Nonequilibrium Dynamics between Catastrophic Disturbances and Old-Growth Forests in Ponderosa Pine Landscapes of the Black Hills

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Abstract: *An emerging goal of ecosystem management is to maintain ecosystems within their range of natural variability, which requires attention to pre-EuroAmerican landscape-scale processes and corresponding landscape structures (e.g., old-growth forest distribution). The prevailing "equilibrium" view of ponderosa pine forest landscapes, for example, holds that frequent, low-intensity surface fires maintained open, park-like forests of large, old trees. Yet a contrasting "nonequilibrium" view suggests that some forest ecosystems are subject to unpredictable catastrophic disturbances that dramatically alter these ecosystems. To assess these views' relevance, we examined early historical accounts and records of natural disturbances in the ponderosa pine forests of the Black Hills in South Dakota and Wyoming (U.S.A.). There is evidence of frequent, low-intensity surface fires and large, catastrophic disturbances before EuroAmerican influence. Several large, stand-replacing fires occurred between 1730 and 1852, and, shortly after EuroAmerican settlement, a major outbreak of mountain pine beetles (*Dendroctonus ponderosae *Hopk.) occurred. The location of these severe disturbances coincides geographically with early explorers' reports of extensive tracts of relatively dense closed-canopy forests, including some very large patches (5000+ ha) of dense old growth. This contrasts with sparse, open-canopy forests thought to be maintained by periodic, low-intensity surface fires. We suggest that the cooler, moister, central and northern Black Hills and topographically protected areas may have been dominated by infrequent, catastrophic disturbances that maintained large patches of dense forests, including large, contiguous patches of old growth, in a relative state of nonequilibrium. The warmer and drier southern Black Hills, south-facing slopes, and exposed areas may have been dominated by frequent, low-intensity surface fires and other small disturbances that maintained open-canopy forests in a relative state of equilibrium. Proposed Black Hills National Forest management plans that exclusively endorse the equilibrium view are misdirected and will move the forest ecosystem farther outside its range of natural variability.*

Desequilibrio Dinámico entre Perturbaciones Catastróficas y Bosques Maduros en Paisajes de Pino Ponderosa de Black Hills

Resumen: *Una meta del manejo de ecosistemas es mantenerlos dentro de su rango de variabilidad natural, lo cual requiere de considerar procesos pre-euroamericanos a escala de paisaje y las correspondientes estructuras del paisaje (e.g., distribución de bosques maduros). Por ejemplo, la visión prevaleciente del "equilibrio" de paisajes de bosque de pino ponderosa sostiene que frecuentes fuegos superficiales de baja intensidad mantenían bosques "similares a parques" abiertos con árboles grandes y viejos. Pero, una contrastante visión de "desequilibrio" sugiere que algunos ecosistemas de bosque están sujetos a perturbaciones catastróficas impredecibles que los altera dramáticamente. Para evaluar la pertinencia de estas visiones examinamos informes históricos tempranos y registros de perturbaciones naturales en los bosques de pino ponderosa de Black Hills en Dakota del Sur y Wyoming (E.U.A.). Hay evidencia de frecuentes fuegos superficiales de baja intensidad y grandes perturbaciones catastróficas anteriores a la influencia euroamericana. Entre 1730 y 1852 ocurri-*

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*eron varios incendios mayores y, poco después de la colonización euroamericana, el escarabajo de pino de montaña (*Dendroctonus ponderosae *Hopk.) causó grandes daños. La localización de estas perturbaciones severas coincide geográficamente con los reportes de exploradores respecto a extensas zonas de bosques de dosel cerrado relativamente densos, incluyendo unas extensiones muy grandes (5000+ha) de bosque maduro denso. Esto contrasta con los bosques de dosel abierto dispersos que se pensaba eran mantenidos por los incendios de baja intensidad periódicos. Sugerimos que, por su mayor frescura y humedad, las Black Hills centrales y del norte y las áreas topográficamente protegidas pudieron haber sido dominadas por perturbaciones catastróficas infrecuentes que mantenían grandes extensiones de bosques densos, incluyendo grandes parches contiguos de bosque maduro, en un relativo estado de desequilibrio. Las Black Hills del sur y las laderas del sur, más cálidas y secas, pudieron haber sido dominadas por incendios de baja intensidad frecuentes y otras perturbaciones pequeñas que mantenían bosques de dosel abierto en un relativo estado de equilibrio. Los planes de manejo propuestos para el Bosque Nacional Black Hills que exclusivamente avalan la visión de equilibrio están mal orientados y llevarán al ecosistema del bosque más allá de su rango de variabilidad natural.*

Introduction

Ecosystem management is becoming the dominant paradigm in public lands management in the United States (Agee & Johnson 1988; Salwasser 1992; Kaufmann et al. 1994; F. D. Robertson, memo, 1992), and this approach often emphasizes large landscapes (Grumbine 1990; Kaufmann et al. 1994). Recently, many scientists and land managers have advocated managing ecosystems within their "range of natural variability" as a means to sustain "ecosystem health" across large landscapes (Kaufmann et al. 1994; Swanson et al. 1994). Range of natural variability refers to the variability in composition, structure, and dynamics of ecosystems before EuroAmerican influence (Swanson et al. 1994). Maintaining ecosystem health across large landscapes may be vital to sustaining native biodiversity and important ecosystem functions (Kaufmann et al. 1994; Kolb et al. 1994). Old-growth forests and natural disturbance processes are two linked ecosystem attributes that have been greatly altered since EuroAmerican settlement but that are increasingly recognized as important to forest ecosystem health and functioning. Yet we have an incomplete understanding of the comparative roles of small, relatively benign and large, catastrophic disturbances in ecosystem health.

For example, a prevailing view of pre-EuroAmerican ponderosa pine (*Pinus ponderosa*) forests of the western United States is that frequent, low-intensity surface fires maintained open, park-like forests of large old trees by thinning the understory while not seriously damaging most old trees (Cooper 1960; Weaver 1974; Harrington & Sackett 1992; Wickman 1992; Covington & Moore 1994; Arno et al. 1995). But most old-growth ponderosa pine forests have been harvested since EuroAmerican settlement, and livestock grazing and fire-suppression have altered their natural disturbance regimes. As a result, many harvested ponderosa pine forests are now composed entirely of dense stands of young trees, whereas unharvested older forests often have an apparently increased density of young trees beneath a remnant canopy of old trees (Covington & Moore 1994; Everett et al. 1994; Arno et al. 1995). Because this increased forest density may elevate the risk of catastrophic fires, diseases, and insect infestations, it is increasingly thought that thinning and prescribed burning are required to return forests to within their range of natural variability and avoid imminent ecosystem collapse (Covington & Moore 1994; Covington et al. 1994; Sampson et al. 1994). This widely accepted view of the range of natural variability of ponderosa pine forest emphasizes an "equilibrium" view of ecosystems (Weaver & Clements 1938; Odum 1969) in which a dynamic balance exists between low-intensity fires and stable, long-lasting, old-growth climax conditions.

An alternative "nonequilibrium" view holds that unpredictable, random, and sometimes catastrophic disturbances create very different dynamics, structures, and components in ecosystems through time (Botkin 1990; Sprugel 1991; Reice 1994). Thus, rather than stable, long-lasting climax conditions, change and turmoil are the true constants in many ecosystems. In many forest ecosystems, for instance, infrequent but large stand-replacing fires and insect outbreaks are a component of the natural disturbance regime (Heinselman 1981; Kilgore 1981). Even in ecosystems where frequent, low-intensity fires are prevalent (e.g., ponderosa pine, Douglas fir, and Sequoia forests), there is evidence that some intense stand-replacing fires occurred before EuroAmerican settlement (Kilgore 1981; Stephenson et al. 1991; Arno et al. 1995). If such stand-replacing disturbances play a more important role than previously thought in ponderosa pine forests, then the nonequilibrium view is more relevant to the range of natural variability and the conservation and management of ponderosa pine forests.

Although it is important to consider the relevance of these two views in all ecosystems, this consideration has immediate conservation implications in the Black Hills of South Dakota and Wyoming. Recently, the U.S. Forest

Service (USFS) concluded that the range of natural variability of the Black Hills ponderosa pine forest consists mainly of open, park-like, and naturally fragmented forest conditions in which large patches of dense old growth are not a significant component (USFS 1994). Before EuroAmerican settlement, these conditions were thought by the USFS to be maintained by predominantly small disturbances, especially frequent, low-intensity surface fires. Thus, the USFS endorsed an equilibrium perspective of the Black Hills ponderosa pine forests. To test this assertion, we examined the pre-EuroAmerican forest landscape structure of the Black Hills, using historical records and disturbance data. We examined the role of large stand-replacing versus small or low-intensity disturbances (e.g., crown fires versus surface fires) in influencing Black Hills forest landscape structure; we then focused on establishing whether characteristic forest landscape attributes associated with large disturbances, such as large patches and dense, old-growth forests, were a significant component of the pre-EuroAmerican forest landscape.

The Black Hills

The Black Hills form an isolated mountain range situated in the prairies of western South Dakota and northeastern Wyoming (Fig. 1). The range consists of gentle to rugged hills encircled by the relatively level "limestone plateau," which has many steep and narrow valleys (Alexander 1987). Elevations range from approximately 1070 m on the plains to 2207 m at Harney Peak. A diverse array of flora and fauna can be found on the Black Hills, including species from the Rocky Mountains, Great Plains, northern boreal forests, and eastern deciduous forests (Stephens 1973).

There are typically no obvious elevational vegetation zones within the Black Hills because of only slight differences in climate from low to high elevations (Hoffman & Alexander 1987). But the northern half of the Black Hills typically receives more rainfall, snowfall, and cloud cover and is colder with a shorter growing season than the southern Hills. For instance, although similar in elevation, Custer, South Dakota receives around 48 cm of precipitation per year compared to 74 cm in Lead, South Dakota (Froiland 1990). The latitude at which Rapid City, South Dakota occurs can be considered a rough dividing line between these two climate regions (Froiland 1990).

Throughout the Black Hills, the forests are dominated by vast stands of ponderosa pine. Dispersed within this pine matrix are patches of white spruce (*Picea glauca*), aspen (*Populus tremuloides*), bur oak (*Quercus macrocarpa*), paper birch (*Betula papyrifera*), and other hardwood species, as well as many grassy mountain "parks" (Hoffman & Alexander 1987). These forests

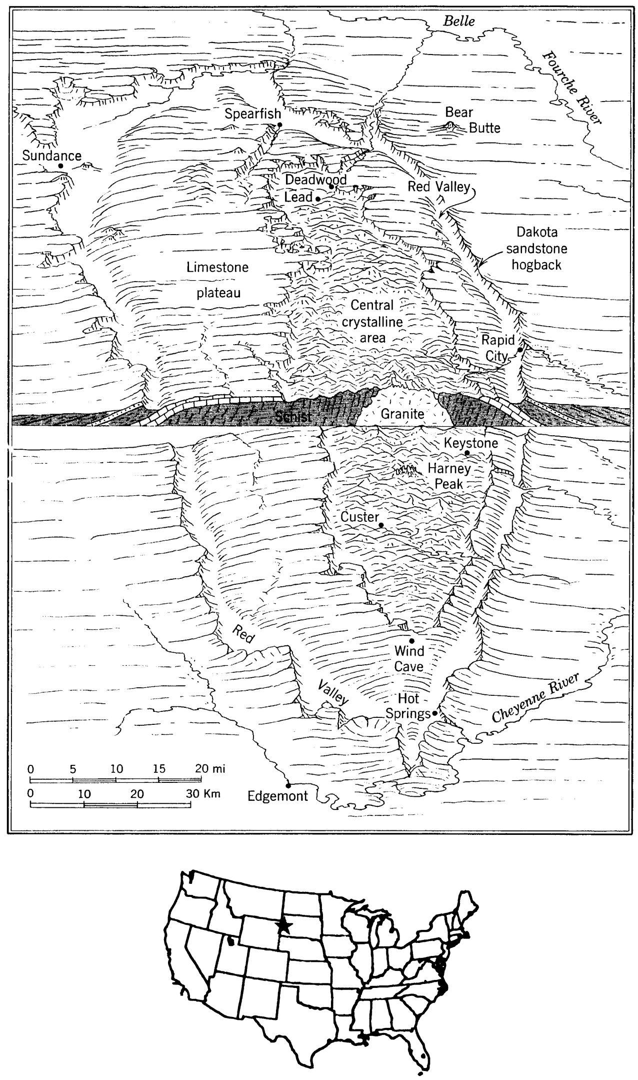

Figure 1. Main geomorphic regions of the Black Hills and general location within the United States (Reprinted from Strahler and Strahler [1992] with permission from Wiley, New York).

have a long history of intensive human use. Nearly every forested acre has been logged or thinned at least twice over the last century, and no other forest type in the Rocky Mountain region has received longer or more intensive management (Alexander 1987). Nearly 83% of the 501,870-ha Black Hills National Forest is currently available for timber harvest, primarily through shelterwood logging techniques (USFS 1994). As a result, there are only a few remaining roadless areas, including one federally designated wilderness, none larger than 7300 ha (USFS 1994), and old-growth forests are rare and dispersed in small remnant patches (Boldt & Van Deusen 1974).

According to Mehl (1992), old growth on the Black Hills historically consisted of both an open- and closed-canopy form. Open-canopy old growth occurred where periodic, low-intensity fires were prevalent, and it consisted of groups of large, old trees with open branches, irregular crowns, and little dead down material or small trees. Closed-canopy old growth occurred where frequent, low-intensity surface fires were not prominent, and it consisted of relatively homogeneous, dense stands with standing dead and down trees, large old trees with irregular crowns and open branches, and multiple canopy layers of various ages. Although they are undoubtedly somewhat variable in structure, we refer to these closed-canopy old forests as "dense old growth," as is implied in Mehl's (1992) definition.

Historical and Disturbance Sources

To establish general pre-EuroAmerican settlement forest conditions, we examined records from pre-EuroAmerican and early post-EuroAmerican expeditions to the Black Hills which had specific missions to inventory the natural resources. Information was obtained mainly from the following exploratory tours: (1) the 1874 General George Custer expedition, which included a report from W. Ludlow and many photographs of the forest (taken primarily of the foothill and central regions); (2) Colonel R. I. Dodge's 1875 expedition, accompanied by scientists H. Newton and W. P. Jenney; and (3) H. S. Graves's 1891–1897 forest inventory.

In our study and in the USFS range of natural variability assessment, "The Black Hills Forest Reserve," written by Henry S. Graves in 1899, was a major source of information. Graves toured most of the Black Hills for the U.S. Geological Survey and sampled dozens of forest plots, described general forest conditions, took photographs of the forests, and produced forest maps of the Black Hills illustrating patches of merchantable timber delineated mainly by classes of board measure (Fig. 2). Moreover, Graves (1899) often distinguished between the uncut, partially cut, and cut-over forests he sampled and described. It should be noted that when Graves arrived in the Black Hills in 1891, widespread logging and many human-caused fires had already occurred. From the beginning of EuroAmerican settlement during the 1875 gold rush through 1898, over 1.5 billion board feet of timber were cut in the northern Black Hills alone (USFS 1948).

Thus, we established pre-EuroAmerican forest conditions by (1) focusing on the corroborative accounts of particular forest conditions from the separate expeditions; (2) looking closely at Graves's (1899) forest data, which were derived from scientifically sampled forest plots; (3) examining Graves's detailed forest maps; and (4) reviewing forest photographs from both the Custer and Graves expeditions. Although there may have been some biases in these early reports to encourage settlement in the Black Hills, this did not seem to be the case with descriptions of the amount of merchantable timber. A greater emphasis was often placed on the profitability of mineral over timber resources, and most presettlement explorers stressed that the timber of the Black Hills was not of particularly high quality overall when compared to that of other regions (Dodge 1876). Moreover, Graves (1899) stressed that much of the Black Hills consisted of large areas of dense second growth not suitable for lumbering and that large areas had already been burned over or subjected to "wasteful" logging practices. Thus, an exaggeration on the part of these men concerning the amount of large, merchantable timber was unlikely.

To evaluate the disturbance regime of the Black Hills, we analyzed data from several compilations of Black Hills disturbance history (USFS 1948, 1994; Gartner & Thompson 1972; Progulske 1974; Raventon 1994), dendrochronological studies (Fisher et al. 1987; Brown 1994; Brown & Sieg 1996), and several historical records (e.g., Graves 1899; J. Murdoch, unpublished data, 1910). We also examined photographic evidence of forest conditions from the Custer expedition as presented by Progulske (1974) and photos from Graves's (1899) report.

Natural Disturbances

The pre-EuroAmerican fire history of the Black Hills is not well understood. There have been only two dendrochronologically based fire studies, both from drier, more open ponderosa pine forest ecosystems (Devils Tower National Monument, Fisher et al. 1987; Jewel Cave National Monument, Brown 1994; Brown & Sieg 1996). These two studies found a mean fire-return interval ranging from 10 to 30 years (during different climatic periods), with generally low-intensity fires. Evidence of low-intensity fires was also reported by Graves (1899:84), who described signs of "surface fires" that "merely burn the surface of the ground," leaving most of the trees relatively undamaged.

But longer mean fire-return intervals and large crown fires may have been important components of the disturbance regime on other portions of the Black Hills (Knight 1994; Parrish et al. 1996), especially in the central and northern Hills. The earliest known fire of great severity occurred in the central Black Hills around 1730–1740 (Graves 1899; Progulske 1974; Raventon 1994; USFS 1994) in an area that the USFS documented in the 1940s as containing even-age stands between 190 and 200 years old (USFS 1948). Another great fire or series of fires occurred around 1790 on the limestone plateau portion of the Hills (Fig. 1), creating a large forest patch encountered by Graves (1899), who described a "great belt" of "second-growth," even-aged timber approximately 100 years old. These two fires were thought to have swept over most of the Black Hills (Graves 1899; USFS 1994). There is also evidence of an immense fire around 1842.

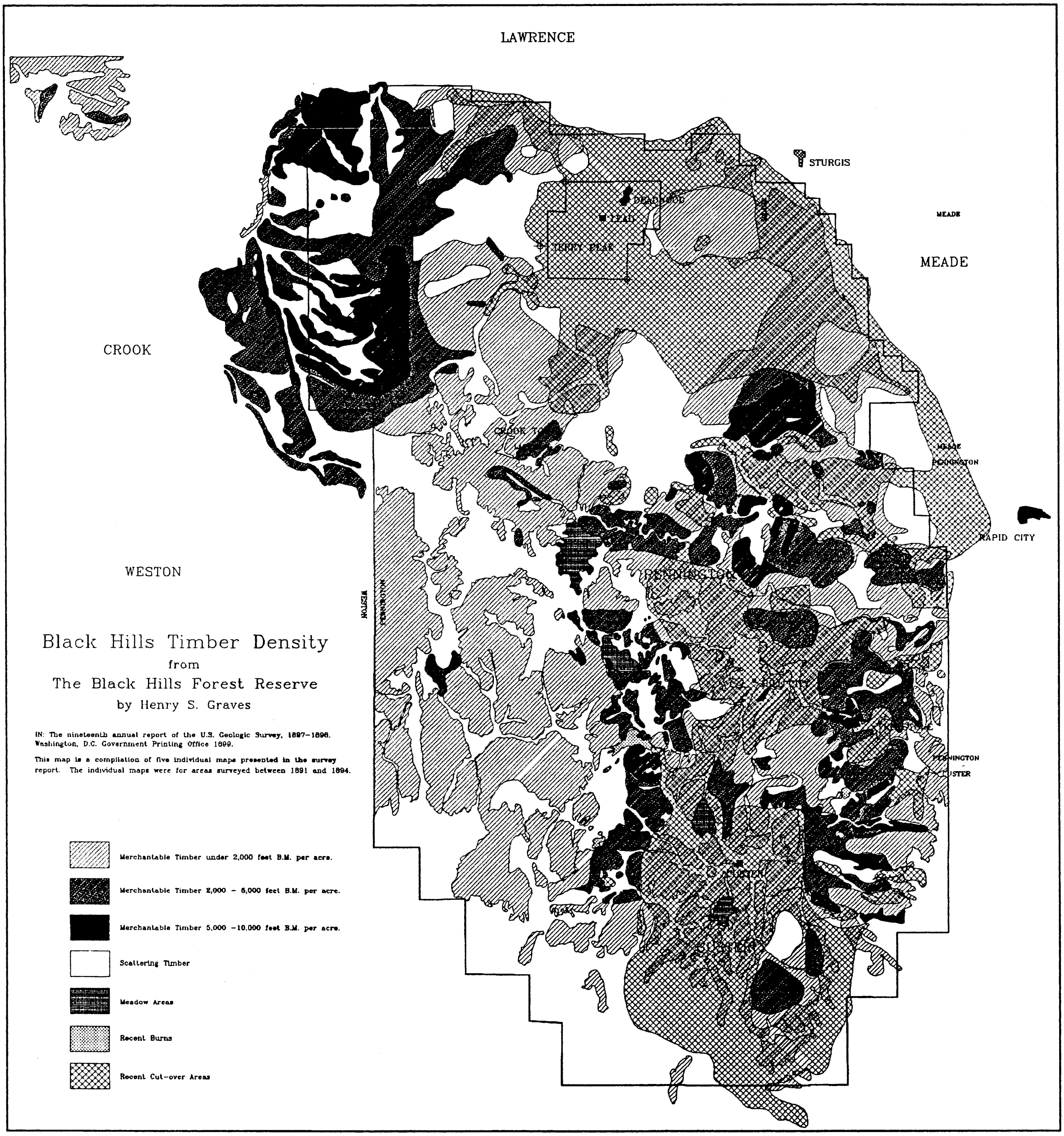

Figure 2. A composite map produced by the USFS (1994) of Graves's (1899) series of forest maps that were produced from forest surveys during 1891–1894. Graves's (1899) maps indicated densities of "merchantable" and "standing" timber in board feet/acre as well as "scattering timber," meadows, and recently "cut-over" and burned areas.

Native Americans reported to early settlers that around this time the "entire Black Hills were ablaze," and today there are many groups of trees approximately 150 years old in the northern hills (Graves 1899; USFS 1948; Raventon 1994). Large fires also burned around 1800 and 1852 (Raventon 1994; USFS 1948, 1994).

The early expeditions all reported the widespread effects of these large and "destructive" crown-fires. During the Custer expedition, for instance, Ludlow (1875, as cited in Gartner & Thompson 1972:46) mentioned ". . .very extensive fires, that have burned the former forest and left the charred trunks and limbs scattered on the surface. . . ." Newton and Jenney (1880:322) also wrote,

> The Black Hills have been subjected in the past to extensive forest fires, which have destroyed the timber over considerable areas. Around Custer Peak and along the Limestone Divide, in the central portion of the hills, on the headwaters of the Boxelder and Rapid Creeks scarcely a living tree is to be seen for miles.

Dodge (1876:62) recorded evidence of severe lightning-caused fires, writing that

> The woods are frequently set on fire and vast damage done. There are many broad belts of country covered with the tall straight trunks of what was only a short time before a splendid forest of trees. . . . The largest of these fires occurred on the head waters of Box Elder Creek. What was evidently a beautiful body of timber fifteen miles long by at least five broad, is now only dead trunks, some standing, but the far larger portion prostrate. . . .

Graves (1899:72) also recorded that "enormous tracts have been entirely denuded by forest fires," as in this account (1899:84): "On the limestone plateau there are apt to be extensive areas of level and rolling ground where fire attains great proportions and burns in the crowns of trees and destroys everything in its path."

The role of Native Americans in setting these pre-EuroAmerican settlement fires is uncertain. Local tribes may have set fires in some foothill regions of the Black Hills to drive out game (Fisher et al. 1987). But Native Americans may not have commonly ventured into, or set fire to, most of the heavily forested interior of the Black Hills, where large game may have been more scarce and difficult to hunt than on the surrounding prairies (Gartner & Thompson 1972). This is compatible with other research indicating that Native Americans in the West typically set fires in grassland and mid- to lower-elevation forests (Gruell 1985). Moreover, many of the pre-Euro-American fires were likely ignited by lightning strikes (Gartner & Thompson 1972), which were witnessed to have started destructive fires during pre-EuroAmerican (Dodge 1876) and early post-EuroAmerican settlement (Graves 1899) and which are more common in the northern than the southern Black Hills (Froiland 1990).

Many large, stand-replacing fires have also burned in the Black Hills since EuroAmerican settlement, with prolific burn periods in the late 1800s, 1930s, and 1980s (Raventon 1994). Several hot fires burned during the 1890s, including a severe 8100-ha fire near Deadwood and Lead (Progulske 1974). Although many early post-settlement fires were likely started by settlers, lightning-caused fires were also witnessed (Graves 1899). In 1898, for example, the naturally caused Iron Creek fire near Crow Peak burned over 8100 ha (Progulske 1974) and "killed nearly all of the standing timber within its path," according to Graves (1899, as cited in USFS 1994:A-31). Large fires continued to occur in the 1900s, as a result of both human and natural causes. In the 1930s, single destructive fires burned areas of 8800, 3400, 3000, and 8900 ha, and from 1980 to 1990 fires burned areas of 8910, 4050, and 6800, and 5670 ha (Raventon 1994).

The mountain pine beetle (*Dendroctonus ponderosae*) has been the other main source of large, destructive disturbance in the Black Hills. The first recorded major mountain pine beetle outbreak affected an initial area of approximately 50,000 ha in the northern Hills in 1895, but it eventually spread over most of the Black Hills, killing an estimated one billion board feet of timber by 1908, with many large areas experiencing over 90% mortality (Murdoch, unpublished data, 1910, as cited in USFS 1994:A-33). Murdoch noted that throughout the forest there were many "larger or smaller patches of insect-killed timber," as well as less-affected areas. Several major outbreaks have occurred since, with at least some level of mortality every year (USFS 1994). Tornadoes may also be an occasional source of large disturbance, because Graves (1899:86) mentioned ". . .considerable tracts. . .swept by hurricanes," and in 1940 a tornado leveled 1.5 million board feet of timber in the northern Hills (Progulske 1974).

Forest Structure

Dense Forests

Large, stand-replacing disturbances often propagate patches of dense, even-aged trees (Wright & Bailey 1982; Agee 1993), and most historical accounts described such dense forests, especially in the central and northern hills before widespread EuroAmerican settlement. For instance, an early map illustrating Black Hills topography and surface features, produced during the 1874 Custer expedition by geologist N. H. Winchell, delineated general forest conditions in the northern and central hills as either "High Hills Heavily Wooded" or "Heavily Timbered" regions (Ludlow 1875). As the Custer expedition traveled south, Ludlow (1875:15) noted that "the character of the country changed significantly as we went south," with ". . .timber more and more scarce."

Dodge (1876) consistently and without exception referred to the forests of the Black Hills as dense. He used the terms "dense forests," "dark green forests of pine," "dense growth of pine," "dense dark forests," "dense jungle of pine," and "dense thickets of pine timber" throughout his general descriptions of the forested landscape. For example, Dodge (1876:100) described the Black Hills forests in the opening paragraph of his section entitled "Timber" as follows: "For one hundred miles from the north to south, by fifty from east to west, the country is more or less thickly covered with pine timber." Similarly, Newton and Jenney (1880:320) began their section entitled "Timber" with this description:

> The Black Hills are a well-wooded country. The plenteous rains and showers in the summer keep the vegetation growing unchecked by drought. The density of the forests clothing the hill-sides have from their somber hue, when viewed from a distance, given the name of the region, the "Black Hills," by which it is known also in the Indian dialects.

Graves (1899:72), in his section entitled "The Forest," described general forest conditions as ". . .in the main, densely timbered" and in this account estimated average densities of "original" (older and larger) and "second growth" (smaller pole-sized/mature) forests (1899:76):

> In many places the second growth is very dense, with as many as 150 to 200 trees per acre. Comparing the forest to one in which the forest floor is entirely under shade and may be said to have a density of 1.0, the second-growth forest is estimated to have an average density of 0.7 within the timber limits. The original forest has an average density of 0.5.

Photographs from the 1874 Custer expedition (see Progulske 1974 for the figures cited in this paragraph) also indicate that relatively dense forests were common. Some of these photos indicate that park-like or less dense forests may have dominated in certain areas, such as the forest/grassland ecotone, mountain parks, rocky outcroppings, and south-facing slopes (e.g., Figs. 7a, 18a, 20a, 21a, & 42a). But many photos also demonstrate that very dense forests dominated (e.g., Figs. B-2, B-9, 24a, 25a, 26a, & 37a). In fact, most photos indicate that a fairly dense forest matrix existed, within which were small patches of snags, younger trees, or sparsely spaced older trees created by severe disturbances (e.g., fire and outbreaks of mountain pine beetle) or less dense forests around the edges of meadows or on rocky outcroppings where environmental factors inhibited growth (e.g., Figs. 14a, 23a, 32a, 35a, 39a, & 40a). Other photos indicate that dense forests were at least a minor component of the landscape, along with less dense patches, likely as a result of severe but often patchy disturbances (e.g., Figs. 9a, 11a, 12a, & 13a).

But most of the Custer photos were taken in two locations (the Deerfield and Custer areas), almost always centered around mountain parks or prairies, and they may not be a representative sample of conditions in the Black Hills forest. In addition, early expedition photogra-

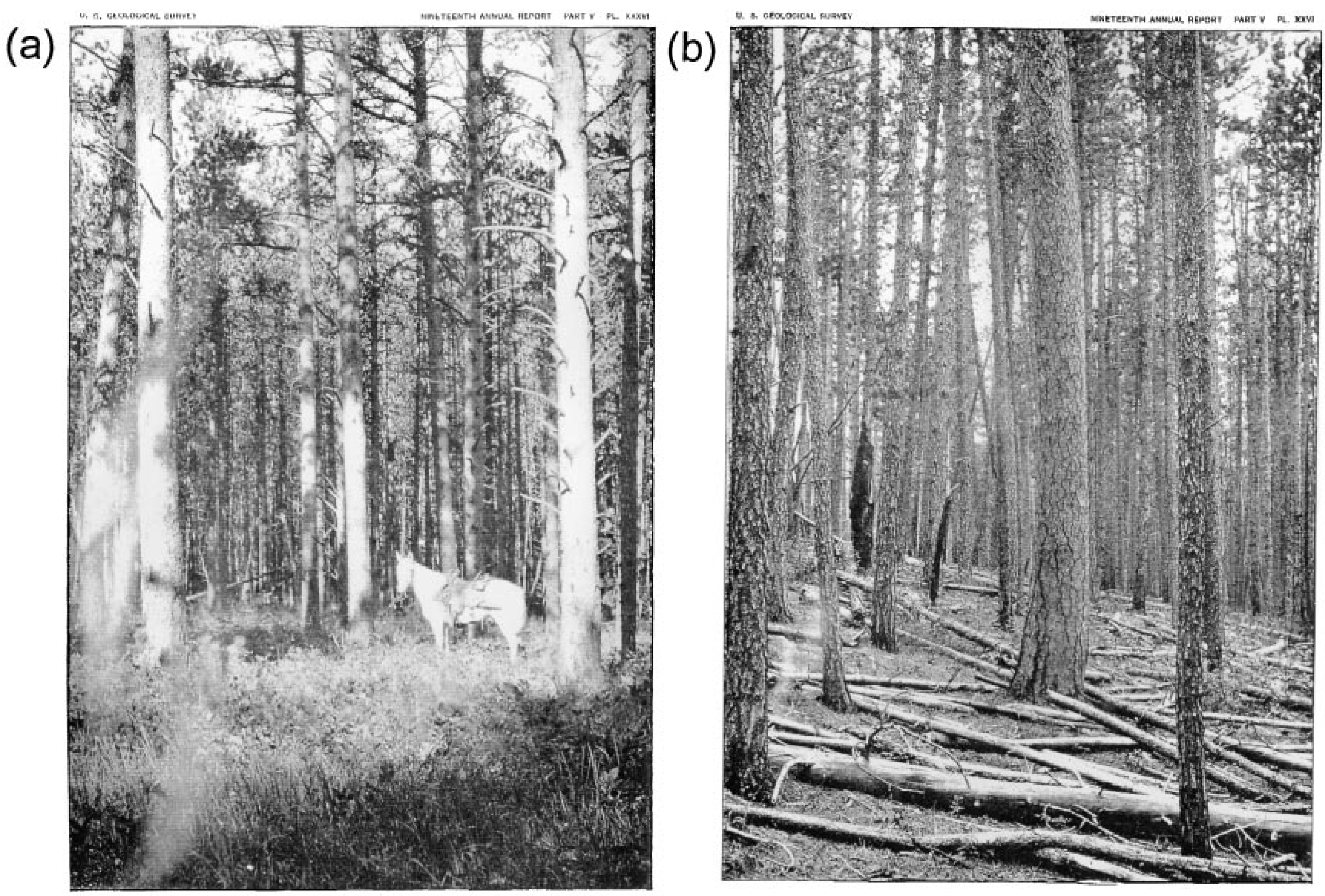

Figure 3. Two photos included in the "Black Hills Forest Reserve," a report to the U.S. Geological Survey by H. S. Graves (1899), demonstrating a forest of "typical" conditions, indicating fairly dense and mature forests (a) and dense pole-sized (20–25 cm) "second-growth" timber, which was often reported by Graves (one of several similar photos included in his report) (b).

phers, such as Custer's, were often concerned mainly with aesthetics and not with documenting characteristic forest conditions (Christensen 1988). Graves (1899) toured most of the forest, however, and was concerned with documenting representative conditions for the newly established U.S. Forest Reserve. Included within his report was a photo of a fairly dense "typical yellow pine forest" (Fig. 3a) as well as several photos of very dense, pole-sized forests (Fig. 3b). Thus, his photos strongly suggest that dense forests were common.

Large Patches of Dense, Younger Forests

There is evidence that these dense forests of the northern and central Black Hills often occurred in large, continuous patches, as a result of large disturbances. Newton and Jenney (1880:321) noted that ". . .extensive tracts are covered by a dense forest of small slender pines from 50 to 60 feet high. . ." and also reported seeing "large forests of young trees" (1880:323). Even clearer yet, Graves (1899:76) specifically mentioned large patches, such as this description of a very large patch of dense second growth, which we've estimated as larger than 60,000 ha:

> Not only is there a large amount of young growth scattered throughout the original forest, but there is a great belt in the northern hills composed almost entirely of second-growth timber. . .thrifty growing trees not yet large enough for lumber. This belt of timber extends, or did extend. . .from a line running from the mouth of Bear Butte Canyon to a point near Greenwood, west to Spearfish Canyon, and thence south through the Limestone Range to the headwaters of Hell and Gillette canyons. The forest is composed of poles 10 to 14 inches in diameter on the stump, and is about 100 years old.

Large Patches of Dense, Mature, and Old-Growth Forests

Large patches of dense mature or old-growth forests were also usually described, although in the early expeditions there is some disagreement as to the extent of mature forest. For example, Dodge (1876) typically reported that much of the forest consisted of smaller trees. In contrast, Newton and Jenney (1880:321) reported that trees of 12–24 inches (30–60 cm) were "common" on the forest. The following is an assessment by Newton and Jenney (1880:323) of the total area, which they later estimated at over 200,000 ha, covered by mature trees of "merchantable quality" on the Black Hills:

> It is difficult to estimate accurately the area covered by valuable timber in the Black Hills. Taking into consideration that the foothills are but sparsely wooded; that there are extensive parks and valleys in the interior destitute of trees, or where there are only scattered groves of pine; that over an aggregate area of several hundred square miles the timber has been destroyed by fire, I estimate that *one-half* [original italics] the surface included within the timberline is covered by forests of more or less mature growth.

Much of this "valuable timber" described by Newton and Jenney (1880) likely existed in fairly dense growing conditions: Graves (1899) often pointed out that the "open" forests produced "coarse and knotty timber" with low branches and that dense forests were required to produce "timber of good quality" with tall, limbless boles.

In fact, large patches of dense, old forest were specifically described, sampled, and mapped (Fig. 2) by Graves (1899). Graves (1899:74–75) classified old-forest patches into "three classes" of "original timber" or "old trees," which were between 250 and 300 years old and over 14 inches in diameter. Each class consisted of a different quality of these large, merchantable trees, based mainly on forest density and bole height. The "third class" was the "smaller and shorter" class of merchantable old trees, although density was not described. The taller and presumably denser "second class" had an average canopy cover of 50% and an average diameter of 20 inches (USFS 1994), and Graves (1899:74) reported that the ". . .second class of original timber is that which covers the *greater portion* [emphasis added] of the Black Hills." The highest quality "first class" of old forests contained the straightest and tallest boles in very dense conditions averaging 80% canopy cover, and it was probably the most limited in extent. Graves (1899:74) specifically sampled and mapped several of these first class forest patches, and described them as follows:

> The first class is found on rich soil and in protected situations. The trees average around 20 inches in diameter and have a maximum size of 3 feet. This timber reaches a height of 100 feet, but the average is not over 80 feet, and the stems are straight and clear of limbs for 30 to 50 feet. Such timber has grown in crowded stands. Forest of this character is found, in places, on the divide west of Spearfish Canyon, on South Box Elder, at the head of Spring Creek, on Soldier, Cold Springs, and Sand creeks, and elsewhere in small amounts. It has an average yield of 4,000 to 8,000 board feet per acre.

These first class patches occurred mainly in the northern and central portions or in well-sheltered canyons of the Black Hills (including those described above), and some of these old-forest patches were very large and dense. For instance, two of Graves's (1899) first class old-forest patches in the Cold Springs/Sand Creek area of the northwest Hills (Fig. 2) were estimated to have been approximately 6000–8000 ha in size (USFS 1994). Here, Graves (1899) describes one of these large, dense, old-growth patches:

> The old forest, which is found on the slopes of the canyons and on the rich flats above the ravines, is in some respects the finest in the Black Hills. This timber, where growing in rich soil, is 80 to 100 feet high, 20–22 inches in diameter on an average, with many trees 30 inches and even three feet through, and with a clear length of 30 to 50 feet. It has grown dense, and has in places a yield of 20,000 to 30,000 board feet per acre.

Some forest patches of this caliber may have been even larger before Graves arrived in the Black Hills. For instance, the large burn that Dodge (1876) described as a formerly "beautiful body of timber" would have been approximately 20,000 ha in size.

Such excellent-quality forests were typically located on "rich flats" (i.e., with good soils) and in topographically protected areas, especially along creeks and in deep gorges; areas presumed to be less susceptible to the large forest fires that had swept over much of the Black Hills (Graves 1899). Earlier expeditions also indicated that these locations generated the best forests for timber. For instance, Newton and Jenny (1880:321) wrote that "On the bottom lands in the lower valley in French Creek specimens of this pine were seen that were fully 100 feet in height, and would measure 35–40 inches through at the ground." Dodge (1876:101) also reported that in the bottoms of gorges and creeks "really fine timber, suitable for merchantable lumber" could be found, and Ludlow (1875:14) reported "heavily timbered ravines" around the Harney Peak region and (1875:12) "heavily timbered" hills in the northern region.

Equilibrium and Nonequilibrium

The natural disturbance data and historical accounts suggest that both the equilibrium and nonequilibrium views are relevant to the Black Hills ponderosa pine forest ecosystem. But these views must be considered within the context of Black Hills geography. Climatic and topographical differences were likely responsible for variations in ponderosa pine forest densities and disturbance regimes. The warmer and drier southern Black Hills, south-facing slopes, and exposed areas (e.g., rocky outcroppings) may have supported a disturbance regime dominated by frequent, low-intensity surface fires and other small disturbances (Gartner & Thompson 1972), which maintained open-canopy forests in a relative state of equilibrium. But the cooler, moister central and northern Black Hills, as well as topographically protected areas (e.g., deep canyons), contained fairly dense forests dominated by occasional large, stand-replacing disturbances such as intense crown fires or severe outbreaks of mountain pine beetle.

This spatial variation in the disturbance regime is consistent with the gradient in climate from the northern to southern Black Hills, as well as the vertical forest structures conducive to each disturbance regime. For instance, Graves (1899) noted that the dense forests contained abundant, dry, downed timber (Fig. 3b). Also, potential ladder fuels (e.g., birch trees, tall shrubs) are more common on the central and northern portion of the Black Hills (Hoffman & Alexander 1987) as are lightning storms (Froiland 1990). These climatic and structural conditions are similar to those in other cooler, moister northern and western U.S. conifer forest ecosystems, where large catastrophic fires often occur on a rare but regular basis (Kilgore 1981; Romme & Knight 1982; Heinselman 1985). As in these forest regions, central and northern Black Hills disturbances covered tens of thousands of hectares, such as the 20,000-ha burn reported by Dodge (1876) or Graves's (1899) contention that nearly the entire Black Hills burned in the 1700s.

As a result, the forest landscape structure of the central and northern Black Hills contained many large, contiguous patches of either recently disturbed areas; dense, pole-sized forests averaging 70% canopy cover; relatively dense, old forests averaging 50% canopy cover; or very dense, old forests with large trees averaging 80% cover (Graves 1899). Small disturbances and environmental gradients may have created a second level of patchiness at a finer scale within large patches of dense or mature forests. For instance, Graves (1899) often mentioned the existence of smaller patches of pole-sized timber and evidence of small, intense burns within large areas of generally old, dense forests (e.g., in the Box Elder watershed). In the contemporary Black Hills, such fine-grained disturbances in unmanaged forest stands produce only subtle variations in canopy density in generally closed-canopy forests (Lundquist 1995). Similarly, the larger patches observed in the pre-EuroAmerican landscape probably maintained contiguous, mature, although somewhat patchy, habitat conditions within, as in this very large and dense old-growth patch mapped (Fig. 2) and described by Graves (1899:159):

> The northern portion of the forest is much broken by burnt areas, but within the canyons there is still an enormous body of excellent timber. This timber begins about the mouth of Spotted Tail Gulch and extends over Sand Creek to and including Dug Out Gulch. The greater portion of this timber is of excellent quality, tall and clear, and most of it sound. In the deep ravines trees 3 feet in diameter are common and are apparently sound, unlike most of the trees on the eastern side of the hills. The forest is broken in places by patches of poles about 10 to 12 inches in diameter, especially on the high, flat ridges. It is estimated that there are about 5,000 board feet per acre over the greater portion.

Thus, although large crown fires may have kept much of the tallest, oldest, and densest forest patches relegated to canyon bottoms and other protected areas, other dense and/or mature forest patches extended over much of the rest of the central and northern Black Hills. Although probably somewhat patchier than the fine-grained mosaic of unmanaged forests today, this horizontal forest structure likely provided similar and interconnecting habitat for species dependent upon dense, old growth, or interior forest conditions. This landscape structure was not within a stable state of equilibrium, however, because large, stand-replacing disturbances were capable of significantly altering the forest structure.

Interpretation of Range of Natural Variability

The Black Hills National Forest management plan (USFS 1994) overlooks the important nonequilibrium dynamics we have documented by emphasizing a widespread maintenance of equilibrium conditions. Forest ecosystems would be stabilized within a manageable, predictable, and "normal" range of conditions by (1) increasing road-construction and maintaining current timber harvest levels to reestablish the "open" and "fragmented" structure of the original forest; (2) "managing" 5% of the forest as old growth in numerous small stands (20–200 ha) throughout the forest; (3) designating no additional wilderness areas because "wilderness designation would allow those areas to move away from the natural fragmentation that was inherent in the presettlement Black Hills toward mature conifer communities" (p. III-171); and (4) suppressing naturally occurring large disturbances, while duplicating low-intensity and small disturbances through logging (USFS 1994).

This management strategy stems from the following conclusions made in the USFS's assessment of range of natural variability (1994): (1) most pre-EuroAmerican fires in the Black Hills "burned cool" and ". . .consumed most of the understory seedlings, which kept much of the forest open and park-like" (p. A-15); (2) "frequent low-intensity fire limited the amount of forest susceptible to stand-replacing fires" (p. A-50); and (3) this disturbance regime created ". . .the highly fragmented forest that was seen by the early explorers" in which ". . .large tracts of contiguous old-growth forest. . .were not the norm. . ." (p. A-7). Thus, "crowded, old conifer stands were limited in extent. . .and not connected by similar habitat" (p. III-116). But the relationship and apparent contradiction between a relatively benign low-intensity fire regime and a "highly fragmented" forest (which would seem to require frequent, intense disturbances) are not well explained by the USFS. Moreover, the USFS also documented large, stand-replacing disturbances and large patches of dense forests (e.g., the "great belt" of dense second growth) yet did not adequately address the prominence of these components in influencing landscape structure.

The USFS apparently classified the forest as park-like and fragmented for three main reasons. First, the USFS relied heavily on descriptive accounts that stressed the "defective" and "irregular and broken" character of the overall forest (Graves 1899). Yet these accounts were undoubtedly influenced by the widespread effects of recent logging and human- and natural-caused fires and by Graves's disappointment in finding that many large bodies of excellent-quality timber had already been logged or burned.

Second, the USFS calculated the total acreage of pre-EuroAmerican park-like, less dense, and old-growth forest (Table 1) by adding patch-type areas from a digitized composite of Graves's maps of standing and merchantable timber (Fig. 2). But many patches included in USFS calculations of less dense or park-like forests may have actually contained dense forests. For instance, the mapped locations of the nebulously described "scattering" and timber patches with less than 2000 feet board measure often contradict the dense patches explicitly described by Graves, especially the great belt of dense, second-growth timber, which Graves (1899:76) wrote had "some old timber. . .*scattered* [emphasis added] through the forest." Moreover, many of the less dense patches drawn under the "cut-over" areas extend conspicuously to the border of more valuable, uncut, dense old-forest patches (Fig. 2). It is unlikely that logging stopped exactly at the border of this valuable timber. Rather, these patches likely indicate what remained standing *after* logging, not before as the USFS contends (and used to calculate patch-type cover in Table 1). The USFS also used only the patches of 5,000–10,000 feet board measure to calculate total old-growth acreage at 23,939 ha (Table 1). But Graves (1899) referred to all "three classes" of extensive "original timber" as "old trees," and Black Hills old-growth ponderosa pine consists of both open- and closed-canopy forms (Mehl 1992). Finally, Graves (1899) mapped only a few small areas of "recent burns," and much of the mapped "scattering" timber may have also represented merchantable trees that remained "standing" after older fires. Thus, the "timber density class" area/percentages included in Table 1 do not incorporate or explain any of these apparent incongruities between Graves's (1899) maps and his text, and they also overlook the map legend, which indicated that only standing and merchantable timber was mapped.

Third, the USFS's assessment of range of natural variability was influenced by a study comparing the Custer expedition photos to contemporary Black Hills ponderosa pine forests (1970s), which suggests that pine encroachment has occurred in many meadows and foothills and that forests are generally denser today (Progulske 1974). Based mainly on the Progulske study, the USFS concluded that ". . .there is considerably more mature ponderosa pine, both in terms of density and acreage, now than at the beginning of the century. . ." due mainly to fire-suppression (USFS:A-35–6). But many of the Custer photos document dense, pre-EuroAmerican forests. Moreover, the photo comparisons demonstrate that a younger and denser forest often exists today, rather

Table 1. Cover of Graves's (1899) timber density classes (in feet board measure per acre) for the Black Hills.*

Class	*Area (ha)*	*Landbase (%)*
Meadows	19,927	4
Scattering timber	143,860	30
<2000 feet	233,363	48
2000–5000 feet	64,490	13
5000–10,000 feet	23,939	5

**Figures based on USFS digitized version of Graves's maps (USFS 1994).*

than older and denser, likely as a result of the elimination of the original forest by logging or severe fires. In Progulske's photos these younger forests are evident by the lack of variation in the canopy height, lack of standing snags, smaller trees, and/or less fine-scale patchiness, compared to the more complex structures of the older forests in the 1870s (see Progulske 1974 [e.g., Figs. 11, 14, 24, 26, 32, & 37]). In fact, Graves (1899) estimated that the "old timber," which covered the "greater portion" of the Hills, had an average age of between 250 and 300 years old. Today, the USFS estimates that 73% of the Black Hills National Forest is less than 120 years old (USFS 1994).

Conclusions

Although thought to be uncommon on most pre-EuroAmerican ponderosa pine forests, some researchers now suggest that intense stand-replacing fires (Knight 1994), mountain pine beetle outbreaks, large patches of dense old forests, and extensive areas of dense second growth may have been significant components of at least portions of the pre-EuroAmerican Black Hills forests (Parrish et al. 1996). But the equilibrium-based management approach advocated by the Black Hills National Forest in its proposed management plan is influenced by prevailing concepts of pre-EuroAmerican ponderosa pine forest ecology (e.g., Covington & Moore 1994), which may not apply to large portions of the Black Hills. The role of large and intense disturbances in influencing ponderosa pine forest dynamics and structure is not well understood and is often overlooked in this equilibrium perspective. Yet there is evidence that stand-replacing events have occurred historically in some other ponderosa pine forests (Swetnam & Brown 1992; Arno et al. 1995). Based on dendrochronological fire-history research, Brown (1994) and Brown and Sieg (1996) speculated that stand-replacing fires may have initiated ponderosa pine stands in the mid-1500s and early 1600s in the drier and more open ponderosa pine forests of present-day Jewel Cave National Monument in the southern Black Hills. But they also postulated that climate change may have been responsible for this stand-initiating event and, thus, further research is needed. Yet large disturbances, and the large patches of continuous dense forests that result, are clearly a feature of the central and northern Black Hills ponderosa pine forest range of natural variability.

The nonequilibrium perspective suggests that such temporal and spatial variations in the natural disturbance regime may be important in perpetuating landscape heterogeneity and native biodiversity. These variable dynamics create a changing mosaic of patch types which influences the occurrence of species as well as subsequent natural processes (Sprugel 1991; Reice 1994). These variations within a disturbance regime may actually be the norm for most ecosystems, as opposed to an ecosystem in equilibrium with homogeneous and stable environments (Reice 1994). Thus, nonequilibrium considerations, such as integrating large and intense disturbances into management plans based on range of natural variability, may be equally important to maintaining ecosystem diversity, health, and integrity.

To accomplish this on public forestlands such as the Black Hills National Forest, large areas may need to be maintained in an unmanaged condition. For instance, large wilderness areas may best encompass and perpetuate all ecosystem components and processes unimpeded, including large patch-producing events such as large-scale fires (Pickett & Thompson 1978; Noss & Harris 1986; Baker 1992*a*). This nonequilibrium-influenced management emphasis may be most appropriate on the Black Hills National Forest, where large patches of dense, older forest with interior and roadless conditions still exist (D. J. Shinneman & W. L. Baker, unpublished manuscript), especially in the central and northern portions of the Black Hills. In contrast, equilibrium-influenced management may be appropriate where restoration efforts are required to preserve valuable, small, remnant old-growth patches or other ecologically valuable areas from impending destructive disturbance (e.g., Baker 1994). Areas where large catastrophic disturbances were historically rare but with current conditions prime for such disturbances may also be appropriately managed for equilibrium conditions, such as in the historically open and mature forest of the southern Black Hills and foothills.

But the equilibrium-based goal of recreating and maintaining most of the Black Hills forests with fragmented and park-like structures, as recommended by the USFS, is unlikely to succeed because it overlooks significant historical evidence of large and intense disturbances. Moreover, selectively harvesting and thinning ponderosa pine stands may move these stands outside their range of natural variability because these activities produce significantly patchier forests, with canopy gaps and tree islands, than do unmanaged forests with naturally occurring canopy gaps (Lundquist 1995). These harvesting techniques may also negatively affect species that depend upon dense, interior forest conditions, as has been demonstrated with avian communities on the Black Hills (Crompton 1994; Dykstra 1996). Even employing more ecologically sensitive equilibrium-influenced management techniques, such as low-intensity prescribed burns, may produce further deviation from the range of natural variability where nonequilibrium conditions prevailed by creating a fine-grained patch mosaic in areas where large disturbances played an important role in creating the landscape structure (Baker 1992*b*, 1994).

Given the limitations of interpreting predominately qualitative historical data about forest patch types, tree densities, and old-growth structure and extent, obtaining quantitative field data for stand age structure and tree densities for unmanaged forest stands of the Black Hills would be helpful in determining appropriate management emphases. It is difficult to obtain useful data of this type on the Black Hills, however, because the effects of grazing, timber harvest, and fire suppression on forest structure have been extensive and intense, even within currently unmanaged forests (Alexander 1987). Recently, McAdams (1995) compared current tree density and basal area conditions to reconstructed pre-EuroAmerican Black Hills forest conditions. She determined that trees in the small diameter class (1–20 cm) have increased significantly in density and basal area within currently unmanaged stands, whereas the larger diameter classes have remained relatively stable. But McAdam's (1995) method of reconstructing presettlement densities and basal areas of smaller-diameter trees from existing snags, stumps, and live, old trees may not be reliable because fire, logging, grazing, and thinning may have prevented many small trees present in the pre-EuroAmerican forest from surviving to the present. Despite this, McAdams (1995) also found that in recently thinned stands tree densities of the smaller-diameter class increased significantly and that the basal area of larger trees (>40 cm) decreased significantly from her reconstructed pre-EuroAmerican forest stands. Unfortunately, uncertainties in reconstructing pre-EuroAmerican forest conditions may be inherent in even quantitative studies of forest landscapes that have been so extensively altered and managed.

Thus, large, unmanaged areas such as wilderness may also be necessary as references by which to compare highly managed landscapes to landscapes where natural processes and components occur in uncontrolled settings (Leopold 1941; Noss 1991). On the Black Hills, this may require more and larger unmanaged areas than currently exist in order to accommodate naturally occurring large disturbances and other ecological processes. This approach complements a strictly equilibrium-based management emphasis, which stresses the protection of forest "health" through intensive and widespread maintenance of a "normal" range of conditions, but which overlooks the role of unmanaged and unpredictable events in maintaining healthy landscapes.

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