Long-term fire history in Great Basin sagebrush reconstructed from macroscopic charcoal in spring sediments, Newark Valley, Nevada

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Running head: Sagebrush fire history from charcoal

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Abstract

We use macroscopic charcoal analysis to reconstruct fire history in sagebrush (*Artemisia tridentata* var *wyomingensis* and *A. tridentata* var. *tridentata*), in Newark Valley, Nevada. We analyzed charcoal at continuous 1 cm intervals, and pollen at ~263 yr intervals in a core spanning the last 5500 yr. A charcoal peak in the historic period was associated with a >1400 ha fire dated to 1986 that burned in the watershed. We reconstructed the pre-historic fire history by inferring fires from similar charcoal peaks that were significantly greater than the background charcoal accumulation. Our results suggest the fire regime is climate and fuel driven. During periods of wetter climate, sagebrush increased and fires were more abundant, and during extended dry periods when sagebrush decreased, fires were less frequent. Our method does not allow calculation of a fire return interval, however our results support models that estimate a mean fire return interval of up to a century in *Artemisia tridentata* var *wyomingensis*. The charcoal record indicates that within the historic period, fires have increased. This contrasts with pinyon/juniper studies that indicate an expansion of woodland associated with fewer fires in the historic period. We suggest that in the central Great Basin, a regime of frequent fires in sagebrush that limits woodland expansion is true for the sagebrush/woodland ecotone, but in sagebrush dominated valleys with lower fuel loads, fires have always been less frequent. Protecting sagebrush-dominated valleys from frequent fire would appear to be consistent with the pre-historic fire regime.

Keywords: Sagebrush, fire history, charcoal, Nevada, Great Basin, *Artemisia tridentata* var. *wyomingensis*

The invasion of *Bromus tectorum* (cheatgrass) throughout much of the Great Basin in the early 1900s (Mack 1981) has changed the fire regime within sagebrush (*Artemisia*) dominated landscapes, resulting in more frequent fires (Whisenant 1990). Total area burned per year has also increased, so that over the last five years, on average, >275,000 has burned in Nevada each year (Western Great Basin Coordination Center 2004). Although it is evident that invasion of *Bromus tectorum* has increased the frequency and extent of fires in sagebrush environments, we still have a poor understanding of sagebrush fire history prior to 1900 A.D. Gruell (1985) reviewed journal accounts for references on fire made by early explorers and naturalists and concluded that fire was a major perturbation in the region prior to European settlement. However, such observations are widely scattered in time and space and provide no quantitative analysis of the frequency of fire in a specific vegetation cover.

Reconstructing fire history within sagebrush is problematic because sagebrush fires are stand replacing. By contrast, in forested environments, evidence of past fires can be reconstructed from fire-scars found on surviving trees. Analysis of tree-rings from fire-scarred trees Tree-ring and fire scar analysis allows us to identify and date pre-historic fire events. This method has been widely utilized throughout the west to reconstruct forest fire histories extending back hundreds of years (Swetnam 1993). In environments where fire-scarring scarred trees grow within or directly adjacent to sagebrush, this technique has been used to infer sagebrush fire history (Houston 1973, Burkhardt and Tisdale 1976, Miller and Rose 1999). It is a question however of whether fire return intervals calculated through this method are representative of treeless valleys of the central Great Basin dominated by sagebrush, primarily *Artemisia tridentata* var. *tridentata* (Great Basin big sagebrush) and *A. tridentata* var. *wyomingensis* (Wyoming sagebrush).

In central Nevada, pinyon juniper woodlands containing *Juniperus oesteosperma* (Utah juniper), *J. occidentalis* (western juniper), and *Pinus monophylla* (single leaf pinyon) typically occupy slopes above sagebrush-dominated valleys. Reconstructing fire histories in these woodlands is difficult because juniper are thin barked and susceptible to fire for at least the first 50 years of growth (Miller and Rose 1999) and pinyon contain abundant resin and typically tend to burn completely when exposed to flame (Robin Tausch personal communication). Further, Relict stands of pinyon and juniper with scarred trees are typically confined to rocky ridges (Burkhardt and Tisdale 1976), and are not representative of the soils that support sagebrush. The few published fire history studies of pinyon and juniper in east-central Nevada (Blackburn and Tueller 1970, Gruell et al. 1994) and southwestern Utah (Tausch and West 1988) give no explicit estimates of pre-historic fire return intervals in sagebrush-dominated environments (Fig. 1).

Our knowledge of sagebrush fire history comes almost entirely from fire scar studies on *Pinus ponderosa* (ponderosa pine), *J. occidentalis*, and *Pseudotsuga mensezii* (douglas fir), growing in association with *A. vaseyana* (mountain big sagebrush) from sites in Oregon (Miller and Rose 1999, Gruell, 1999), Idaho (Burkhardt and Tisdale 1976) and Wyoming (Houston 1973) respectively (Fig 1). These studies suggest a fire return interval of 15 to 25 years in *A. vaseyana* (Miller and Tausch 2001), but the study sites have more mesic climates than are found in central Nevada and fuel loads are likely far greater. Annual precipitation at these sites ranged from 300 to 500 mm as compared with 185 mm at the central Nevada Field Lab near Austin, Nevada or 240 mm in Ely, Nevada. We argue that a 15 to 25 year fire return interval is not representative for sagebrush-dominated valleys in the central Great Basin where the primary species are *A. tridentata* var. *tridentata* and *A. tridentata* var. *wyomingensis*.

Miller and Rose (1999) were able to collect twelve fire scarred western juniper stumps and logs in *A. arbuscula* (low sagebrush) in what they considered a fuel-limited environment in Oregon. They identified only two fires in the last 300 years with a period of 130 years between these events. This is the only published study that documents pre-historic fire history in sagebrush habitat that is not dominated by *A. vaseyana*.

Miller and Taush (2001) presented a conceptual model of fire return intervals in forested and sagebrush habitats dependent upon climate and fuel loads. For sagebrush, they suggested that as climate becomes more arid, fuel loads decrease and fire return interval increases. The shortest fire return interval (15 – 25 yrs) occurred in mountain big sagebrush (*A. vaseyana*), which also occupied the wettest habitat and had the highest fuel loads. Next in order they suggested Wyoming big sagebrush (*A. tridentata* var. *wyomingensis*) at 50-100 yrs, low sage (*A. arbuscula*) at 100 – 200 yrs and then salt desert (*Atriplex* spp.) at >500 years. This conceptual framework is supported by seven published studies of *A. vaseyana* throughout the intermountain west, and only one study in *A. arbuscula*. The fire-return intervals for Wyoming big sagebrush and salt desert are undocumented estimates. Wright and Bailey (1982) speculated that the natural fire return interval in sagebrush may be 100 years, but this argument was simply based on the time needed for sagebrush to succeed *Tetradymia canescens* (horsebrush) following fires in southeastern Idaho.

Sagebrush in valleys in the central Great Basin is dominated by *A. tridentata* var. *wyomingensis* and *A. tridentata* var. *tridentata*. Changes in fire regime in this habitat type due to invasion of cheat grass is leading to conversion of sagebrush to annual grasses, and the demise of species dependent upon sagebrush. The increase in fine fuels in the interspaces between native shrubs has created a situation where some areas now burn every 3 to 5 years (Whisenant 1990). The model presented by Miller and Tausch (2001) suggests that the pre-historic fire return interval for *A. tridentata* var. *wyomingensis* may be on the order of a century, rather than a decade or two. It is critical to gain a better understanding of the pre-historic fire regime to support fire management policy. But, as described above, this will be difficult if not impossible using existing methods because of the problem finding trees with fire scars growing in these environments.

The purpose of this paper is to present a new approach to reconstructing fire history in sagebrush. In this study, we test the use of macroscopic charcoal recovered from sediments as a proxy for past fire activity. Our goal is to provide the first quantitative charcoal analysis of fire history from a sagebrush-dominated valley in central Nevada.

Charcoal analysis is one of the few methods available for reconstructing fire history within treeless landscapes. Mensing et al (1999) used charcoal analysis to reconstruct fire history in shrub-dominated chaparral environments in California.

Unlike dendrochronologic studies that examine annual tree rings and are able to identify the exact year of a fire, charcoal studies utilize sediment cores extracted from lakes, bogs, or springs, and, except in cases of annually laminated sediments, each sample may represent several years to decades and specific fire events cannot necessarily be resolved. Although this loss of temporal resolution means that we cannot reconstruct a specific fire return interval, we are able to quantify changes in charcoal accumulation over time and relate this to changes in fire activity at the landscape level. Charcoal in the upper sediments is typically compared with local fire history to calibrate charcoal accumulation rate and verify that peaks correspond with known fire events (Millspaugh and Whitlock 1995). In the past century, invasion of cheat grass has increased fire activity in the Great Basin [delete, already said above]. We can compare modern charcoal accumulation rates under the current fire regime with pre-historic accumulation rates prior to the invasion of cheat grass as an estimate of the extent to which invasion of cheat grass has altered the fire regime. We can also examine changes in fire activity in relation to climate change over long periods of time. This study attempts to characterize the fire regime in a sagebrush dominated valley over the last 5500 years and compare this with the historic period, which has been influenced by increased human activity and invasion of annual grasses. [I still like it even if it is a tad long, I can’t see much that I’d take out]

STUDY AREA AND METHODS

Site Selection and Core Recovery

To reconstruct local fire history using charcoal analysis, the ideal coring site would be a small (<10ha), deep (>10m) lake with steep catchments and no stream input (Whitlock and Millspaugh 1996). In addition, an independent record of recent fire history is required, from historic records or dendrochronological reconstructions (Whitlock and Anderson 2003). Charcoal derived from known fires should be evident in the near surface sediments of the core to calibrate the charcoal record with the known fire history.

A challenge to such research in Nevada is the absence of small deep lakes; however, many valleys hold permanent springs fed by groundwater from adjacent mountain ranges. The unique snail fauna found in many Nevada springs suggest that most have persisted continuously since the last glacial maximum, about 18,000 years ago (Taylor 1985) and are a potential source for long continuous sediment cores. We used a Geographic Information System (GIS) to identify lake and spring sites that had recent fires nearby in order to have a site with a known fire history to calibrate the charcoal signal. We obtained a digital data layer of springs in Nevada and compared this with a Bureau of Land Management digital map of fires from 1980 – 2000 to identify all fire events within 2 km of springs that were located in sagebrush cover types. Our analysis identified two fires that occurred in 1986 (>1400 ha) and 1999 (>400 ha) and were mapped within close proximity to a spring complex in Newark Valley, central Nevada (Fig. 1).

We visited the site in October 2001 and were able to identify an old burned area ~500m from a large spring. A qualitative survey easily differentiated the burned and unburned areas. The burned area, (assumed to be from the 1986 fire judging from the regrowth), was dominated by widely spaced *Chrysothamnus viridis* (rabbitbrush) and small sagebrush plants (*Artemisia tridentata* var. *wyomingensis*) (<50 cm height) with a thick growth of cheatgrass (*Bromus tectorum*). In the unburned area sagebrush plants were ≥1m tall and spaced more closely with only scattered *Chrysothamnus viscidiflorus* and little *Bromus tectorum*.

Our site, which we refer to as Newark Valley Pond (NVP) (39˚ 40'N lat. 115˚ 44'W long.), is one of many springs in the valley (1750 m elev). NVP is ~7 m diameter and flows through a wet meadow ~30 m by 40 m to a pool approximately 20 m in diameter with a maximum water depth of 50 cm. The Diamond Mountains to the west of Newark Valley rises to 3216 m at Diamond Peak. The range is composed of Paleozoic sedimentary and metasedimentary rocks, including several limestone formations (Stewart and Carlson 1978).

The center of the pool had open water, surrounded by cattails (*Typha* sp.) and in shallow water grew sedges (*Carex* spp). Moist ground contained rushes (*Juncus* spp.) and grasses (*Distychlus* spp.). Surrounding the pond were *A. tridentata* var. *tridentata*, *A. tridentata* var. *wyomingensis*, *Chrysothamnus viscidiflorus*, *Sarcobatus vermiculatus* (greasewood), and *Atriplex confertifolia* (shadscale). On the rocky slopes above the site grew scattered *Juniperus osteosperma*. *Pinus flexilis* (limber pine) grow in the highest elevations above

~3,000 m. Moving towards the playa in the center of the valley *Sarcobatus baileyii* (Bailey's greasewood) and *Atriplex confertifolia* increase in abundance.

We recovered two overlapping 3.3 m cores (NV01A and NV01B) using a 5-cm diameter modified Livingstone corer. Core segments ranged in length from 10 – 60 cm and averaged 30 cm. Cores were extruded into plastic tubes for transport and storage and kept refrigerated at 4˚C. A 5-cm plastic tube was pushed into the upper sediments to recover the sediment-water interface with a minimum amount of disturbance. Core NV01A was used for analysis and core NV01B was archived.

The cores were split in the laboratory and the stratigraphy was described. Continuous 1 cm^3 sub-samples were weighed, then dried for 24 hours at 100° C to obtain percent water content, and finally burned in a furnace at 550° C to determine percent organic matter (Dean 1974). Other studies have found that fire-induced erosion sometimes leads to peaks in magnetic susceptibility associated with charcoal peaks. We ran magnetic susceptibility analyses on our cores but readings throughout the entire length were negligible. Does this mean erosion was probably minimal? See p. 14, sedimentation rate higher in historic period.

Charcoal Analysis

Macroscopic charcoal (>125 and >250 μm) was counted from continuous 1 cm samples for the upper 1 meter of core (Whitlock and Millspaugh 1996). Numerous studies have confirmed that charcoal fragments of >125 μm size collect in depositional environments near burned areas and are representative of local fires (Whitlock and Anderson 2003).

Charcoal analysis followed the macroscopic sieving method described in Whitlock and Anderson (2003). We took 2.5 cm^3 samples from continuous 1 cm sections of the core. Sediments were disaggregated for 48 hrs in sodium hexametaphosphate (5%) and then washed with tap water through 63, 125, and 250μm sieves. Charcoal fragments were counted in water on grided rectangular petri dishes at 40X magnification using a stereomicroscope. The 63-125 μm fraction proved too small and numerous to be feasible to count, but every sample in the 125-250μm and >250μm fraction was counted. Charcoal fragments were identified by color (black to very dark brown) and structure (obvious cellular structure). All fragments were counted in each sample and samples were then archived in vials.

Charcoal concentration ($particles^{-1}cm^{-3}$) was calculated from charcoal counts and this was divided by the number of years in a sample to calculate charcoal accumulation rate ($particles^{-1}cm^{-2}yr^{-1}$). Charcoal accumulation rate data was analyzed for peaks that may represent fires using the CHAPS charcoal analysis program (Long et al. 1998). The CHAPS program decomposes charcoal accumulation time series into two components: 1) the "background" charcoal signal which reflect average charcoal produced as a result of fuel, climate and transport processes, and 2) "peaks" that represent higher than average accumulation rates assumed to be associated with a local fire event.

Charcoal accumulation rates were log transformed for analysis to enhance the variability in the record. To calculate charcoal "background", accumulation rate data was resampled into 10-yr intervals to produce a decadal time series. The time series was then fit to a temporal window that produced a running average that smoothed the data but still captured the variability. We fit 250, 500 and 750-yr windows and selected the 500-yr window as the best fit. “Peaks” were identified as points in time where charcoal accumulation exceeded the moving average. Values above 1.0 represent charcoal accumulation greater than the “background” value; the higher the value, the greater the positive deviation above the “background”. We tested threshold values of 1.0, 1.1 and 1.2 to identify peaks that represent inferred fires. The frequency of peaks per thousand years was calculated using the most conservative threshold value (1.2).

Pollen Analysis

Twenty-two 1-cm-thick samples were taken for pollen analysis. Sample interval ranged from 2-10 cm apart and was determined from the age model so that the average time between samples was 263 years. Pollen preparation followed standard methods (Faegri and Iversen 1985). A known quantity of *Lycopodium* spores was added to each sample to calculate pollen concentration (Stockmarr 1971). Pollen was identified to the lowest possible taxonomic level using modern reference material and published pollen keys (Kapp et al. 2000, Moore and Webb 1978). TCT (Taxodiaceae/Cupressaceae/Taxaceae) pollen was assumed to be *Juniperus* since no other member of these families occurs in the region. Algae (*Pediastrum*) was also identified (Jankovská and Komárek 1982).

A minimum of 200 pollen grains were counted in each sample. Pollen percentages were calculated from the sum of terrestrial pollen. Pollen accumulation rates were calculated by dividing the pollen concentration by the number of years represented by the sample. We calculated a ratio between *Artemisia* and Chenopodiaceae/Sarcobataceae pollen as a proxy for climate change, where increased *Artemisia* indicates a wetter climate and increased Chenopociaceae/Sarcobataceae indicate a drier climate (Mensing et al. 2004).

RESULTS

Age Model and Sediment Analysis

We were unable to find seeds, twigs or large enough quantities of charcoal to date directly using commercial AMS methods, therefore radiocarbon dates were obtained on bulk organic sediment from 2-cm thick core sections using AMS radiocarbon techniques (Table 1). The basal radiocarbon date for core NV01A was 22,000 years B.P. (Before Present), indicating that in fact the spring has persisted since the last glacial maximum. There were no discontinuities or sand layers that might indicate a cessation of flow or erosion event. Since this research represents a test of the methodology we did not analyze the entire core, and in this paper we present results from the upper meter of sediment (the last 5,500 years).

The presence of calcium carbonate nodules in the core suggested that the sediments were probably enriched with old carbon and could give old dates. Springs emerging from calcareous rocks such as are in the Diamond Range often carry dissolved ‘dead’ carbon that is not in equilibrium with atmospheric carbon. Subaqueous organisms incorporate this old carbon in their structure. We obtained one date from the surface sediments (0-2 cm depth) to test for old carbon reservoir effects. The surface sediments returned a date of 640 ±50 B.P. (Beta-183676) suggesting a hard water effect in the organic sediments. We assume that the water source for the spring has not changed over time and that incorporation of old carbon by organisms in the spring has been constant over time. To account for the reservoir effect, 640 years were subtracted from all dates to get an adjusted radiocarbon age. All dates were then calibrated using Calib 4.4 (Stuiver and Reimer 1993, Stuiver et al. 1998) and are presented in calendar years before present (cal yr B.P.).

The age model (Fig. 2) indicated that the upper 20 cm of sediment represented the historic period (0-150 years ago) with a rapid sedimentation rate of 1 cm every 7 years (0.133 $cm^{-1}yr^{-1}$). From 20 – 41 cm (150 – 1100 years ago), sedimentation slowed to 1 cm every 47 years (0.021 $cm^{-1}yr^{-1}$). Sedimentation was slowest from 41 – 70 cm (1100 – 4700 years ago) accumulating at a rate of 1 cm every 127 years (0.008 $cm^{-1}yr^{-1}$). Sedimentation was fairly rapid from 70 – 100 cm (4700 – 5500 years ago) at 1 cm every 28 years (0.036 $cm^{-1}yr^{-1}$).

From the sediment water interface down to 20 cm depth, the sediments were dark brown in color and high in organic matter (17% organic) as compared with the remainder of the core (Fig. 3). Between 20 and 50 cm depth, the sediments were clay with silt, color shifted from a dark gray to a medium light gray and percent organics decreased from 17% to 5%. Many fragments of unidentified snail shells were mixed throughout the sediments. Between 50 and 85 cm depth the sediments became an inorganic (5%) light gray clay and calcium carbonate nodules ranging from 0.25 to 1 cm3 in size were encountered between 58-62 cm, 71-77 cm and 80-82 cm depth. Between 85 and 100 cm depth the color changed to dark gray green but the sediment remained inorganic clay.

Charcoal Analysis

There was an excellent correspondence between the 125 and 250 μ fractions (Fig. 3) suggesting that both size fractions were likely recording local fires (i.e. from the adjacent hill slopes). All charcoal analyses were done using the 125 μ fraction. Charcoal accumulation rates are highest within the last 130 years with accumulations an order of magnitude greater than during the pre-historical period. Within the historic period, there is one distinct charcoal peak centered about 100yr B.P. (15 cm depth). The down core sediments show fluctuations in charcoal accumulation that are muted but still apparent, centered on 600, 1000, 2400, and 5250 years ago.

The smoothed charcoal background level of the log transformed data identified distinct charcoal peaks (Fig. 4). All three threshold values identified a series of closely spaced charcoal peaks (50 – 110 years apart) between 5500 and 4700 years ago. After 4700, the lowest threshold (1.0) continues to indicate regular charcoal peaks about every 350 years. The more conservative threshold (1.2) includes long periods with no charcoal peaks, between 4700 and 3800 years ago, 3800 and 2900 years ago, and 2400 and 1100 years ago. All thresholds indicate charcoal peaks centered on 1070, 960, 540, and 100 years ago. The inferred fire frequency ranges from about eight fires per thousand years between 5500 and 5000 years ago, to only 1 or 2 per thousand years between 4000 and

1000 years ago. In the last 1000 years there have been more events, but these are still widely spaced in time.

Pollen Analysis

Total pollen accumulation (Fig 5) is very low for much of the core (<500 $grains^{-1}cm^{-2}yr^{-1}$). Accumulation rates are highest about 5000 years ago, and within the last 500 years. The ponded water on the site today appears to be largely historical. Aquatic pollen types (*Typha* (cattails), Cyperaceae (sedges), *Myriophyllum* (water milfoil) and *Potamogeton* (pondweed) are only abundant within the upper 20 cm. The percentage of unknown pollen grains is also highest in the surface sediments, probably the result of exotic species invading the pond edge. Although the core has no indication of a break in sedimentation and prolonged desiccation, the presence of Cyperaceae pollen in nearly every sample indicates that for much of the site's history, it was a wet meadow. The high percentage of indeterminate pollen types (average 19%) is evidence of poor preservation as compared to a lake environment. *Typha* is present 5200 years ago suggesting that at that time the site must have had standing water. Pollen accumulation rates area also higher at that time and pollen is better preserved.

Between 5500 and 4400 years ago, the pollen record has high percentages of *Artemisia* (31 – 57%) and *Pinus* (18 – 30 %) and low percentages of Chenopodiaceae and Sarcobataceae (2 – 9%, hereafter referred to as Chenopodiaceae, the more common pollen type) and *Juniperus* (0 – 1%) (Fig. 5). Beginning about 4000 years ago, Chenopodiaceae increases averaging 19% over the remainder of the core. *Artemisia* is generally less abundant over the last 4000 years, averaging 22%. *Artemisia* increases in importance about 3000 and 800 years ago. The A/C ratio provides a measure of the change in relative importance of *Artemisia* (sagebrush) and Chenopodiaceae (saltbush) over time. Sagebrush grows on the slopes above the basin and requires more moisture than saltbush, which dominates on the valley floor. The A/C ratio indicates an abundance of sagebrush between 5500 and 4000 years ago, with a shift to saltbush dominance about 3400 years ago. Sagebrush again predominates between 3200 and 2500 years ago. From 2500 to about 1000 years ago, saltbush is generally abundant. Sagebrush increases again between 1000 and 400 years ago, and then saltbush again dominates from 400 years ago to about the beginning of the historic period.

Juniperus is uncommon in the record until about 1400 years ago. It reaches its maximum percentage 350 years ago and declines in the present period. Poaceae (grass) is generally abundant between about 3000 and 1000 years ago, reaching a maximum of 17% about 2100 years ago. Asteraceae (sunflower species) vary little over the record.

DISCUSSION

Calibrating the Fire Record

To correlate charcoal abundance with fire history, charcoal peaks in the upper sediments are compared with known local fires (Millspaugh and Whitlock 1995). The record clearly demonstrates that the amount of charcoal produced in the historic period is significantly greater than in the pre-historic period, indicating that fires increased following settlement. In the historic period, charcoal reaches its highest peak at 15 cm depth, dating to about 100 years ago. Our knowledge of local fire history is not comprehensive enough to be able to correlate this peak with one specific event, but the abundance of charcoal in the surface sediments supports our hypothesis that charcoal peaks should be associated with known fire events and indicates that the charcoal record can be used as a proxy for local fire history.

The charcoal peak at 15 cm most likely represents the 1986 fire which burned >1400 ha within the local drainage. If our age model is correct, evidence for this fire should have appeared closer to the surface, about 5 cm depth. Given the difficulties of dating the historic period with radiocarbon techniques, there is some error in the exact depth to expect the1986 event. However, there is ample evidence to establish that the upper 20 cm contains the historic period, including a sharp increase in sedimentation rate, an increase in percent organic matter and the sudden appearance of plants that require standing water, probably associated with improvements to the spring, designed to provide permanent water for livestock.

It is likely that charcoal has been mixed down core through bioturbation and trampling by cattle. The pond is clearly used by livestock for watering, and it is reasonable to expect that the upper sediments have been mixed downward. The high rates of charcoal deposition may also be a reflection of sediment focusing resulting from paths leading off hillslopes towards the water holes. There is also the possibility that some charcoal in the historic period is the result of fires set by early settlers. We have no direct evidence of fires from the late 1800s and early 1900s near the site, however Eureka, located about 65 km to the south, was an active mining community and it is possible that settlers in the Newark Valley set fires.

Although we cannot eliminate the possibility that the historic charcoal peak is the accumulation of more than one fire event, we have verified that the occurrence of a known very large fire event is associated with a significant peak in charcoal. This evidence indicates that small spring-fed pools in low elevation valleys capture charcoal and can be used as a proxy for reconstructing fire history. The slow sedimentation rate in portions of our core restricts our interpretation to changes in fire activity on time scales of about one century. In this reconstruction, we do not identify a specific fire return interval for sagebrush, since charcoal cannot be linked to an exact location; however, we use the charcoal evidence to infer the occurrence of local fires or distinct periods in time when fire activity increased.

Reconstruction of Fire, Vegetation and Climate History

Since this is the first attempt to use charcoal to reconstruct fire history in sagebrush, it is unclear which threshold value best characterizes past fire history. The peak in the historic period has the greatest deviation from the background level (Fig. 4) and is evident at each of the three threshold values. The 1.0 threshold value identifies 24 inferred fires in the pre-historic period. Using more restrictive criteria reduces the number of inferred fires to 16 or 13 (1.1 and 1.2 threshold values respectively). Comparison of the charcoal and pollen records suggests that number of fires is a function of the amount of fuel available.

There is a fairly good correlation between abundance of sagebrush and number of fires (Fig. 6). The inferred fire frequency generally parallels the a/c ratio, with more fires occurring during periods when sagebrush is more abundant. Fire activity was greatest between 5500 and 4700 years ago with 7-11 inferred fires occurring every 50-110 years. At this time, sagebrush was much more abundant on the landscape than today and saltbush was nearly absent from the site. Evidence of *Typha* pollen (Fig. 5) indicates that the site held standing water, suggesting a wetter climate. *Pinus* pollen was at its highest levels at this time. A number of proxy records in the Great Basin indicate a wetter climate about 5000 years ago. Archeological sites increase in abundance beginning about 5000 years ago (Grayson 1993). At Ruby Marsh, just north of Newark Valley, about 5000 years ago there is evidence of deeper water and a decline in shadscale (Thompson 1992). The Great Salt Lake, Utah was also fresher and deeper at this time (Madsen et al. 2001).

Beginning about 4700 years ago the number of fires decreases-d as saltbush begins-an to steadily increase in comparison with sagebrush. The pollen record indicates a general drying trend, with a dominance of saltbush and a minimum of sagebrush culminating about 3400 years ago. This corresponds with an absence of fires between 3800 and 3000 years ago.

By 3200 years ago, sagebrush increases-d in abundance and remains-ed dominant until about 2500 years. The timing corresponds with the Neoglacial period (3500 to 2600 years ago) defined by Tausch et al. (2004), as dominated by cool and wet climate. Sagebrush increased within the Great Basin at this time and saltbush decreased (Wigand and Rhode 2002). Two fires were identified during this period, one at 2900 years ago and the other near the end of the period at 2450 years ago.

Between 2450 and 1100 years ago there are no charcoal peaks that are greater than the background charcoal signal and we infer a minimum amount of fire activity (Figs. 4 and 6). The period between 2600 and 1600 years ago has been recognized as a period of extended drought in the Great Basin (Tausch et al. 2004). The a/c ratio is low throughout most of this period, supporting the interpretation of an extended drought. Grass becomes important during this period (Fig. 5). In wet meadow environments, grasses will replace sedges as the water table drops, resulting in a dry meadow. A pollen core from Kingston Meadow, in the Toiyabe Range about 100 km to the west indicates that that wet meadow was converted to a grassy flat about 2100 years ago (Tausch et al. 2004). Plant macrofossils found in woodrat middens adjacent to riparian zones within the Toiyabe Range show a decrease in species diversity during this time period. Elsewhere in the Great Basin saltbush and greasewood expanded at this time (Wigand 1987, Wigand and Rhode 2002). Expansion of grass may also have occurred due to increased summer monsoonal precipitation (Wigand 1987). Summer rainfall does not favor shrubs however and would not have increased shrub density. During this period it appears that salt desert expanded in Newark Valley, total fuel decreased, and fires were probably rare.

Sagebrush again increased between 1100 and 600 years ago and fire activity increased as well. Higher resolution records from across the Great Basin have identified great variability at this time, with century long droughts interspersed with wet periods (Tausch et al. 2004, Mensing et al. 2004). The resolution of the NVP pollen record is insufficient to capture this variability, but the pollen and charcoal record both indicate an increase in fuel and fires when compared with the previous period.

Sagebrush Fire Patterns

The results of this study are the first attempt to reconstruct the long-term fire history in Great Basin sagebrush using charcoal analysis and therefore the conclusions are preliminary. Nevertheless, some intriguing patterns have emerged. {don't break paragraph}

The data suggests [data plural] that within Great Basin sagebrush, fires are climate and fuel driven. During wetter periods, sagebrush increases-d in abundance and density, increasing the fuel load and decreasing plant interspaces. Fire is more likely to carry under such conditions and the period between fires becomes [became] shorter. This conclusion supports the conceptual Great Basin fire model proposed by Miller and Tausch (2001) that described a longer fire return interval as climate became drier and fuel loads decreased.in treed environments

Although using charcoal we are unable to calculate fire return intervals, the data support the Miller and Tausch (2001) model that suggests fire return intervals may beas long as a century for *Artemisia tridentata* var. *wyomingensis*, not decades as has been documented for *Artemisia tridentata* var. *vaseyana*. Charcoal peaks were consistently separated by periods of 100 to 200 years or longer. During periods of drought, when saltbush dominated, the time between fires lengthened. Miller and Tausch (2001) proposed a fire return interval of >500 years in salt desert habitat, and our results support that estimate. Our results also indicate that in dense stands, created during periods of wetter climate, or on wetter sites, the time between charcoal peaks shortened to 50 – 110 years, suggesting that fires will burn more frequently as the landscape changes in response to climatic change. Similar conclusions were reached in One study of sagebrush recovery following prescribed burns in south-western Montana. In that area it was found that on at least one site *Artemisia tridentata* var. *wyomingensis* had not returned to pre-burn canopy cover 32 years after the fire (Wambolt et al. 2001).

We also found that the total quantity of charcoal produced during the historic period is an order of magnitude greater than at any time during the pre-historic period. The increase in charcoal in historic times indicates an increase in fire activity, quite likely associated with the invasion of *Bromus tectorum*, but also probably due to an increase in ignitions associated with settlement. This result contrasts with studies done in pinyon juniper woodland that note a clear absence of fire during the last century associated with fire suppression, logging and grazing (Blackburn and Tueller 1970, Tausch and West 1998, Gruell 1994, Miller and Rose 1999).

In the Great Basin, pinyon-juniper woodland density is increasing and along woodland-sagebrush ecotones, trees are invading sagebrush. Since juniper are most susceptible to fire within their first 50 years of growth (Miller and Rose 1999) it would indicate that on these sites fires must have burned at frequencies of <50 years. But a long-term observational study of *Artemisia tridentata* in southwestern Montana in a sagebrush/grassland habitat concluded that in the absence of disturbance such as fire, sagebrush will maintain itself indefinitely (Lommasson 1948). In a 61 yr old stand, *Artemisia tridentata* seedlings established in the interspaces between mature shrubs, and there was no evidence of invasion of woodland in the absence of fire.

Where soil and climate support pinyon and juniper, woodlands can expand in the absence of fire. However, inferred sagebrush fire frequencies from such mesic sites may not be representative of sagebrush fire frequencies on xeric sites. Pollen evidence from this study (Fig. 5) and the Ruby Valley (Thompson 1991) support the interpretation that during the last 10,000 years woodlands have not invaded valley floors, which have remained dominated by sagebrush and salt desert vegetation. We suggest that in the central Great Basin, a regime of frequent fires in sagebrush that limits woodland expansion is restricted to the sagebrush/woodland ecotone, and that on valley bottoms with low fuel loads where sagebrush dominates, fires have always been less frequent. Prior to the historic period, charcoal production in these environments was very low and fires appear to have been uncommon. Protecting sagebrush-dominated valleys from frequent fire would appear to be consistent with the pre-historic fire regime.

Finally, this method warrants further testing. We plan to identify sites with faster sedimentation rates to increase our temporal resolution. We also hope to recover cores from sites in the southern central Great Basin where *Bromus tectorum* invasion is limited (Peterson 2003) and historic fire history may be different. The Free Air Carbon Dioxide Enrichment studies (FACE) being conducted on the Nevada Test Site have demonstrated that with increased global CO^2, *Bromus madritensis* (red brome) and *Bromus tectorum* (cheatgrass) gain a competitive advantage and become more invasive (Smith et al. 2001). Efforts to prevent these species from invading sagebrush habitats where they do not currently dominate will be important for keeping fire out of these environments. Maintaining sagebrush environments also has implications for the preservation of habitat utilized by endangered species in the Great Basin such as the sage grouse (*Centrocercus urophasianus*) and pygmy rabbit (*Brachylagus idahoensis*).

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Figure Captions

Fig. 1. Location map of the study site and general location of fire studies referred to in the text. Symbols are as follows: cross (+) core site; solid squares (■) recent fires >400 ha; triangles (▲) *Artemisia tridentata* var.*vaseyana* fire studies; open circle (○)*Artemisia tridentata* var.*arbuscula* fire study; open squares(□) pinyon juniper fire studies that do not give an explicit fire return interval for sagebrush. Numbers refer to highways.

Fig. 2. Age model for core NVP01-A. Open diamonds represent dated samples. Sedimentation rates between dated samples are shown.

Fig. 3. Total charcoal particles counted by size fraction (125 and 250 μ), charcoal accumulation rate for the 125 μ fraction, and percent organic matter of the sediments. The unfilled line in the accumulation rate figure represents five times exaggeration.

Fig. 4. Log transformed charcoal accumulation rate is plotted over a smoothed background level using a 500 year smoothing window. Crosses represent charcoal peaks at three different threshold levels indicating inferred fire events. Inferred fire frequency is calculated for the 1.2 threshold-ratio value.

Fig. 5. Pollen diagram of the most common pollen types for Newark Valley Pond. Core chronology is in calendar years before present. The A/C ratio (*Artemisia* / Chenopodiaceae + Sarcobataceae) is calculated as (a-c)/(a+c) where ‘a’ represents

percent *Artemisia* pollen and ‘c’ represents percent Chenopodiaceae + Sarcobataceae pollen. Positive values represent increased *Artemisia* (wetter climate) and negative values represent increased Chenopodiaceae + Sarcobataceae (drier climate). Aquatic pollen are given as accumulation rate. An ‘x’ indicates >10 and <40 $grains^{-1}cm^{-2}yr^{-1}$ and a cross (+) indicates <10 $grains^{-1}cm^{-2}yr^{-1}$.

Fig. 6. The A/C ratio plotted with inferred fires. Crosses represent charcoal peaks at three different threshold levels indicating inferred fire events. Inferred fire frequency is calculated for the 1.2 threshold-ratio value. The A/C ratio (*Artemisia* / Chenopodiaceae + Sarcobataceae) is calculated as (a-c)/(a+c) where ‘a’ represents percent *Artemisia* pollen and ‘c’ represents percent Chenopodiaceae + Sarcobataceae pollen. Positive values represent increased *Artemisia* (wetter climate) and negative values represent increased Chenopodiaceae + Sarcobataceae (drier climate). THIS DIAGRAM IS JUST PLAIN COOL!