RESEARCH ARTICLE

Fire History of Piñon-juniper Woodlands on Navajo Point, Glen Canyon National Recreation Area

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ABSTRACT: Navajo Point, on the southeast tip of the Kaiparowits Plateau, supports *Pinus edullis* Engelm. var *edulis-Juniperus osteosperma* (Torrey) Little (piñon-juniper) woodlands undisturbed by large wildfires in the recent past. We developed a fire history and characterized the current fuel structure and plant biodiversity in the piñon-juniper woodlands on Navajo Point. Using a combination of 18 stand ages, stand structural characteristics classified from satellite imagery, and line intercept sampling, we determined that it would take 400-600 years to burn a cumulative area equal in extent to Navajo Point. Despite a long history of livestock grazing and fire suppression policies, the woodlands on Navajo Point still retain most of their primeval character. Specifically, the landscape patch mosaic on Navajo Point has not been fundamentally altered by 20th century fire exclusion. We conclude that the old-growth woodlands that cover at least half of Navajo Point are a natural and ecologically significant component of this ecosystem, resulting from the combination of the area's soils, climate, and inherently infrequent disturbance regime. Today, the rich understory supports 207 plant species of which only 6% are exotic. Despite the current pristine character of this woodland, the greatest potential threat comes from *Bromus tectorum* L. (cheatgrass), which occurs intermittently throughout the area. If expansion occurs, this flashy fuel (which has no native counterpart) could significantly shorten the centuries-long fire cycle that has allowed for the development of the biologically rich woodland on Navajo Point.

Index terms: fire history, Kaiparowits Plateau, old-growth piñon-juniper

INTRODUCTION

Glen Canyon National Recreation Area (GLCA) in southeastern Utah and northern Arizona was established to manage water resources, generate hydro-electrical power, and provide recreational opportunities on Lake Powell. Rugged topography and varied geology support a rich diversity of flora, fauna, and vegetation typical of the Colorado Plateau. Navajo Point, on the southern tip of the Kaiparowits Plateau, rises 1000 m on the north side of the canyon of the Colorado River and Lake Powell in a series of cliffs and steep slopes, creating an isolated island of montane microclimate and mature piñon-juniper (*Pinus edulis* Engelm. var. edulis and *Juniperus osteosperma* (Torrey) Little) woodland surrounded by the deserts and semi-deserts. The National Park Service is revising its fire management plan for GLCA with a goal of managing fire to maintain the special ecological characteristics of these woodlands and the biological diversity of the area. However, little is known about the historical role of fire within GLCA or in this region of the Colorado Plateau as a whole. Thus, this study was undertaken to reconstruct the fire history of Navajo Point and to evaluate potential future fire behavior and fire effects on the vegetation.

The tremendous variation in natural disturbance regimes and post-disturbance dynamics of piñon-juniper woodlands is not well understood. It is often assumed that stands burned frequently at low severity before 1900, and that 20th century fire suppression (e.g., Gruell 1999; Schmidt et al. 2002) and grazing (Harris et al. 2003) has led to abnormally dense stands and, in some cases, severe fire behavior. While this interpretation may be accurate in some areas, piñon-juniper vegetation exhibits a wide variety of natural stand structures, fire regimes, and stand dynamics (Romme et al. 2003; Baker and Shinneman 2004). The few previous studies available from the northern Colorado Plateau region have reported historical fire regimes in piñon-juniper that were characterized by centuries-long fire intervals, predominantly high-severity fires, and naturally high-density stands prior to the land use changes of the 20th century (Eisenhart 2004; Floyd et al. 2004). The diversity of historical stand structures and fire regimes throughout the piñon-juniper vegetation type underscores the need for local information to guide management, especially where, as in GLCA, preservation of natural ecological conditions is a primary management goal.

One reason for our inadequate understanding of piñon-juniper disturbance dynamics is the methodological difficulty of reconstructing fire history in these systems. Fire scars tend to be rare or absent, making precise reconstruction of prehistoric fire history difficult or impossible (Baker and Shinneman 2004). Lack of fire scars is partially because piñon and juniper are both easily killed by fire and because historical fires in many areas were very infrequent or were of high severity (Romme et al. 2003). We previously reconstructed the historical fire regime of piñon-juniper woodlands in southwestern Colorado based primarily on stand age structures (Floyd et al. 2004). Here we used similar methods to reconstruct fire history of Navajo Point.

We also evaluated potential behavior and severity of future fires on Navajo Point. In addition to all other live and dead fuels, we measured the distribution and abundance of *Bromus tectorum* L. (cheatgrass), an invasive non-native species that has altered fire regimes and threatened the ecological integrity of native plant communities in many parts of the arid West (Mack 1981; Dukes and Mooney 2004; Ziska et al. 2005). It was known that cheatgrass was present on Navajo Point, but its extent, and its potential impact on the natural fire regime of the area, was unknown.

We addressed four questions: (1) What was historical (pre-1900) fire severity (i.e., were historical fires predominantly high-severity (stand-replacing) or low-severity (under-burning without killing the canopy) and what can we infer about fuel conditions in these stands); (2) What was the historical fire rotation (i.e., how many years were required for a cumulative area equal to the entire Navajo Point study area to burn); (3) What is the current landscape patch structure on Navajo Point, and to what extent does this structure reflect the effects of past fires; and (4) Given current fuel conditions in the area, how are future fires likely to burn on Navajo Point?

METHODS

Study Site

Established in 1972, GLCA includes Lake Powell, the second largest man-made lake in North America. The National Park Service (NPS) manages 500,868 ha, including extensive undeveloped landscapes with wilderness qualities. This includes the Navajo Point study area, the southernmost 2330 ha of the Kaiparowits Plateau (Figure 1). Navajo Point slopes gently downward overall from north to south with a central ridge, and then falls off in a sheer drop along the east, south, and west edges. The maximum elevation is 2292 m at the north end of NPS land, sloping down to 2180 m at the southern tip before dropping precipitously into Driftwood Canyon and Lake Powell 1000 m below. The area is remote and consequently there is little sign of recent human use. However, livestock grazing persisted from the late 19th century until ca. 2000, with a few intermittent strays making forays into the area after that time.

No weather stations exist on or near Navajo Point; therefore, the climate of the study area has been estimated by extrapolation from other areas of GLCA (Spence 2001). Estimated annual precipitation for Navajo Point ranges from 294-317 mm. Most precipitation falls in two peaks, one in late winter and the second in late summer, derived from Pacific frontal storms and the Arizona Monsoon, respectively. Potential evapotranspiration rates (calculated with standard Thornwaite calculations using extrapolated mean precipitation and temperatures) are relatively high (525-573 mm/year), exceeding precipitation in all but the winter months. Freezing conditions and snow are common from November through March.

Soils on Navajo Point are sandy and shallow, with extensive outcrops of sandstone slickrock of the cretaceous Straight Cliffs Formation. The soils in the area include two principal Natural Resource Conservation Service soil families: the Palma-Lanver Family and the Quazo-Lanver Family Complex. Palma-Lanver soils tend to consist of fine sandy loams, and cover about 70% of the study area. The Quazo-Lanver soils consist of shallow cobbly sandy loams and upland stony loams, including sandstone outcrops that cover the remaining 30% of the area (Soil Conservation Service 1984).

The most extensive vegetation type on Navajo Point is piñon-juniper woodland. In low elevation southern and western portions of the study area, soils are typically deep and sandy, the aspect is generally flat, and the canopy consists of exclusively of piñon and juniper. The understory is dominated by *Artemisia tridentata* Nutall, plus other shrubs including *Purshia tridentata* (Pursh) deCandolle, *Quercus gambelii* Nutall, *Amelanchier utahensis* Koehne, and *Ephedra viridis* Coville. The herbaceous layer is sparse, with much bare sand exposed. Native grasses include *Poa fendleriana* (Steudel) Vasey, *Hesperostipa comata* (Trin. & Rupr.) Barkworth, *Elymus elymoides, Vulpia octoflora* (Walt.) Rydb., *Bouteloua gracilis* (Willd. *ex* Kunth) Lag. *ex* Grif, and *Achnatherum hymenoides* (Roemer & J.A. Schultes) Barkworth (cover less than 1%) and the invasive *Bromus tectorum* L. A rich diversity of native forbs occurs in the understory, with some 207 plant species documented for the Navajo Point area, only 6% of which are non-native (Welsh et al.1978; Hill 2006). In shallow soils and where sandstone occurs on or near the surface, the canopy is more open and the trees tend to be smaller. In deeper sandy soils, the woodland canopy is denser and the trees reach larger sizes. The piñon-juniper woodlands give way abruptly to open patches dominated by *Artemisia tridentata* (sagebrush). Sagebrush tends to be most abundant where the soils are deeper and loamy. In protected areas around shrubs, well-developed biological soil crusts are found, but because of a legacy of grazing and the presence of feral animals, most crusts have been eliminated from the area.

Sampling Methods

Field Sampling of Fire History, Severity, Stand Age Structure, and Fuels

In May 2003 and May 2004, 18 randomly selected sites were sampled (Figure 1). Three parallel 45 m transects were laid 15 m apart at each site. This created a 30-m x 45-m plot that was then subdivided into six 15-m x 15-m subplots. We recorded basal diameter, diameter at breast height (dbh), and lower crown height (distance from ground to lower crown) on each tree within the plot. Every piñon over 10 cm basal diameter was cored as close as possible to the base (ca. 20 cm); a total 450 cores were collected. The presence or absence of obvious signs of past fire (e.g., basal fire scars, burnt juniper snags,

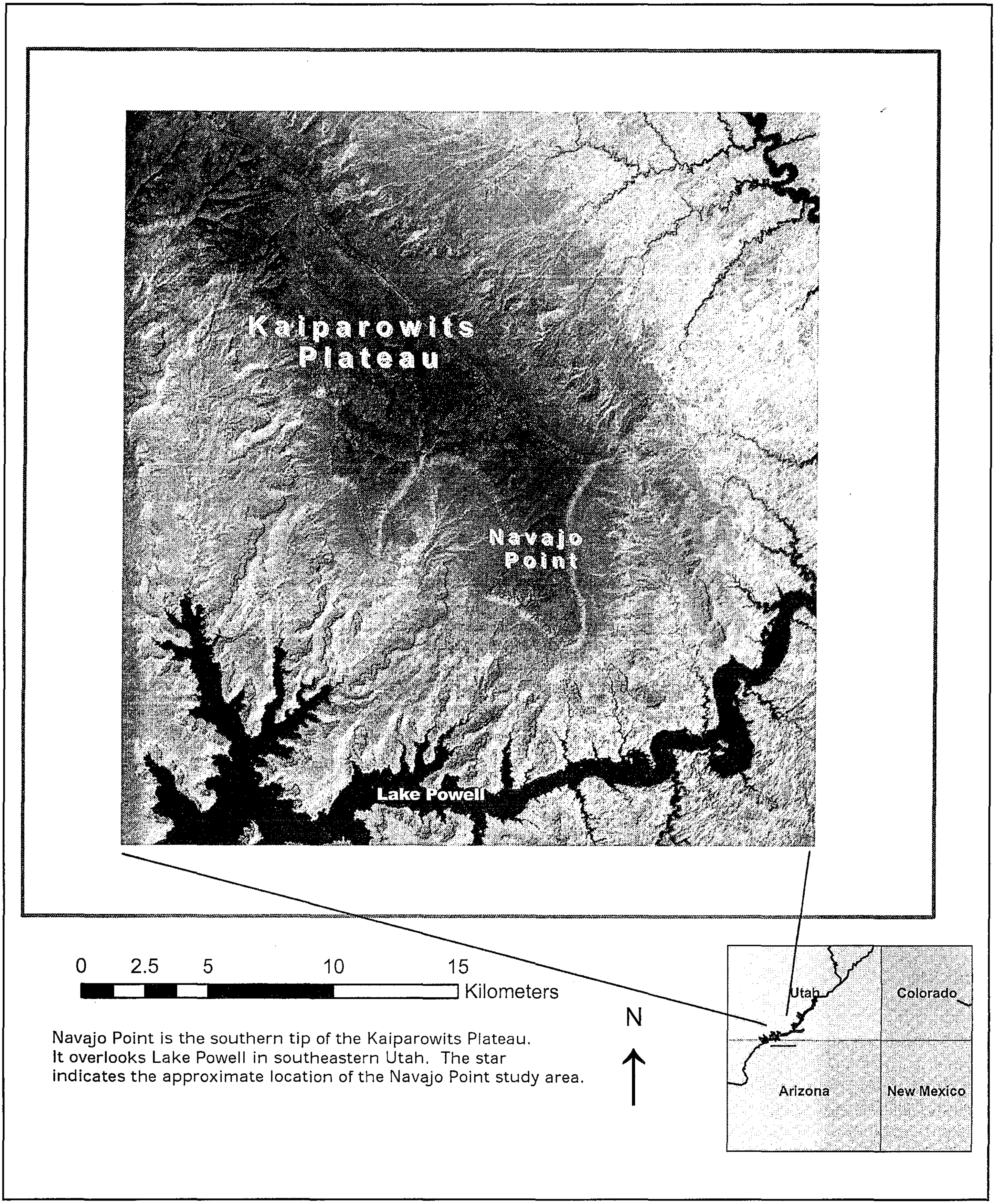

Figure 1. Navajo Point Fire History Study Project Overview.

or charred wood) was recorded. The cores were later sanded and cross-dated using standard dendrochronology methods (Grissino-Mayer 2001; Peter Brown website <www.rmtrr.org>. The nearest master chronology was from Navajo Mountain, Arizona, ca. 100 km to the south. We also developed a local chronology specifically for the Navajo Point study site extending back to 1470.

The three 45 m transects were then used to estimate the frequency of canopy fuels, ground fuels, and cheatgrass. At each meter mark, we classified the ground cover directly below the mark as live fine fuel, dead fine fuel, live coarse fuel, dead coarse fuel, or no fuel (i.e., base ground or rock). This provided an easily measured index of fire behavior likely to occur under dry weather conditions. Live fine fuels, mostly leaves and stems of forbs and grasses, would be the main fuels carrying a spreading surface fire (after the plants had dried and cured). Dead fine fuels, composed mostly of needle litter from piñon and juniper trees or fragments of highly decomposed coarse dead wood, also might carry a surface fire under dry conditions, but would not do so as readily as the cured and dried live fuels. The live and dead coarse fuels would not carry surface fire readily, but if ignited would contribute substantially to total heat release. For an indication of canopy continuity, we also recorded if there was tree or shrub canopy intercepted above the point. Finally, we noted whether cheatgrass was present or absent within a 0.5 m radius surrounding the point.

Seven of the stands were visibly less dense than the others, and these seven stands contained numerous large charred juniper snags – evidence of a high-severity fire at some unknown time in the past – and lacked fire scars. We estimated the minimum time since fire by coring piñon trees growing within 1 m of a large burned snag. Our assumptions were: (1) that the tree (resulting in a snag) was killed in the fire, and (2) that the living piñon growing in such close proximity could not have possibly survived the event and, thus, had germinated after the fire. It was not possible to precisely date the fires with this method because we do not know how long after the fire the piñon germinated. Nevertheless, this may be the best information possible in such a system where fire-scarred trees are rare or absent (Baker and Shinneman 2004). We cored over 250 piñon trees adjacent to snags, but did not attempt to use junipers because they cannot be dated with confidence (Gruell 1999; Eisenhart 2004).

In addition, we estimated the age of six stands that appeared especially old (large trees, no evidence of fire) by coring at least 10 of the largest trees (diameter approaching 1 m). This was done to further verify the seemingly ancient character of the woodlands and to extend the master chronology for cross-dating our core samples.

Image Interpretation and Classification

Digital Orthophoto quarter quads (DOQQ) and a Landsat TM image were used in evaluating the spatial extent of the historic fires identified from the field sampling and for characterizing the general landscape structure of the study area. Several classification algorithms were used in this analysis using IDRISI GIS software. These provide a set of images that indicate the degree (or "belief") to which a pixel can be categorized as a given training class. Inputs to the classification were: (1) raw DOQQ, (2) texture image (the texture image input was a dominance index (Turner 1989), and (3) NDVI image derived from the TM imagery (standard implementation of the normalized difference vegetation index using bands 3 and 5). A classification algorithm based upon Dempster-Shafer theory was chosen for this analysis (Eastman 1997).

Training sites were digitized from the DOQQ imagery using known locations identified during field sampling. The training categories included: (1) areas of dense canopy cover, (2) areas of open canopy cover, (3) areas known to have burned relatively recently, (4) sagebrush openings, (5) bare rock, and (6) masked background.

Images generated by the classification were visually inspected and then input to a "hardening" algorithm that chose the class with the greatest confidence value to provide a final classification image. For this procedure, the rock and sagebrush categories were ignored as they were insignificant in area or indistinguishable from burns, respectively. This resulted in a final image depicting areas of dense canopy, sparse canopy, and open burns. Initial sampling polygons (defined by visual interpretation of DOQQ, see above) were adjusted after comparison with this image to derive the areas of each canopy or burn type.

Refinement of Image Classification and Estimation of Historical Fire Rotation

Estimating historical fire rotation (the number of years required for a cumulative area equal to the entire study area to burn) is difficult because fire-scarred trees were very rare and, therefore, a precise fire chronology could not be developed. We estimated the total area burned during the past few centuries based on the extent of obviously burned areas containing charred juniper snags. As described below, the conspicuously burned areas were mapped effectively by the image analysis. However, some smaller and possibly older burns (as evidenced by only occasional snags and charcoal) now supported relatively dense canopies and were not detected in the imagery. To estimate the extent of these less conspicuous burned areas, we employed, in May 2005, a line intercept technique to measure the percent cover of fire history categories along eight 1-km transects. The transects were scattered among the three canopy types defined by the GIS analysis and were used to refine our interpretation of these broad landscapes. The five categories were:

- old growth woodland, lacking any evidence of fire and having at least some canopy trees >300 years old (old trees were usually easy to identify based on size and crown morphology, and we periodically verified our visual interpretations of tree age by taking increment cores)
- younger mature woodland, also lacking any evidence of fire but with all canopy trees <300 years,
- older burned areas, with charred

juniper snags present, either standing or fallen, and with 100-300 year old piñon trees
- recently burned areas, with charred juniper snags present, mostly standing, and with <100 year old piñon trees
- single tree fires, where a single charred snag was present, surrounded by old trees, suggesting that a fire was ignited but failed to spread

To refine our interpretation of fire history in the canopy polygons (defined above), we multiplied the total area occupied by each canopy type by the relative percent of these five fire history categories.

RESULTS

Stand Structures and Stand Ages of Piñon-Juniper Woodlands

Age structures in all 18 randomly distributed stands were similar in that trees of many age classes were present, from saplings that had established within the past two decades to the oldest trees in a stand. Most stands contained a large cohort of trees that established early in the 20th century, but in no case did we find evidence of a single-aged stand structure. Stand age (time since the last major disturbance) was assumed to be older than the age of the oldest sampled tree, but because of the typical delay in re-colonization of burned areas by piñon and juniper, and the lack of fire scars, we could not determine precise stand age. We defined three broad stand types (Table 1). Six of the 18 stands were characterized as old-growth, lacking any evidence of fire and containing at least a few living piñon 300-600 years old. Five stands were classified as mature, again with no evidence of fire but maximum piñon ages of <300 years. Seven post-fire stands were sampled, characterized by conspicuous charred juniper snags and adjacent piñon trees up to 100-200 years old. It was not possible to determine actual years when these fires occurred – only a minimum time since fire, based on the oldest piñon trees growing close to charred snags. We do not know whether the adjacent living trees established either immediately or up to several decades after the fire that created the snags; therefore, we estimate conservatively that these fires occurred between 100-300 years ago. The seven additional old-appearing stands were very old, with piñon trees up to nearly 600 years in age (Table 1). All of the old-growth stands also contained juniper trees that appeared as old or older than the piñon. The largest piñon and juniper trees were 0.5-1.0 m dbh.

Table 1. Estimated age (time since last fire) of piñon-juniper woodland stands on Navajo Point, Glen Canyon National Recreation Area, USA.

Stand	Oldest Tree	Pith Date	Estimated Stand Age	Stand Age Category	Charred Snags?
Randomly Selected Stands					
21	568	1436	600	> 300 yrs old-growth	N
31	430	1574	450	> 300 yrs old-growth	N
7	428	1576	450	> 300 yrs old-growth	N
5	389	1615	400	> 300 yrs old-growth	N
34	378	1626	400	> 300 yrs old-growth	N
16	339	1665	350	> 300 yrs old-growth	N
38	265	1739	275	Unburned < 300 yrs	N
35	183	1821	200	Unburned, 300 yrs	N
6	158	1846	160	Unburned, <300 yrs	N
3	141	1863	150	Unburned, <300 yrs	N
23	107	1897	100	Unburned, <300 yrs	N
22	198*	1841	200	Burned 100-300 yrs	Y
32	176 *	1828	180	Burned 100-300 yrs	Y
17	144 *	1860	144	Burned 100-300 yrs	Y
36	143*	1867	150	Burned 100-300 yrs	Y
10	135*	1869	135	Burned 100-300 yrs	Y
37	129 #	1875	130	Burned 100-300 yrs	Y
33	126 #	1878	130	Burned 100-300 yrs	Y
Additional Old-Growth Stands, Subjectively Selected					
CW-3	578	1427	600	> 300 yrs old-growth	N
ES	575	1429	600	> 300 yrs old-growth	N
CW-4	565	1440	600	> 300 yrs old-growth	N
E-2	489	1516	500	> 300 yrs old-growth	N
SW-rim	485	1520	500	> 300 yrs old-growth	N
CW-1	464	1530	475	> 300 yrs old-growth	N
CW-2	411	1593	420	> 300 yrs old-growth	N

*The oldest tree sampled was adjacent to a charred snag.

A single tree substantially older than the rest also was detected; this tree was not in proximity to a charred snag and probably was a relict that survived last fire.

Historical Fire Severity and Fire Rotation

Although we searched for fire-scarred trees throughout the course of our field studies on Navajo Point, we located only two trees having possible fire scars – one juniper and one piñon – each with a single basal scar surrounded by rotten wood (therefore, they could not be sampled).

Spatial analyses of remote data identified dense piñon-juniper canopy, sparse piñon-juniper canopy, and open areas that have burned within the past 300 years (Figure 2). We further interpreted stand structural categories into stand age categories by multiplying the area of each structural category (determined by imagery classification in Figure 2) by the proportions of stand age categories measured along transects. For example, the dense canopy woodlands and the sparse canopy woodlands corresponded with old-growth woodlands and mature woodlands, respectively (Table 2). However, a small proportion of both the dense and sparse canopy woodlands contained evidence of localized fires not detectable in the imagery but apparent on the ground (Table 2). Areas that had burned within the last 100-300 years (Table 1) were well demarcated on the imagery.

We used the data in Table 2 to estimate the historical fire rotation (i.e., the time it would take to burn a cumulative area equal in size to the entire study area). Because the southern end of Navajo Point, with much open canopy, appeared unique from the northern end, which had a relatively dense canopy, we separated the two areas for calculation. However, results were much the same. Old-growth woodland (>300 year old trees and no evidence of fire) occurs on more than 50% of both portions of Navajo Point; therefore, we assumed that less than 50% of the total study area has burned within the last 300 years. If exactly 50% had burned, then it would theoretically take 600 years (300 yrs times 2) to burn a cumulative area equal to the size of the study area. The fact that >50% of the study area is occupied by stands >300 years old with no evidence of fire leads to a conservative estimate of fire rotation of approximately 600+ years.

However, it may be necessary to adjust this estimate by taking into account cattle grazing that occurred on the Kaiparowits Plateau throughout the 20th century. Nearly all of the burned area that we detected appeared to have been burned prior to the 20th century; in fact, GLCA has only three records of very small fires (< 1 ha) on Navajo Point since 1988 and one relatively large 2000 burn that was clearly demarcated in the imagery but primarily extends north of the study area. It is possible that a more extensive area would have burned after 1900 had not intensive grazing removed fine fuels, thereby reducing the potential for spreading fire. If we assume that ca. 50% of the study area burned during the 200 y period between 1700 and 1900, then this would yield a 400 y fire rotation rather than the rotation developed above. Combining our two estimates, we conclude that it would take 400-600+ years to burn a cumulative area equal in extent to the Navajo Point area.

Although the overall fire rotation appears similar between the northern and southern portions of the study area, the spatial patterning of historic fires varies considerably across the landscape. In the southern portion of Navajo Point, soils tend to be sandy and deep, and the pattern of historical burning is very patchy. Sagebrush or other shrubs, with conspicuous charred juniper snags and only occasional piñon or juniper seedlings or saplings, now dominate severely burned patches. The outline of these small (<10 ha) stand-replacing fires forms a complex pattern of sinuous interconnected patches. The result is frequent openings in the otherwise old-growth woodland and a very fine-grained landscape pattern where charred remains of a stand-replacing event are found only meters away from patches

Table 2. Areas occupied by each type of piñon-juniper woodland on Navajo Point, Glen Canyon National Recreation Area, USA. The "section of study area" is the area defined by classification of satellite imagery; open canopy occurs primarily on the southern end of Navajo Point and dense canopy on the northern portion (Figure 2).

Section of Study Area	Stand Age Category	Area (ha)	Proportion of Total Area (%)
Open canopy	Old-growth woodland (>300 years since fire)	344	60
	Mature woodland (no evidence of fire, but trees <300 years old)	23	4
	Areas burned within past 100-300 years	203	35
	Very localized fires within old-growth or mature woodland	8	1
	Total Area	578	100
Dense canopy	Old-growth woodland (>300 years since fire)	708	57
	Mature woodland (no evidence of fire, but trees <300 years old)	146	12
	Areas burned within past 100-300 years	335	27
	Very localized fires within old-growth or mature woodland	57	4
	Total Area	1246	100

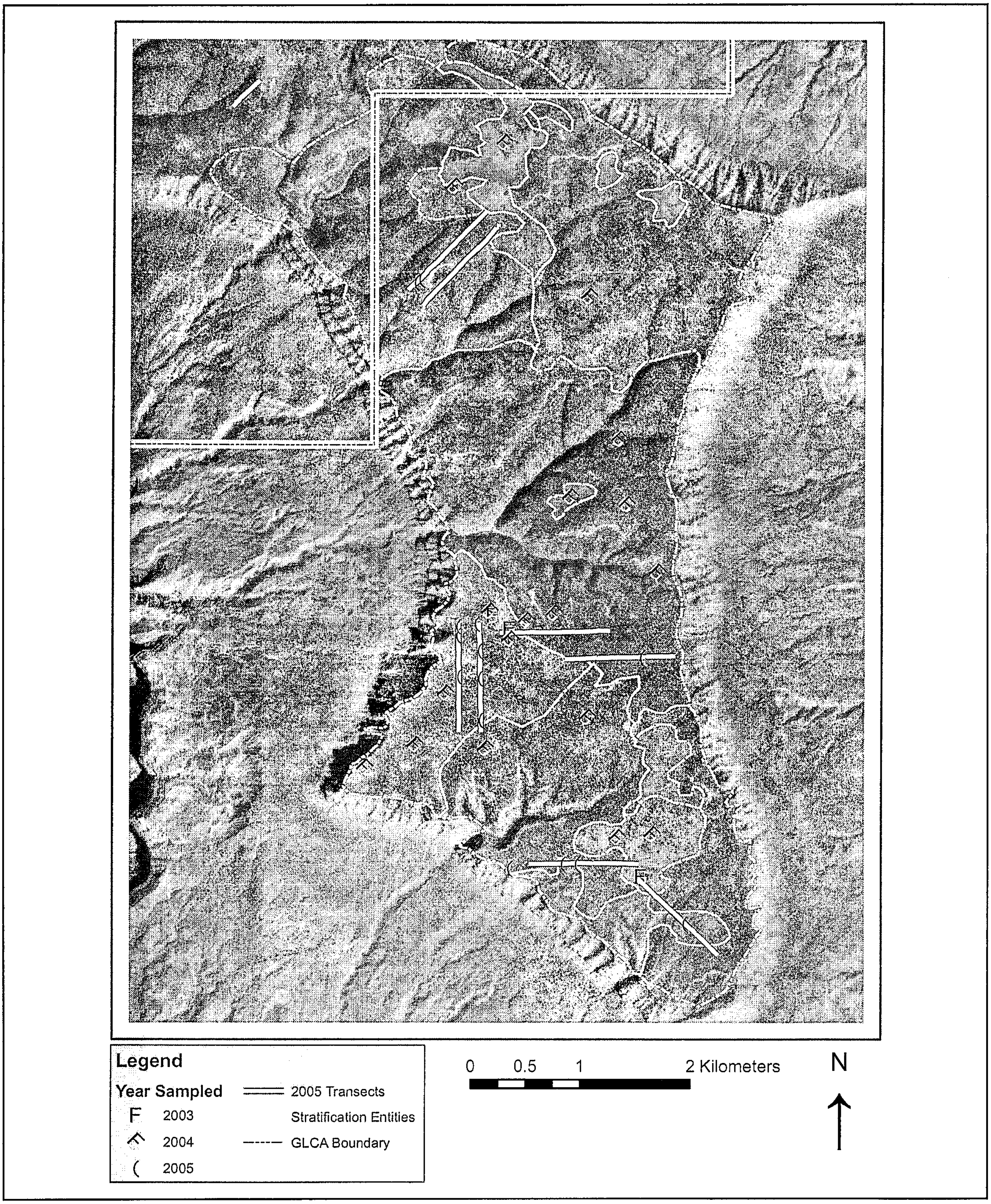

Figure 2. Navajo Point Fire History Study Sampling Strategy.

of undamaged trees that may be 600+ years old. It does not appear that those locally severe fires burned through the adjacent patches of old trees: the adjacent patches lack any evidence of charred wood, the old trees lack fire scars, and many have low-hanging branches (< 1 m from the ground) that would have been scorched and killed had a surface fire burned under them. In contrast to the southern area, the fires in the northern portion of Navajo Point generally were larger stand-replacing events with less complex perimeters. Burned areas support a denser and more diverse shrub understory in the north than is seen in the southern portion of the study area. Soils in the northern portion of Navajo Point tend to be relatively shallow and rocky.

Current Fuel Characteristics and Potential Fire Behavior

Live fine fuels, capable of readily carrying a surface fire when dried and cured, exhibited low frequency of occurrence (average 10%) in each of three broad woodland types and in all types combined (Table 3). Frequency of fine live fuels was somewhat greater in the two woodland types that lack evidence of recent fire than in the areas developing after crown fire within the past 300 years. Frequency of dead fine fuels, which could also contribute to surface fire spread under dry conditions, was higher and did not differ among woodland types, with mean frequency of 46% for all types combined (Table 3). Frequency of coarse fuels, which would contribute to heat release if ignited but would not speed the advance of a spreading surface fire, was low and did not vary among woodland types: mean frequencies were 1% for coarse live fuels and 16% for coarse dead fuels (Table 3). The frequency of occurrence of live canopy directly above sampling points along the transects, a rough estimate of canopy fuel continuity, was significantly different among the three woodland types, ranging from 26% in areas that had burned within the past 300 years, to 42% in open woodlands, to 54% in dense woodlands (Table 3). Cheatgrass exhibited an overall frequency of 41%, with no significant differences among woodland types.

DISCUSSION

Navajo Point in GLCA supports a floristically rich piñon-juniper woodland that is climatically and compositionally distinct from the surrounding deserts. Many of the woodland stands are ancient, with large piñons up to 600 years old and no evidence of fire or other major disturbance. However, parts of Navajo Point have burned within the past 300 years, and fires will undoubtedly occur again in the future. We first address the four questions posed in the Introduction, and then close with an assessment of the current ecological integrity of this ecosystem and of the challenges associated with conservation of these ecologically significant woodlands in GLCA.

(1) What was historical (pre-1900) fire severity (i.e., were historical fires predominantly high-severity (stand-replacing) or low-severity (under-burning without killing the canopy))?

Although it is widely assumed that spreading, low-severity fires were an important

Table 3. Frequency of fuels (i.e. percentage of sample points along three 100-m transects that intercept a particular fuel type) in three structural types of pinon-juniper woodland on the Kaiparowits Plateau, UT. In addition, the frequency of *Bromus tectorum* L. (cheatgrass) is reported as the percentage of points along the same transects at which cheatgrass was present within a 0.5-m radius of the point. Numbers are mean frequency with standard deviation in parentheses. Where ANOVA revealed overall significant differences among woodland types, individual differences determined by posthoc tests are indicated by letters (same letter means no significant difference at P<0.05). Sample units in the analyses are stands, and number of stands sampled in each woodland type is designated by n. All sampling was conducted in May, 2004.

Fuel Type	Open canopy woodland (n = 8)	Dense canopy woodland (n = 6)	Woodlands with abundant evidence fire (n = 4)	All combined (n = 18)	F	p
Live fine fuels below point (%)	6.1 (4.3) a	11.4 (5.6) b	14.5 (8.7) b	9.7 (6.8)	11.92	<0.001
Dead fine fuels below point (%)	43.8 (13.5)	50.1 (12.4)	42.6 (15.4)	45.6 (13.7)	1.079	0.365
Live coarse fuels below point (%)	1.0 (1.7)	1.0 (1.3)	1.0 (0.8)	1.0 (1.9)	0.944	0.6
Dead coarse fuels below point (%)	16.7 (8.3)	15.2 (8.2)	14.1 (4.0)	15.6 (7.5)	0.331	0.723
Live canopy above point (%)	41.9 (14.9) a	54.3 (14.1) b	26.3 (20.1) c	42.6 (18.7)	10.406	<0.001
Cheatgrass (%)	26.7 (31.4)	55.2 (40.3)	48.9 (50.1)	41.1 (40.6)	0.952	0.408

component of pre-1900 fire regimes in piñon-juniper woodlands (e.g., Schmidt et al. 2002), we found no evidence to support this idea on Navajo Point. In all of the area that we surveyed in 2004 and 2005, we located only two trees having small basal scars that could possibly represent single fire scars. Moreover, many of the 300+-year-old trees had low-hanging branches with live foliage < 1 m above the ground – foliage that would have been killed and dropped if fires had burned along the ground below the crowns. In contrast, we found irrefutable evidence of past high-severity fires – notably charred juniper snags, both standing and fallen. These charred remains were concentrated in discrete patches distributed throughout the study area – the sites of stand-replacing fires that burned 100-300 y ago. We also found occasional isolated charred trees that apparently represent lightning ignitions that failed to spread and had little impact on the vegetation. Thus, we conclude that the historical fire regime on Navajo Point was dominated by infrequent but high-severity fires, and that low-severity surface fires were insignificant in shaping stand structure or in driving stand dynamics. The same conclusion has been made for piñon-juniper woodlands in southwestern Colorado (Floyd et al. 2000, 2004; Baker and Shinneman 2004; Eisenhart 2004) and elsewhere (Romme et al. 2003).

(2) What was the historical fire rotation (i.e., how many years were required for a cumulative area equal to the entire Navajo Point study area to burn)?

Based on the extent of woodlands that have not burned in at least 300 years, and accounting for grazing history, we determined that the pre-1900 fire rotation was between 400 and 600 years. Although this fire rotation is an estimate, it is far longer than the < 100 y fire interval commonly assumed for piñon-juniper woodlands in the West (e.g., Schmidt et al. 2002). Floyd et al. (2004) determined a similar fire rotation for piñon-juniper woodlands on the Mesa Verde cuesta in southwestern Colorado. Eisenhart (2004) also concluded that historical fire intervals were very long on the Uncompahgre Plateau in western Colorado. It is important to stress that some portions of the study area would burn more than once during this 400-600 year rotation, while other portions would not burn at all.

(3) What is the current landscape patch structure on Navajo Point, and to what extent does this structure reflect the effects of past fires?

Piñon-juniper woodland on Navajo Point exhibits a heterogeneous, fine-grained mosaic of structural types. This mosaic reflects fine-scale gradients in soil texture and topography – as would be expected – but also apparently has been influenced by the local fire history, which is patchy in part because of the variable soil depths and gradual changes in elevation and aspect. Ancient piñon-juniper stands, with piñon trees up to 600 years in age, low-hanging live branches, and no evidence of past fire, are distributed throughout the study area. These stands are commonly ≤10 ha in extent on the deep sandy soils of the southern section of Navajo Point, and tend to be somewhat larger on the shallower soils in the northern section. Interspersed with the ancient stands are younger woodland patches, consisting of smaller piñon and juniper trees mixed with sagebrush, but also with no evidence of past fire. These stands (1-10 ha in extent) may represent gradual tree encroachment into former sagebrush communities because of past grazing or 20th century climatic changes (Eisenhart 2004). Other young woodlands have clearly developed after stand-replacing fire (perhaps in the mid-19th century) and now consist of piñon and juniper, in sapling or small tree size classes, within a matrix of sagebrush and large (0.5-1.0 m diameter) charred juniper snags, both standing and fallen.

(4) Given current fuel conditions in the area, how are future fires likely to burn on Navajo Point?

The current fuel conditions in the piñon-juniper woodlands of Navajo Point do not appear conducive to widespread, low-severity surface fires. Live and dead fine fuels are infrequent and discontinuous (mean frequency 10% and 46%, respectively). On the other hand, fuels that could carry high-severity fires are relatively abundant. Both live and dead coarse fuels on the ground are sparse (mean frequencies of 1% and 16%, respectively), but canopy fuels were present above 43% of the points along our transects. The canopy fuels occur in clumps of nearly continuous leaves and branches plus large boles, but between the clumps, there is no canopy fuel.

Thus, although lightning ignitions may occur every year, fires of significant spatial extent on Navajo Point are likely only during conditions of drought and high wind. Without wind, extensive fire probably is unlikely because both surface and canopy fuels are generally discontinuous. Under dry conditions without wind, fire potentially can move from surface fuels into the canopy (especially where shrubs extend into the low crowns of the trees), resulting in passive crown fire or "torching." However, if the wind is strong enough, the fire may move from tree crown to tree crown, becoming an active crown fire. It is these kinds of fires – wind driven active crown fires – that are most likely to cover large areas on Navajo Point. The combination of ignition plus suitable weather conditions for active crown fire occurs only rarely in this area, and it is possible that years, or even decades, will elapse before another extensive crown fire occurs as a natural ecosystem process on Navajo Point.

We found cheatgrass throughout the study area. Fortunately, however, cheatgrass distribution and abundance was very patchy. In some stands, it dominated the understory with >50% cover; in other stands, it was a rare component. We conclude that cheatgrass has not yet dramatically altered the surface fuel conditions on Navajo Point, but acknowledge that the situation could change rapidly in future years. Continued monitoring of cheatgrass distribution and abundance is warranted.

Overall Assessment of the Woodlands on Navajo Point

Despite a long history of livestock grazing and fire suppression policies, the piñon-juniper woodlands on Navajo Point retain much or most of their primeval character. Specifically, the landscape patch mosaic on Navajo Point does not appear to have been fundamentally altered by fire suppression efforts during the 20th century. Even though some fires that might have burned during this time were prevented, we note that fires having a measurable impact on landscape structure were apparently infrequent in this area even prior to the 20th century. Had fire suppression not occurred, we might see more very young post-fire woodland patches on Navajo Point than are now present, but the overall landscape structure probably would not be greatly different. Notably, the old-growth woodlands that cover at least half of Navajo Point are not an artifact of 20th century fire exclusion. On the contrary, these extensive old-growth woodlands are a natural and ecologically significant component of this ecosystem, resulting from the combination of the area's soils, climate, and inherently infrequent disturbance regime. Past livestock grazing may have influenced the landscape mosaic, notably as a mechanism driving recent tree establishment in open areas of sagebrush; however, additional research is needed to evaluate the relative importance of grazing vs. climatic fluctuation in causing tree densities to increase during the past century (e.g., Eisenhart 2004).

We also conclude from our measurements and qualitative assessment of current fuels conditions that fuels and potential future fire behavior in the piñon-juniper woodlands on Navajo Point today are not altogether different from historical conditions. We suspect that live fine fuels were somewhat more abundant before 1900 than today, because the native grasses and forbs were preferred forage for livestock. However, we observed that grasses and forbs were not particularly abundant in 2004 and 2005 even in pockets of deep soil within depressions in rock outcrops that are inaccessible to livestock. Thus, we speculate that the discontinuous nature of fine fuel today is not due entirely to the long history of grazing, but results also from the nature of the soils and climate in the area. It is impossible to determine to what extent the composition of the understory herbaceous community may have been altered by 20th century grazing, but we note that the area still supports >200 native plant species. Now that grazing has been eliminated from the area, it is likely that understory composition will gradually move back towards historical conditions. In sum, it appears that the Navajo Point ecosystem remains within, or not far outside, its historical range of variability with respect to fire rotation, fire severity, landscape patch structure, and overall biotic composition.

Yet, we must caution that the ecological integrity of the Navajo Point woodlands may be threatened in the future, especially by climate change and by continued expansion of cheatgrass. Large fires have become increasingly frequent in the last 20 years in many parts of western North America and Canada, apparently in large part because of higher temperatures and longer fire seasons (Westerling et al. 2006). Climate projections indicate that the warming trend will likely continue, both because of natural atmospheric circulation patterns in the Pacific and Atlantic Oceans (McCabe et al. 2004) and because of anthropogenic greenhouse gases (IPCC 2007). If cheatgrass becomes more abundant and more widely distributed throughout the woodlands of Navajo Point, then the currently discontinuous nature of the fine fuels could be transformed into a relatively continuous and "flashy" fuel bed, as has occurred elsewhere (Mack 1981; Dukes and Mooney 2004; Ziska et al. 2005). This change could lead to a qualitative and perhaps irreversible change from the historical pattern of infrequent fires to a new pattern of frequent fires. The presence of cheatgrass, and climatic or land use changes that encourage its expansion, are rightly considered important management concerns in GLCA and elsewhere.

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