic forest. The Black Hills region is home to the Black Hills National Forest (BHNF), Mount Rushmore National Memorial, Devils Tower National Monument, Custer State Park, Crazy Horse Memorial, Wind Cave National Park, Jewel Cave National Monument, Spearfish Canyon Scenic Byway, and the George S. Mickelson 108-mile biking and hiking trail. With so many places to experience the outdoors, these isolated mountains are a popular tourist destination that supports a strong and vibrant local economy (Stubbles 1992). The Black Hills and surrounding prairie are also a popular hunting destination where state residents and nonresidents alike are drawn to hunt elk (*Cervus elaphus nelson*), white-tailed deer (*Odocoileus virginianus dakotensis*), mule deer (*Odocoileus hemionus*), pronghorn antelope (*Antilocapra americana*), turkeys (*Meleagris gallopavo merriami*), and other small and large game animals.

Disturbances are major determinants of forest structural diversity and composition within the Black Hills (Shepperd and Battaglia 2002). Weather (e.g., wind, hail, tornados, and snow), wildfire, insects, parasites, pathogens, and animals individually and in combination kill trees, create openings, and promote vegetative diversity (Lundquist 1995). Of these disturbances, insects, wildfire, and weather have been the most noticeable causes of tree mortality (Brown et al. 2008; Graves 1899; Ludlow 1875; Negrón et al. 2008; Shepperd and Battaglia 2002). The forests of the Black Hills have experienced cyclic mountain pine beetle (*Dendroctonus ponderosae*; MPB) epidemics (fig. 4), impacting different locations with various amounts of severity (fig. 5). In addition to MPB, frequent wildfires also burned the forests of the Black Hills (fig. 6); these wildfires are ecologically important in perpetuating regeneration and contributing to the development and disturbance resilience of ponderosa pine forests (Fiedler and Arno 2015). Before European settlement, average wildfire return interval ranged from 10 to 31 years, depending on elevation (Brown and Sieg 1996; Brown and Sieg 1999; Brown et al. 2008; Hunter et al. 2007). However, with the onset of fire exclusion, logging, and grazing in the early 1900s, fire frequencies decreased resulting in an increase in forest density and contiguous multistoried stands (Brown and Cook 2006; Grafe and Horsted 2002; Hunter et al. 2007).

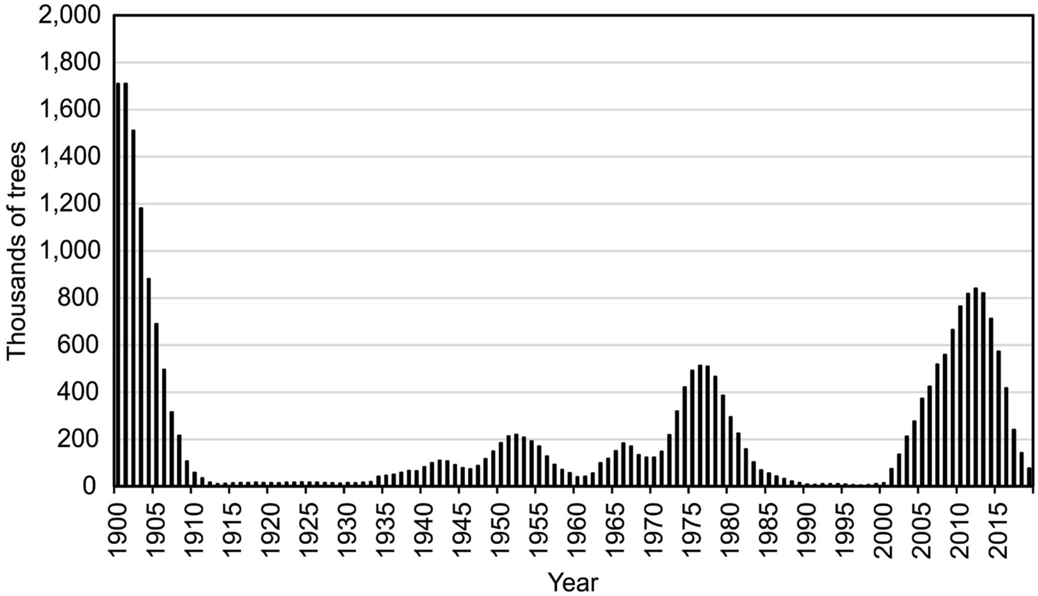

Figure 4—Within the forests of the Black Hills, there has been a continuous endemic and several epidemics of mountain pine beetles over the last 129 years (see Graham et al. 2016, fig. 31). From 2000 through 2017, over 8,000,000 trees were estimated to have been killed. Values reported are the 5-year moving average.

At the beginning of the 21st century, standing live ponderosa pine volume was at its highest levels in recorded time. These high volumes provided forested stand and landscape conditions that were classified at moderate to high hazard for MPB and wildfire (USDA FS 2013). In addition, results from long-term and recent studies across the BHNF showed that current high stand densities were susceptible to MPB and needed to be lowered across the landscape (Graham et al. 2016; Negrón et al. 2008; Negrón et al. 2017; Schmid et al. 2007). During this same time period, the BHNF started to experience an MPB epidemic (fig. 5) and several large mixed severity wildfires (fig. 6). Within the wildfire perimeters, areas with low stand densities burned less severely (Lentile et al. 2006). This local information combined with the incorporation of reducing surface fuel loads, increasing height to live crown, decreasing crown density, and maintaining large fire-resistant trees (Agee and Skinner 2005) provided additional science-based guidance for forest management that would help reduce MPB and wildfire hazard.

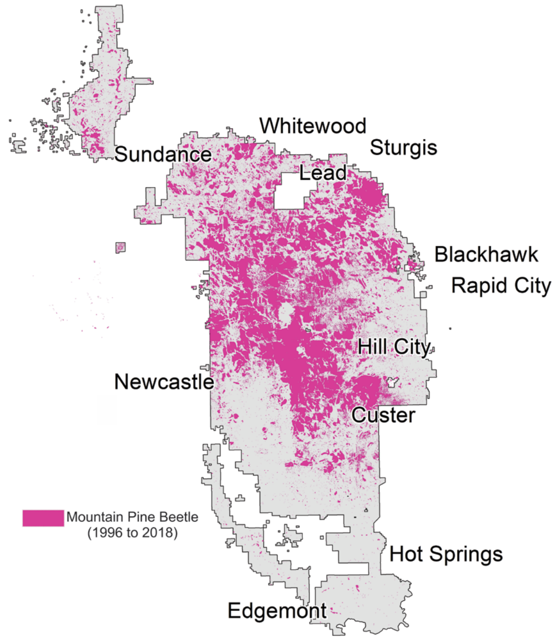

Figure 5—The most recent (i.e., 1998) MPB epidemic started with many isolated areas of endemic MPB populations throughout the Black Hills. As the endemic populations increased in numbers, the MPB spread throughout the central and northern Black Hills. Notably, the MPB infestation was less in Wyoming portions of the Black Hills and Bear Lodge Mountains (see Graham et al. 2016, figs. 65–69, for details on the extent and impact of mountain pine beetles in the Black Hills). This disturbance can have a substantial impact on post-disturbance recovery.

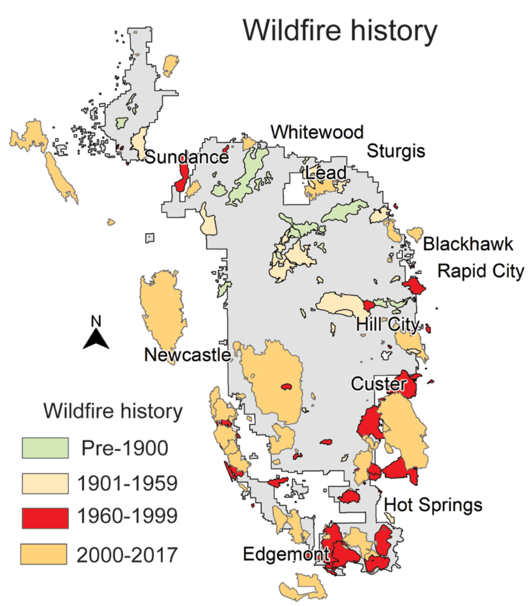

Figure 6—Spatial representation of wildfires in the Black Hills since the late 1800s (USDA FS 2020c). Wildfires in the Black Hills have been increasing since 2000, with more acres burned between the years 2000 to 2017 than from 1960 to 1999.

In response to the increased MPB and wildfire activity, the USDA Forest Service (USFS) adjusted its timber sale program to reduce forest susceptibility to these disturbances (Thom et al. 2020). Based on USFS timber volume sold records, from 1997 to 2011, an average of 154,543 CCF/yr (hundreds of cubic feet) of sawtimber was sold (file on record at BHNF). In 2010, a collaborative approach including local, state, and federal agencies, conservation/natural resource districts, private industry, landowners, and citizens was formed to create the Black Hills Regional Mountain Pine Beetle Strategy (Thom et al. 2020). This strategy coordinated efforts across all lands and provided education and monetary resources to shift and coordinate management strategies to reduce MPB mortality (Thom et al. 2020). Through this collaborative effort, the BHNF developed the landscape-level Mountain Pine Beetle Response Project (USDA FS 2012a) to lower forest density through mechanical harvest to reduce tree mortality. This approach led to landscape-level treatments that lowered stand densities to minimize MPB mortality and reduce wildfire hazard (USDA FS 2012b). Between 2012 and 2017, approximately 188,000 acres of ponderosa pine sawtimber was commercially harvested across all land ownerships, with the majority of the acres treated occurring on National Forest lands (Thom et al. 2020). Based on USFS timber volume sold records, from 2012 to 2017, an average of 193,107 CCF/yr of sawtimber was sold (file on record at BHNF). While sawtimber harvest volumes were increasing, most treated stands were adjacent to MPB infested stands rather than in the infested stands themselves (fig. 7); the combination of MPB and harvesting of green trees contributed to the reduction of the standing live sawtimber volume on the BHNF.

Figure 7—Mountain pine beetle impacted ponderosa pine sawtimber that was not harvested. USDA Forest Service photo by Mike Battaglia.

Recognizing an Information Need

Land use and natural disturbances constitute the fabric of the Black Hills forests. This public land is administered and managed by the USFS BHNF. Over the past century, the BHNF maintained an active timber program that helped support mining, paper, and lumber industries (Freeman 2015). For much of the 1900s, harvesting was extensive, often with logs processed with portable mills that were moved to harvest areas. The Multiple Use—Sustained Yield Act of 1960 affirmed the USFS's commitment to produce timber. The act required "the achievement and maintenance in perpetuity of a high level or regular periodic output of the various renewable resources of the national forests without impairment of the productivity of the land" (Multiple Use—Sustained Yield Act of 1960). As a result, timber harvesting began to increase in the 1960s on the BHNF
(Swanson 2012). Today, the USFS mission is to "sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations" (USDA FS 2020a). For many people, this forested island in the Great Plains is a special place and balancing land use is at the forefront of actions by local to national stakeholders and land managers (Stubbles 1992; USDA FS 2016). The Black Hills are cherished, valued, and used by a wide range of stakeholders including tourists, miners, hunters, loggers, and ranchers. The Black Hills provide a sense of place for local to international citizens and are a sacred place for Native Americans. There is strong interest to develop management options that can maintain a vibrant and sustainable timber industry in the Black Hills while also supplying abundant scenery, wildlife and domestic animal habitat, and recreational opportunities.

Over the last two decades (2000–2020), multiple disturbances have changed the forest characteristics of the Black Hills (figs. 5 and 6). Recognizing these changes, in June 2017 the BHNF Leadership convened a working group to develop questions of interest on how these changes may impact the ability of the BHNF to provide forest products to the timber industry. These questions centered on developing a comprehensive understanding of the forests growing on BHNF suitable timberlands (Appendix A). This working group consisted of BHNF staff, industry representatives, and representatives from the South Dakota and Wyoming State Foresters' offices. The working group and the leadership of the BHNF recognized an information need that required a rigorous inventory of the forest resources of the Black Hills and agreed to have the Forest Service's Northern Research Station Forest Inventory and Analysis Program (NRS-FIA) provide the data for the assessment.

Therefore, the working group agreed to assess the current trends in forest standing live volume, growth, and mortality of the BHNF using an FIA sampling design and data collection protocol. As a result, from 2017 through 2019, the NRS-FIA inventoried the forests of the BHNF. Rather than using the normal plot intensity of one plot for every 6,000 acres, they increased the number of plots to one for every 3,000 acres and measured them over a 3-year period. The working group agreed to have the NRS-FIA use data from this survey to address the following questions:

- What is the standing live volume estimate?
- What is the annual gross growth estimate?
- What is the annual net growth estimate?
- What is the net growth to removal ratio?
- What is the ability to produce an available sustained yield on the Forest (timberlands/suitable base) for the next decade and what is the methodology for producing this estimate?

Upon reviewing these questions, the leadership of the BHNF asked the USDA Rocky Mountain Research Station (RMRS) to form a team to address the following questions:

1. What impact does the current 2019 forest condition (i.e., standing volume, mortality, and growth) have on the out-year timber program of harvesting at current levels compared to other harvest level scenarios using probable growth and mortality estimates?
2. What is a sustainable timber harvest estimate for the BHNF using the 2019 NRS-FIA data assuming rational tree mortality and growth rates informed by those of the past?
3. What would be the standing inventory volume necessary using reasonable growth and mortality estimates to sustain a sawtimber allowable sale quantity (ASQ) of 181,000 CCF?

To address the three questions, we needed estimates of volume growth and mortality rates (hereafter referred to as growth and mortality rates). We assessed past FIA resource bulletins and data to provide historical context and variability of standing live volume, growth and mortality rates, and harvest levels. We also evaluated the role that various disturbances contributed to mortality within the Black Hills and in ponderosa pine forests across the Interior West. Finally, we considered potential future climate to incorporate an element of uncertainty in mortality rates. These assessments, when combined, provided the framework to develop 60 scenarios to inform future potential changes in standing live sawtimber (> 9 inches diameter at breast height; d.b.h.) volume by varying degrees of mortality and growth rates and harvest levels. We report 5-year trends to address question 1 (above). We report 20-year and 80-year trends to address question 2. To determine the level of standing live sawtimber volume required to sustain 181,000 CCF/yr for each growth and mortality rate (question 3), we determined at what volume would net growth equal harvest level.

Approach

Understanding Disturbance and Tree Mortality

Ponderosa pine mortality from pathogens, animals, insects, weather, and wildfire varies over space, time, and intensity in the Black Hills (Graham et al. 2016; Shepperd and Battaglia 2002). Although most historical mortality information is descriptive, these observations indicate that disturbances have always shaped the character of the Black Hills forests. For example, Ludlow (1875), when he accompanied General Custer to the Black Hills in 1874, observed large tracts of pines likely killed by insects and large fires burning in the prairie and forests that were either ignited by lightning or Native Americans. Graves (1899) described several expanses of ponderosa pine trees killed by insects and wildfire when he surveyed the Black Hills Forest Reserve. The Bureau of Entomology and Plant Quarantine provided intermittent reports on forest insect and disease conditions in the United States in the 1930s. Forest Service Research Stations and Forest Service Regional staffs in the 1950s (Ostmark and Wilford 1956; Wilford 1951) and Forest Health and Protection began providing similar information in the 1990s (Liebhold et al. 2016; O'Neil 1993).

Pathogens, Animal Damage, and Weather

Ponderosa pine regenerates profusely in the Black Hills creating multistoried structures that contain numerous and often dense patches (e.g., thousands of trees per acre) of suppressed saplings (< 5 inches d.b.h.) and seedlings (< 4.5 ft tall), making them vulnerable to a wide range of mortality agents. Saplings are killed by root and stem pathogens (e.g., *Armillaria* spp., red rot [*Dichomitus squalens mellea*], western gall rust [*Peridermium harknessii*]), and needle cast (*Elytroderma deformans*). Similarly, animal damage can also contribute to ponderosa pine mortality such as mice (*Microtus* spp., *Peromyscus* spp.), cottontail (*Sylvilagus floridanus similis*) and jackrabbits (*Lepus townsendii*), which can girdle and kill seedlings. Deer (*Odocoileus* spp.), elk (*Cervus* spp.), cattle (*Bos* spp.), and sheep (*Ovis* spp.) also damage and kill ponderosa pine trees by trampling, rubbing, and browsing but the amount of trees killed does not appreciably modify stand structures (Boldt and Van Deusen 1974).

Weather, in the form of wind, snow, ice, tornados, and hail, intermittently damages and kills ponderosa pine trees throughout the Black Hills. These events can occur both singly and in concert with other endemic damaging agents. Straight-line winds kill individual trees yearly and tornados are known to kill small (e.g., 10 to 15 acres) patches to large (e.g., 7,000 acres) areas of trees occasionally. Also, large (≥ 1 inch diameter) hail associated with thunderstorms can defoliate and damage sapling- to pole-sized (5 to 8.9 inches d.b.h.) trees (Boldt and Van Deusen 1974; Shepperd and Battaglia 2002). Damage from wind and snow can bend and break sapling-sized trees and break or topple pole-sized trees (Collins and Green 1988; Johnson and Averill 1983; Lundquist 2007; Lundquist and Negrón 2000). As a result, weather and mortality caused by diseases and animals were the major contributors to tree mortality observed in the Black Hills during the 1980s through the 1990s (table 1).

Table 1—Volume mortality rates based on standing live volume of growing stock trees (> 5 inches d.b.h.), throughout the last several decades in the Black Hills region. Values of mortality category (rounded to 2 significant digits) are based on the proportion that each disturbance contributed to the overall total mortality rate. Values might not add up due to rounding.

Year	Mortality rate (%)	Insect (%)	Fire (%)	Disease (%)	Weather (%)	Other (%)	Mortality (%) without insect included
1962[a]	0.15	0.03	0.00	0.08	Not reported	0.03	0.12
1984[b]	0.26	0.03	0.03	0.00	0.17	0.03	0.23
1999[c]	0.27	0.03	0.03	0.03	0.19	0.00	0.24
2011[d]	1.24	0.80	0.13	0.00	0.27	0.04	0.44
2019[e]	3.07	2.60	0.20	0.05	0.20	0.02	0.47

[a]1962: Mortality and standing live volume based on softwoods across all land ownerships in South Dakota on suitable timberlands (data source: Choate and Spencer 1969).

[b]1984: Mortality and standing live volume based on ponderosa pine across all land ownerships in South Dakota on suitable timberlands (data source: Collins and Green 1988). Mortality by disease was 0.002).

[c]1999: Mortality and standing live volume based on ponderosa pine on the Black Hills National Forest (South Dakota and Wyoming) on suitable timberlands (data source: DeBlander 2002). Mortality by disease was 0.025 and fire was 0.025.

[d]2011: Mortality rate was based on ponderosa pine on the Black Hills National Forest in South Dakota on suitable timberlands. Walters et al. 2013 reported mortality of 1.04%, which included Wyoming and South Dakota; however, when FIA provided the values for 2011 by mortality category, it was only for South Dakota lands.

[e]2019: Mortality and standing live volume based on ponderosa pine on the Black Hills National Forest (South Dakota and Wyoming) on suitable timberlands (source: USDA FS 2021).

Mountain Pine Beetle

The Black Hills have experienced MPB epidemics periodically somewhere on the Forest approximately every 20 years, with notable events in the early 1900s, the late 1960s to the early 1980s, and the most recent epidemic from 2000 through 2017 (fig. 4; Graham et al. 2016; Lessard et al. 1987; Thompson 1975). Ponderosa pine tree susceptibility to MPB is related to stand density and tree diameter (Graham et al. 2016; Negrón et al. 2008). Mountain pine beetles can attack pole-sized ponderosa pine trees but prefer sawtimber-sized trees (Graham et al. 2016; Negrón et al. 2008; Negrón et al. 2017; Schmid et al. 2007). From 1960 through 1999, it is estimated that MPB killed 5,733,550 ponderosa pine trees (Graham et al. 2016; Lessard et al. 1987). During this period, insect mortality contributed 0.03% to the total mortality rate (table 1). In the 1960s through mid-1970s, mortality caused by MPB was most evident in the northern Black Hills (Thompson 1975). By the mid-1970s, tree mortality from MPB was clearly evident along the Wyoming and South Dakota border, south and west of Spearfish, South Dakota, and within portions of the southern Bear Lodge Mountains, near Sundance, Wyoming (Fuller and Hostetler 1980; Gillman and Bailey 1977; James and Linnane 1979; Raimo and Sharon 1981). By the early 1980s, mortality caused by MPB decreased in the South Dakota Black Hills but mortality from MPB were observed in the Bear Lodge Mountains in Wyoming (Johnson and Averill 1983; Lessard and Fuller 1982; Lister and Hildebrand 1984). During that time, a major contribution to the high mortality rate of 4.19% reported for ponderosa pine by Green and Conner (1989) was caused by MPB. From 2000 to 2017, approximately 8,631,500 ponderosa pine were killed by MPB (Graham et al. 2016; Harris 2016, 2017, 2018) (fig. 4). This recent epidemic occurred within the central portions of the BHNF (fig. 5). Total insect mortality in 2011 accounted for 0.80% of the 1.24% annual tree mortality rate (table 1). In contrast, total insect mortality contributed 2.60% of the 3.07% mortality rate recorded in 2019, demonstrating the full impact of the 2000 through 2017 bark beetle epidemic. As of 2019, the MPB epidemic has subsided in the BHNF (Harris 2019).

Wildfires

Prior to European settlement (circa 1875), wildfires burned in the forests of the Black Hills on average every 10 to 31 years depending on elevation (Brown and Sieg 1996; Brown and Sieg 1999; Brown et al. 2008; Hunter et al. 2007). While ponderosa pine is considered a fire-adapted species, seedling- and sapling-sized trees are still susceptible to low-intensity surface fires (Battaglia et al. 2009). Pole- and sawtimber-sized trees are also susceptible to wildfire if the fire is intense enough to scorch a substantial amount of the foliage, consume the foliage, and/or kill the cambium (Keyser et al. 2006). By the early 1900s, European settlement of the Black Hills and the rise of the gold mining industry resulted in the suppression of fires to protect the towns and timber (Freeman 2015). Fire suppression, along with timber harvesting activities, altered the structures of the forests by removing the large diameter tree component, increasing small tree densities, and decreasing the amount of open-canopied forests (Boldt and Van Deusen 1974; Brown and Cook 2006; Grafe and Horsted 2002; Shepperd and Battaglia 2002).

Wildfire ignitions are common within the Black Hills and have the potential to burn thousands of acres. For example, from 2000 to 2019, approximately 100 fires burned each year on public lands within the Black Hills, but most remained small and were suppressed (NIFC 2020). However, under conducive weather conditions, large wildfires can occur (fig. 6). From 1960 to 2019, across the Black Hills region, 547,449 acres burned, with over 75% of the burned area occurring in the last 20 years. Before 2000, wildfires burned 141,481 acres, averaging 3,628 acres per year. However, most of these fires were not extensive nor did they burn in areas where the FIA plots were located (Choate and Spencer 1969; Collins and Green 1988; DeBlander 2002; Green and Conner 1989). As a result, the contribution wildfire made to the total annual mortality from the 1960s through 1990s ranged from 0.00 to 0.03% (table 1). From 2000 through 2017, a total of 406,331 acres burned, averaging 22,574 acres burning per year with wildfire contributing 0.13% to 0.20% of the total annual tree mortality in the Black Hills (table 1). Included in that 406,331 acres was the 2000 Jasper Fire, which burned 83,500 acres in the south-central Black Hills. Although DeBlander (2002) commented that over 130,000 acres of the BHNF had been impacted by large fires, the mortality caused by these fires was not included in the report since the measurements were made before the wildfires. However, Walters et al. (2013) did report tree mortality from the Jasper fire as well as other wildfires. During the last 20 years, the increase in the extent and severity of wildfires burning the forests of the Black Hills in the 2000s and 2010s is reflected in the higher tree mortality rates (fig. 6; table 1).

Mortality Trends Across the Interior West

Recent mortality in ponderosa pine forests is not limited to the Black Hills region. FIA resource bulletins have reported increases in ponderosa pine mortality across the Interior West of the United States over the past few decades (Goeking 2015). Mortality rates ranged between 0.12 (Utah) to 1.30% (Montana) with an average mortality of 0.79% (table 2). Wildfires, followed by insects and disease, were the main contributor of mortality on a land area basis across the Interior West (DeRose et al. 2018; Goeking and Menlove 2017; Shaw et al. 2018; Thompson et al. 2017; Werstak et al. 2016; Witt et al. 2018, 2019). Several studies have reported that the number of wildfire events, along with the amount of acres burned, have increased across the western United States and Canada (Coop et al. 2020; Hanes et al. 2018; Parks and Abatzoglou 2020; Westerling 2016). In addition, increases in tree mortality due to increased regional warming and drought stress have been observed across unmanaged older forests in the western United States (van Mantgem et al. 2009).

Table 2—Volume gross growth and mortality rates for Interior West states from the 2000s to mid-2010s. Data is based on Forest Inventory Analysis annual forest inventory of ponderosa pine growing stock (> 5 inches d.b.h.) on national forest lands that were classified as timberland. The mortality rate is primarily a result of insects and fire across all ownerships.

State	Sampling period	Gross growth rate (%)	Mortality rate (%)	Source
Arizona	2001–2014	1.5	0.90	Shaw et al. 2018
Colorado	2004–2013	1.4	0.88	Thompson et al. 2017
Idaho	2006–2015	1.7	1.22	Witt et al. 2018
Montana	2006–2015	1.7	1.30	Witt et al. 2019
New Mexico	2008–2014	1.6	0.73	Goeking and Menlove 2017
Utah	2003–2015	1.3	0.12	Werstak et al. 2016
Wyoming	2011–2015	2.2	0.36	DeRose et al. 2018
Average	—	**1.63**	**0.79**	—

Changing Climate

Since the beginning of the 20th century, South Dakota has observed a 2 °F increase in average annual temperature (Frankson et al. 2017; Rice et al. 2018). Most of this temperature increase has taken place in the winter and spring months as well as nighttime temperatures throughout the year. By the middle of the 21st century, it is predicted that mean annual temperatures will exceed those of the past 100 years. Projected precipitation estimates are less certain, but current models suggest an increase in precipitation during the winter and spring months (Frankson et al. 2017). While precipitation is expected to increase during these cooler months, the increase in temperature would influence the moisture deficit during the summer months and increase the vulnerability to periodic drought. Future droughts that coincide with warmer temperatures, often referred to as "hot droughts," are expected to happen as well. During these hot droughts, evapotranspiration demand increases while soil moisture and fuel moistures decreases (Frankson et al. 2017).

How might these climate change projections impact wildfire, MPB, and ponderosa pine mortality in the Black Hills region? Warmer temperatures throughout the year may result in earlier snowmelt and longer growing seasons. Moreover, higher temperatures in winter may shift snow to rain. These changes in growing season and precipitation type could result in fire seasons starting earlier and ending later, a situation that is being observed across the western United States (Coop et al. 2020; Rocca et al. 2014; Westerling 2016; Westerling et al. 2006). These changes may increase fire frequency (Rocca et al. 2014), increase wildfire extents (Parks and Abatzoglou 2020), and prolong fire seasons (Brown et al. 2004). These events may diminish regeneration and growing stock potential. For example, 20 years after the 2000 Jasper Fire, large areas of high burn severity still have limited or no ponderosa pine regeneration establishment (fig. 8; Keyser et al. 2008; Lentile et al. 2005; Lentile et al. 2006; Ziegler et al. 2017); similar occurrences are being observed across the western United States (Coop et al. 2020). Furthermore, in these high-severity burned areas, surface fuels are increasing from the dead and down trees (fig. 9a; Keyser et al. 2008) and a reburn in this area could result in adverse post-fire outcomes (fig. 9b; Coop et al. 2020; Stevens-Rumann et al. 2012). Mountain pine beetle impacted areas that have not burned also can produce a fire hazard due to their heavy fuels (fig. 10; Sieg et al. 2016). Warmer temperatures directly impact MPB population dynamics (Bentz et al. 2010). Mountain pine beetles are often in the larvae stage during the cold, winter months. While the larvae can cold harden to survive the cold winter temperatures, extreme cold temperatures can reduce MPB populations (Bentz and Mullins 1999). However, with warmer winter temperatures, MPB will not succumb to this mechanism of population control. These factors could lead to more frequent outbreaks. If these estimates come to fruition, then mortality rates could exceed the historically lower rates observed in the 20th century.

Figure 8—Many high-severity burned areas in the 2000 Jasper Fire footprint have still not revegetated with ponderosa pine seedlings after 20 years. Instead, these areas are dominated by graminoids, forbs, ponderosa pine snags, and downed woody debris. USDA Forest Service photo by Mike Battaglia.

Figure 9—(a) A high severity burned area in the 2000 Jasper fire footprint that has revegetated with ponderosa pine seedlings post-wildfire. Notice the abundant ponderosa pine seedlings surrounded by standing snags and downed woody debris. (b) This photograph is 1 year after the area reburned in a fire. Notice the high seedling mortality, reduction in ponderosa pine snags, and reduction of downed woody debris. Fires occurring in these types of fuel complexes are expected to result in high tree mortality and other adverse outcomes. USDA Forest Service photos by Mike Battaglia.

Figure 10—A typical fuel complex observed in mountain pine beetle impacted stands that were not harvested. Fires occurring in these types of fuel complexes are expected to result in high tree mortality and other adverse outcomes. USDA Forest Service photo by Mike Battaglia.

Assessing Past FIA Reports

Since 1930, the FIA mission is to manage and update a comprehensive inventory and analysis of the present and future conditions of the renewable resources of the forest and rangelands of the United States (USDA FS 2018a). The FIA program and data collection protocol have evolved over the years. For example, data collected in the 20th century was based on periodic surveys on forested lands every 10 years, one state at a time, progressing from state to state until all forested land within each unit's region were inventoried (Frayer and Furnival 1999). The specific measurement years and protocols varied among states; therefore, each report provided the methods and definitions. Beginning in 2000, the FIA program implemented an annualized inventory, referred to as the "annual" inventory, which is nationally consistent with sampling across land ownerships and forest types spatially and temporarily unbiased (Goeking 2015). It is important to note that the periodic and annual inventory data are not directly comparable, but both provide good descriptions of forest resources (Goeking 2015). Since different inventory methodologies were used, values from the periodic (pre-2000s) and annualized (post-2000s) inventories may have discrepancies in broad-scale estimates. This doesn't negate the data from periodic inventories, since it is the best available information from that time, but it does suggest that users of this older data need to be careful in its interpretation and not use it to quantify trends. Instead, we used these data to provide context and identify mortality and gross growth rates to inform our scenario development. Jointly, the USDA RMRS Interior West (IW-FIA, Ogden, Utah) and the NRS-FIA (St. Paul, Minnesota) units were and are currently responsible for the BHNF inventories. Below is a list of the reports and the information we obtained from them to provide historical context of mortality and growth.

Using data collected from 1960 through 1962, within the boundaries of the BHNF and Custer National Forest (NF), Choate and Spencer (1969) described the forestland conditions of western South Dakota. Rather than establishing new random plots, they visited 137 locations that were established from 1953 through 1954. They used a nested rectangular plot design to describe growing stock (≥ 5.0 inches d.b.h) reported in cubic feet for trees with a 1-foot stump to a 4-inch top. The estimates derived from this report are based on softwoods that included both ponderosa pine and white spruce. The amount of growing stock volume killed by fire, insects, disease, animals, weather, and suppression was estimated on each plot. Timber removals were approximated from timber and mill residue production of local wood processing plants.

Collins and Green (1988) described the forest resources collected from 1979 to 1983 of South Dakota west of the 103rd meridian. The area they included incorporated 90% of the forestlands of South Dakota, of which 58% are NFS lands (BHNF and Custer NF) and the remaining amounts on private and other public forest lands. It was not clear if this included lands withdrawn by statute or administrative regulation. They described metrics including mortality and growing stock volume (≥ 5 inches d.b.h) on stands with at least 10% of trees in these size classes and had a 1-foot stump to 4-inch top diameter (outside bark). The estimates derived from this report are based on softwoods, which included both ponderosa pine and white spruce.

DeBlander (2002) described data collected in 1999 on BHNF forestlands in Wyoming and South Dakota. Phase one of the survey used grid points systematically located every ≈ 0.6 miles (1,000 meters) across all lands within the BHNF. A second sampling phase selected one of these plots every ≈ 3 miles (5,000 m) stratified by ownership and vegetation type. Two-hundred and five plots were sampled on the NFS lands; of these, 173 were forest, 22 were both forest and nonforest, and 10 were nonforest. In 1995, a mapped plot design was adopted by FIA nationwide that was used in this survey. At each location, four, 1/24th acre plots were used to describe growing stock (≥ 5.0 inches d.b.h.) of trees that had a 1-foot stump to a 4.0-inch outside bark top. Tree mortality was estimated for both standing and down trees that died in the past 5 years. Estimates derived from this report are for ponderosa pine only. In addition, the estimates include values from all lands administered by the BHNF, including reserved lands, which made up 1% of the total land base.

Annualized inventory was reported by Walters et al. (2013). Volume estimates came from the 5-year (2007 to 2011) inventory period for the South Dakota portion of the BHNF, and the 2005 data collected in Wyoming. Under annualized inventories, growth, removals, and mortality (GRM) are estimated using two time periods. For South Dakota, these time periods were from 2002 to 2006 and 2007 to 2011. For Wyoming the time periods were 2000 and 2005. An annualized measurement scheme was conducted using remotely sensed data and data from one plot, consisting of 4-subplots, established every 6,000 acres. The four subplots are measured on a 5-year rotating basis. Estimates derived from this report are for ponderosa pine (≥ 5 inches d.b.h.) only on BHNF nonreserved lands.

The 2019 (2017 to 2019) data were specific inventories requested by the BHNF from FIA to address changes in forest conditions observed most noticeably by recent MPB and wildfire activity (figs. 5 and 6). The data have been quality checked by NRS-FIA but have not been published (data on file). Data for these measurements cover both South Dakota and Wyoming portions of the BHNF. Tree growth, mortality, removals, and standing live volume for ponderosa pine trees > 5 inches d.b.h. and sawtimber-sized trees (> 9 inches d.b.h.) were described. Merchantable volume for trees > 5 inches d.b.h used a 4-inch top and sawtimber volumes were computed to a 7-inch top. Both merchantable volume classes used a 1-foot stump.

Values for the 2019 data came from three sources: (1) plots that were remeasured from previous FIA inventories that fell within the normal measurement cycle (panel base plots); (2) plots that were remeasured from previous FIA inventories but that were measured ahead of schedule (off-panel base plots); and (3) new plots that were installed in 2017 and 2018 field seasons to increase the sample size and spatial extent (one plot every 3,000 acres; 2X PLOTS). Data from panel base plots and off-panel base plots (table 3) were used to calculate GRM because these values require two separate measurements over a time period (Time 1 and Time 2). Typically, the time period between the two measurement periods is on a 5- to 10-year measurement cycle, depending on the state. However, the 2019 final inventory for the analysis used in this document includes repeat measurements that vary in time between measurements to facilitate the most-up-to-date estimates. For example, the 2019 GRM estimates include plots that were initially measured (Time 1) between 2011 and 2016 and remeasured (Time 2) between 2017 and 2019 for a total of 225 plots (table 3). Estimates of volume do not require two separate measurements over a time period. Therefore, the panel base plots, the panel off-base plots, and the 2X PLOTS contributed to estimates of volume for a total of 438 plots. Although the 2X PLOTS that were established in 2017 and 2018 did not contribute to the GRM estimates, the BHNF has the option to remeasure these new plots to get additional GRM estimates to reduce sampling error in the future. These measurements would be useful to detect any additional mortality or the anticipated decline in mortality related to MPB.

Table 3—The number of plots measured for 2017 and 2019 evaluation for the off-panel base and panel base plots. Walter et al. 2013 reported growth, removals, and mortality measured prior to 2012. The 2019 evaluation includes plots remeasured from 2011 through 2016 for growth, removals, and mortality.

Time 2 Year and plots remeasured	Time 1 Plot establishment year												
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
Before 2012*	20	3	38	45	40	37	38						221
2017 evaluation													
2011	20	3	—	—	—	—	—	—	—	—	—	—	23
2012	—	—	38	—	—	—	—	—	—	—	—	—	38
2013	—	—	—	45	—	—	—	—	—	—	—	—	45
2014	—	—	—	—	29	—	—	—	—	—	—	—	29
2015	—	—	—	—	11	17	2	—	—	—	—	—	30
2016	—	—	—	—	—	20	7	—	—	—	—	—	27
2017	—	—	—	—	—	—	29	—	—	—	—	—	29
Total	**20**	**3**	**38**	**45**	**40**	**37**	**38**	—	—	—	—	—	**221**
Established plots before 2017	—	—	—	—	—	—	56	38	45	29	30	27	225
2019 evaluation													
2017	—	—	—	—	—	—	29	—	—	—	—	—	29
2018	—	—	—	—	—	—	15	20	—	—	—	—	35
2019	—	—	—	—	—	—	12	18	45	29	30	27	161
Total	—	—	—	—	—	—	**56**	**38**	**45**	**29**	**30**	**27**	**225**

*Reported by Walters et al. 2013.

It should be noted that the 2017 evaluation presented in this document was summarized and presented to the stakeholder group in 2018 to provide preliminary results and progress; however, these data were not the complete data set until the 2019 evaluation data was added to be used for the final analysis.

As shown by the previous reports, BHNF FIA data from 1962 through the present covered a wide variety of areas, used various sampling methods, presented different forest metrics, and assessed different time frames.

These data provide context that can be used in helping to understand how the forests of the Black Hills have changed and provide insights of how they may change and be managed in the future.

Growth, Mortality, Harvests, and Standing Live Tree Inventory Over Time

Standing live tree inventory changes through time because of tree growth, mortality, and harvest between measurement periods. Gross growth is defined as the annual increase in tree volume in the absence of mortality and harvest. Gross growth includes accretion plus gross ingrowth (see Box 1 for detailed definitions and calculations), net growth is gross growth minus mortality, and net change is net growth minus harvest (Bechtold and Patterson 2005).

The FIA resource bulletins provided some challenges in interpretation. Choate and Spencer (1969) and Collins and Green (1988) only reported acreage of South Dakota and their estimates include ponderosa pine and white spruce together as softwoods. DeBlander (2002) and Walters et al. (2013) reported ponderosa pine and white spruce separately for the entire BHNF, which includes acreage in South Dakota and Wyoming. The FIA estimates prior to the year 2000 used periodic inventory to gather inventory data that include resource bulletins by Choate and Spencer (1969), Collins and Green (1988), and DeBlander (2002). The years when data were collected were not at regular intervals through time. The older resource bulletins reported volume in cubic feet for growing stock (> 5 inches d.b.h). However, when sawtimber-sized trees (> 9 inches d.b.h.) were reported separately, the data were in board feet. The 2017 and 2019 data were reported in both board feet and cubic feet.

Even with these identified nuances among the resource bulletins, they do provide general estimates of standing live volume, growth, and mortality on the Black Hills for growing stock > 5 inches d.b.h. (table 4; fig. 11). Over the past 60 years, gross growth, based on the percent of the standing live inventory, ranged between 2.33% and 2.74%. While mortality rates from the 1960s to 1990s were 0.16% and 0.27%, mortality rates started to increase in the 2000s, with values of 1.04% in 2011, 2.72% in 2017, and 3.07% in 2019. From 1962 to 1999, net growth, as a percentage of standing live volume, was positive with rates of 2.20% to 2.57%, which reflected the high gross growth and low mortality rates of those measurement periods. Although the 2011 measurement period still showed a positive gross growth of 2.66%, it coincided with a higher mortality rate of 1.04%, resulting in a decline in net growth to 1.62% (table 4). By 2017, gross growth was 2.74%, but mortality was 2.72%, resulting in a 0.02% net growth. In the most recent 2019 measurements, gross growth had decreased to 2.33% while mortality increased to 3.07%, resulting in a net growth of -0.75% (table 4).

Box 1—Gross Growth, Net Growth, and Net Change

For reporting growth and change, the individual components are usually combined as follows, and they are expressed either in terms of growing-stock or all live volume (Bechtold and Patterson 2005):

Gross ingrowth = I+R, *where*:

I = Ingrowth; includes the volume of trees at the time that they grow across the minimum d.b.h. threshold between time t and time t+1. Estimate is based on the size of trees at the d.b.h. threshold, which is 1.0 inches for all live trees and 5.0 inches for growing-stock trees.

R = Reversion; includes volume of trees on and that reverse from a nonforest land use to a forest land use (land that reverses from any source to timberland).

Accretion = $G_S+G_I+G_R+G_M+G_C+G_D$, *where*:

G_S = Survivor growth is the growth on trees tallied at time of initial inventory (t) that survive until terminal inventory (t+1).

G_I = Growth on ingrowth.

G_R= Reversion growth is the growth of reversion trees from midpoint of measurement interval to time t+1.

G_M = Mortality growth is the growth of trees that died from natural causes between time t and the midpoint of the measurement interval. Tree size at the midpoint is modeled from tree size at time t. This term also includes the subsequent growth on ingrowth trees that achieve the minimum diameter threshold prior to mortality.

G_C = Cut growth is the growth of cut trees between time t and midpoint of the measurement interval. Includes the ingrowth trees that achieve the minimum diameter threshold prior to being cut.

G_D = Diversion growth is the growth of diversion trees from time t to the midpoint of the measurement interval. Tree size at the midpoint is modeled from tree size at time t.

Gross growth = gross ingrowth + accretion

Mortality = M, *where*:

M = Mortality is the volume of trees that dies from natural causes between time t and time t+1.

Removals = C+D, *where*:

C = Cut (Harvest) is the volume of trees cut between time t and time t+1.

D = Diversion is the volume of trees on land diverted from forest to nonforest or land diverted to reserved forest land and other forest land.

Net growth = gross growth – mortality

Net change = net growth – removals

Table 4—Merchantable volume of ponderosa pine trees (> 5 inches d.b.h.), in CCF, on suitable timberland of the Black Hills National Forest. See Box 1 for a description of gross growth as described by FIA.

Date	Average annual volume (CCF)					Standing live inventory (CCF)
	Gross growth	Mortality	Net growth	Harvest[a]	Net change	
1962[b]	213,010	12,180	200,830	109,780	91,050	7,810,000
1984[c]	339,540	34,910	301,660	199,540	102,120	13,449,000
1999[d]	380,000	42,120	337,880	204,628	133,252	15,353,000
2011[e]	358,170	140,460	217,710	246,630	-28,920	13,477,960
2017[f]	247,768	246,122	1,646	261,721	-260,075	9,050,031
2019[f]	185,049	244,703	-59,654	183,592	-244,804	7,958,314
	Average annual volume (% of inventory)					
1962[b]	2.73	0.16	2.57	1.41	1.17	—
1984[c]	2.52	0.26	2.24	1.48	0.78	—
1999[d]	2.48	0.27	2.20	1.33	0.87	—
2011[e]	2.66	1.04	1.62	1.83	-0.21	—
2017[f]	2.74	2.72	0.02	2.89	-2.87	—
2019[f]	2.33	3.07	-0.75	2.31	-3.08	—

[a]To ensure consistency in calculations, FIA estimates of harvest levels were reported in the table. The United States Forest Service utilizes a series of systems: Timber Information Manager (TIM) and Forest Products Financial System (FPFS) for a more accurate record of sold and cut volume (https://www.fs.fed.us/forestmanagement/products/cut-sold/index.shtml). Note: Sawtimber utilization standards for FIA estimates use a 7 inch top and current utilization on the BHNF use a 6 inch top.

[b]Estimates are for softwoods on timberlands (commercial lands) within the Black Hills and Custer National Forest portions of South Dakota only. Softwoods include ponderosa pine and white spruce (Choate and Spencer 1969). Area of commercial forest land estimated for the National Forest was 957,000 acres, but it was not apparent how many acres were classified as suitable timberland.

[c]Estimates are for softwoods on timberlands within the Black Hills and Custer National Forest portions of South Dakota only. Softwoods include ponderosa pine and white spruce. Area of timberland for the national forest was 952,500 acres, but it was not clear if timberlands included lands withdrawn by statute or administrative regulation or which were classified as suitable timberland (Collins and Green 1988).

[d]Estimates are for ponderosa pine on forest land within the Black Hills National Forest including South Dakota and Wyoming. These estimates included values from all forest lands administered by the Black Hills National Forest, including reserved lands, which make up 1% of the total land base. Area of total forest lands for the National Forest was 1,150,627 acres, but it was not clear which lands were classified as suitable timberland (DeBlander 2002).

[e]Estimates are for ponderosa pine on timberlands within the Black Hills National Forest including South Dakota and Wyoming. Area of timberlands estimated for the National Forest was 1,135,200 acres, but it was not clear which lands were classified as suitable timberland (Walters et al. 2013).

[f]Estimates are for ponderosa pine on timberlands within the Black Hills National Forest including South Dakota and Wyoming. Area of total timberland was 1,062,776 acres, of which 765,734 were classified as suitable timberland.

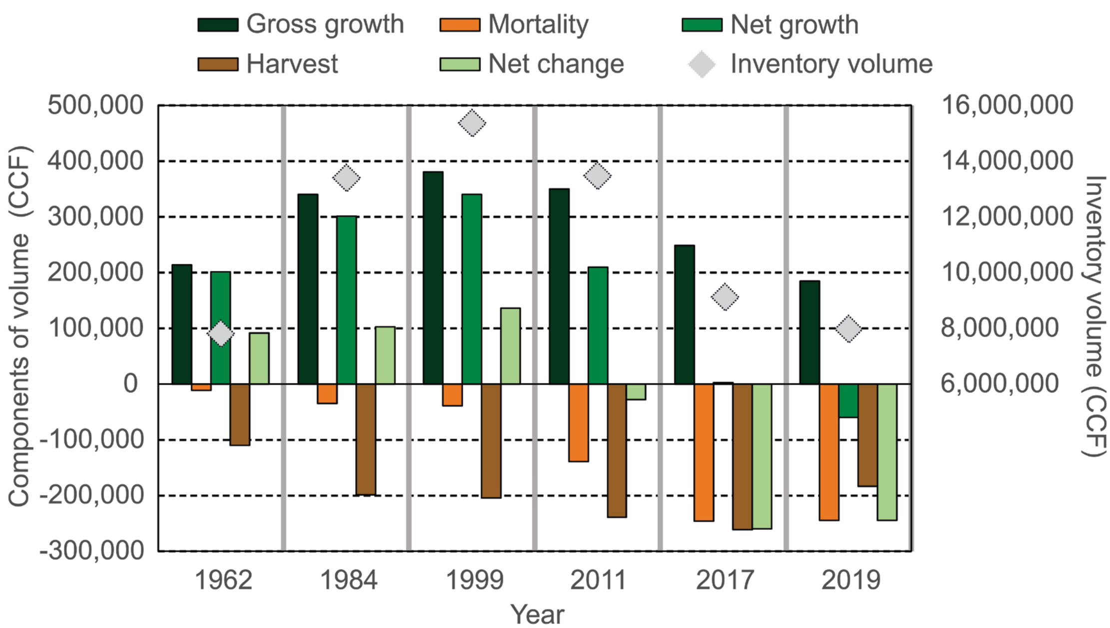

Figure 11—Gross growth, mortality, net growth, harvest, and standing inventory for trees > 5 inches d.b.h. (table 4) for several measurement periods from 1962 to 2019.

Direct comparisons of absolute values of standing live volume of 1962 and 1984 to later values are complicated by the measurement methodology and geographic region measured. However, an assessment of how harvest levels impacted net change to standing live inventory is still valid within each measurement period. For the past 60 years, timber harvesting of growing stock > 5 inches d.b.h. in the Black Hills has ranged from 1.33% to 2.89% of standing live volume (table 4). From the 1960s to 1980s, positive net growth exceeded the harvest amount, resulting in a positive net change of 0.78% to 1.17% and a subsequent increase in standing live volume, from 7,810,000 to 13,449,000 CCF within the South Dakota acres (table 4; fig. 11). In 1999, harvest levels were 1.33% of standing live inventory, resulting in a positive net change of 0.87% and a standing live volume of 15,353,000 CCF across the entire BHNF. The 2011 survey (Walters et al. 2013) demonstrated the influence of wildfires and MPB and their influence on net growth and net change (net growth minus harvest). While net growth was still positive (albeit lower than the previous decades), harvest levels concurrently increased (table 4; fig. 11), resulting in a negative net change (-0.21%) to standing live inventory. In 2017 and 2019, while mortality was at the highest levels and net growth was at its lowest levels in decades, harvesting exceeded net growth and resulted in net change of -2.87% and -3.08%, respectively, and a substantial decrease in merchantable standing live volume to 7,958,314 CCF of trees ≥ 5 inches d.b.h across the BHNF (table 4; fig. 11).

Examination of the merchantable sawtimber (> 9 inches d.b.h.) shows a similar pattern as merchantable volume of > 5 inches d.b.h. Ponderosa pine tree data from 2017 and 2019 demonstrated high levels of mortality and harvests contributing to a decrease in standing live volume (table 5). In 2017, gross growth exceeded mortality, resulting in a net growth of 44,215 CCF. However, the harvest removal of 206,411 CCF resulted in a net change of -162,196 CCF in standing live tree volume. In 2019, gross growth declined while the amount of mortality increased, resulting in a net growth of -27,715 CCF. While harvest did decrease to 153,534 CCF, this still led to a net change of -182,558 CCF and a further decline in standing live sawtimber volume of ponderosa pine to 5,995,428 CCF (table 5).

Table 5—Merchantable ponderosa pine sawtimber volume (> 9 inches d.b.h., 7-inch top, and 1-foot stump) in CCF and rates on suitable timberland in the Black Hills National Forest.[a,b]

Date	Average annual volume (CCF)					Standing live inventory (CCF)
	Gross growth	Mortality	Net growth	Harvest	Net change	
2017	215,371	171,156	44,215	206,411	-162,196	6,893,367
2019	150,694	178,409	-27,715	153,534	-182,558	5,995,428
Average annual volume (% of inventory)						
2017	3.12	2.48	0.64	2.99	-2.35	—
2019	2.51	2.98	-0.46	2.56	-3.04	—

[a]Sampling errors for the 2019 sawtimber means represent 68 percent confidence interval.

- Average annual growth: 150,694 CCF ± 8.0%
- Average annual mortality: 178,409 CCF ± 22.4%
- Inventory volume: 5,995,428 CCF ± 5.5%

[b]Note: Sawtimber utilization standards for FIA estimates use a 7 inch top and current utilization standards on the BHNF use a 6 inch top.

Scenario Development

To address the questions related to the future timber program for the BHNF, 60 scenarios were developed that were based on and put in context with the 1962 through 2019 FIA data (tables 4, 5, and 6). The assumptions for future tree growth and mortality rates were informed by using Forest Survey (precursor to FIA) and FIA data from the 1960s through 2019 for timberlands in the Black Hills (tables 1, 4, 5). In addition, we used fire history and cyclic MPB epidemics on the Black Hills and other ponderosa pine forests throughout the western United States to inform our mortality estimates. There is an element of uncertainty associated with future mortality rates, particularly if local climate begins to shift influencing disturbance and growth; therefore, we evaluated a range of mortality rates.

Table 6—Sixty scenarios were evaluated by applying four levels of harvest, five mortality rates, and three rates of gross growth.

Mortality (%)	Harvest (CCF)			
2.33% Gross Growth				
0.26	72,400	90,500	126,700	181,000
0.60	72,400	90,500	126,700	181,000
1.04	72,400	90,500	126,700	181,000
1.52	72,400	90,500	126,700	181,000
2.00	72,400	90,500	126,700	181,000
2.54% Gross Growth				
0.26	72,400	90,500	126,700	181,000
0.60	72,400	90,500	126,700	181,000
1.04	72,400	90,500	126,700	181,000
1.52	72,400	90,500	126,700	181,000
2.00	72,400	90,500	126,700	181,000
2.73% Gross Growth				
0.26	72,400	90,500	126,700	181,000
0.60	72,400	90,500	126,700	181,000
1.04	72,400	90,500	126,700	181,000
1.52	72,400	90,500	126,700	181,000
2.00	72,400	90,500	126,700	181,000

All scenarios were for ponderosa pine sawtimber (trees > 9 inches d.b.h.) growing on suitable timberlands as defined by FIA (Appendix A). The BHNF Forest Plan constraints such as slope steepness, wildlife, recreation, grazing, or other values were not considered in the scenarios. All scenarios started with the NRS-FIA 2019 ponderosa pine standing live sawtimber volume estimate of 5,995,428 (± 646,307; 95% CI) CCF (table 5). Numerous combinations of annual growth rates, annual mortality rates, and harvest levels could have been modeled. However, three growth rates and five mortality rates that were reflected in the 1962 through 2019 FIA data were chosen. These ranges of growth and mortality rates were combined with four harvest levels to produce 60 short-term (5 and 20 years) and long-term (80 years) scenarios (table 6). These 60 scenarios showed how combinations of mortality and growth rates along with harvest levels would impact the suitable timberlands of the BHNF.

Gross Growth Rates

The growth rates were the average annual gross growth as a percentage of the standing live volume for merchantable ponderosa pine trees > 5 inches d.b.h. (table 4). Growth rates for the > 9 inches d.b.h. were not used due to the lack of historical data. There is an element of uncertainty associated with how fire, MPB, and weather (wind and drought) will influence growth rates. Furthermore, forest growth across the Black Hills is variable, especially when comparing the southern Hills to the northern Hills and Bear Lodge Mountains of Wyoming (fig. 1). Therefore, we included a range of growth rates to account for this uncertainty. An average growth rate of 2.54% was derived from the 1962, 1984, 1999, 2011, and 2019 values (table 4). The 2017 value was excluded since it was included in the 2019 calculation. The average gross growth rate was bracketed with the minimum gross growth rate of 2.33% that was reported in 2019 and the maximum gross growth rate of 2.73% reported in 1962 (table 4). By using observed low and high growth rates from the 1960s through 2019 and a mean value in the scenarios, the variation in forest growth over the entire Black Hills region and the uncertainty of a future climate was represented (table 6).

Mortality Rates

Over the past 60 years, MPB, wildfire, and other causes of tree mortality rates ranged from 0.16% to 3.07% (table 4). A range of mortality rates used in the scenarios reflected those occurring in the past. An annual mortality rate of 0.26% was chosen to reflect both minimal MPB- and wildfire-induced mortality that occurred over multiple decades as shown in the 1984 and 1999 surveys by FIA (table 1). For a moderate amount of MPB- and wildfire-caused tree mortality, a rate of 1.04% was chosen, which was the mortality rate reported in 2011 (table 4). To reflect a mortality rate between the low (0.26%) and moderate (1.04%) values, the mean of reported values between 0.16% and 1.04% (table 4) was calculated (0.60%) (table 6). While a mortality rate of 3.07% was observed in the 2019 FIA measurement period, this rate occurred during high MPB and wildfire activity and is highly unlikely to occur for an extended length of time.

Instead, we set 2.0% as the maximum mortality rate based on the average of the reported rate of 1.04% and the maximum reported rate of 3.07% (table 4). The medium to high mortality rate of 1.52% was calculated by averaging the medium and high mortality rates. These chosen mortality rates reflect those that have been reported across the western United States over the past several decades (table 2; DeRose et al. 2018; Goeking and Menlove 2017; Thompson et al. 2017; Shaw et al. 2018; Werstak et al. 2016; Witt et al. 2018; Witt et al. 2019; van Mantgem et al. 2009). Furthermore, mortality caused by wildfire and MPB has been historically cyclic; but as we progress through time, there is uncertainty associated with climate-disturbance interactions. Therefore, by evaluating a range of mortality rates, we can better represent these different disturbance cycles. In total, five mortality rates (0.26, 0.60, 1.04, 1.52, and 2.00%) were used in the scenarios (table 6).

Harvest Levels

An exploration of sustainable harvest amounts using different growth and mortality rates was performed to determine the amount of growing stock necessary to sustain the current BHNF Forest Plan ASQ of 181,000 CCF of sawtimber (table 6). However, because of declining standing live tree volume, we assumed that harvest levels would not be able to increase but rather there may be a need to decrease harvest levels to identify a reasonable sustainable harvest of sawtimber for the short- and long-term. For this reason, three additional harvest levels were examined by reducing the maximum sawtimber harvest level by 30% (126,700 CCF), 50% (90,500 CCF), and 60% (72,400 CCF).

Scenario Outcomes

The objectives of this report were to address questions of future sustainable sawtimber harvest levels given the current vegetative conditions on the BHNF. NRS-FIA estimates for 2019 demonstrated that current net growth and net change are negative, indicating that current harvest levels when combined with mortality exceeded gross growth. Therefore, to ensure a sustainable harvest, the priority is to identify the combined harvest and mortality rates that allow the forest to produce positive net growth and net change.

Our first challenge was how to define “sustainable harvest.” There are three terms in the Society of American Foresters’ Dictionary of Forestry (Deal 2018) that define sustainable forest management, sustained yield, and long-term sustained yield (Box 2). In addition, the 2012 Planning Rule now directs the U.S. Forest Service to use the sustained yield limit when revising Forest Resource Management Plans (USDA FS 2015). We used the definitions of these terms to provide context for how we evaluated our scenarios. First, while there is not a specific value or threshold, a key component of sustained yield management implies a balance between increment and cutting. Currently, net growth (gross growth minus mortality) and net change (net growth minus cutting or harvest) are not in balance with growth, because mortality and harvest combined exceeded gross growth (fig. 11). Our first assumption was that a sustainable harvest level must (1) initially allow for positive net growth by accounting for mortality caused by disturbance and (2) harvest levels cannot exceed net growth but can be equal to net growth. Our second assumption was that if we wanted to return to harvest levels more in line with past harvest levels, a period of recovery to the standing live volume may be necessary; and to accomplish this, net growth must exceed harvest, at least in the short term. Our third assumption was that although mortality levels are likely to decline due to the end of the MPB epidemic, other disturbances such as wildfire, weather related disturbances, and harvesting will continue to impact net growth and net change in standing live volume. This provides unique challenges, because a recovery period is needed for net growth and net change to become positive for standing live inventory to increase to levels that allow for sustainable harvests while also considering other resources. Our results from our scenario exercise are organized by the three questions we were asked to address.

Box 2 - Sustainable Forest Management, Sustained Yield, Long-Term Sustained Yield, and Sustained Yield Limit

“Sustainable forest management” is a concept that continues to evolve and has several definitions. The Dictionary of Forestry (Deal 2018) definition contains two components. The first is “the practice of meeting the forest resource needs and values of the present without compromising the similar capability of future generations.” The second component is “the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, and regeneration capacity, vitality, and potential to fulfill, now and in the future, relevant ecological, economic, and social functions at local, national, and global levels, and that does not cause damage to other ecosystems.”

Criteria for sustainable forestry (Deal 2018) include “(a) conservation of biological diversity, (b) maintenance of productive capacity of forest ecosystems, (c) maintenance of forest ecosystem health and vitality, (d) conservation and maintenance of soil and water resources, (e) maintenance of forest contributions to global carbon cycles, (f) maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of societies, and (g) a legal institutional, and economic framework for forest conservation and sustainable management.”

Sustained yield is defined (Deal 2018) as the “yield that a forest can produce continuously at a given intensity of management” and sustained-yield management “implies continuous production so planned as to achieve, at the earliest practical time, a balance between increment and cutting.”

Long-term sustained yield (Deal 2018) is the “highest uniform wood yield that may be sustained under a specific management intensity consistent with multiple-use objectives on lands being managed for timber production.”

The 2012 Planning Rule now directs the U.S. Forest Service to use the sustained yield limit when revising Forest Resource Management Plans. “Sustained yield limit (SYL) is the amount of timber, meeting applicable utilization standards, “which can be removed from [a] forest annually in perpetuity on a sustained-yield basis” (NFMA at section 11, 16 USC 1611; 36 CFR 219.11(d)(6)). It is the volume that could be produced in perpetuity on lands that may be suitable for timber production. Calculation of the limit includes volume from lands that may be deemed not suitable for timber production after further analysis during the planning process. The calculation of the SYL is not limited by land management plan desired conditions, other plan components, or the planning unit’s fiscal capability and organizational capacity. The SYL is not a target but is a limitation on harvest, except when the plan allows for a departure” (USDA FS 2015).

What impact does the current 2019 forest condition (i.e., standing volume, mortality, and growth) have on the out-year timber program of harvesting at current levels compared to other harvest level scenarios using probable growth and mortality estimates?

Harvest Level of 181,000 CCF/yr: Current BHNF Forest Plan

Standing live sawtimber volume decreased in all 15 scenarios with a harvest level of 181,000 CCF/yr, regardless of growth and mortality rates (table 7; figs. 12 and 13; Appendix B). In all cases, harvest levels exceeded net growth resulting in a decrease in standing live sawtimber volume. Depending on mortality and growth rates used, average standing live sawtimber volume could decrease between -172,897 (± 83,861; 95% CI) and -811,413 (± 10,735; 95% CI) CCF within 5 years (table 7). Within 20 years, a decline of -838,215 (± 406,560; 95% CI) to -3,327,413 (± 44,021; 95% CI) CCF is predicted (fig. 12).

Table 7—The change in ponderosa pine average standing live sawtimber volume (CCF) after 5 years under various volume growth and mortality rates and harvest levels. Starting volume was 5,995,428 ± 646,307 CCF (95% confidence interval). Values in bold represent scenarios that decrease standing live volume. Values with an "*" represent values that are not significantly different from zero (95% confidence interval). Values presented are based on a range of volume gross growth and mortality rates for ponderosa pine on the Black Hills National Forest.

Harvest level (CCF/yr)	Mortality rate				
	0.26%	0.60%	1.04%	1.52%	2.0%
			-------------------Gross growth rate = 2.33%-------------------		
181,000	**-296,496**	**-399,998**	**-531,840**	**-672,999**	**-811,413**
126,700	-13,521*	**-118,940**	**-253,254**	**-397,065**	**-538,115**
90,500	175,129	68,432	**-67,514**	**-213,109**	**-355,916**
72,400	269,454	162,118	25,351*	**-121,131**	**-264,817**
			-------------------Gross growth rate = 2.54%--------------------		
181,000	**-231,855**	**-336,239**	**-469,209**	**-611,583**	**-751,192**
126,700	52,311*	-53,998*	**-189,441**	**-334,487**	**-476,744**
90,500	241,755	134,162	-2,929*	**-149,757**	**-293,779**
72,400	336,477	228,243	90,327	**-57,392**	**-202,296**
			-------------------Gross growth rate = 2.73%-------------------		
181,000	**-172,897**	**-278,083**	**-412,081**	**-672,999**	**-696,258**
126,700	112,350	5,232*	**-131,248**	**-277,409**	**-420,765**
90,500	302,515	194,108	55,974*	**-91,975**	**-237,103**
72,400	397,598	288,546	149,585	741*	**-145,272**

Harvest Level of 126,700 CCF/yr: 30% Reduction in Sawtimber Harvest

Standing live sawtimber volume was sustainable for 5 of the 15 scenarios with a harvest level of 126,700 CCF/yr (table 7; figs. 12 and 13; Appendix B). Net growth exceeded harvest levels only when growth rates exceeded 2.73% and mortality rates were ≤ 0.26% (table 7; figs. 12 and 13; Appendix B) resulting in an increase in average standing live sawtimber volume of 112,350 (± 83,861; 95% CI) CCF. Harvest levels did not exceed net growth (i.e. change in volume was not significantly different from zero) in 4 of the 15 scenarios (designated with an asterisk in table 7). Within 20 years, on average, up to 544,679 (± 406,561; 95% CI) CCF could be added to the standing live sawtimber volume (fig. 12) depending on mortality and growth rates.

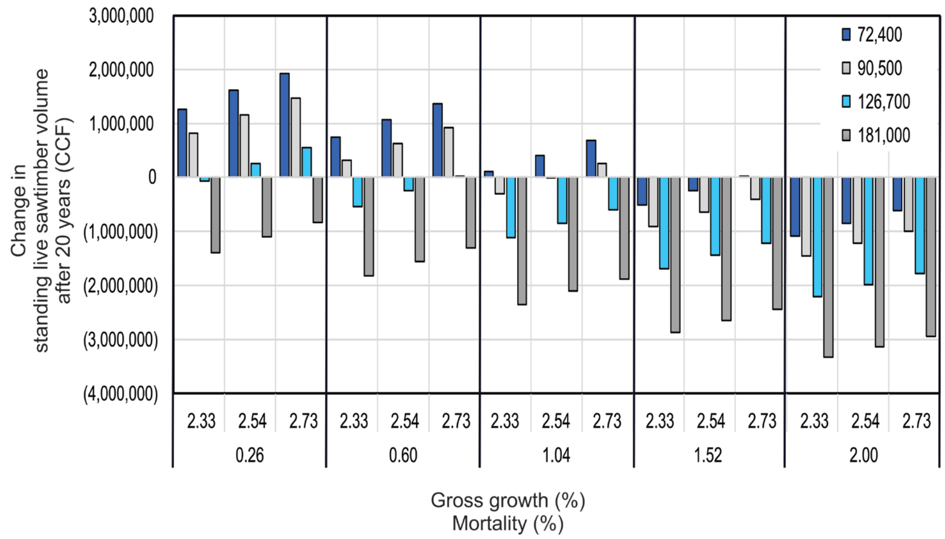

Figure 12—Twenty-year change in average standing live sawtimber volume for 60 evaluated scenarios. Scenarios are reported by gross growth rate (2.33%, 2.54%, 2.73%) and harvest level (181,000 CCF/yr, 126,700 CCF/yr, 90,500 CCF/yr, and 72,400 CCF/yr) for each of the five mortality rates (0.26%, 0.60%, 1.04%, 1.52%, and 2.0%).

Standing live sawtimber volume decreased in 10 of the 15 scenarios with a harvest level of 126,700 CCF/yr (table 7; figs. 12 and 13; Appendix B). In those 10 scenarios, harvest levels of 126,700 CCF still exceeded net growth, resulting in a reduction in standing live sawtimber volume. All scenarios with mortality rates ≥ 1.04% and those at the lower growth rate of 2.33% and mortality rates ≥ 0.60% predicted a decline in volume. Within 5 years, depending on mortality and growth rates used, an average decline of -118,940 (± 57,874; 95% CI) to -538,115 (± 10,735; 95% CI) CCF was predicted (table 7). Within 20 years, an average decline of -543,564 (± 264,486; 95% CI) to -2,206,683 (± 44,021; 95% CI) CCF was predicted (fig. 12).

Harvest Level of 90,500 CCF/yr: 50% Reduction in Sawtimber Harvest

Standing live sawtimber volume was sustainable in 8 of the 15 scenarios with a harvest level of 90,500 CCF/yr (table 7; figs. 12 and 13; Appendix B). Net growth exceeded harvest levels when growth rates were 2.33% and 2.54% and mortality rates were ≤ 0.60% (table 7; figs. 12 and 13) or when growth rates exceeded 2.73% and mortality rates were ≤ 1.04% (table 7; figs. 12 and 13), resulting in an increase in standing live sawtimber volume. Harvest levels did not exceed net growth when the growth rate was 2.54% and the mortality rate was 1.04%. Depending on mortality and growth rates evaluated, within 5 years, 55,974 (± 56,490; 95% CI) to 302,515 (± 83,861; 95% CI) CCF could be added to the average standing live sawtimber volume (table 7). Within 20 years, 254,998 (± 257,351; 95% CI) to 1,466,608 (± 406,560; 95% CI) CCF could be added to the average standing live sawtimber volume (fig. 12).

Standing live sawtimber volume decreased in 7 of the 15 scenarios with a harvest level of 90,500 CCF/yr (table 7; figs. 12 and 13; Appendix B). In those seven scenarios, harvest levels of 90,500 CCF still exceeded net growth, resulting in a reduction in standing live sawtimber volume. Most scenarios with growth rates of 2.33% and 2.54% and mortality rates > 1.04% and growth rates of 2.73% with mortality rates ≥ 1.52% predicted a decline in volume. Within 5 years, depending on the scenario, a decline of -91,975 (± 40,060; 95% CI) to -355,916 (± 10,735; 95% CI) CCF in average standing live sawtimber was predicted (table 7). Within 20 years, an average decline of -403,542 (± 175,761; 95% CI) to -1,459,530 (± 44,021; 95% CI) CCF was predicted (fig. 12).

Harvest Level of 72,400 CCF/yr: 60% Reduction in Sawtimber Harvest

Standing live sawtimber volume was sustainable in 10 of the 15 scenarios with a harvest level of 72,400 CCF/yr (table 7; figs. 12 and 13; Appendix B). Net growth exceeded harvest levels in 8 scenarios, when growth rates were 2.33% and mortality rates ≤ 0.60 and growth rates were 2.54% or 2.73% and mortality rates were ≤ 1.04% (table 7; figs. 12 and 13; Appendix B), resulting in an increase in average standing live sawtimber volume. Harvest levels did not exceed net growth when growth rate was 2.33% and mortality rate was 1.04% or growth rate was 2.73% and mortality was 1.52%. Depending on the growth and mortality rates used, within 5 years, 741 (± 40,059; 95% CI) to 397,598 (± 83,861; 95% CI) CCF could be added to the average standing live sawtimber volume (table 7). Within 20 years, 3,252 (± 175,761; 95% CI) to 1,927,573 (± 406,561; 95% CI) CCF could be added to the average standing live sawtimber volume (fig. 12).

Standing live sawtimber volume decreased in 5 of the 15 scenarios with a harvest level of 72,400 CCF/yr (table 7; figs. 12 and 13; Appendix B). In those five scenarios, harvest levels of 72,400 CCF still exceeded net growth, resulting in a reduction in average standing live sawtimber volume. All scenarios with growth rates of 2.33% and 2.54% and mortality rates ≥ 1.52% and growth rates of 2.73% with mortality rates ≥ 2.0% predicted a decline in volume. Depending on mortality and growth rates used, within 5 years, a decline of -57,392 (± 33,641; 95% CI) to -264,817 (± 10,735; 95% CI) CCF in average standing live volume was predicted (table 7). Within 20 years, an average decline of -248,122 (± 145,440; 95% CI) to -1,085,954 (± 44,020; 95% CI) CCF was predicted (fig. 12).

What is a sustainable timber harvest estimate for the BHNF using the 2019 NRS-FIA data assuming rational tree mortality and growth rates informed by those of the past?

Based on the scenarios explored, it was evident that rational tree growth and mortality rates interacted with harvest levels to influence the sustainability of sawtimber. If the goal is to have a sustainable timber harvest, then net growth (gross growth minus mortality) needs to exceed annual harvest levels while accounting for other resources identified in the Forest Plan. However, this scenario exercise does not include these other resources' needs. Furthermore, it may take additional time to accumulate enough volume to meet all Forest Plan objectives.

The 2019 forest conditions and probable growth and mortality estimates suggest that an average annual harvest for the timber program on the BHNF in the range of 72,400 to 90,500 CCF/yr appears to be the best option, in the short-term, for sustainable harvest levels (table 7). Over the next several decades (figs. 12 and 13), if mortality rates stay below 1.04%, both harvest levels of 72,400 and 90,500 CCF/yr appear to favor an increase in standing live sawtimber volume, allowing for some recovery regardless of the growth rate modeled. If mortality exceeds 1.04%, most of the harvest levels are unsustainable unless growth rates are 2.73% and mortality is ≤ 1.52%.

A 50% reduction in harvest levels to 90,500 CCF/yr achieved sustainability in 8 of the 15 scenarios explored. Sustainability at the 90,500 CCF level was achieved when growth rates were 2.33% or 2.54% and mortality rates were < 1.04% (table 7; figs. 12 and 13; Appendix B). If growth rates exceed 2.73%, sustainability could still be achieved up to mortality rates of 1.04%. A 60% reduction in harvest levels to 72,400 CCF/yr achieved sustainability in 10 of 15 scenarios explored when growth rates were 2.33% or 2.54% and mortality rates were ≤ 1.04% (table 7; figs. 12 and 13; Appendix B). If growth rates exceed 2.73%, sustainability can still be achieved up to mortality rates of 1.52%.

Factors such as growth, mortality, and land use all contribute to creating a dynamic forest. Therefore, forest harvest levels also need to reflect a similar pattern. Although some of the long-term (80 years) projections in figure 13 may exceed what is realistic and to a certain extent are over simplified, the figure still shows that harvest levels set today may need to change over time.

Within the context of the growth and mortality rates we evaluated, standing live sawtimber volume continues to decrease and eventually reaches zero when harvest levels are 181,000 CCF/yr (fig. 13; Appendix B). The BHNF cannot maintain this harvest level unless growth rates exceed 2.73% and mortality rates are < 0.26%, even in the long-term. In contrast, within 50 years, if harvesting continues between 72,400 CCF/yr and 90,500 CCF/yr, and mortality rates stay ≤ 0.60%, harvest level may need to change (fig. 13; Appendix B). Depending on how the forest responds, harvest levels will most likely need to increase to maintain some resilience to MPB and other disturbances; however, adjustments will need to be determined through continued monitoring.

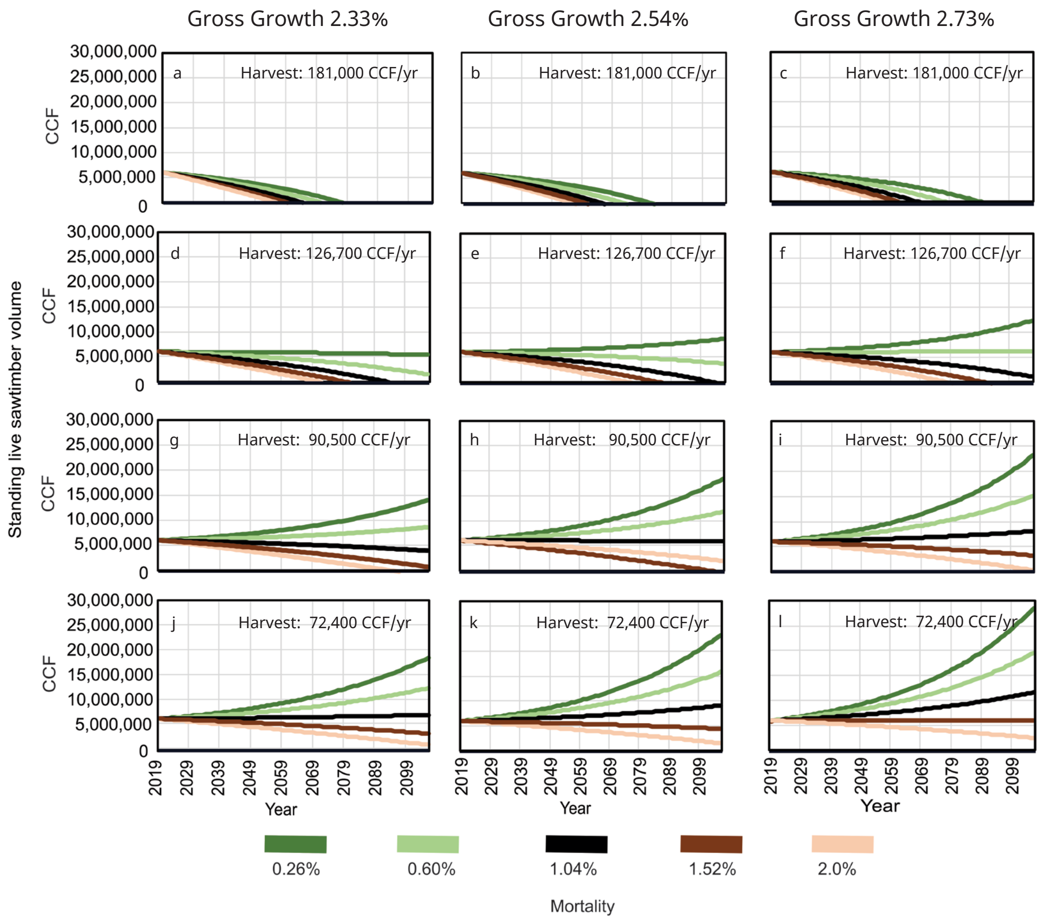

Figure 13—Long-term (80 years) average standing live volume outcomes for all the scenarios evaluated. Eighty-year outcomes when harvest levels are 181,000 CCF/yr when gross growth rates are (a) 2.33%, (b) 2.54%, and (c) 2.73%. Eighty-year outcomes when harvest levels are 126,700 CCF/yr when gross growth rates are (d) 2.33%, (e) 2.54%, and (f) 2.73%. Eighty-year outcomes when harvest levels are 90,500 CCF/yr when gross growth rates are (g) 2.33%, (h) 2.54%, and (i) 2.73%. Eighty-year outcomes when harvest levels are 72,400 CCF/yr when gross growth rates are (j) 2.33%, (k) 2.54%, and (l) 2.73%. Sustainability is achieved when harvest levels do not exceed net growth.

What would be the standing inventory volume necessary using reasonable growth and mortality estimates to sustain a sawtimber allowable sale quantity (ASQ) of 181,000 CCF?

The amount of standing live sawtimber volume necessary to sustain the current Forest Plan ASQ of 181,000 CCF/yr is dependent upon future growth and mortality rates. Nevertheless, based on the scenarios, the current standing live sawtimber volume of 5,995,428 CCF is not enough to sustain this harvest level without a substantial decrease in future volumes (table 7; figs. 12 and 13; Appendix B). Even when mortality rates are low (0.26%), standing live sawtimber volumes would need to be 7,327,950 to 8,743,950 CCF to be sustainable for the current ASQ level (table 8). Scenarios where moderate (0.60 to 1.04%) levels of disturbance are impacting standing live sawtimber volumes would require 8,497,670 to 14,031,000 CCF, volumes that were present before the recent MPB outbreak and wildfires of the 21st century. In scenarios where mortality rates exceeded 1.52%, standing live sawtimber volumes would need to exceed levels that could be subject to large mortality events like those observed in the early 21st century (table 8).

Table 8—The amount of ponderosa pine average standing live sawtimber volume (CCF) required to sustain a harvest level of 181,000 CCF/yr as defined by the Black Hills National Forest Land and Resource Management Plan (Forest Plan) Phase II Amendment analysis (USDA FS 2005). Values presented are based on a range of volume gross growth and mortality rates for ponderosa pine on the Black Hills National Forest.

Mortality (%)	Gross growth (%)	Standing live sawtimber volume (CCF)
0.26	2.33	8,743,950
0.26	2.54	7,938,600
0.26	2.73	7,327,950
0.60	2.33	10,462,400
0.60	2.54	9,329,900
0.60	2.73	8,497,670
1.04	2.33	14,031,000
1.04	2.54	12,066,650
1.04	2.73	10,710,050
1.52	2.33	22,345,700
1.52	2.54	17,745,100
1.52	2.73	14,958,650
2.00	2.33	54,848,500
2.00	2.54	33,518,500
2.00	2.73	24,794,500

Moving Forward

Continuous monitoring and flexibility to adjust harvest levels based on realized mortality rates is crucial if long-term timber sustainability is to continue. In addition, growth rates also need to be adjusted going into the future because there is uncertainty on how climate will specifically influence subsequent disturbance and growth rates. Some assume that, by using harvesting alone, management can control mortality, but disturbances such as drought, tornados, and wildfires are also driven by climate and seasonal weather. If seasonal weather becomes extreme as suggested in the future climate literature (Frankson et al. 2017, Rice et al. 2018), then the potential for weather driven events could increase mortality rates, regardless of harvest levels. In addition, there is still uncertainty in exactly how climate will influence localized disturbances; thus, mortality and growth together will need to be monitored and considered when current and future harvest levels are evaluated. Because forests and disturbances are becoming more dynamic, shifts in harvest levels in the short term and reevaluations through time may be required because of the uncertainty associated with a future climate. In these potentially dynamic forested ecosystems, harvest levels and the forest products industry may also need to reflect a dynamic nature. Short-term monitoring can provide information on changing growth and mortality rates allowing for subsequent harvest levels to be adjusted. These adjustments may need to occur quickly, particularly if there are large stand-replacing wildfires.

It is important to acknowledge that the scenarios presented in this document assume that all the standing live tree volume on the suitable timberlands is available for harvesting. However, national forests provide a variety of resources to the public including timber, water, wildlife habitat, recreation, and a sense of place. To balance the various needs for these resources, the Forest and Rangeland Renewable Resources Act of 1974 as amended by the National Forest Management Act of 1976 (16 U.S.C. 1604 (g)) requires that Forest Plans consider these resources. Within the current Black Hills National Forest Land and Resource Management Plan (Forest Plan) Phase II Amendment analysis (USDA FS 2005), a desired distribution of structural stages that would aid in sustaining these resources is defined (table 9). Structural stages are based on tree d.b.h. and crown cover. Because of the recent MPB epidemic and other disturbances, existing structural stage distributions are above or below objectives set in the Forest Plan (table 9). Forest management actions can be implemented across the landscape to move forest structural stages to stand development trajectories to meet those objectives.

Table 9—Structural stage distribution of ponderosa pine defined in the current Black Hills National Forest Land and Resource Management Plan (Forest Plan) Phase II Amendment (USDA FS 2005) analysis and currently based on 2020 FSVeg database layer within the suitable timber base (Johnson 2020). Structural stages (SS) are based on tree d.b.h. and crown cover. SS stage 1 consists of grasses and forbs. SS stage 2 consists of seedlings (trees < 1 inch d.b.h.) and shrubs. SS stage 3 is young forests of trees 1 inch to 9 inches d.b.h. while SS stage 4 is mature forests with trees > 9 inches d.b.h. SS 3 and 4 also have a crown cover class of A (11–40%), B (40–70%), and C (> 70%). SS 5 is late succession forest.

Structural stage number	Forest plan objectives (%)	Current distribution (%)
1	5	8.2
2	5	5.8
3A	10	8.7
3B	15	5.1
3C	5	2.9
4A	25	38.8
4B	25	19.8
4C	5	10.1
5	5	0.6

As an example, the Black Hills Resilient Landscapes Project (USDA FS 2018b) was developed as an attempt to address the issue of moving forest structure to desired conditions defined in the current Black Hills Forest Plan (USDA FS 2005). Based on the recent 2020 FSVeg database layer, the estimate of structural stages within the suitable timber base demonstrates that not all the sawtimber within a structural stage is available for harvest (Johnson 2020). As a result, the FIA standing live sawtimber volume estimate of approximately 5.9 million cubic feet is not fully available for harvest. Discussions on appropriate sustainable sawtimber removals are required to keep these limitations in mind when developing plans. Furthermore, identifying the target amount of standing live sawtimber desired for the BHNF will help inform sustainable harvest levels.

Management Opportunities

As the ponderosa pine forests of the Black Hills recovers from the recent MPB epidemic, management opportunities to enhance tree growth and reduce future mortality rates while sustainably managing for forest products and multiple benefits can be pursued. These opportunities can be realized through a variety of approaches including, but not limited to: (1) management of the ponderosa pine advanced regeneration; (2) ponderosa pine density management to reduce drought stress and susceptibility to disturbance; and (3) utilizing a range of silvicultural systems to create a heterogeneous landscape to potentially meet other management objectives, create a diversity of forest conditions that may increase disturbance resilience, and provide a sustainable timber harvest.

Across the Black Hills, it is common to see dense ponderosa pine regeneration. Areas that have experienced mortality or partial removal of the overstory, either through mechanical, wildfire, or MPB, often have ponderosa pine seedling and sapling densities exceeding 5,000 to 10,000 per acre (fig. 3; Battaglia et al. 2008; Shepperd and Battaglia 2002). Even though tree mortality from wind, snow, and suppression in such stands can be substantial, it is inadequate to reduce stand density across the entire BHNF (Myers 1958; Myers and Van Deusen 1960b; Shepperd and Battaglia 2002). Excessively dense stands decrease individual tree growth rate, preventing them from reaching a merchantable tree size. If there are remaining overstory trees, these small trees may become ladder fuels that can transition from a surface fire to the crown. However, more importantly, live sawtimber volume is at risk because a wildfire could kill most of the stand (Battaglia et al. 2008; Lentile et al. 2006), leading to a loss of standing volume and subsequently limiting harvest opportunities.

There are several methods that can treat nonmerchantable size trees; the best treatment will vary depending on the management objective, topography, tree density prior to treatment, and tree size. The use of prescribed fire to reduce tree density is warranted (Battaglia et al. 2008, 2009) in these fire-adapted ponderosa pine ecosystems (Brown and Sieg 1996; Brown and Sieg 1999; Brown et al. 2008; Hunter et al. 2007). Using prescribed fire could reduce tree regeneration densities (fig. 14), reduce surface fuels, and increase nutrient cycling. The reduction of surface fuels could result in less intense wildfires and help reduce tree mortality; particularly in places with heavy surface fuel loadings caused by MPB epidemics (fig. 10) or unsalvaged areas after high-severity wildfires (fig. 9a) (Keyser et al. 2009; Sieg et al. 2016). Where prescribed fire is limited due to smoke and/or narrow prescribed burning parameters, mechanical treatments could provide an alternative method to treating nonmerchantable trees. Mastication has shown to be effective at treating nonmerchantable material on gentle slopes (Jain et al. 2018) and provides flexibility in spacing trees to enhance individual tree growth. However, in the short term, masticated fuels do increase surface fuels, but eventually material decomposes over time (Keane et al. 2018). Other mechanical treatments, such as slashing small diameter trees, is also an option when tree densities are not excessive, they are in localized areas, or they are on steep slopes that prevent mechanical treatments.

Figure 14—The use of prescribed fire can aid in the reduction in ponderosa pine seedling density. This prescribed fire resulted in a mosaic of living and dead ponderosa pine seedlings with limited damage to the overstory. USDA Forest Service photo by Mike Battaglia.

Tending of nonmerchantable ponderosa pine can help accelerate the production of sawtimber. While thinning will not increase the productivity of a site, which is inherently controlled by climate and soils, these management actions can distribute the growth to fewer stems and reduce the time to grow sawtimber. The importance of tending even-aged stands early in their development has been demonstrated by several research studies within the Black Hills region (Graham et al. 2019; Myers 1958). In 1931, a thinning study was initiated in stagnated stands that were 28, 40, and 55 years old with d.b.h. ranges of 1.0 to 5.1 inches (Myers 1958). In these stands, a substantial increase in diameter and volume growth was reported compared to the dense unthinned areas (Myers 1958). In 1961, a long-term thinning study to examine tree growth response across a range of growing stock levels was installed on the Black Hills Experimental Forest in dense 65-year-old sapling and pole-sized stands with initial diameters of 2 to 8 inches d.b.h. (Graham et al. 2019; Myers 1967). After 48 years, this long-term study demonstrated that ponderosa pine trees in treated stands increased in both diameter and merchantable volumes compared to untreated stands (fig. 15). Depending on the initial density reduction and starting diameters (sapling- vs. pole-sized trees), tree diameters ranged from 9 to 18 inches d.b.h. (fig. 15a-f), compared to 8 inches d.b.h. in the dense untreated stands (fig. 15g). Both studies demonstrate that tending to the desired stand density early in stand development would yield larger diameter trees and volume outputs much sooner. Furthermore, Graham et al. (2019)

noted that several precommercial thinnings over the course of the 48-year study to maintain the density treatments did not produce commercial material at the time of thinning. Therefore, Graham et al. (2019) suggested that one precommercial thinning to the desired tree density and basal area for a future stand of 10-inch d.b.h. trees (table 1 in Myers 1967) would produce diameters and volumes that would produce sawtimber-sized material in an even-aged silvicultural system.

The desire to maintain an active timber industry while managing for a resilient and sustainable landscape will require management options that help mitigate the potential for high mortality rates through density management. While the high levels of standing live ponderosa pine volumes in the 1980s to 2000s provided the ability to sustainably harvest over 150,000 CCF/yr, the last 20 years have demonstrated that maintaining such volumes can lead to high tree mortality. Furthermore, as a changing climate manifests its impacts in the Black Hills region, adaptation strategies to limit mortality and enhance forest resiliency are warranted. Competition for moisture in the semi-arid Black Hills ponderosa pine forests is likely to increase, especially in higher density stands and during periods of severe drought (Bottero et al. 2017; Gleason et al. 2017). Stands grown at lower stand densities were shown to sustain growth and recover from drought quicker than higher stand densities in the Black Hills Experimental Forest long-term thinning plots (Bottero et al. 2017). Stand density management can reduce tree drought stress and result in reduced tree mortality levels (Graham et al. 2016; Negrón et al. 2008; Schmid et al. 2007), especially if applied across the landscape (Negrón et al. 2017). Furthermore, a reduction in stand density can reduce fire severity during wildfires (Lentile et al. 2006) and aid in the ability to use prescribed fire as a maintenance tool (Battaglia et al. 2008).

Both mechanical thinning and prescribed fire are warranted to produce a resilient landscape that results in a heterogeneous mix of BHNF forest structural stages and densities, while also producing timber products. Much of the ponderosa pine research in the Black Hills has focused on the volume and resiliency outcomes of even-aged silvicultural systems. The limited research in multi-aged ponderosa pine stands in the Black Hills have shown that mean wood production efficiency was not different from those observed in even-aged stands (Ex and Smith 2013; O'Hara and Nagel 2006); however, more research is needed to understand the tradeoffs of multi-aged silviculture (Ex and Smith 2013; Jain et al. 2014; Palik et al. 2020). Depending on the frequency of management activities and the number and juxtaposition of trees left, a wide variety of stand structures, tree sizes, and timber volumes can be produced while also increasing resiliency to disturbances (Battaglia et al. 2008; Ex and Smith 2013; Graham et al. 2019; Jain et al. 2014; Negrón et al. 2008; Negrón et al. 2017).

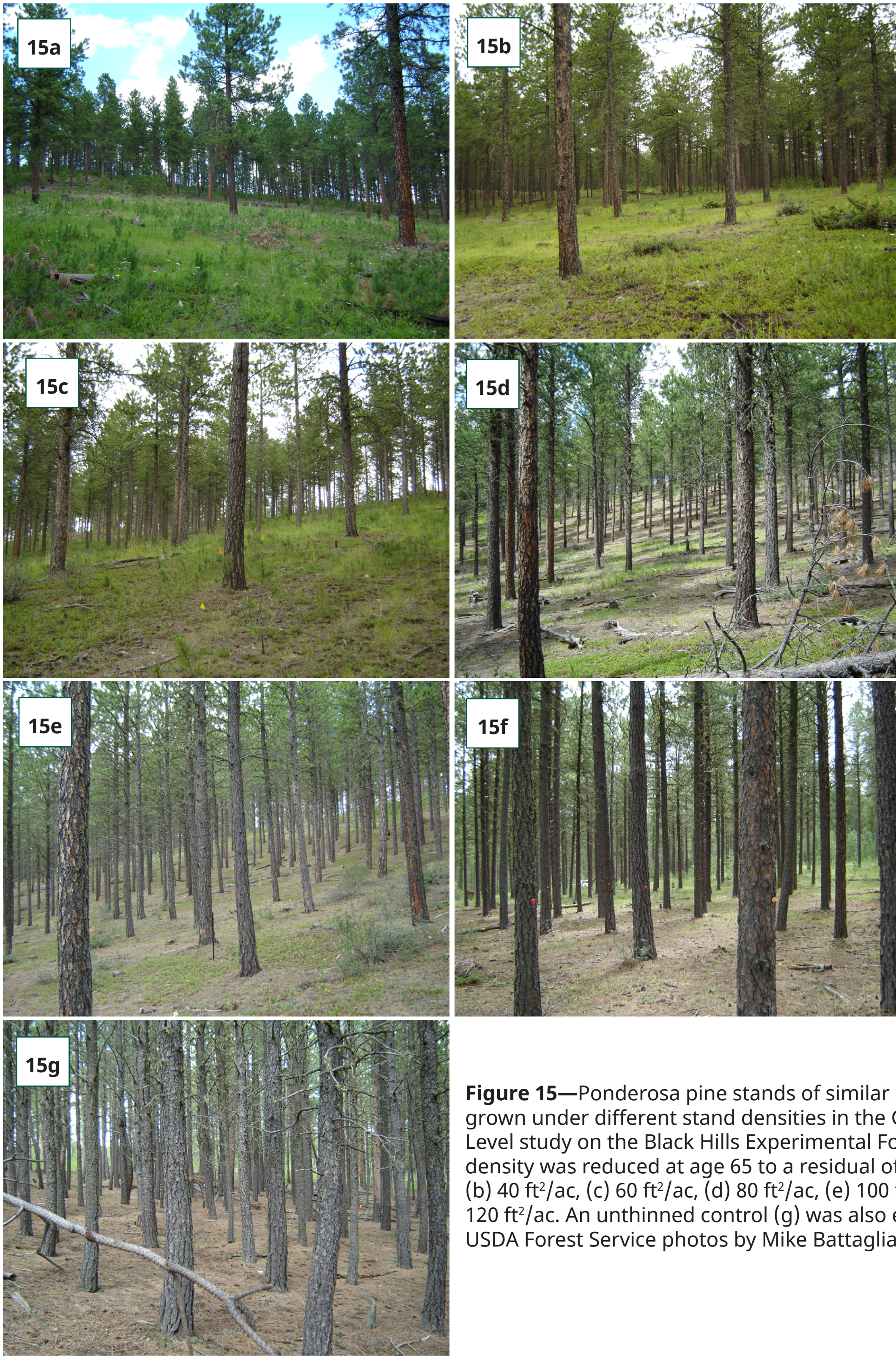

Figure 15—Ponderosa pine stands of similar age that were grown under different stand densities in the Growing Stock Level study on the Black Hills Experimental Forest. Stand density was reduced at age 65 to a residual of (a) 20 ft^2/ac, (b) 40 ft^2/ac, (c) 60 ft^2/ac, (d) 80 ft^2/ac, (e) 100 ft^2/ac, and (f) 120 ft^2/ac. An unthinned control (g) was also established. USDA Forest Service photos by Mike Battaglia.

A diversity of silvicultural systems could be applied on the BHNF depending on the management objectives. Shepperd and Battaglia (2002) discuss different regeneration methods including even-aged, uneven-aged, and hybrid silvicultural systems with their benefits and applicability on the BHNF. Strict even-aged systems include clearcuts, shelterwoods, and seed tree regeneration methods. Uneven-aged systems included individual tree and group selection. Hybrid systems are not strictly even-aged or uneven-aged but rather they create and maintain two to three storied stands comprised of trees of two or three distinct age classes. In addition, the entire BHNF does not need to only focus on one silvicultural system, but possibly a diversity of silvicultural systems may be applied across the entire Forest. There are nuances associated with each of these methods and each method needs to be placed within the context of the disturbances and management objectives.

Conclusion

Over the past two decades, multiple disturbances have changed the landscape of the Black Hills. There is strong interest in developing management options to maintain a sustainable timber industry while honoring the USFS mission of "sustaining the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations" (USDA 2020a). Our analysis suggested that the current standing live sawtimber volume does not support the current harvest level of 181,000 CCF/yr identified in the BHNF Plan. This creates unique challenges, because some time is needed for net growth and net change to become positive for standing live inventory to increase to levels that allow for sustainable harvests while also considering other resources. Furthermore, consideration of future climate and disturbances are needed to account for potential increases in mortality. Taking these factors into consideration, our results indicated that sawtimber harvest levels of 72,400 to 90,500 CCF/yr appear to meet sustainability when only the available timber resource within the suitable timberlands is considered without including other resource needs.

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Appendix A: Land Area

The Black Hills National Forest administers approximately 1.2 million acres across western South Dakota and northeastern Wyoming of which approximately 1.1 million acres are considered forested. However, not all that land is considered available and suitable for timber production. Lands administered by the Black Hills National Forest are categorized in several different ways and within these categorizations different management activities are approved (USDA FS 2005). Within the Forest Plan, management areas are defined by the management practices allowed and the types of resource and use opportunities that are offered to the public. Lands are also classified by suitability for timber production (i.e., suitable timber base or suitable timberlands), which is used to determine the allowable sale quantity (ASQ) of timber. Suitability is determined through an analysis of the economic and environmental factors.

Total lands within the Black Hills National Forest are separated by non-Forest Service lands embedded within the National Forest boundary, non-forested lands, and administratively withdrawn lands. Some of these management areas are administratively withdrawn from the suitable timberlands such as wilderness and research natural areas. Other areas are withdrawn from the suitable timberlands due to unstable soils, accessibility, and areas that cannot be restocked within 5 years. The remaining forested lands are categorized as tentatively suitable timberlands. Tentatively suitable timberlands are then partitioned based on other classifications. For example, management areas defined in the Forest Plan that emphasize other objectives (i.e. wildlife habitat, late-successional landscapes, riparian, Spearfish Canyon and developed recreation sites) are removed from the suitable timberlands. In addition, areas that are not commercially viable due to low productivity, steep slopes, and accessibility are also removed from the suitable timberlands. While timber harvesting may be allowed in these management areas to meet specific recreational, wildlife, or forest structural objectives and reduce susceptibility to insects, the volume from these activities do not contribute to the ASQ.

Direct comparison of acreage from the Black Hills National Forest and FIA is challenging due to differences in how area is calculated, sampling intensity, timing of inventory, and classification protocols (USDA FS 2020b). Of the 1.2 million acres that the Black Hills National Forest administers, approximately 865,890 acres are identified as suitable and available for timber harvest in the Forest Plan Phase II Amendment (USDA FS 2005, Appendix G-3). The suitable and available acres have decreased since then due to expansion of wilderness, land exchanges, and designation of a research natural area. The 2015 FSVeg layer indicated 824,240 acres were in the Black Hills National Forest suitable timberlands.

For this analysis, the USDA Forest Service, Forest Inventory and Analysis Program (USDA FS 2021) identified and analyzed 765,734 acres of suitable timberland: the subset of the suitable and available acres that are forestland that is producing or is capable of producing 20 cubic feet per acre per year of industrial wood in natural stands and not withdrawn from timber utilization by statute or administrative regulation. The difference here is predominately due to non-forested areas which were included within the Black Hills National Forest suitable timberlands but that do not meet the FIA definition of timberland (USDA FS 2020b).

Appendix B: Expanded Graphs From Figure 13

To facilitate a closer look at the long-term outcomes of the different scenarios shown in figure 13, we have separated the figures by growth rate.

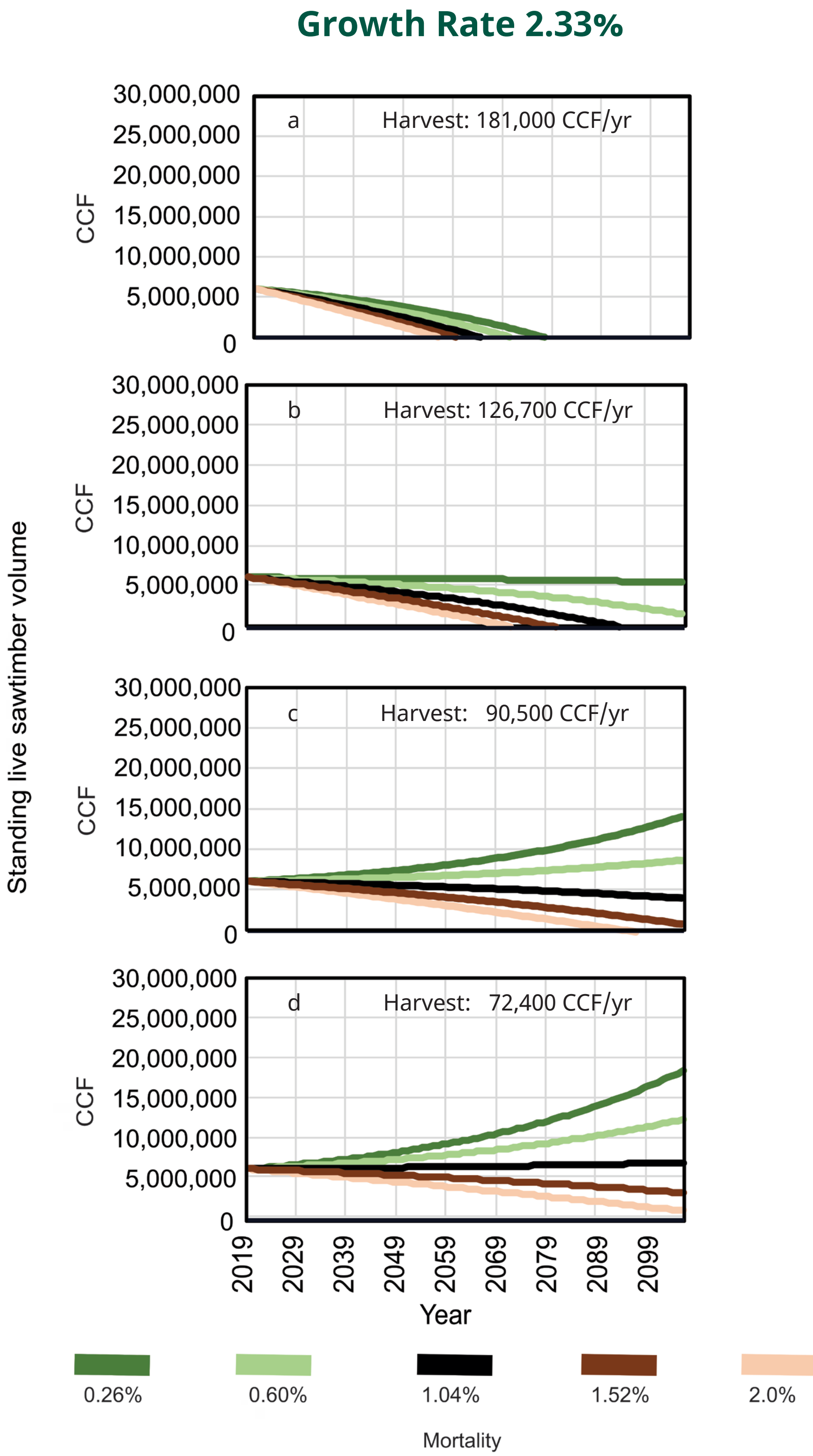

Figure B.1—Long-term (80 years) outcomes when growth rates are 2.33% and harvest levels are (a) 181,000 CCF/yr, (b) 126,700 CCF/yr, (c) 90,500 CCF/yr, and (d) 72,400 CCF/yr using five mortality rates.

Growth Rate 2.54%

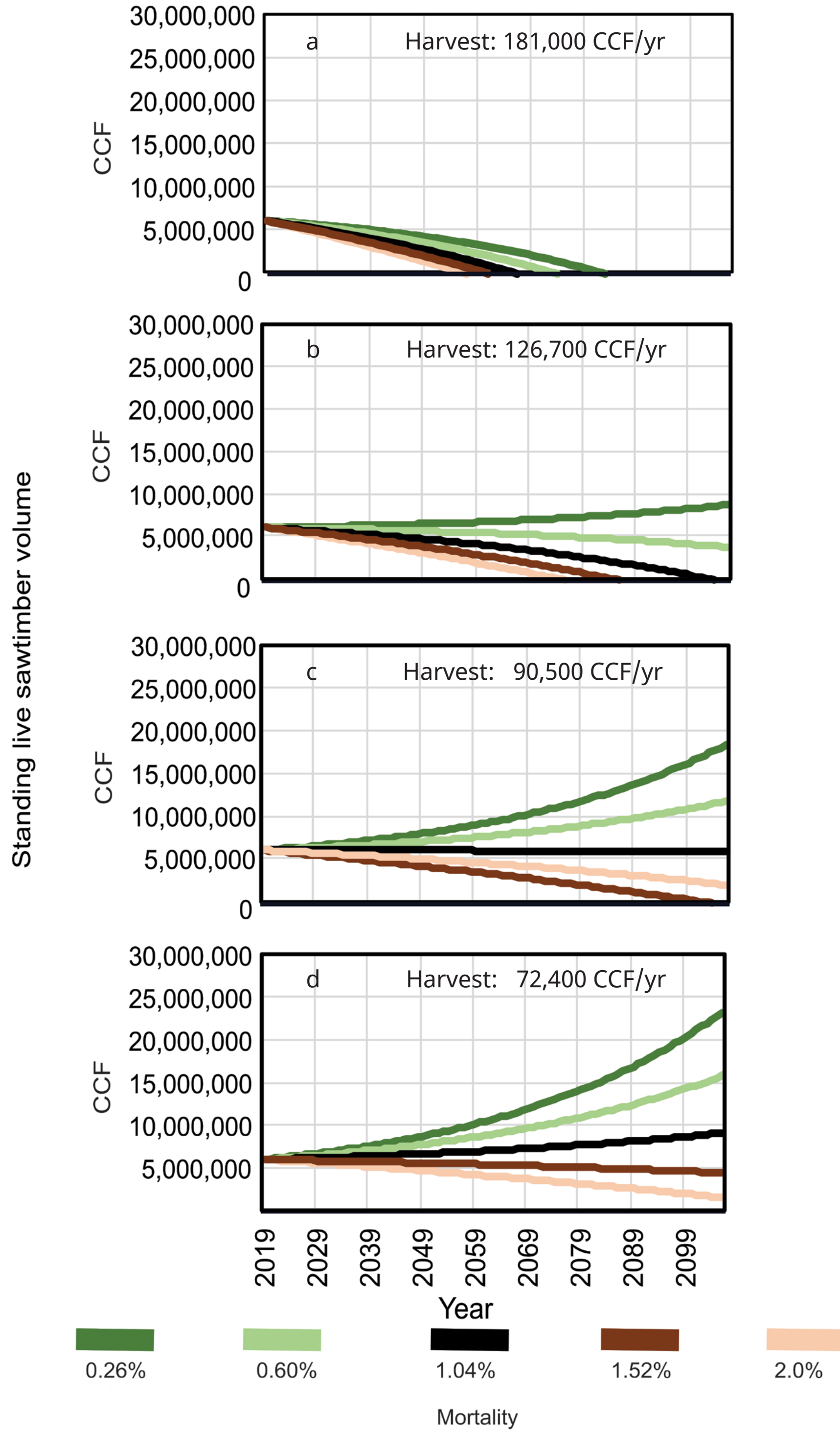

Figure B.2—Long-term (80 years) outcomes when growth rates are 2.54% and harvest levels are (a) 181,000 CCF/yr, (b) 126,700 CCF/yr, (c) 90,500 CCF/yr, and (d) 72,400 CCF/yr using five mortality rates.

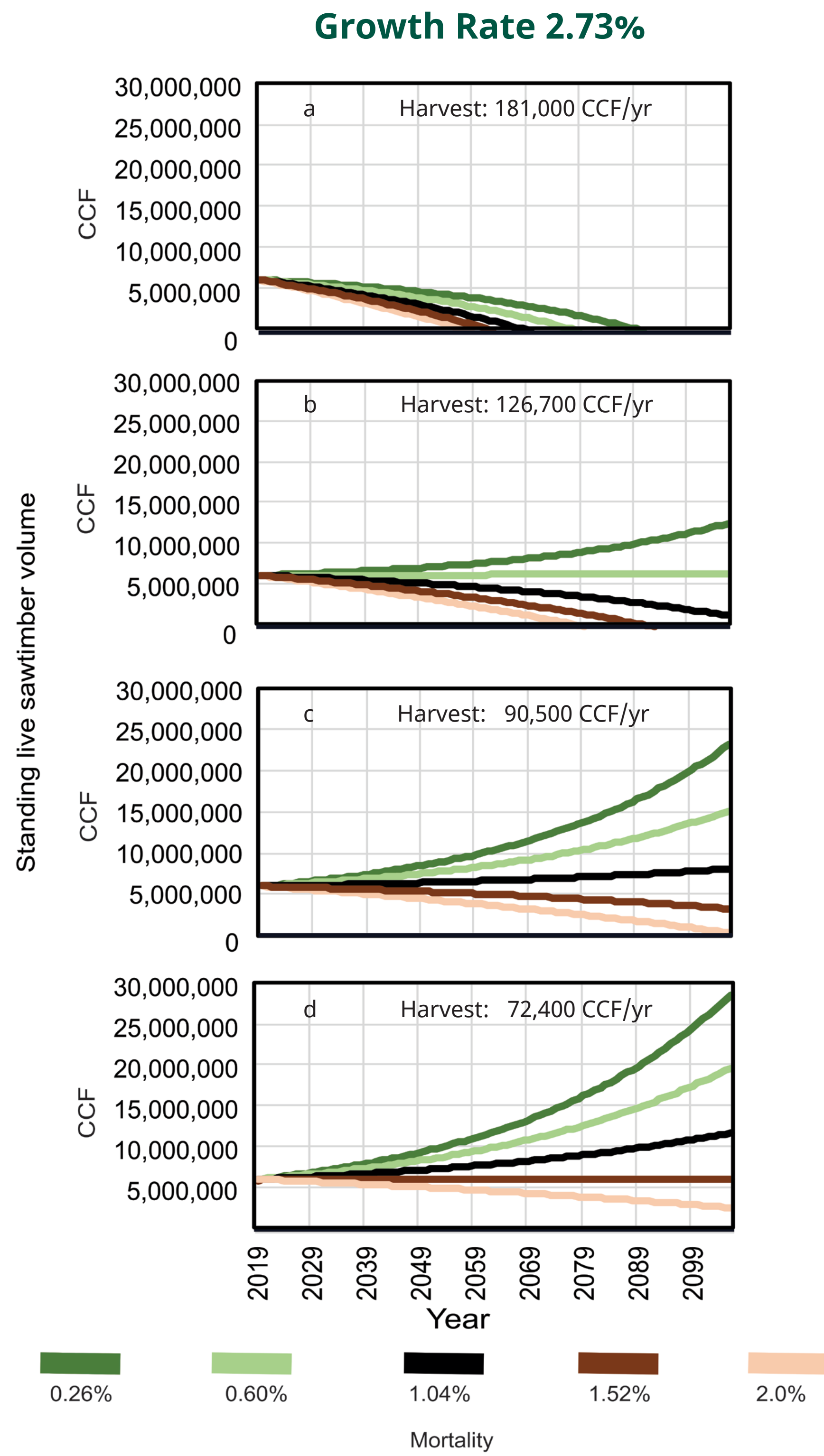

Figure B.3—Long-term (80 years) outcomes when growth rates are 2.73% and harvest levels are (a) 181,000 CCF/yr, (b) 126,700 CCF/yr, (c) 90,500 CCF/yr, (d) 72,400 CCF/yr using five mortality rates.

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