

**HABITAT AND LIFE HISTORY CHARACTERISTICS OF**  
***ASTRAGALUS BARRII* (FABACEAE)**  
**IN THE SOUTH DAKOTA BADLANDS**

By

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## ABSTRACT

*Astragalus barrii*, Barr's milkvetch, is a rare plant species endemic to the dynamic badlands of South Dakota, Wyoming, and Montana and it is one of a distinct group of *Astragalus* species, known as the *Orophaca* group, that are regionally endemic. A study was undertaken in Badlands National Park, located in southwestern South Dakota, to develop predictive habitat models, describe the physical habitat characteristics, and study the life history of *A. barrii* to aid local conservation efforts and to further understanding of the *Orophaca Astragali*.

Deductive habitat similarity modeling, classification based on discriminant analysis, and probabilistic modeling based on logistic regression were used to predict the occurrence of *A. barrii* in Badlands National Park based on soils, vegetation, slope, and geology. Presence of *A. barrii* was associated with simple vegetation shapes, low shade levels, complex soil shapes, silty clay soil textures, simple slope shapes, and a range of slopes. Presence was also observed to coincide with the Chadron and Brule formations as well as the presence of coarse substrate materials, such as chalcedony cobble and limestone gravel. Plants were found in both the Cheyenne and White River watersheds but no plants were found above the Badlands Wall, thus indicating that topography is a major regional influence on seed dispersal with the Badlands Wall serving as an effective barrier to colonization.

Populations were varied in their number of plants, mean plant size, mean density, and proportion flowering. Almost all plants flowered and all plants greater than 177 cm<sup>2</sup> surface area flowered. The smallest plants showed the largest percent growth and small plants were much more common than large plants. Flowering resulted in viable seed that contributes to population growth. Recruitment was low at 4% while plant mortality was relatively high at 16%.

Findings of this study indicate that *A. barrii* is an edaphic specialist specialized to grow in dynamic badlands habitats. Results contribute directly to the design of future studies and conservation of *A. barrii* and its habitat. Results also have implications for understanding speciation and adaptation in the *Orophaca Astragali* and meta-population dynamics.

Approval:

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Dr. Kaius Helenurm, Thesis Advisor

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Date

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## I. INTRODUCTION

The flora of the Great Plains is thought to be recent and adventive in origin where species from adjacent floristic provinces colonized the area as the forests gave way to grasslands when the Pleistocene glaciers melted and the climate warmed in the last 14,000 years (Great Plains Flora Association 1986). Thus, the flora of the Great Plains is composed mostly of wide spread species and a few species that are uncommon in the Great Plains but relatively common in adjacent areas, referred to as edge of range species (Great Plains Flora Association 1986). *Astragalus barrii* Barneby (Fabaceae) is one of only a few plant species that are considered locally endemic to the northern Great Plains (Great Plains Flora Association 1986). Following the typology of Kruckeberg and Rabinowitz (1985), the type of endemism exhibited by *A. barrii* is described as “locally abundant in a specific habitat but restricted geographically” resulting from a small geographic range, narrow habitat specificity, but locally large populations that can be dominant in some places.

While there are many factors that influence a species’ distribution, the primary factor in the success of any organism to occupy space is its inherited tolerance to environmental conditions, which for vascular plants are manifested primarily through climate, geology, topography, soils, or the presence of other organisms (Kruckeberg and Rabinowitz 1985). Organisms do not occur where they cannot survive, but often they do not occur where

they seemingly could survive, raising persistent questions about endemic species (Kruckeberg and Rabinowitz 1985): Are they restricted to the places in which they reside because they cannot exist beyond these bounds, or could they occur over large areas if they were brought there? Are endemics ecologically or physiologically narrow or fastidious? Are the restricted ranges of endemics a reflection of their small niches?

As is often the case with narrow endemics, and a trait commonly exhibited in *Astragalus* (Isely 1998), *A. barrii* has a range that occupies only a tiny fraction of a habitat that is regionally widespread but patchy in its distribution, namely the sedimentary badlands (Schassberger 1990) that are associated with many large, low gradient modern or ancient river systems in the arid and semi-arid western United States. The occurrence of *A. barrii* in this dynamic badlands setting, a sparsely vegetated environment characterized by rapid rates of erosion and deposition, highlights another common characteristic of certain rare and endemic species: the occupation of transient or unstable habitats where the existence of the taxa could be obliterated by stochastic environmental events or the gradual loss of that specialized habitat to the process of succession (Kruckeberg and Rabinowitz 1985). The relationship between endemic species and their habitat is of interest to conservation biologists, and understanding this relationship has practical utility for those organizations responsible for the conservation of rare and endemic species.

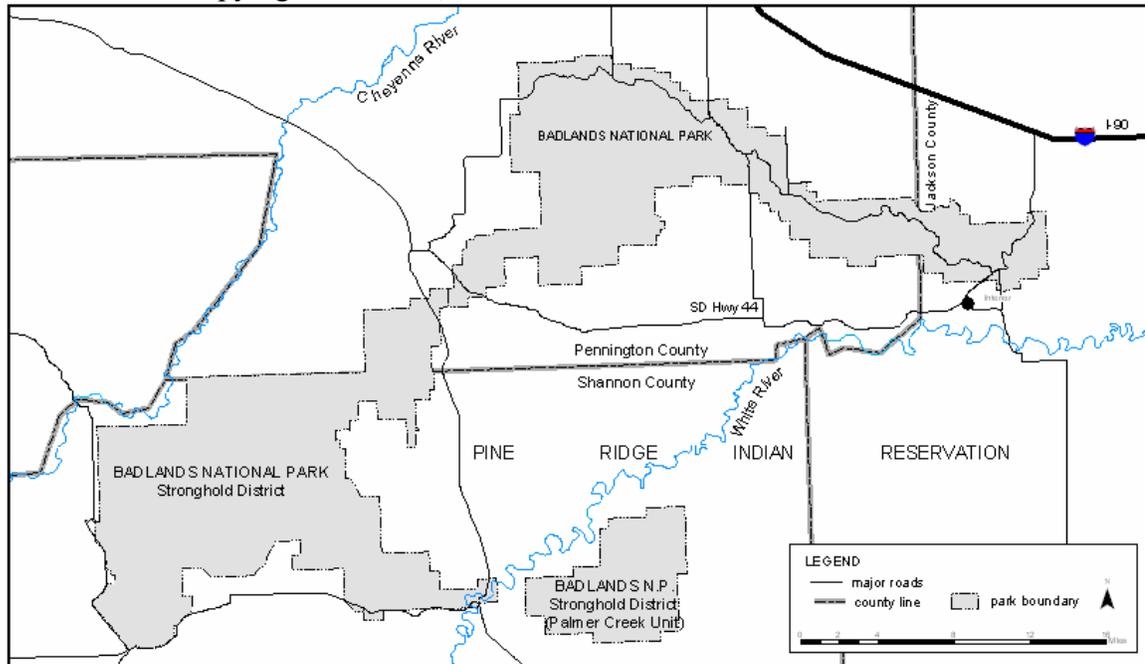
One tool to further this understanding is the development of habitat models that predict a species' presence, absence, or even abundance. The development of such predictive habitat models has rapidly increased in ecology concurrently with statistical techniques that are easily performed using powerful computational tools, such as geographic information system (GIS) and statistical software (Guisan and Zimmerman 2000, Store and Jokimaki 2003). Such models have become valuable resource management tools for study and conservation of a variety of taxa, including rare plants (Wiser et al. 1998, Boetsch et al. 2003). Knowledge of which habitat parameters most accurately predict the occurrence of a rare plant species, and the likelihood that species will occur given specific site conditions is fundamental to effective management of rare species (Simberloff 1988, Brussard 1991, Falk and Olwell 1992, Wiser et al. 1998, Wu and Smeins 2000). Predictive habitat models can be used by managers to focus field inventory efforts, evaluate potential restoration or reintroduction sites, assess impacts, and provide a framework for further research on specific physiological requirements (Wiser et al. 1998, Boetsch et al. 2003).

The land managers responsible for conserving *A. barrii* and its habitat are in need of predictive habitat models to aid in finding populations so that further conservation action can be taken. The plant is found in the Cheyenne and White River basins of southwestern South Dakota and extreme northwestern Nebraska as well as in the Powder River basin of northeastern Wyoming and southeastern Montana; it is a state-listed rare species throughout its range (Fertig and Beauvais 1999, Montana Natural Heritage Program

2003, South Dakota Natural Heritage Program 2002). It has also been identified as a species of management concern for the U.S. Forest Service, National Park Service, and Bureau of Land Management, the three agencies responsible for managing the lands that contain most of the known *A. barrii* populations. All three agencies currently lack the autecological and demographic data needed to fulfill responsibilities for conservation of this species (Schassberger 1988, 1990, Schmoller 1993), and simply finding the plants in the rugged landscape in which it grows has been problematic for the agencies that are charged with managing vast acreages while being chronically under-staffed and under-funded.

A project to develop predictive habitat models for *A. barrii* and to characterize its life history was undertaken in Badlands National Park in southwestern South Dakota, located in Pennington, Jackson, and Shannon counties (Figure 1). At 98,750 hectares, Badlands National Park is the largest mixed-grass prairie in the National Park System, and one of the park's primary purposes is to protect native flora. National Park Service management policies direct that state-listed species are to be given the same protection as federally-listed species (USDI NPS 2000), yet the park lacks basic inventory and distribution information about its rare plants (USDI NPS 1998). Furthermore, the lack of basic life history information creates difficulty in planning research and monitoring efforts. Without some knowledge of the distribution of rare plant populations, the park cannot take action to protect and perpetuate rare plant species.

Figure 1: Map of Badlands National Park (study area) located in southwestern South Dakota and occupying almost 100,000 hectares



The objectives of this study of *A. barrii* in Badlands National Park were to:

- A. Develop predictive habitat models for *A. barrii* to focus field inventory efforts, analyze potential impacts, and develop conservation strategies.
- B. Characterize the physical habitat (geology, soils, and topography) associated with *A. barrii* to aid in future field inventory efforts.
- C. Characterize the life history of *A. barrii* to better understand the major life history features of this species.

## II. BACKGROUND

*Astragalus barrii* is a long-lived perennial herb that is essentially stem less, growing in dense mats less than 10 cm in height. Leaves are trifoliate with narrowly lance-shaped leaflets that are 1 to 4 cm long. Leaves and stems are densely covered with short, white hairs. Relatively large, legume-like purple or pinkish-purple flowers are borne on short stalks, blooming in abundance from late April to early June. The fruit is a sessile dehiscent legume pod, bearing 1 to 3 seeds (Great Plains Flora Association 1986).

In the Angiosperm Phylogeny Group classification (Angiosperm Phylogeny Group 1998), *A. barrii* belongs to the following lineage based on molecular and morphological phylogenies: Angiosperms – Eudicots – Eurocids – Fabales – Fabaceae. The assignment of the *Astragalus* genus to the family Fabaceae and the order Fabales is unchanged from previous systems of classification.

*Astragalus* L. is a large genus of herbaceous annuals and perennials with an estimated 2000-3000 species distributed mainly in cool arid continental regions of the Northern Hemisphere and South America, including about 400-450 species in western North America (Wojciechowski et al. 1999). Many *Astragalus* species are narrow endemics, often found in marginal habitats or in habitats requiring edaphic specializations, while relatively few are widespread (Wojciechowski et al. 1999).

Within the genus is a small, morphologically-distinct group known as the *Orophaca* that has long been recognized by taxonomists. First segregated at the generic level by Britton and Brown (1897), and later ascribed to the sub-generic *Orophaca* phalanx by Barneby (1964), it has most recently been suggested as its own genus (Isely 1983, 1998). Presently the *Orophaca* are treated as a sub-generic rank within the *Astragalus* genus and this group of species remains assigned to the *Astragalus* genus (retrieved December 13, 2004 from the Integrated Taxonomic Information System (ITIS) <http://www.itis.usda.gov>). While the taxonomic rank of the group remains unresolved, the seven morphologically distinct species are all considered endemic and geographically restricted to the Northern Great Plains and foothills east of the Northern Rocky Mountains. *A. barrii* is one of the seven *Orophaca Astragali* described by Isely (1998), the other six species are *A. aretioides* (M.E. Jones) Rydb., *A. tridactylica* (A. Gray) Rydb., *A. sericea* (Nutt.) Britton, *A. hyalina* (M.E. Jones) Isely, *A. proimantha* (Barneby) Isely, and *A. triphylla* (Eaton and Wright) Britton. Isely (1998) includes *A. gilviflorus* Sheldon within *A. triphylla* as var. *triphylla*.

The *Orophaca Astragali* are distinguished by a number of morphological features, most notably hyaline stipules, palmately trifoliate leaves, small, unilocular deciduous pods, long, medifixed hairs, and often caespitose habit (Wojciechowski et al. 1999). These characteristics combine to give plants within this group a cushion shape where the stem is not usually visible and the leafy crown of the plant sits directly on the soil surface. The leafy crowns are elevated year by year on the divisions of a closely forking suffruticulose

caudex, eventually forming low cushions up to 1.5 dm or exceptionally 4.5 dm in diameter (Barneby 1956).

Recent molecular phylogenetic study has assigned the *Orophaca* group to the large, monophyletic *Neo-Astragalus* clade which possesses chromosome numbers in an aneuploid series of  $n = 11, 12, 13, 14,$  or  $15$  in contrast to the Old World species which possess euploid chromosome numbers of  $n = 8, 16, 32...$  . The distribution of *Neo-Astragalus* is restricted to North and South America. Molecular study of *A. gilviflorus* and *A. aretioides* as representatives of *Orophaca* found a base chromosome number of 12, supporting its inclusion in *Neo-Astragalus*, although its closest relatives in North America have not been identified (Wojciechowski et al. 1999). Relationships between members of the *Orophaca* group are entirely unresolved with respect to other North American species, according to Wojciechowski et al. (1999). So this is a group whose morphological divergence from other North American *Astragalus* is unaccompanied by comparable molecular divergence, a condition not uncommon in recently evolved taxa.

*A. barrii* was first reported by Claude Barr in 1952 on his Prairie Gem Ranch in Fall River County, South Dakota, and was later described by Barneby (1956). It is now commonly referred to as Barr's milkvetch, but may also be cited in the older literature as Barr's orophaca or mis-identified as *A. tridactylus* Pursh - Stevens (Barneby 1956, Barr 1951).

Within Badland National Park, *A. barrii* co-occurs with one other *Orophaca Astragalus* species: *Astragalus gilviflorus* sometimes classified as *A. triphylla*, a multiracial species that includes a blue or purple flowered variety, *A. triphylla* var. *purpurea*, as well as the more common white-flowered variety, *A. triphylla* var. *triphylla* (Isely 1998). *A. barrii* and *A. gilviflorus* are similar in appearance and habitat but are easily distinguished in this study area during the flowering season because *A. gilviflorus* exhibits creamy white flowers as opposed to the purple flowers of *A. barrii*. These two species can also be distinguished with difficulty when they are not in flower by the relatively smaller leaves and more compact growth form of *A. barrii*. In the more western and northern portions of its range in the Powder River Basin of Wyoming, *A. barrii* occurs within the range of *A. gilviflorus* (Isely 1998, Schassberger 1990), *A. hyalina* (Isely 1998, Schassberger 1990) , and *A. aretioides* (Schassberger 1990). In the extreme southern portion of its range along the border between South Dakota and Nebraska, the range of *A. barrii* adjoins but does not overlap with the more abundant and also purple flowered *A. sericea* (Isely 1998).

As of 2002, *Astragalus barrii* was known only from about 100 locations in the Cheyenne and White River basins of southwestern South Dakota and extreme northwestern Nebraska and the Powder River basin in northeastern Wyoming and southeastern Montana. It was formerly considered a plant under notice for potential listing as a threatened species under the U.S. Endangered Species Act of 1973. While it is no longer considered under review for federal status, it is still a state-listed rare species and is considered a species of concern for the National Park Service, U.S. Forest Service, and

Bureau of Land Management. While it has a restricted range and is rare within that range, it can be locally abundant with populations frequently comprised of hundreds or even thousands of individual plants (Schassberger 1988, Schmoller 1993).

Throughout its distribution, the general habitat of *A. barrii* is described as sparsely vegetated, usually on calcareous substrate (Barneby 1964, Schassberger 1990, Schmoller 1993). Schmoller (1993) surveyed *A. barrii* on the Wall District of Buffalo Gap National Grasslands adjacent to Badlands National Park, observing its affinity for specific geologic formations, soil types, disturbance regime, associated vegetation, slope, light exposure, vegetation structure, and range type. None of the other records of occurrence in Montana or Wyoming have included such site-specific habitat details, but none of their more general descriptions (Fertig et. al 1994, Schassberger 1990, Weedon et al. 1991) contradict the observations of Schmoller (1993).

While *A. barrii* and the other *Orophaca Astragalus* species are of conservation concern and the group has several traits that make it ecologically and taxonomically interesting, there have been very few studies published about these species. Most of the published literature consists of taxonomic descriptions (Barneby 1956, 1964; Isely 1983, 1998) and a few recent phylogenetic studies of the *Astragalus* genus (Sanderson and Doyle 1993, Sanderson and Wojciechowski 1996, Wojciechowski et al. 1999). The only life history data published is in a thesis written on the systematics of the *Orophaca Astragalus* species that included a few pages related to ecology, reproduction, flowering, and

phenology (Roberts 1977). The remainder of the written information about these species is in the form of database entries and conservation reports conducted by the various public agencies and institutions with the responsibility to conserve these species (Locklear 1987, Schmoller 1993, Schassberger 1988, 1990, Fertig et al. 1994, Fertig and Beauvais 1999, Weedon et al. 1991).

### **III. DESCRIPTION OF THE STUDY AREA**

In southwestern South Dakota there is a landscape known as the White River Badlands (O’Harra 1920) that is characterized by the presence of barren erosional features interspersed with mixed-grass prairie. Badlands have been defined by Easterbrook (1999) as “a region nearly devoid of vegetation where erosion has cut the land into an intricate maze of narrow ravines and sharp crests and pinnacles.” These landforms are found in arid and semiarid landscapes in the temperate latitudes of the world, generally in the interior of continents, and most commonly in association with shortgrass steppes in colder latitudes and desert grasslands in warm arid regions. Badland landforms are characterized by having unusually high drainage density (total length of the streams in a given drainage basin divided by the area of the drainage basin, Horton 1945) and occur where the following conditions prevail: 1) clay substrates of low permeability, 2) little vegetation to impede runoff, 3) rainfall concentrated in widely scattered showers, and 4) downcutting (sediment carried in suspension that abrades the bottom and sides of the channel thus incising the streambed, Plymate 2004) of the drainage system (Easterbrook 1999).

The surface features of the White River Badlands consist of steep inclines, narrow gorges, knife-edged ridges, flat-topped buttes, peaks, chalcedony beds, outwash plains, and intermittent drainage channels (Butler and Batt 1995). These features form a dynamic land surface prone to landslides and rapid erosion, creating new land surfaces in the form

of outwash plains at the base of buttes and scoured gullies with each geologic formation lending unique soil chemistry and texture to its deposition (O’Harra 1920, USDA NRCS 1996, USDA SCS 1971, 1987). Deeper soils mantling the buttes, hills, and alluvial valleys support relatively dense and diverse grasslands and occasionally shrublands and woodlands. Soils on and adjacent to barren badland formations and in drainage channels are rapidly deposited, and support a sparse plant community (Von Loh et al. 1999). As most of the soils are derived from mudstone or claystone parent materials, they have a high clay content resulting in high shrink-swell potential in response to soil moisture. These processes have shaped a variety of habitats for plant species that are able to cope with a rapidly changing substrate and variable moisture. *A. barrii* is one such species.

Environmental constraints in the form of climate, geology, topography, soils, and the presence of other organisms largely determine the distribution of a given species. The habitat parameters of geology, topography, soil, and vegetation have been mapped and/or researched in the study area and are used to predict the occurrence of *A. barrii*.

## **A. Geology**

Geologic deposition of the White River Group in southwestern South Dakota was the result of the interaction of tectonics and climate change. Faults radiating away from the Black Hills created a slightly northwest-southeast trending asymmetric basin southeast of

the Black Hills (Ritter and Wolff 1958, Seedfeldt and Glerup 1958, Clark et al. 1967, and Clark 1975). This regional graben (a block that has been downthrown along faults relative to the rocks on either side, Easterbrook 1999) is bounded on the northeast by the Sage Creek fault zone and on the southwest by the Pine Ridge fault zone with a variety of small folds parallel to the faults.

During the Oligocene epoch, the basin filled with fine-textured sediments deposited by low-gradient streams (Harris and Kiver 1985). During much of the Oligocene, the relatively dry climate resulted in reduced runoff, and these sluggish streams were capable of carrying only fine silt and clay materials, interlaced with sand and gravel channel deposits. During this same period of fluvial deposition, at least 30 major pyroclastic volcanic eruptions occurred to the west in the area that is now known as the Great Basin (Larson and Evanoff 1998). These volcanic events are expressed in the strata as tuffs (lithified volcanic ash beds that are deposited from an ash cloud downwind from a volcanic eruption, Cas and Wright 1988). The tuff strata are interspersed with fluvial strata and often with reworked tuffaceous material where ash particles were incorporated into the interbedded fluvial sediments as the ash deposits were eroded by wind and water. Meanwhile soils developed that supported various terrestrial ecosystems. The remaining paleosols and fossil evidence indicate a progression toward a more arid climate, with the evolution of a true grassland in the Sharps formation in the late Oligocene, the uppermost strata exposed in the study area.

Mountain building through deformation and uplift due to isostatic adjustment began near the end of the Cretaceous Period and continued into the Tertiary, resulting in the uplift of the Rocky Mountains, including the outlier Black Hills (Harris and Kiver 1985, Lisenbee and DeWitt 1993, Gries 1996). The late Pliocene uplift elevated the Rocky Mountains to their present height and elevated the Great Plains slightly (Harris and Kiver 1985). The uplift of the Black Hills steepened the gradients of streams originating in them, thus increasing both the erosion of the uplands and deposition of sediment in the lowlands. As the primary drainages of the basin lying southeast of the Black Hills, the ancestral White River and Cheyenne Rivers captured many of the available east-flowing streams.

During the middle Pleistocene, these same streams were dammed by the Illinoian ice sheet that covered what is now eastern South Dakota. The dam caused the water to flow southward along the edge of the ice sheet and, supplemented by water from the melting glaciers, rapidly scour a new channel of the Missouri River to a depth of 300 to 700 feet below the old surface (Gries 1996). Thus, when the glaciers melted, the steepened gradient resulted in an increase in erosive force of these major rivers so that they incised their channels into the non-resistant rocks below, increasing the gradients of their tributaries and causing their tributaries to cut headward into the highlands adjacent to the entrenched main channels. The underlying fine-textured materials offered little resistance to erosive processes, and even small rivulets were able to cause erosion (Harris and Kiver 1985) resulting in a high drainage density and intricate drainage pattern. Thus, steep and barren badland slopes developed adjacent to the stream channels. Over time, the tributary

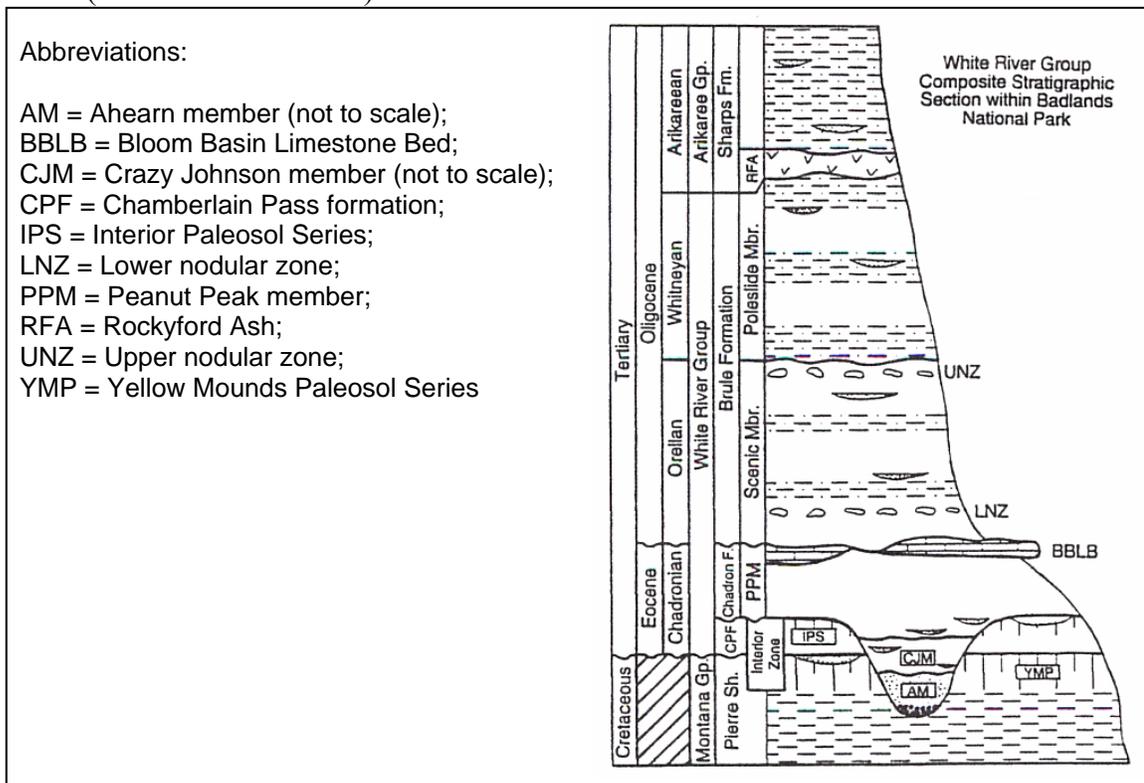
streams continued to cut headward, causing the scarp (such as the one known as the Badlands Wall) to retreat northward and leave behind highly dissected badlands. Differential erosion caused by variation in the velocity of streams and localized resistance in the form of channel sandstones, limestones, and thick tuffs resulted in the varied badlands features such as buttes, pinnacles, and knife-edged ridges. While headward erosion was causing the scarp to migrate away from the main channel, the tributaries were cutting laterally, planing off the hills along the lower courses of the streams and forming a pediment (a gently inclined erosional surface carved in bedrock, thinly veneered with fluvial gravel, developed at the foot of mountains, Easterbrook 1999) along the main channel. The enlargement of the pediment area and headward migration of the badlands scarp continues today (Harris and Kiver 1985).

This combination of tectonic basin development, fluvial and eolian deposition, and fluvial erosion in response to base level change resulted in the White River Badlands that are exposed today. In other areas of western South Dakota, the wet climate and strong rivers of the middle Miocene stripped off most of the Tertiary sedimentary formations down to the underlying Cretaceous Pierre Shale. Preserved in a large graben (Clark et al. 1967), the White River Badlands are one of the few tableland remnants of those Tertiary sediments that once blanketed a large area of the Great Plains (Gries 1996).

The Eocene-Oligocene White River Group in the Badlands National Park vicinity contains the Chamberlain Pass, Chadron, and Brule formations (Figure 2). It sits

unconformably (pertaining to an unconformity, an erosional break within a series of sedimentary layers, Gries 1996) upon the late Cretaceous Pierre Shale and the Fox Hills formation (Stoffer and Chamberlain 1996). The stratigraphic unit overlaying the White River Group is the Oligocene Arikaree Group, including the Rocky Ford Ash and the Sharps formation.

Figure 2. White River Group composite stratigraphic section within Badlands National Park (Ashworth et al. 1996)



The Chamberlain Pass formation is composed of white channel sandstones, red overbank mudstones that were modified by pedogenesis into the Interior Paleosol Series (Retallack

1983), and greenish proximal overbank mudstones and siltstones that were modified into the Weta Paleosol Series (Terry and Evans 1994).

The Chadron formation is up to 55 meters thick (Gries 1996) and is composed of the Ahearn, Crazy Johnson, and Peanut Peak members. The Ahearn and Crazy Johnson members are confined to the Red River Valley, covering only a small area along the north edge of the Stronghold District of Badlands National Park. The overlying Peanut Peak member covers large areas of Badlands National Park. It is described as six to nine meters thick of massive buff and green claystones that contain numerous discontinuous limestone lenses and occasional, sharply restricted greenish sandstone lenses (Terry 1998). An investigation by Evans and Welzenbach (1998) indicates that at least four lacustrine limestone beds occur in the upper part of the Chadron formation. These lacustrine limestones have limited aerial extent and represent short-lived features concentrated in the upper Chadron formation that are virtually absent from the underlying Chamberlain Pass formation or the overlying Brule formation. The lacustrine limestones are almost pure carbonate containing less than 1% siliciclastic materials and are thought to represent deposition at structurally controlled places of paleogroundwater discharge.

Clark (1937, 1954) recognized the contact with the overlying Brule formation by the decrease in the amount of sandstone and changes in fossil fauna. Other workers identify the contact by a marker bed of prominent calcareous claystone breccia (Harksen and Macdonald 1969) or the paleosol that contains this calcareous horizon (Retallack 1983).

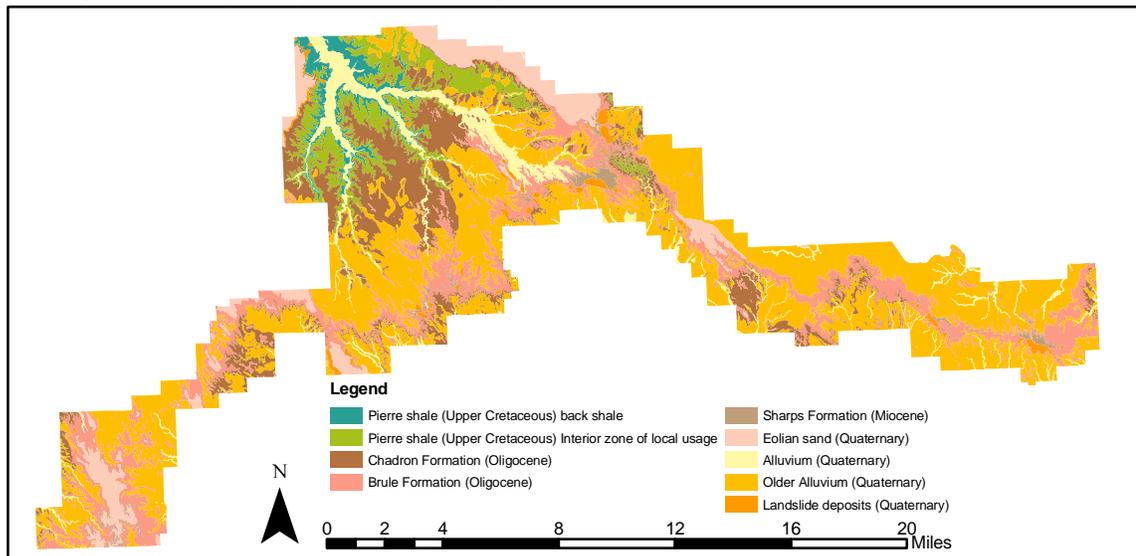
In either case, the contact is readily apparent in the field by the topographic change from “haystack” weathering of the Chadron formation to “tread and riser” weathering of the Brule formation (Evans and Welzenbach 1998).

The steep-sided Brule formation is the characteristic geologic formation in the Badlands Wall and is composed of the Scenic and Poleslide members (Bump 1956). It is distinguished from the underlying Chadron formation by a change from greenish-gray hummocky mudstones to brown and beige cliff-forming mudstones, siltstones, and channel sandstones (Terry 1998). The Scenic member is 49 meters thick (Bump 1956) and is dominated by siltstones and sheet sandstones (Terry 1998), some of which contain clay-lime concretions which oxidize to a rusty color and give this formation its distinctive red bands (Bump 1956). The Scenic member contains at least four major lithographic units (Bump 1956). The overlying Poleslide member is 91 meters thick (Bump 1956) and is dominated by gray and buff colored siltstones with occasional fluvial sandstones (Terry 1998). The Poleslide member contains at least four major lithographic units (Bump 1956).

In many areas of the White River Group, earlier strata are obscured by Quaternary alluvium or colluvium deposits (Figure 3). Most common are alluvial deposits within modern drainages and sod tables composed of reworked materials from the dissection of older land surfaces. These deposits consist of light gray channel sands, gravels, silts, and overbank silts and muds. Several episodes of cutting and filling by fluvial processes are

evident. Colluvium deposits are associated with landslide activity within the Sage Creek fault zone. Most notable is the concentration of landslides along the Badlands Wall which is generally parallel to and corresponds with the northwest-trending fault zone (Shurr et al. 1996). The Quaternary alluvium and colluvium generally exhibit textural and chemical characteristics of the parent material, but they may have been modified by surface erosion and deposition processes as well as biological activity.

Figure 3. Geologic map of a portion of Badlands National Park as mapped by the U.S. Geological Survey (Raymond and King 1974a-f, 1976)



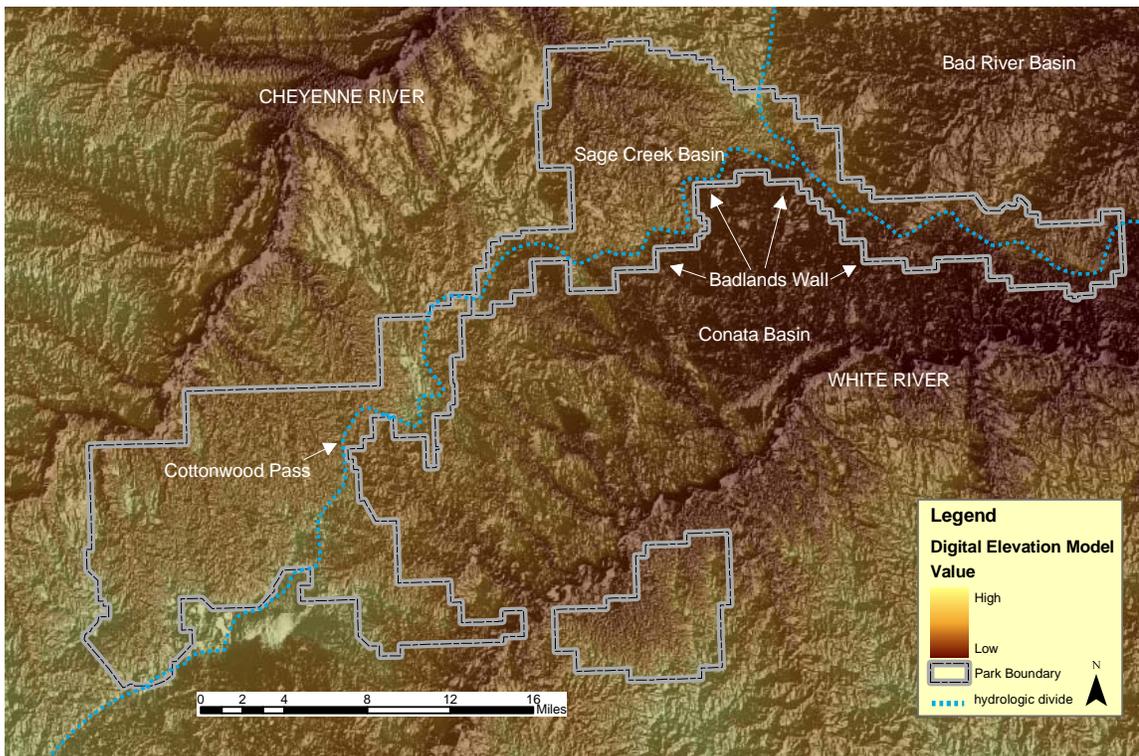
## B. Topography

Badlands topography is a mixture of relatively flat plains, moderately wide floodplains associated with the White and Cheyenne Rivers, hills and tablelands of eolian sands, and highly dissected erosional features. The study area lies in the Pierre Hills and Tertiary

Table Lands divisions of the Great Plains (USDA NRCS 1996). Elevation ranges from 700 to 1000 meters above sea level.

The study area drains into three major drainage basins (Figure 4). A small area in the northeast area drains northward to the Bad River. The western area, including the Sage Creek Basin above the Badlands Wall drains westward to the Cheyenne River. The southern and eastern areas, including the Conata Basin, drain southward to the White River. All three of these major rivers drain eastward into the Missouri River.

Figure 4. Topography of Badlands National Park, including drainage basins, based on hillshade relief of the digital elevation model (USDI 1999)



Structurally, the White River Badlands area is one of essentially horizontal sedimentary rocks with a few flexures and faults. There is a slight regional dip of 1°- 2° in the Tertiary formations. One major fold in the area is an anticline that trends approximately parallel to the Wall and extends from the Sage Creek drainage basin to just beyond the eastern edge of the park. The anticline is asymmetrical with a northeast limb that dips 3° and a southern limb that dips 14° (Smith 1958).

Ward (1922) divided the Big Badlands in the vicinity of the town of Interior into four approximately parallel topographic subdivisions that trend approximately east-west; physiographic descriptions were further developed by Smith (1958):

- 1) The White River floodplain: a meandering drainage with steep cut banks where substrates consist mostly of recent sands and gravels.
- 2) The Lower Prairie: an area of subdued topography that slopes from the Wall to the White River floodplain. It is mostly covered with sod but isolated buttes and groups of buttes rise above the general level of the prairie as outliers of the retreating Wall to the north. The buttes have steep slopes and generally lack vegetation. It is deeply dissected by intermittent tributary streams of the White River. The Lower Prairie forms deep embayments in the Wall where they have been stripped of their sod cover by erosion and miniature pediment areas have developed on the newly exposed bedrock beneath.
- 3) The Wall: an irregular, 60 mile long, erosional scarp of the Badlands trending east-west between the Lower Prairie and the Upper Prairie. The highest elevations

in the Badlands occur in this area. Widely-spaced, elongate spurs extend southward from the Wall but in general it presents a straight front along the southern side. The highest points of the Wall are capped by dense, resistant volcanic ash.

- 4) The Upper Prairie: a sod covered surface of relatively low relief similar to the Lower Prairie but lacking remnant buttes. The Upper Prairie drains toward the Bad River and the Cheyenne River.

Rothrock (1943) described the major factors involved in the development of the White River Badlands. Easily eroded clays are alternated with less easily eroded beds of sand and volcanic ash, allowing the sand and ash beds to protect the softer underlying clays and thereby resulting in differential erosion. Gumbo clays dry and crack, leaving a mass of loose rubble a foot or more deep that is rapidly washed away during thunder showers, leaving steep bare slopes. The height of the Badlands above the White River results in steep gradients that cause rapid erosion of the Badlands Wall, a condition in which the stream bed slope and channel characteristics are constantly changing because they are not in equilibrium with the discharge and bed load. Summer rainfall, largely thundershowers, deepens gullies more quickly than they are widened. The result of these factors is a dynamic landscape characterized by rapid rates of erosion and deposition.

The Chadron formation is easily eroded and causes the development of subdued badlands topography with small, rounded convex hills, commonly referred to as “haystacks.” The

Chadron is characterized by broadly rounded interfluves with a mean maximum slope angle of  $33^\circ$  (Schumm 1956). Creep (slow, continuous, plastic deformation that results in the downslope movement of rock fragments and soil, Easterbrook 1999) is the dominant erosional process acting upon the Chadron resulting in its characteristic shape. Erosion rates of 0.5 in/year were documented in one study in the White River Badlands (Schumm 1956). The dry Chadron surface is composed of a loose mass of clay aggregates.

Individual aggregates move downslope by swelling from wetting and shrinking from drying, thus filling the desiccation cracks from the uphill side. In this way the aggregates move downslope in response to gravity until they come into contact with the next lower aggregate on the slope, all sliding downslope on the underlying fine-grained surface which apparently becomes sealed when wet (Schumm 1956). A pediment also forms at the base of the steeper lower slope by basal sapping (erosion process where overlying strata collapse due to undermining as less-resistant, underlying strata are eroded, Easterbrook 1999) (Schumm 1956).

The Brule formation is the primary stratigraphic unit of the Badlands Wall and contains several well consolidated layers among thicker, softer layers, creating a topography that is complex and rugged with many ridges and high terraces. The Brule formation is characterized by steep, sharp-crested slopes with a mean maximum slope angle of  $44^\circ$  (Schumm 1956). The Brule formation is especially prone to erosion by rainwash. Erosion rates of 1 in/year were documented in one study in the White River Badlands (Schumm 1956). Creep erosion and deposition augment rainwash erosion and deposition. In a dry

condition the Brule surface is hard, and the presence of numerous rill channels (a very small trickle of water, Easterbrook 1999) indicates large volumes of runoff. The resulting landform is characterized by steep, straight slopes interrupted by narrow terraces that form the characteristic tread and riser topography of the Brule formation. Silts derived from the Brule formation are deposited downslope by intermittent, braided streams in shallow basins on the Chadron formation or Quaternary alluvium.

Both the Chadron and Brule formations include small amounts of limestone. In the Chadron formation, limestone cobbles tend to collect in shallow topographic depressions sometimes creating continuous surface cover of cobbles. In the Brule formation, limey nodules are not very abundant but are sometimes concentrated in narrow terraces of resistant sandstone lenses along the otherwise steep slopes of the formation. Both formations are also characterized by the presence of chalcedony, formed from silicious aqueous solution that fills and solidifies in voids and cracks in rocks. It is more abundant in the Chadron formation, where it forms sharp vertical fins of hard chalcedony protruding several inches from the surrounding clayey sediments. As they are exposed, the fins break into flat angular pieces, generally 1-3 cm thick and 12-15 cm wide. These chalcedony pieces form a resistant surface layer that is apparent on the top of small hills where it reduces erosion of the underlying sediments. Over time, these chalcedony cobbles break down into angular chalcedony gravels armoring quaternary alluvium and colluvium deposits.

### **C. Soils**

Regional soils represent four orders: entisols, aridisols, mollisols, and vertisols (Batt 1991). Vertisols are upland clays with very high shrink/swell potential characterized by deep, wide cracks formed at the soil surface. Mollisols are prairie soils found on grassy bluffs and exhibit a dark color due to the relatively high organic content. Aridisols are found in arid uplands and are typically dry for more than 50% of the year. Entisols are newly formed upland soils developed from the erosion of steep slopes, alluvial floodplain deposition, and eolian deposition (Von Loh et al. 1999).

Soils have been mapped to the series level in Badlands National Park in three separate soil surveys completed by the National Soil Survey (USDA SCS 1971, 1987, USDA NRCS 1996). The majority of the park falls within the following four soil associations:

- 1) Cedarpass-Denby-Interior association: Deep, well drained, nearly level to gently sloping, silty, loamy, and clayey soils on terraces, fans, and floodplains. This association occurs on alluvial fans and terraces along the base of badlands. Deep, entrenched channels are common in most areas. Slopes are smooth. In most areas the drainage pattern is well defined.
- 2) Orella-Fairburn-Badlands association: Shallow, well drained, moderately sloping to steep, clayey, and loamy soils as well as barren badlands of poor soil formation. This association occurs on dissected plains. Slopes generally are

convex and are moderately sloping to steep but they are very steep in some areas of Badlands. In most areas the drainage pattern is well defined.

- 3) Blackpipe-Norrest-Wortman association: Moderately deep, well drained, nearly level to gently sloping, silty soils on plains. This association occurs in uplands. In most areas the drainage pattern is poorly defined.
- 4) Badlands association: Barren badlands with little or no soil development intermingled with clayey and loamy soils on mesas, escarpments, buttes, and tablelands and in basins. This association consists of small mesas, eroded walls, escarpments, and basins in which there are light-colored, calcareous soils and scattered, eroded buttes. The slope ranges from almost vertical to nearly level dissected by numerous drainages that are gullied and have vertical walls.

One of the most distinctive physical features of the White River Badlands, and perhaps one of the most influential edaphic factors in the distribution of *A. barrii*, is the predominance of fine textured soils. Texture is a soil property that reflects the relative percentage of clay, silt, and sand particles. The soil triangle is used to classify soils based on texture as indicated in Figure 5. As indicated on the soil texture map in Figure 6, the majority of the soils in the study area have a high percentage of silts and clays with sandy soils concentrated along major drainage channels and as tableland eolian deposits.

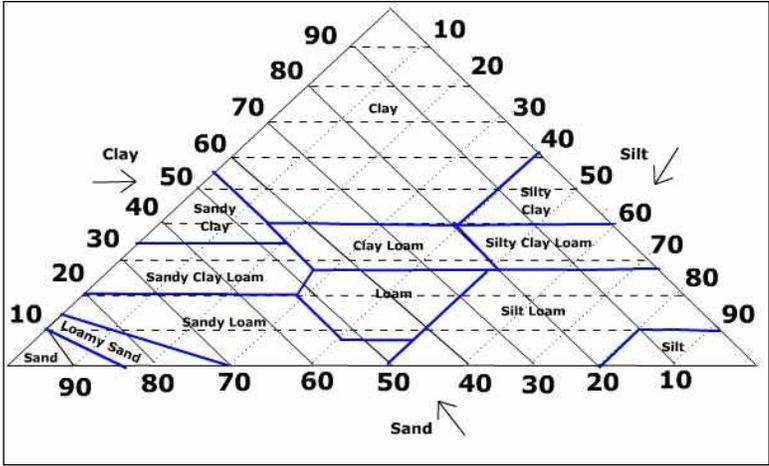
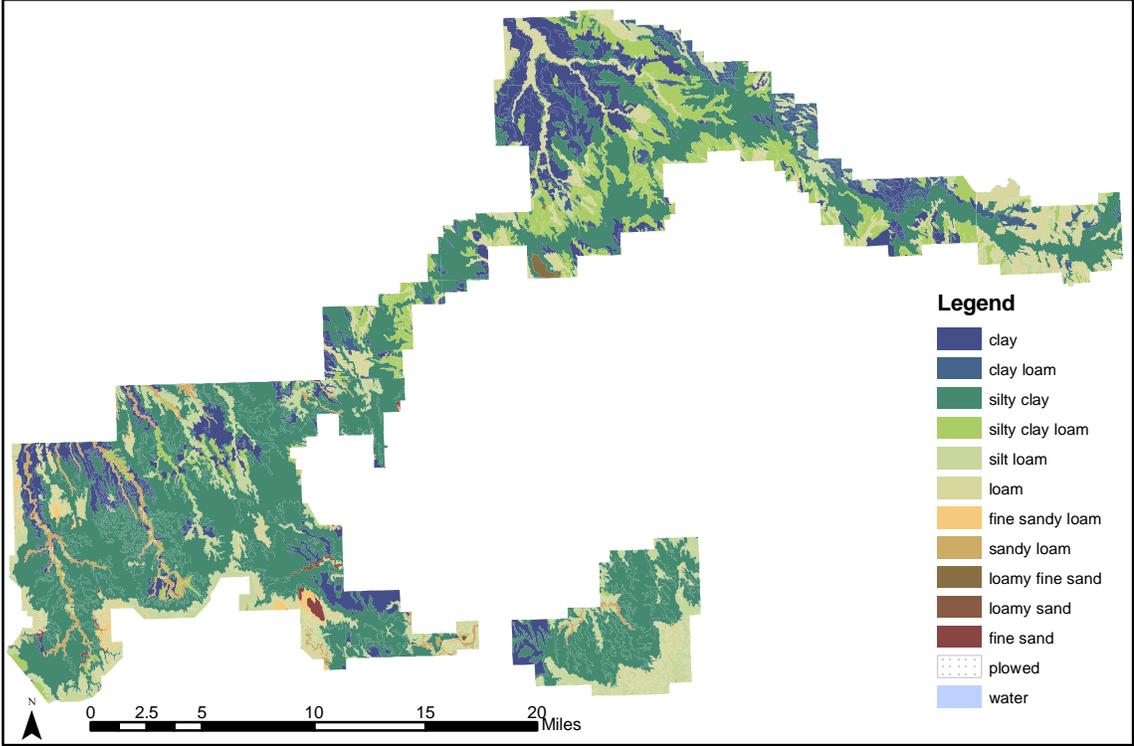


Figure 5. Soil texture triangle where the intersection of the three sides on the triangle give the texture class (Ritter 2003)

Figure 6. Soil texture in Badlands National Park as mapped and classified in soil surveys completed for Pennington, Jackson, and Shannon Counties (USDA NRCS 1996, USDA SCS 1987, 1971)



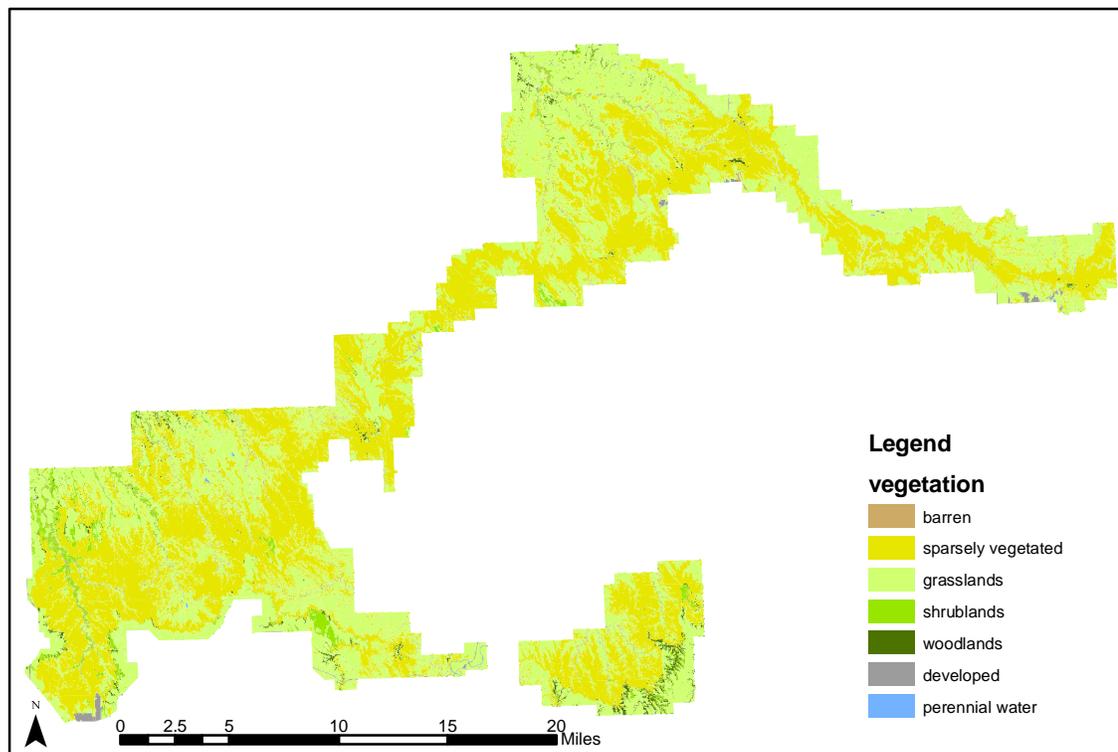
## D. Vegetation

Completed in 1999, the park's Vegetation Map project (Von Loh et al. 1999) classified and digitally mapped 0.9 million acres including the entire park and immediately surrounding areas. Vegetation map classes were determined through extensive field reconnaissance, data collection, and analysis in accordance with the National Vegetation Classification System (The Nature Conservancy and Environmental Research Systems Institute 1994). The vegetation map was created from photographic interpretation of 1:12,000 scale color infrared aerial photography conducted in 1997. The National Vegetation Classification System for the Badlands study area includes twenty-eight natural and semi-natural associations and two complexes (Figure 7). The natural associations are comprised of four woodland, ten shrubland, six upland herbaceous/grassland, four wetland and four sparse vegetation types. The semi-natural associations are comprised of one woodland type and three grassland types (Von Loh et al. 1999).

Woodlands occupy 1,443 ha and are minor components of the regional vegetation, covering approximately 1.5% of the park. These are generally restricted to floodplains, drainage bottoms, toeslopes of sandhills, draws associated with eroding buttes, and slumps on butte and cliff faces. Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) forms the most common woodland in the project area, occurring as its purest form on drier slopes, along butte edges, and in upper draws. Green ash (*Fraxinus pennsylvanica*

Marsh.) and American elm (*Ulmus americana* L.) are the most common hardwood trees present, occupying bottoms of draws, river floodplains, and toeslopes of sand hills. The upper portions of hardwood draws are commonly dominated by various shrub species, particularly American plum (*Prunus americana* Marsh.) and western snowberry (*Symphoricarpos occidentalis* Hook.). Wetter sites with high soil moisture support stands of Eastern or plains cottonwood (*Populus deltoides* Marsh.) trees. Along with peachleaf willow (*Salix amygdaloides* Anderss.), these typically occur as small clumps along minor streams, around seeps, springs, and around ponds.

Figure 7. Vegetation map of Badlands National Park based on physiognomic categories (Von Loh et al. 1999)



Shrublands occupy 4,076 ha and compose approximately 4.2% of the park's area.

Shrublands occur mainly along river and creek floodplains, and on sand deposits, slopes with more soil moisture, and draws. The most widespread of all shrubland species is silver sagebrush (*Artemisia cana* Pursh.), which occurs regularly on floodplains and adjacent slopes. Silver sagebrush is also found sparsely scattered throughout western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve) grasslands. Sand hills support extensive stands of sand sagebrush shrubland (*Artemisia filifolia* Torr.), particularly in the southern half of the park. Where sand hills are reduced to sandy ridges or flats, stands of yucca (*Yucca glauca* Nutt.) may replace or intermingle with sand sagebrush. Most yucca stands are located along the margins of buttes, on low sandy ridges, and on dry canyon sides.

Draws, swales, slopes, and drainages throughout the study area provide enough moisture to sustain patches of various broad-leaved shrubs in addition to silver sagebrush. Among the more common are western snowberry, American plum, and three-leaved sumac (*Rhus trilobata* Nutt.). Western snowberry is the most prevalent; occurring as relatively small stands or clones at the heads of draws or covering low swales. American plum often occurs adjacent to western snowberry or within openings of green ash. Three-leaved sumac occurs as sparse stands along the rims of buttes. The remaining shrublands represent relatively rare types found only in a few locations in and around the park.

There is a diverse mixture of grassland species and alliances that intermingle in small units across the landscape. Grasslands occupy 44,139 ha and compose 45% of the park's area. Western wheatgrass is the overwhelmingly dominant grass occurring in the park. This sod-forming species thrives on clayey soils where it ranges from almost pure, monotypic stands on clay to a true mixed grass prairie on silty/sandy clays or loamy clays. Common associated species include various forbs and grasses such as prairie coneflower (*Ratibida columnifera* (Nutt.) Woot. & Standl.), white milkwort (*Polygala alba* Nutt.), needle-and-thread (*Hesperostipa comata* (Trin. & Rupr.) Barkworth), and prairie dropseed (*Sporobolus heterolepis* (Gray) Gray). Two non-native annual grasses, Japanese brome (*Bromus japonicus* Thunb. ex Murr.) and downy brome (*B. tectorum* L.) are also usually present to some degree in all grassland associations, especially western wheatgrass stands. Western wheatgrass is sometimes replaced by blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths) in drier areas or places with increased grazing. This shorter grass often grows in association with needle-and-thread and threadleaf sedge (*Carex filifolia* Nutt.), especially around the dry edges of buttes and small tables. On gravelly soils, side draws, and broad swales, little bluestem becomes dominant, often in association with side-oats grama (*Bouteloua curtipendula* (Michx.O) Torr.).

Prior to the park's establishment, agricultural or transportation activity disturbed approximately 2064 ha that has been primarily re-vegetated by non-native grass species. Locations include road corridors in the Park seeded with smooth brome (*Bromus inermis*

(Leyss.), old fields seeded with crested wheatgrass (*Agropyron cristatum* (Linnaeus) Gaertn.), and old pastures invaded by or seeded with Kentucky bluegrass (*Poa pratensis* L.). Other common non-native species found in various disturbed sites include alfalfa (*Medicago sativa* L.), Canada thistle (*Cirsium arvense* (L.) Scop.), and giant ragweed (*Ambrosia trifida* L.). A biennial, yellow sweetclover (*Melilotus officianalis* (L.) Pall.) is an exotic that is widespread in the park and it is one of the few non-native species that can occasionally invade sparsely vegetated lands, occasionally even becoming established on small terraces on steep-sided buttes.

Approximately 44,401 ha of the park are unvegetated or sparsely vegetated, comprising 45% of the park's area. The Great Plains Badlands Sparse Vegetation Complex is found on eroded formations where soils are undeveloped, poor, loose, and easily eroded. Vegetation rarely exceeds 10% cover and is usually < 5% vegetative cover. The sparse vegetation is relatively evenly distributed across flat and rolling sites, but is patchy or linear on steeper slopes where it is interspersed with truly barren cliffs, slopes, and mounds. Plant species that are often present in these sparsely vegetated areas include small-flowered wild buckwheat (*Eriogonum pauciflorum* Pursh.), snakeweed (*Gutierrezia sarothrae* (Pursh) Britt. & Rusby), silverscale saltbush (*Atriplex argentea* Nutt.) and gumbo lily (*Oenothera caespitosa* Nutt.) (Von Loh et al. 1999). It is in this sparsely vegetated landscape that two rare and endemic species occur and can be locally abundant: Barr's milkvetch (*Astragalus barrii* Barneby) and Dakota buckwheat (*Eriogonum visherii* A. Nels.).

Approximately 1964 ha of the park host a different sparse vegetation type that can be found within areas of established prairie dog towns, covering approximately 2% of the park. Prairie dog towns occupy deeper soils on large flats dissected by drainages, such as in the Conata Basin. Prairie dogs through their cycle of burrow establishment, grazing, and burrow abandonment, may alter grassland vegetation types over time. This constant use causes the native vegetation to revert back to an early successional state dominated by annual forbs, many of which are nonnative weeds.

#### **E. Relationships between geology, topography, soils, and vegetation**

The geology, topography, soils, and vegetation of the study area are spatially related to each other. The geologic formations give rise to specific landforms, including the steep-sided buttes of the Brule formation and the convex mounds of the Chadron formation. These specific formations also contribute the parent material for soil formation, thus affecting the chemistry and texture of the soils both in the immediate vicinity of the geologic formation as well as downslope as materials are redeposited as colluvium or alluvium. Soils largely derived from Brule formation parent material tend to be silty, while soils largely derived from Chadron formation parent material tend to be clayey. Local inclusions of lacustrine limestones contribute to the formation of calcareous soils, and ancient channel sandstones contribute fine to coarse sand textures to the soils in a few places.

Topography is both a reflection of the underlying geology as well as a major influence on erosion processes, influencing where materials are eroded and deposited. Thus, topography gives rise to the surface processes for mixing of the soils or parent materials derived from various geologic formations, and it is the primary determinant of where soils of specific characteristics are developed. Where slopes are steep, high erosion rates generally preclude soil development, and vegetation is largely absent except on narrow, discontinuous ledges that are able to support opportunistic annual or biennial plant species for short periods of time. Likewise, the flat areas along the base of badland buttes serve as zones of deposition. The zone of active deposition is barren to sparsely vegetated. It is in this zone that *A. barrii* and a few other species are able to persist, including *Eriogonum visheri* - another one of the few rare and endemic species of the Great Plains.

As the Badlands Wall scarp retreats, the badlands formations are eroded into subdued land surfaces that eventually become mantled with rich soils that support a diverse and abundant flora. Within this grassland area, local topographic variations give rise to shallow swales that hold water for short periods of time and can support a few shrub species and herbaceous plants that require more water than the surrounding grasslands offer. Where perennial and intermittent drainages flow or springs reach the surface, the abundance of water supports a variety of shrubland and woodland plant species. Along the White and Cheyenne Rivers and their major tributaries, true floodplains exist as characterized by the channel gravels and sands that drop out of the bed load in and

immediately adjacent to the channel, giving rise to sandy soils that support thick riparian woodlands.

## **IV. HABITAT MODELS**

### **A. Objective**

The first objective of this study of *A. barrii* in Badlands National Park was to develop predictive habitat models for *A. barrii* to focus field inventory efforts, analyze potential impacts, and develop conservation strategies.

### **B. Methods**

#### **1) Sampling design**

In fall 2002, a simple deductive model was built using limited data (Store and Jokinaki 2003, Wu and Smeins 2000) as a first step to understanding the known distribution of *A. barrii*. The extent (a component of scale that represents the total range over which an analysis is conducted, Gurevitch et al. 2002) of this analysis was 98,750 ha, the entire Badlands National Park. The grain (a component of scale that represents the size of the primary unit of analysis, Gurevitch et al. 2002) was 200 m<sup>2</sup>.

Using ESRI ArcGIS 8.2 with the Spatial Analyst extension, I scored four habitat variables (Table 1) based on their association with *A. barrii*, as indicated in the literature, on existing herbarium vouchers from the Badlands National Park Herbarium and the

University of South Dakota Herbarium, and from eight documented populations in Badlands National Park (Table 2).

Table 1. Geospatial habitat layers used in GIS analyses.

Habitat Parameter	Map Resolution	Minimum Map Unit	Source
Slope	1:24,000	30 m <sup>2</sup>	USDI U.S. Geological Survey 1999
Vegetation	1:12,000	5000 m <sup>2</sup>	Von Loh et al. 1999
Soils	1:24000 (Jackson County) 1:24000 (Pennington County) 1:20000 (Shannon County)	Unreported	USDA Natural Resource Conservation Service 1996; USDA Soil Conservation Service 1987, 1971
Geology <sup>1</sup>	1:24000	Unreported	Raymond and King 1974a, 1974b, 1974c, 1974d, 1974e, 1974f, 1976

<sup>1</sup> coverage limited to 46132 ha, approximately 47% of the study area

Table 2. Known *A. barrii* occurrences in Badlands National Park used to define sampling strata.

Site Name	Geology	Soil	Slope	Vegetation
North Neck 1	Tc	Bb	0-3%	2
North Neck 4	Qoa	Bb	0-3% 3-6% 6-10%	2/16
Hwy 44 Neck	Tb/Tc	Bb	0-3% 3-6% 6-10%	2
South Neck	Qoa	CH	0-3%	2
Sheep Mtn Rd 1	Qoa	CeA/Bb	0-3%	2
Sheep Mtn Rd 2	Qoa	CeA	3-6%	16
Cottonwood Pass 1	Unknown	Br	0-3%	2
Cottonwood Pass 2	Unknown	Br/Ba	6-10%	2

For soil, vegetation, and geology, the original map units in their original resolution were converted from vector to raster formats using ESRI ArcGIS 8.2 with Spatial Analyst, and each raster cell was assigned a score based on the map unit (ie. soil series, vegetation class, geologic formation). For slope, the continuous numeric slope value from the National Elevation Dataset was categorized into ranges of slope values and these

categories were scored in the same way as the soil, vegetation, and geology layers.

Geologic mapping has never been completed for the study area, so only the 46,132 ha (47% of the study area) in the northern portion of the study area which have been mapped were scored for geology.

Each record in each layer was given a score of 0, 1, or 2, where 0 represented no association with *A. barrii*, 1 represented weak or imprecise association with *A. barrii*, and 2 represented strong association with *A. barrii*. Each habitat parameter was given equal weight. Details regarding this scoring process are provided for each variable considered.

#### **a. Geology**

Geology coverage of the South Unit is not available in digital format so only the North Unit was analyzed with geology as a habitat parameter.

Occurrences of *A. barrii* in South Dakota are known to be strongly associated with the Tertiary Chadron formation (Schmoller 1993), map code Tc. However, the two confirmed sites along Sheep Mtn Rd were found in the Scenic member of the Tertiary Brule formation, which sets directly above the Chadron in the section. *A. barrii* populations found in association with the Brule formation were actually in alluvium at the base of Brule buttes. Where the contact between the Brule and Chadron is near

ground level, as is the case along Sheep Mtn Road, this deposition of Brule alluvium tends to intermix with Chadron parent material so the presence of *A. barrii* is still likely associated with the Chadron. Alluvium deposits that are relatively stable are mapped as older quaternary alluvium, map code Qoa. Unfortunately, the parent material for the alluvium is not discernable from the original map data and older Quaternary alluviums are associated with many geologic formations in the Badlands environment. So an intermediate GIS analysis was used to interpret the parent material of the older Quaternary alluvium. Using ESRI ArcGIS 8.2 3-D Spatial Analyst, the slope coverage was analyzed with the Geology coverage to find the older Quaternary alluvium that were adjacent to and downslope from the Chadron formation.

The Chadron formation (Tc) and the older Quaternary alluvium (Qoa) located adjacent to and downslope from the Chadron formation were given a habitat score of 2, consisting of 17,118 polygons and occupying 68,472 hectares. The Brule formation (Tb) and the older Quaternary alluvium (Qoa) that was not derived from the Chadron formation were given a habitat score of 1, consisting of 8837 polygons and occupying 35,348 hectares. All other map classes were given a score of 0.

## **b. Soils**

The study area spans three counties: Pennington, Jackson, and Shannon. As soils are generally surveyed by county, three separate coverages (one for each county) were

merged for this analysis. While digitally the maps were merged for this project, they were not correlated so essentially the same soil may be identified with a slightly different map code and description depending on which county it is located in. This issue with correlation is further exacerbated by the disparate ages of the three surveys and the relative detail available in each. Pennington County, covering most of the North Unit, is the most recent (1996) and therefore most closely reflects current taxonomy and standards. Shannon County, covering the entire South Unit, is of a coarser resolution and much older (1971); therefore some of the taxonomy is outdated. Jackson County, covering the far eastern edge of the North Unit, is intermediate of the other two in terms of date (1987) and currency with taxonomy and standards.

Schmoller (1993) found that *A. barrii* populations on the adjacent Buffalo Gap National Grasslands were associated with Badland “soil”, map code Bb, and Interior loam soils, map codes In and Io, based upon a soil classification and map that pre-dates the one used in this analysis. In the current classification (USDA 1996), Interior loam soils are deep and well-drained soils that support abundant vegetation and are thus unlikely to support *A. barrii*. Note that Badland “soil” is not a true soil in that it has not developed horizons, rather it is a land form composed of exposures of parent material and recently deposited alluvium. The probable and confirmed sites found in the park were primarily located on Badland “soil”, map codes Ba and Bb. However, the Sheep Mtn Rd sites were located on Cedarpass silty clay loam, map code CeA, and the South Neck site was located on Cedarpass-Interior-Badland complex, map code Ch. The Cedarpass-Interior-Badland

complex is composed of all three soils that are so closely intermingled or so small that mapping them separately is impractical (USDA 1996). So it is expected that the *A. barrii* occurred in the Badland “soil” components of this complex. The occurrence of *A. barrii* in the Cedarpass silty clay loam soil is more difficult to resolve, as this soil does not generally have Badland inclusions and is typically vegetated.

The Badlands soil map unit (Ba or Bb) was given a habitat score of 2, consisting of 6294 polygons and occupying 25,176 hectares. The Cedarpass silty clay loam (CeA) and Cedarpass-Interior-Badland complex (Ch) were each given a habitat score of 1, consisting of 1669 polygons and occupying 6676 hectares. All other map classes were given a score of 0.

### **c. Slope**

Slope was derived from a seamless digital elevation model of the National Elevation Dataset based on satellite imagery. After re-projection to reconcile vertical and horizontal coordinate systems and mapping units, ESRI ArcGIS 8.2 Spatial Analyst was used to create a percent slope coverage on a 30m x 30m gridcell, the highest resolution data source used in this analysis. This slope grid was then re-classed into discrete integer classes of 0-3%, 3.1-6%, 6.1-10%, 10.1-15%, 15.1-50%, > 50%. These classes were selected because they correspond with slope classes used in soil mapping. Analysis found that most *A. barrii* sites were associated with 0-3% slope class. North Neck 4 and Hwy

44 Neck were mapped as polygons where most of the polygon was in the 0-3% slope class, with the peripheral of the population commonly extending into 3.1-6% and the very edge extending into 6-10% slope class. Only one point site, Cottonwood Pass 2 was found to occur exclusively on a slope class of 6-10%.

Slope classes 0-3% and 3.1-6% were given a habitat score of 2, consisting of 11,715 polygons and occupying 46,860 hectares. Slope class 6.1-10% was given a habitat score of 1, consisting of 3564 polygons and occupying 14,256 hectares. All other map classes were given a score of 0.

#### **d. Vegetation**

*A. barrii* is associated with very open light conditions where cover is less than 10% (Schmoller, 1993). Specifically it is part of the *Eriogonum pauciflorum* – *Gutierrezia sarothrae* Badlands Sparse Vegetation type as defined by the National Vegetation Classification System. This vegetation type was mapped as part of the Badlands Sparse Vegetation Complex, map code 2, by the Vegetation Mapping Program of the National Park Service and U.S. Geological Survey-Biological Resources Division. In some sites, such as North Neck 4, it was found to grade into the edge of the adjacent Western Wheatgrass Alliance, mapped as map code 16. A known source of error in this map classification that is especially relevant to this analysis is the misidentification of

chalcedony beds as western wheatgrass due to similar photo signatures. This is likely the cause of site Sheep Mtn Rd 2 site being classified as western wheatgrass where the site was mapped as western wheatgrass where in reality it is a large, dense chalcedony bed with sparse vegetation occurring between chalcedony cobbles. At the North Neck 4 site, this large population of *A. barrii* primarily occurs on Badlands Sparse, but the edges of the population grade out into land mapped as Western Wheatgrass Alliance. Based on these observations, the association with the Western Wheatgrass Alliance map unit appears to be either the edge of a distribution primarily situated on Badlands Sparse map unit or was an error in photointerpretation. While certainly less suitable than the Badlands Sparse Vegetation, the Western Wheatgrass Alliance map code cannot be completely discounted as potential *A. barrii* habitat. None of the known *A. barrii* occurred on any other map class and there is no indication in the literature or on existing vouchers that would indicate any other vegetation community would be potential habitat.

Badlands Sparse Vegetation, map code 2, was given a habitat score of 2, consisting of 11,184 polygons and occupying 44,736 hectares. Western Wheatgrass Alliance, map code 16, was given a habitat score of 1, consisting of 9206 polygons and occupying 36,824 hectares. All other map codes were given a score of 0.

### **e. Scoring**

All four layers were then summed on a 200m<sup>2</sup> grain. The result was that the entire surface of the park was scored on a linear scale of 0 to 8, with 8 representing the most likely habitat for *A. barrii* and 0 representing the least likely habitat for *A. barrii*. These scored raster cells were then converted into polygons with generalized lines representing contiguous habitat with the same score. These polygons ranged in size from 25,541 m<sup>2</sup> to 38,867,515 m<sup>2</sup>.

### **f. Sampling**

A major consideration in selecting a sampling design was the need to maximize the efficiency of the field inventory efforts during the short flowering season as *A. barrii* is cryptic and easily overlooked when it is not in flower. Because of this narrow flowering season from late April to early June, a sampling design was selected that would maximize efficiency while still yielding a large enough sample size to detect presence or absence and provide opportunities for correlation with habitat parameters. At a regional level (10-50 km<sup>2</sup>) stratified random sampling draws an accurate picture of the small-scale vegetation pattern at low sampling effort (Goedickemeier et al. 1997) and so a GIS-based stratified random sample design was selected using the polygons from the simple deductive model as the sampling unit. In the stratified random sample, the strata were defined by habitat scores of 0, 1, 2...8, representing the full range of habitat scores for

the species. Using the GIS tables without spatial reference, five polygons each of score 0-5 were randomly selected to cover a range of polygon sizes, resulting in 30 independent polygons of the least likely habitat to be surveyed. Ten polygons each of score 6-8 were randomly selected to cover a range of polygon size, resulting in 30 independent polygons of the most likely habitat to be surveyed. These 60 search polygons were then targeted for field inventory (table 3).

Table 3. Summary of scored polygons and selection of sample sites

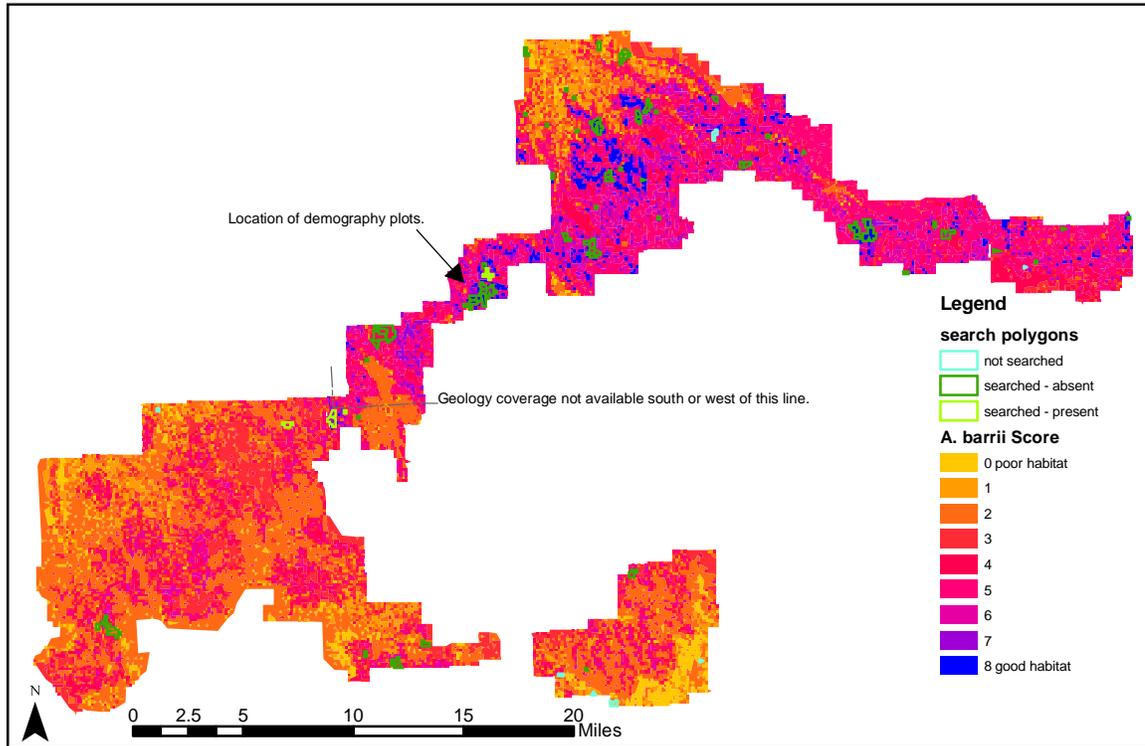
Score (strata)	Number of Polygons	Min area (m <sup>2</sup> )	Max area (m <sup>2</sup> )	Mean area (m <sup>2</sup> )	Total area (ha)	# Polygons to survey
0	414	25541	3284042	89542	3707	5
1	858	25541	2003028	78861	6766	5
2	1115	25541	38867515	234373	26133	5
3	1492	25541	13959491	101380	15126	5
4	1600	25541	5582687	82147	13144	5
5	1172	25541	9050160	155899	18271	5
6	1101	25541	1473910	81211	8941	10
7	485	25541	689177	63564	3083	10
8	247	25541	1504397	97173	2400	10
Total	8484	-	-	-	97571	60

## 2) Data Collection

During May and early June of 2003, 53 of the 60 targeted polygons were surveyed. Seven targeted search polygons were not searched. Two targeted polygons were inaccessible due to weather and terrain. Five targeted search polygons located inside of the park boundary in Pine Ridge Indian Reservation could not be accessed because of the risk of physical violence against park employees posed by a hostile pro-Indian encampment that was in place for the duration of the study. The 53 polygons that were searched covered

1197 hectares (1.2%) of park land. A Trimble GeoExplorer XT Global Positioning System (GPS) was used to navigate to each search polygon. The entire polygon was searched for the presence of *A. barrii*. In each search polygon, the geology, soil, vegetation, and slope as indicated by GIS were verified in the field. If *A. barrii* was present, GPS was used to map the perimeter of the population(s) and life history observations and population measurements were collected. GPS files were post-processed, differentially corrected, and exported as shapefiles using Pathfinder Office 2.90 software. Differentially corrected GPS locations had a mean horizontal precision of 1.03 meters. A total of 42 *A. barrii* populations were found in four of the 53 polygons searched. An additional 59 populations were opportunistically encountered and mapped outside of the targeted polygons. This survey effort yielded 101 geographically discrete confirmed cases of *A. barrii* “presence” where plants were occupying 9.8 hectares and 49 confirmed cases of “absence” occupying 1098 hectares (Figure 8).

Figure 8. Sampling design based on the 2002 simple deductive model where search polygons were assigned a score of 0 = least likely habitat for *A. barrii* and 8 = most likely habitat for *A. barrii*. Sixty search polygons were selected and 53 were surveyed. *Note that a minor change in the park boundary shown on this 2002 map and the other maps used in this document reflects a change in the Park's data standard that occurred in 2003.*



### 3) Analysis

Habitat data were spatially analyzed using ESRI ArcGIS 8.3 with the Spatial Analyst extension, ESRI ArcView 3.3 with the Spatial Analyst extension and the Patch Analyst extension (Rempel and Carr 2003). Statistical analysis was performed using Statistical Application Software (SAS) version 8.1.

## **a. Variables**

The habitat variables used in all of the habitat analyses were derived from existing geospatial layers listed in Table 1. Geology was not used as a variable in the discriminant analysis and the logistic regression models because the geospatial coverage was incomplete.

The digital elevation model was used to derive a percent slope layer where percent slope is a continuous numeric variable that was used to directly calculate mean slope, (*meanslope*), maximum slope (*maxslope*), and minimum slope (*minslope*).

Field investigation of physical and chemical soil properties indicated that texture might be a very useful soil property to differentiate between presence and absence of *A. barrii*. Using the published soil surveys (USDA NRCS 1996, USDA SCS 1987, 1971), each soil map unit was coded on a continuous numeric scale for percent fine particle fraction (percent fines) defined as passing the 200mm sieve as indicated in the engineering properties tables of the published soil surveys for Jackson, Pennington, and Shannon counties. Where a range of values was listed, the mean value was used. Where the soil series was composed of more than one major component, the mean value of the dominant soil component was used. For those map units that represent miscellaneous land units rather than soil series, such as “barren badlands”, engineering properties were not published so the percent fine particle fraction was estimated by best professional

judgment of a soil scientist experienced in soils of the area (R. Ford, pers. comm., USDA ret.). The fine fraction passing the 200 mm sieve is composed of clays and fine silts. Low values of percent fines indicate soils high in sands, moderate values indicate soils high in silts, and high values indicate soils high in clay. The percent fines were used to calculate minimum percent fine, *pfmin*, maximum percent fine, *pfmax*, and area weighted percent fines, *pfaw*.

*A. barrii* is a shade intolerant plant (Barneby 1964, Great Plains Flora Association 1986, Schassberger 1988, 1990, Schmoller 1993) so vegetation was classified based on shading effect. Vegetation values were derived from the park's published vegetation map (Von Loh et al. 1999) which includes map units based on the National Vegetation Classification System (The Nature Conservancy and Environmental Research Systems Institute 1994). I assigned an ordinal numeric value to represent the relative shade provided by each vegetation map unit based on the shading value represented by the published physiognomic categories (Faber-Langendoen et al. 1996). Shading was determined to reflect the estimated effect of shading at 10 cm above ground level, the approximate height of *A. barrii* (Table 4). That is, the lower the value the less affected by shading or cover and more light is potentially available to the ground level plants. Conversely, the higher the value the more the plants are affected by shading or cover and light is less available to ground level plants. These shading values were used to calculate minimum shading, *vegmin*, maximum shading, *vegmax*, and area weighted shading, *vegaw*.

Table 4. Ordinal vegetation shading value assigned to each physiognomic category (Faber-Langendoen et al. 1996) for each vegetation map unit (Von Loh et al. 1999) classified based on the National Vegetation Classification System (The Nature Conservancy and Environmental Research Systems Institute 1994), where shading value 1 = no shade and 7 = complete shade.

<b>Physiognomic category</b>	<b>Map units based on National Vegetation Classification System (map unit number)</b>	<b>Assigned ordinal value</b>
Perennial water	Rivers – Perennial (#50) Reservoirs (#57)	7
Developed	Transportation, Communications, and Utilities (#51) Mixed Urban (#52) Croplands and Pasture (#53) Seeded Mixed Grass Prairie (#54) Other Agricultural Land (#55)	6
Forest and Woodlands	Green Ash – (American Elm) / Chokecherry Woodland (#42) Ponderosa Pine / Rocky Mountain Juniper Woodland (#43) Rocky Mountain Juniper / Littleseed Ricegrass Woodland (#44)	5
Shrublands	Soapweed Yucca / Prairie Sandreed Shrubland (#21) Silver Buffaloberry Shrubland (#25) Silver Sagebrush / Western Wheatgrass Shrubland (#31) Sand Sagebrush / Prairie Sandreed Shrubland (#32) Rabbitbrush Shrubland (#33) Chokecherry – (American Plum) Shrubland (#34) Three-leaved Sumac / Threadleaf Sedge Shrubland (#35) Western Snowberry Shrubland (#37) Sandbar Willow Temporarily Flooded Shrubland (#38) Greasewood / Western Wheatgrass Shrubland (#39) Eastern Cottonwood – (Peachleaf Willow) / Sandbar Willow Shrubland (#41)	4
Grasslands	Switchgrass Grassland (#12) Emergent Wetland Grassland (#14) Little Bluestem – Grama Grass – Threadleaf Sedge Grassland (#15) Western Wheatgrass Alliance Grassland (#16) Introduced Grassland (#17) Blue Grama Grassland (#18) Western Wheatgrass – Green Needlegrass Grassland (#19)	3
Sparsely Vegetated	Prairie Dog Town Complex (#1) Badlands Sparse Vegetation Complex (#2)	2
Barren	Intermittent Drainages (#56) Beaches and Sandy Areas other than Beaches (#58) Strip Mines, Quarries, and Gravel Pits (#59)	1

## **b. Park-wide Deductive Habitat Similarity Model**

A deductive model was developed to capture the full range of habitat values in the study area in their native mapping units to locate areas with habitat characteristics that were similar to places where *A. barrii* occurs. The extent of this model is park-wide and the grain-size was 30m<sup>2</sup>, the finest resolution of the habitat datasets used. Using the same process described for development of the deductive model used for the sampling design, all 109 known *A. barrii* populations in Badlands National Park were used to develop a park-wide deductive model, including 101 populations found in 2003 as well as the original 8 populations known in 2002. Habitat parameters considered were the native mapping units (categorical variables) for: geologic formation (does not include most of the Stronghold District), soil series, vegetation map unit, and categorized percent slope. Analysis was performed on raster cells using a 30m<sup>2</sup> grain. For cells where geospatial coverage for geology was available, the similarity value represents the total similarity score out of a possible high of 8 (eg. a score of 2 for each of the four habitat parameters). For cells where geospatial coverage for geology was not available, the similarity value represents the total similarity score out of a possible of 6 (eg. a score of 2 for each of the three habitat parameters, not including geology). The closer a map value is to 1, the more similar it is to occupied *A. barrii* habitat. Classification was performed using ESRI ArcGIS 8.3 to divide the data values into five classes based on Jenks natural breaks. Using this method, classification is based on natural clusters and gaps inherent in the data and class boundaries occur where there are relatively large jumps in data values.

### **c. Park-wide Discriminant Analysis Model**

The discriminant analysis statistical technique was used to identify the relationship between presence/absence (qualitative criterion variable) and habitat values (quantitative predictor variables) based on a discriminant function that classifies observations into mutually exclusive classes, such as presence or absence. The procedure uses linear combinations of variables that best discriminate between sites defined by the presence or absence of a given species (Manel et al. 1999), in this case *A. barrii*. Similar to the logistic regression model, this modeling technique is an inductive model rather than a deductive model such as the habitat similarity model previously described. However, it differs from the logistic regression model in that it uses all known presence/absence data collected from the entire park; therefore, it can be used to predict *A. barrii* presence or absence in any search polygon in the entire park.

Variables used in the park-wide, discriminant analysis model included only habitat values and did not include landscape metrics. The extent was park-wide and the grain was variable in size, ranging from 25,541 m<sup>2</sup> to 38,867,515 m<sup>2</sup>, based on the size of the search polygons where each search polygon was composed of contiguous habitat of the same score developed in the simple deductive model used to develop the sampling design. All 2003 observations were used: 101 mapped populations (presence) found on 63 search polygons resulting in n=63 in the presence class, and 49 search polygons where *A. barrii* was searched for but not found resulting in n=49 in the absence class. This analysis was

performed using Statistical Application Software (SAS) version 8.1. The stepwise discrimination procedure (ProcSTEP) with forward selection was used to select variables with a significance criteria of 0.15 to find a subset of variables that best reveals differences between the “*A. barrii* presence” class and the “*A. barrii* absence” class. The results from backward elimination, step-wise selection, and forward selection at the 0.15 significance level were compared. The three variables selected using forward selection and stepwise selection were identical, while backward selection selected two of the three variables selected by the other methods plus two additional variables. I made the decision to use the variables selected using forward selection because of the consistency with the other selection methods, thus indicating the variables possessed discriminatory power and their selection was not just an artifact of method. Forward selection began with no variables in the model, at each step the stepwise discrimination function was used to enter the variable that contributes most to the discriminatory power of the model as measured by Wilks’ Lambda, the likelihood ratio criterion. When none of the unselected variables met the entry criterion, the forward selection process stopped.

The selected variables were then analyzed in SAS 8.1 using the discrimination procedure (ProcDISCRIM) with Mahalanobis distance to determine proximity based on the full covariance matrix and priors equal. This procedure was used to compute a discriminant function for classifying presence/absence observations according to the formula in Figure 9.

$$L = b_1x_1 + b_2x_2 + \dots + b_kx_k + c$$

Figure 9. Linear discriminant function where  $b$  = discriminant coefficients,  $x$  = discriminating variable, and  $c$  = constant.

#### d. Patch-based, Logistic Regression Model

A multiple logistic regression with a logit link and binomial error distribution was used to relate the presence and absence of *A. barrii* to habitat characteristics for vegetation, soil, and slope. This analysis was performed using Statistical Application Software (SAS) version 8.1. The logit transformation of the probability of presence/absence ( $\pi$ ) weighted for abundance of *A. barrii* was modeled as a linear function of 26 possible explanatory variables using the formula in Figure 10.

$$\ln \left[ \frac{\pi(x)}{1 - \pi(x)} \right] = \beta_0 + \sum_{i=1}^{26} \beta_i x$$

Figure 10. Formula for logistic regression where  $\beta_0$  and  $\beta_{1i}$  are the regression constants.

A patch-scale model was fitted using a maximum likelihood method with backwards elimination to select the variables in the final model (Olden and Jackson 2000). The model-fitting process continued by eliminating each consecutive variable with the highest p-value until the Akaike's information criterion (AIC) reached its lowest value indicating the most parsimonious model. The AIC is used to test the relative value of different competing models (i.e. alternative regression equations for a dependent variable). When

one model has a lower AIC-value than another model, the model with the lowest AIC is preferred.

Variables used in the logistic regression model included both habitat values and landscape metrics that quantify landscape structure including composition, spatial configuration, and shape complexity. Only the four search polygons that contained *A. barrii* were used to create this model. Using the Patch Analyst extension in ESRI ArcView 3.2, a 0.5-hectare hex layer was generated and intersected with the native map units in the vegetation, soil, and slope layers listed in Table 1 as well as the coverage of *A. barrii* populations in the four search polygons. The 0.5 hectare size is approximately twice the mean size of known populations and was selected as a biologically meaningful scale to encompass existing *A. barrii* populations as well as a buffer of habitat that might reasonably include dispersal and mapping error. Each 0.5 hectare hex is considered a patch and there were 326 patches used to create this model. Each patch that included a mapped *A. barrii* population was coded as ‘present’ and those that did not were coded as ‘absent.’ This resulted in 107 present patches and 219 absent patches. Those patches that were coded for presence were weighted for the proportion of the patch actually occupied by *A. barrii*. The extent of this study was the four disjunct search polygons where *A. barrii* was found, a total of 160 ha or 0.16% of the total study area, and the grain was the 0.5 ha hex patch.

Again using the Patch Analyst extension, landscape metrics (Table 5) were generated for each patch in each habitat layer. A correlation matrix was generated in SAS for these metrics. To reduce redundant contributory variables, metrics with an r-value greater than 0.07 were considered correlated and one metric of each correlated pair was dropped from further analysis. The remaining uncorrelated metrics were analyzed in logistic regression to yield parameter estimates.

Table 5. Description of landscape metrics used in the logistic regression model.

<b>Variable</b>	<b>Description</b>
Pfaw	Soil: Area weighted percent of fine particle fraction
Pfmin	Soil: minimum percent of fine particle fraction
Pfmax	Soil: maximum percent of fine particle fraction
Maxpslope	Slope: maximum percent slope
Meanpslope	Slope: mean percent slope
Vegaw	Vegetation: area weighted shading
Vegmin	Vegetation: minimum shading
Vegmax	Vegetation: maximum shading
vNumP	Vegetation metric: number of patches
vMPS	Vegetation metric: mean patch size
vMedPS	Vegetation metric: median patch size
vPSSD	Vegetation metric: patch size standard deviation
vPSCoV	Vegetation metric: patch size coefficient of variance
vTE	Vegetation metric: total edge
vED	Vegetation metric: edge density
vMPE	Vegetation metric: mean patch edge
vMPAR	Vegetation metric: mean perimeter-area ratio (shape complexity)
vMSI	Vegetation metric: mean shape index (shape complexity)
vMPFD	Vegetation metric: mean patch fractal dimension (shape complexity)
vAWMPFD	Vegetation metric: area weighted mean patch fractal dimension (shape complexity adjusted for shape size)
sNumP	Soil metric: number of patches
sMPS	Soil metric: mean patch size
sMedPS	Soil metric: median patch size
sPSSD	Soil metric: patch size standard deviation
sPSCoV	Soil metric: patch size coefficient of variance
sTE	Soil metric: total edge
sED	Soil metric: edge density
sMPE	Soil metric: mean patch edge
sMPAR	Soil metric: mean perimeter-area ratio (shape complexity)
sMSI	Soil metric: mean shape index (shape complexity)
sMPFD	Soil metric: mean patch fractal dimension (shape complexity)
sAWMPFD	Soil metric: area weighted mean patch fractal dimension (shape complexity adjusted for shape size)
slNumP	Slope metric: number of patches
slMPS	Slope metric: mean patch size
slMedPS	Slope metric: median patch size
slPSSD	Slope metric: patch size standard deviation
slPSCoV	Slope metric: patch size coefficient of variance
slTE	Slope metric: total edge
slED	Slope metric: edge density
slMPE	Slope metric: mean patch edge
slMPAR	Slope metric: mean perimeter-area ratio (shape complexity)
slMSI	Slope metric: mean shape index (shape complexity)
slMPFD	Slope metric: mean patch fractal dimension (shape complexity)
slAWMPFD	Slope metric: area weighted mean patch fractal dimension (shape complexity adjusted for shape size)

To apply this logistic regression model to a larger landscape within the study area, five basins were targeted. Patch Analyst was used to generate a 0.5 hectare hex layer where each 0.5 hectare hex was considered a patch. The hex layer was then intersected with the native map units in the vegetation, soil, and slope layers listed in Table 1 for the focus areas and values for habitat parameters selected in the logistic regression model were calculated. Again using Patch Analyst, landscape metric variables selected in the logistic regression model were then derived for each 0.5 ha patch in each habitat layer. Then in Microsoft Excel, the probability of finding *A. barrii* in the patch was calculated using the formula in Figure 11 based on the parameter estimates of the nine explanatory variables selected in the logistic regression model. Calculated probabilities ranged from 0 to 1, where 1 represents highest probability of finding *A. barrii* and 0 represents the lowest probability of finding *A. barrii*. These probabilities were then displayed in a map for each patch developed in ESRI ArcGIS 8.3.

$$p(y = 1 | x) = \frac{\exp(\beta_0 + \beta_1'x)}{1 + \exp(\beta_0 + \beta_1'x)}$$

Figure 11. Logistic regression formula as used to calculate probability of *A. barrii* occurrence where  $x$  is the data vector for a patch and  $y$  is the value of the binary outcome variable.

### **e. Model Performance**

For both the discriminant analysis model and the logistic regression model, model performance was assessed with a leave-one-out cross-validation technique where each case was used sequentially as a single test sample, while the remaining “n-minus-one” cases formed the training set (Fielding 2002, Pearce and Ferrier 2000). For the discriminant analysis model, the leave-one-out cross-validation was accomplished using the crosslist command in the discriminant procedure in SAS. For the logistic regression model, the leave-one-out cross-validation was accomplished using a SAS macro created by Mabelle Wilson (unpublished).

Following the methodology of Fielding and Bell (1997), the cross-validation results for each model were summarized in a confusion matrix, a cross-tabulation of the number of cases correctly and incorrectly assigned to each of the classes. The confusion matrix was then used to calculate several measurements of classification accuracy as described in Fielding and Bell (1997).

## C. Results

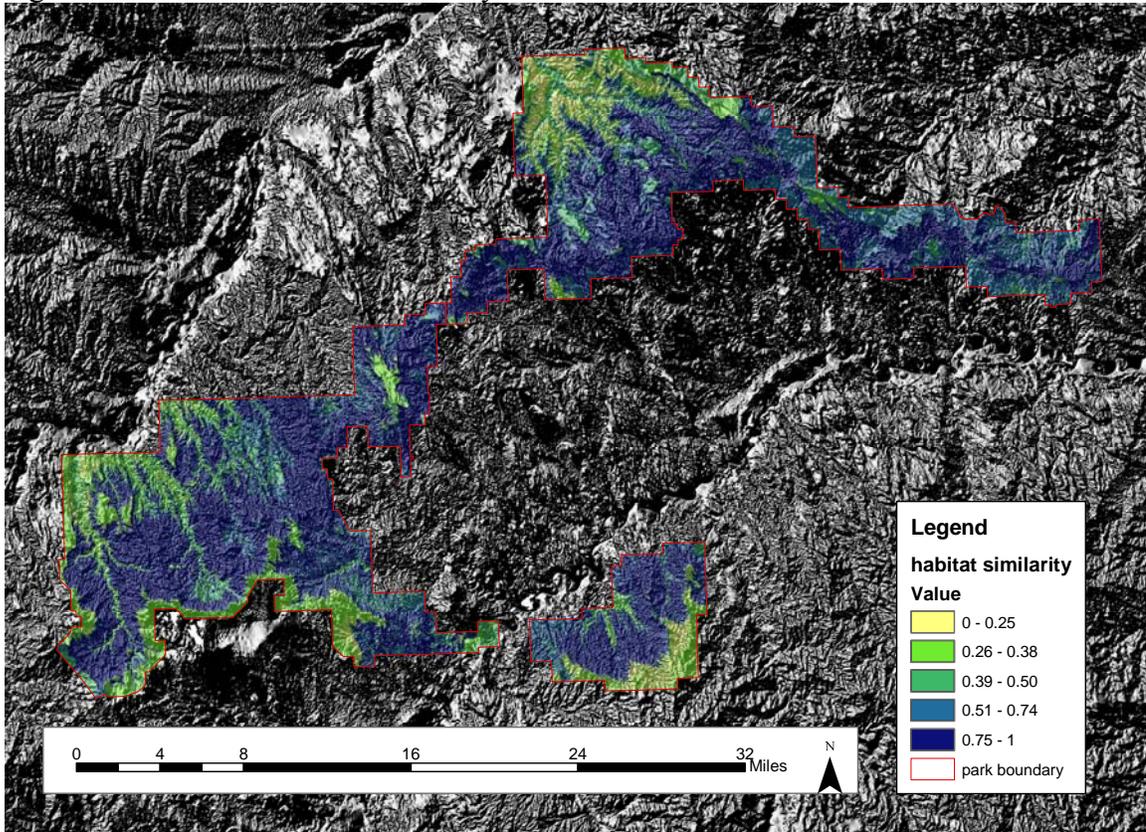
### 1) Park-wide, Deductive Habitat Similarity Model

The entire study area was classified into five habitat similarity values as shown in Table 6. Approximately 96% of all known *A. barrii* populations occur in areas with a habitat similarity score of 0.75 - 1.0. The remaining 4% of known *A. barrii* populations occurred in areas with a habitat similarity score of 0.375.

Table 6. Habitat similarity scores

Habitat similarity score	Area occupied (ha)	% of study area
0 – 0.25	5436	6
0.26 – 0.38	12,016	12
0.39 – 0.5	10,785	11
0.51 – 0.74	26,952	27
0.75 – 1.0	43,561	44

Figure 12. Deductive habitat similarity model overlaid on hillshade relief



## 2) Park-wide, Discriminant Analysis Model

For the discriminant analysis model, nine habitat variables were considered in stepwise discriminant analysis and a subset of three variables were used to calculate a discriminant function for use in classifying observations into presence or absence of *A. barrii* (Table 7).

Table 7. Variables used in discriminant analysis habitat model where column A lists all variables considered in Proc STEPDISC, and column B lists the variables selected in Proc STEPDISC and then analyzed in Proc DISCRIM. Symbol (+) indicates the variable was used in the analysis described for that column and symbol (-) indicates the variable was not used in the analysis described for that column.

Variable	Description	A	B
Pfaw	Soil: Area weighted percent fine soil fraction	+	+
Pfmin	Soil: minimum percent fine soil fraction	+	-
Pfmax	Soil: maximum percent fine soil fraction	+	+
Maxpslope	Slope: maximum percent slope	+	-
Meanpslope	Slope: mean percent slope	+	-
Minpslope	Slope: minimum percent slope	+	+
Vegaw	Vegetation: area weighted shading	+	-
Vegmin	Vegetation: minimum shading	+	-
Vegmax	Vegetation: maximum shading	+	-

The three significant habitat variables in order of selection were maximum percent fine soil fraction, minimum percent slope, and area-weighted percent fine soil fraction (Table 8). These three variables were then used to develop a discriminant criterion to classify each observation into either presence or absence (Table 9).

Table 8. Summary statistics for variables selected for discriminant analysis

Variable	Partial R-square	F value	P	Wilks' Lambda
Maximum percent fine soil fraction [Pfmax]	0.1158	14.4	0.0002	0.8842
Minimum slope [Minslope]	0.0334	3.77	0.0547	0.8546
Area-weighted percent fine soil fraction [Pfaw]	0.0224	2.48	0.1183	0.8355

Table 9. Linear discriminant function values for park-wide model.

Parameter	0 (absence)	1 (presence)
Constant	-1525	-1564
Minimum slope [Minslope]	15.27915	14.77198
Area-weighted percent fine soil fraction [Pfaw]	7.75009	7.89052
Maximum percent fine soil fraction [Pfmax]	26.36223	26.66105

Using the leave-one-out cross-validation technique, the discriminant analysis model correctly classified 71 out of 112 observations, a correct classification rate of 63.4%. Of the 41 observations that were incorrectly classified, 24 were false negatives and 17 were false positives.

Table 10. Confusion matrix for the discriminant analysis model based on leave-one-out cross-validation.

	Actual Presence	Actual Absence	Actual Total
Predicted Presence	a = 46 73.02%	b = 24 48.98%	70 62.50%
Predicted Absence	c = 17 26.98%	d = 25 51.02%	42 37.50%
Predicted Total	63 100.00%	49 100.00%	N = 112 100.00%

Using the values for a, b, c, d, and N listed in the confusion matrix shown in Table 10, classification accuracy measures presented in Table 11 were calculated following the methodology of Fielding and Bell (1997). Of particular interest are prevalence, sensitivity, specificity, and kappa. The correct classification rate was 63.4% and is partially dependent upon the prevalence which was relatively low at 0.565 as expected for a rare species. Sensitivity was 0.730 and represents the probability that presence cases are correctly classified as presence and is an important measure for recognizing omission error, sometimes referred to as Type II or false negative error. This type of error is of particular concern in a conservation setting because failure to recognize the presence of a species, population, or habitat might result in unintentional impacts. Specificity was 0.510 and represents the probability that absence cases are correctly classified as absence and is an important measure for recognizing commission error, sometimes referred to as Type I or false positive error. Sensitivity and specificity are not sensitive to prevalence (Manel et al. 2001). The kappa statistic is an unbiased measure of classification accuracy (Boyce et al. 2002) that adjusts classification rates for random agreement by measuring the actual agreement minus the agreement expected by chance (Cohen 1960). This is a particularly useful measure when species prevalence is low because it distinguishes both false positives and false negatives (Fielding and Bell 1997). Kappa is marginally affected by prevalence (Manel et al. 2001). For the discriminant analysis model, Kappa was low at 0.244, a reflection of the relatively high false positive error of the model and the low prevalence of the species.

Table 11. Discriminant analysis classification accuracy measures based on the confusion matrix (Table 10)

Accuracy Measure	Calculation	Park-wide Model Value
Prevalence	$(a + c) / N$	0.565
Overall Diagnostic Power	$(b + d) / N$	0.438
Correct Classification Rate	$(a + d) / N$	0.634
Sensitivity	$a / (a + c)$	0.730
Specificity	$d / (b + d)$	0.510
False positive rate	$b / (b + d)$	0.490
False negative rate	$c / (a + c)$	0.270
Positive predictive power	$a / (a + b)$	0.657
Negative predictive power	$d / (c + d)$	0.595
Misclassification rate	$(b + c) / N$	0.366
Odds ratio	$(ad) / (cb)$	2.819
Kappa	$[(a + d) - (((a + c)(a + b) + (b + d)(c + d)) / N)] / [N - (((a + c)(a + b) + (b + d)(c + d)) / N)]$	0.244

### 3) Patch-scale, Logistic Regression Model

A total of 44 habitat variables were considered, 26 uncorrelated variables were modeled using logistic regression, and nine significant habitat variables were used in the final fitted logistic regression model (Table 12).

Table 12. Variables used in logistic regression model where column A lists all variables considered in the correlation matrix, column B lists uncorrelated variables used in the full model, and column C lists the variables used in the fitted model; (+) = variable used, (-) = variable not retained.

<b>Variable</b>	<b>Description</b>	<b>A</b>	<b>B</b>	<b>C</b>
Pfaw	Soil: Area weighted percent of fine particle fraction	+	+	+
Pfmin	Soil: minimum percent of fine particle fraction	+	+	+
Pfmax	Soil: maximum percent of fine particle fraction	+	+	-
Maxpslope	Slope: maximum percent slope	+	+	+
meanslope	Slope: mean percent slope	+	+	+
Vegaw	Vegetation: area weighted shading	+	+	+
Vegmin	Vegetation: minimum shading	+	+	-
Vegmax	Vegetation: maximum shading	+	+	-
vNumP	Vegetation metric: number of patches	+	+	-
vMPS	Vegetation metric: mean patch size	+	-	-
vMedPS	Vegetation metric: median patch size	+	-	-
vPSSD	Vegetation metric: patch size standard deviation	+	+	-
vPSCoV	Vegetation metric: patch size coefficient of variance	+	-	-
vTE	Vegetation metric: total edge	+	-	-
vED	Vegetation metric: edge density	+	-	-
vMPE	Vegetation metric: mean patch edge	+	+	-
vMPAR	Vegetation metric: mean perimeter-area ratio (shape complexity)	+	+	-
vMSI	Vegetation metric: mean shape index (shape complexity)	+	+	+
vMPFD	Vegetation metric: mean patch fractal dimension (shape complexity)	+	+	-
vAWMPFD	Vegetation metric: area weighted mean patch fractal dimension (shape complexity adjusted for shape size)	+	-	-
sNumP	Soil metric: number of patches	+	+	-
sMPS	Soil metric: mean patch size	+	-	-
sMedPS	Soil metric: median patch size	+	-	-
sPSSD	Soil metric: patch size standard deviation	+	+	+
sPSCoV	Soil metric: patch size coefficient of variance	+	-	-
sTE	Soil metric: total edge	+	-	-
sED	Soil metric: edge density	+	-	-
sMPE	Soil metric: mean patch edge	+	-	-
sMPAR	Soil metric: mean perimeter-area ratio (shape complexity)	+	+	-
sMSI	Soil metric: mean shape index (shape complexity)	+	+	+
sMPFD	Soil metric: mean patch fractal dimension (shape complexity)	+	+	-
sAWMPFD	Soil metric: area weighted mean patch fractal dimension (shape complexity adjusted for shape size)	+	-	-
sINumP	Slope metric: number of patches	+	+	-
sIMPS	Slope metric: mean patch size	+	-	-
sIMedPS	Slope metric: median patch size	+	+	-
sIPSSD	Slope metric: patch size standard deviation	+	-	-
sIPSCoV	Slope metric: patch size coefficient of variance	+	+	-
sITE	Slope metric: total edge	+	-	-
Sled	Slope metric: edge density	+	+	-
sIMPE	Slope metric: mean patch edge	+	-	-
sIMPAR	Slope metric: mean perimeter-area ratio (shape complexity)	+	+	-
sIMSI	Slope metric: mean shape index (shape complexity)	+	+	-
sIMPFD	Slope metric: mean patch fractal dimension (shape complexity)	+	+	+
sIAWMPFD	Slope metric: area weighted mean patch fractal dimension (shape complexity adjusted for shape size)	+	-	-

Logistic regression was used to calculate the parameter estimates of the fitted model and their associated statistics (Table 13) for nine explanatory variables. The logistic regression model found that as the values for vMSI, sPSSD, slMPFD, vegaw, pfaw, and meanslope decreased, the probability of *A. barrii* occurrence increased. As sMSI, pfmin, and maxslope increased, the probability of *A. barrii* occurrence increased.

Table 13. Parameter estimates for the fitted logistic regression model.

Parameter	Estimate	Standard Error	Wald $\chi^2$	P
Intercept	-0.3645	3.0241	0.0145	0.9041
vMSI	-0.6445	0.4046	2.5368	0.1112
sPSSD	-3.5E-8	1.782E-8	3.8580	0.0495
sMSI	0.1783	0.0608	8.6039	0.0034
slMPFD	-4.6845	1.8607	6.3386	0.0118
Vegaw	-0.7292	0.4446	2.6897	0.1010
Pfaw	-0.0177	0.0109	2.6309	0.1048
Pfmin	0.1111	0.0318	12.2144	0.0005
Meanslope	-0.5416	0.1617	11.2164	0.0008
Maxslope	0.1593	0.0831	3.6682	0.0555

Using the leave-one-out cross-validation technique, the logistic regression model correctly classified 247 out of 326 observations, a 75.8% correct classification rate. The 79 observations that were incorrectly classified included 44 false negatives and 35 false positives. The classification accuracy is summarized in a confusion matrix (Table 14).

Table 14. Confusion matrix for the logistic regression model based on leave-one-out cross-validation.

	Actual Presence	Actual Absence	Actual Total
Predicted Presence	a = 63 58.88%	b = 35 15.98%	98 30.06%
Predicted Absence	c = 44 41.12%	d = 184 84.02%	228 69.94%
Predicted Total	107 100.00%	219 100.00%	N = 326 100.00%

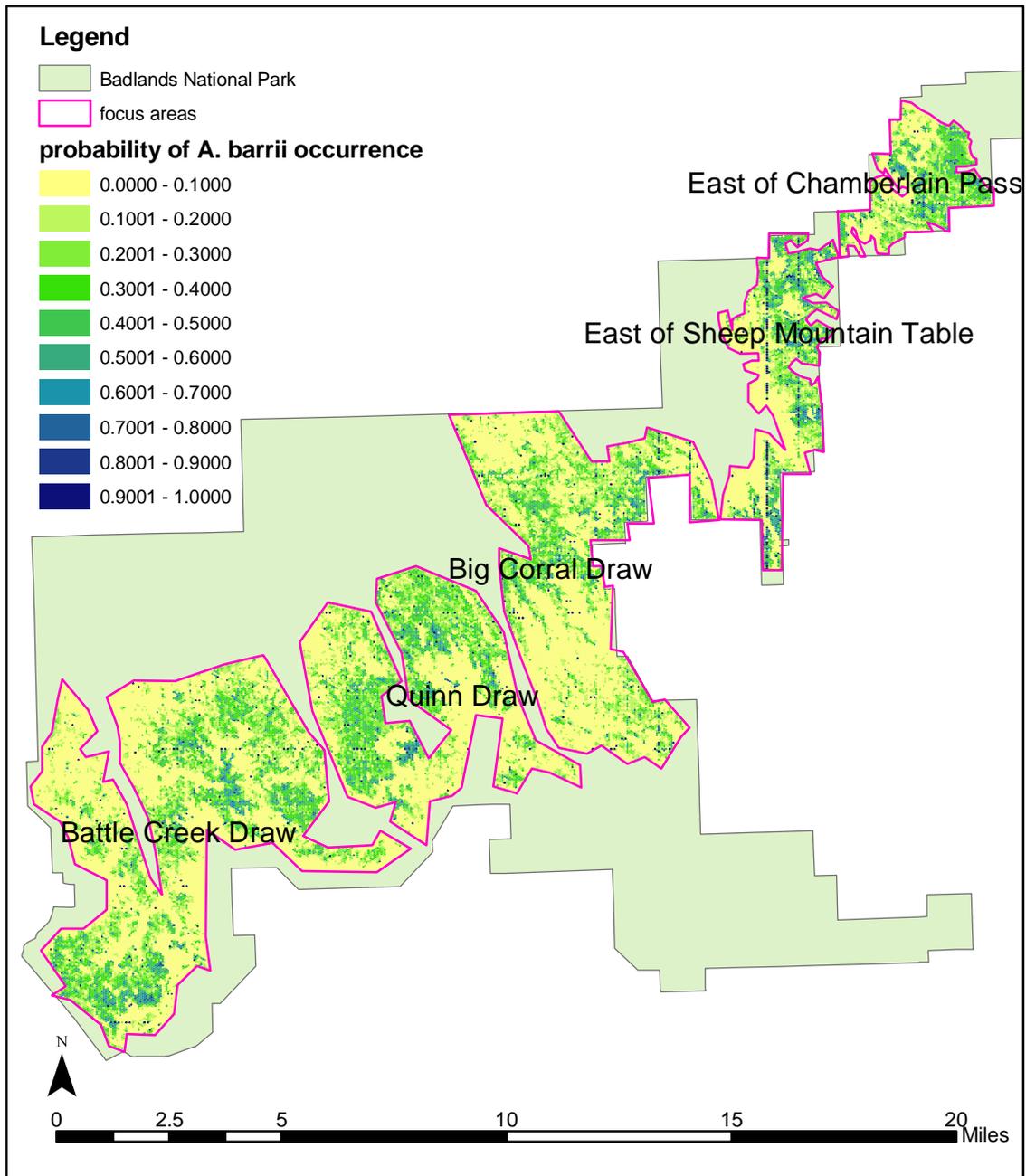
Using the values for a, b, c, d, and N listed in the confusion matrix shown in Table 15, classification accuracy measures for the patch-scale model were calculated. Of particular interest are prevalence, sensitivity, specificity, and kappa. Correct classification rate is dependent upon the prevalence, which was relatively low at 0.328 as expected for a rare species. Sensitivity was 0.589. Specificity was 0.840. Kappa was moderate at 0.438.

Table 15. Logistic regression classification accuracy measures based on the confusion matrix (Table 14).

Accuracy Measure	Calculation	Value
Prevalence	$(a + c) / N$	0.328
Overall Diagnostic Power	$(b + d) / N$	0.672
Correct Classification Rate	$(a + d) / N$	0.758
Sensitivity	$a / (a + c)$	0.589
Specificity	$d / (b + d)$	0.840
False positive rate	$b / (b + d)$	0.159
False negative rate	$c / (a + c)$	0.411
Positive predictive power	$a / (a + b)$	0.643
Negative predictive power	$d / (c + d)$	0.807
Misclassification rate	$(b + c) / N$	0.242
Odds ratio	$(ad) / (cb)$	7.527
Kappa	$[(a + d) - (((a + c)(a + b) + (b + d)(c + d)) / N)] / [N - (((a + c)(a + b) + (b + d)(c + d)) / N)]$	0.438

The parameter estimates for the nine explanatory variables (Table 13) were used to calculate probability values ranging from 0 to 1 for 44,490 hexagonal, 0.5 ha patches located in five areas targeted for future inventory (Figure 13). The habitat parameter values in these five focus areas were similar to those used to develop the logistic regression model.

Figure 13. Map of logistic regression probabilities of finding *A. barrii* in each 0.5 ha patch in 5 areas targeted for future inventory.



## D. Discussion

The deductive habitat similarity model found that 44% of the park is very similar to the habitat in which *A. barrii* is found, yet only a small portion of that habitat is actually occupied by *A. barrii*. This highlights a persistent issue of rare and endemic plants and a common short-coming of predictive habitat models (Boetsch et al. 2003, Wiser et al. 1998): the prevalence of presumably suitable, but currently unoccupied habitat. One explanation for this pattern is one of model accuracy. As this habitat similarity model is rather broadly defined based on coarse-scale habitat data such as vegetation alliances and soil series, there is a possibility that *A. barrii* shows some affinity for habitat characteristics that were not discernable from the geospatial data available either because of the habitat attributes mapped, the interpolation used to draw the original maps, or the scale of the data in relation to the variability of the habitat within the study area.

The issue of geospatial data resolution is highlighted by the use of 30-by-30 meter elevation data, which is generally considered to be reasonably high resolution and it is certainly one of the highest resolution data sets that is widely available in the United States. But the fine-scale topographic variations found in the badlands make this 30 x 30 meter mapping unit too coarse to fully capture the unique habitat features of *A. barrii*. This is particularly true when you consider that *A. barrii* often occupies narrow flat areas immediately adjacent to steep buttes such that the small scale flatness and small scale steepness get averaged into some intermediate value based on a 30 x 30 meter pixel. In

fact, this averaging of slope helps explain the 4% of *A. barrii* populations that were found in a habitat similarity score of 0.375. These small populations are located along the narrow margin of Sheep Mountain Table in the Rocky Ford Ash geologic formation. As these populations occupy very small ledges less than 10 meters wide, the geospatial data used in this model is too coarse in scale to adequately describe the flatness of the micro-sites in which these populations occur.

While the habitat similarity map has some application for park-wide resource management decisions, such as identifying if *A. barrii* is a potential issue in a given project area, it also highlights the need for a predictive model with more accuracy. Discriminant analysis and logistic regression were both attempts to develop a model with more precision, and, in the case of logistic regression, to capture spatial relationships characterized by landscape metrics.

Used in the logistic regression model, mean shape index is a measure of shape complexity where the more complex the shape, the higher the mean shape index value; when all patches are the same shape it equals one. The negative parameter estimate for vegetation mean shape index indicates that *A. barrii* presence is associated with vegetation shapes that are relatively simple. This is likely an artifact of the 0.5 ha minimum mapping unit used in the vegetation dataset as well as the broad classification of the “badlands sparse” vegetation type which includes most of the areas occupied by *A. barrii* as well as a total of 44.9% of the park, thus giving rise to simple vegetation

patterns in areas dominated by the “badlands sparse” vegetation type. Conversely, the positive parameter estimate for soil mean shape index indicates that *A. barrii* presence is associated with soil shapes that are relatively complex. This is consistent with field observations that *A. barrii* often occurs along the edges of unincised drainage channels and along the base of badland buttes, both areas that tend to have complex soil shapes due to the rapid deposition and erosion that characterizes these environments.

Area weighted vegetation shading value is a measure of the average amount of shading within the patch where a low area-weighted vegetation shading value represents less shading and a high value represents more shading. The negative parameter estimate for area-weighted vegetation shading indicates that *A. barrii* presence is associated with open sites with little shade. This relationship is consistent with field observations and other studies that find *A. barrii* growing in sparsely vegetated or barren environments (Schassberger 1990, Schmoller 1993). Similarly, area-weighted percent fines is a measure of the average percent fine soil particle fraction in the patch and minimum percent fine is a measure of the minimum percent fine soil particle fraction in the patch. Low values of percent fines indicate soils high in sands, moderate values indicate soils high in silts, and high values indicate soils high in clay. Considering a continuous scale of percent fines ranging from 0 to 100%, the positive parameter estimate for minimum percent fines defines a lower bound and the negative parameter estimate for area-weighted percent fines defines an upper bound, such that presence of *A. barrii* is associated with values in a moderate range between these two bounds. This is consistent

with field observations that *A. barrii* tends to grow in soil texture classes high in silts, including silty clay, silty clay loam, silt loam, and clay loam.

Slope mean patch fractal dimension is a measure of shape complexity where values approach one for shapes with simple perimeters and approach two when shapes are more complex. The decreasing value of slope mean patch fractal dimension indicates that *A. barrii* is associated with slope shapes that are relatively simple. Mean percent slope and maximum percent slope are direct measures of percent slope within the 0.5 ha patch. The negative parameter estimate for mean percent slope indicates that *A. barrii* is associated with relatively flat slopes, while the positive parameter estimate for maximum percent slope indicates that *A. barrii* is associated with steep slopes. Since both values represent conditions within a 0.5 hectare patch, both may be true. Both values are in fact consistent with field observations that *A. barrii* grows in the zone of active deposition along the base of badlands buttes, where the flatness of the deposition zone is juxtaposed with the steepness of the butte.

Consistent with other studies of rare plant habitats (Wu and Smeins 2000, Wisser et al. 1998, Boetsch et al. 2003), soil and slope characteristics were found to be significant habitat variables in both the discriminant analysis model and the logistic regression model. Both models found area weighted percent fine soil fraction to be a significant variable. However, the two models differ for the other variables. The logistic regression model selected minimum percent fine soil fraction while the discriminant analysis model

selected the maximum percent fine soil fraction. Additionally, the logistic regression model selected maximum percent slope while the discriminant analysis model selected the minimum percent slope. The grain and extent of these two analyses were different: the logistic regression model used only a small dataset from a standardized 0.5 ha patch-scale while the discriminant analysis used all known presence and absence locations from variable sized search polygons. Variable sized observation units could introduce bias into the analysis by confusing relationships that are occurring at different scales. It is possible that differences in the habitat variables selected by the two models are due to the differences in biological scale, differences in the range of habitat values captured in the extent used in each model, or the statistical processes used to derive the models. Conversely, it could be an ecological reality that the limiting habitat variables change with the scale of consideration, as has been observed in other plants that occupy dynamic habitats (Gurevitch et al. 2002).

Finally, all three models share a common trait: the prediction of occurrence in areas that are currently unoccupied, expressed as commission or false positive error in the two quantitative models. Aside from the issues of variable specificity and model accuracy already discussed, another explanation is the failure of these models to account for ecological processes, namely evolutionary history and meta-population dynamics of local extinction and colonization (Hanski and Gilpin 1997). Prediction of the suitability of a habitat to support a species may be correct, but the limiting factor of dispersal or recent extinction prevents the predicted population from being actually observed (Huston 2002).

This is a reasonable explanation for the absence of *A. barrii* above the “Badlands Wall,” where this barren, steep scarp serves as an effective barrier to the dispersal of seeds by gravity (Barneby 1964). Such phenomena as local extinction and colonization, particularly given the rapid rates of erosion and deposition that characterize the White River Badlands, could likewise account for presence/absence of this species at higher resolution where one badlands embayment is occupied but the adjacent embayment (sharing the same parent material, soils, slope, aspect, and vegetation) is unoccupied.

## **V. PHYSICAL HABITAT CHARACTERIZATION**

### **A. Objective**

The second objective of this study of *A. barrii* in Badlands National Park was to characterize the physical habitat (geology, soils, and topography) associated with *A. barrii* to aid in future field inventory efforts.

### **B. Methods**

During the course of the field inventory effort, four different physical settings where *A. barrii* was found in Badlands National Park were selected for detailed study of the physical habitat characteristics:

- Site one was located north of Highway 44 at Chamberlain Pass in older Quaternary alluvium derived from the Chadron and Brule formations characterized by rolling clay hills and basins interspersed with steep Brule outcrops and relatively sparse chalcedony cobble.
- Site two was located north of Sheep Mountain Table Road in older Quaternary alluvium derived from the Chadron and Brule formations characterized by

chalcedony covered hills dissected by silty washes and interrupted by steep Brule outcrops.

- Site 3 was located northwest of Cottonwood Pass in the Chadron formation, probably Ahearn or Crazy Johnson member. The site was located on a sandstone bench where the bench dips back into the slope above forming a sediment catchment with sandstone gravels and coarse sands. The slope above the bench includes several limestone lenses as well as mica and Red River outwash.
- Site 4 was located on the eastern edge of Sheep Mountain Table along a ledge of Rocky Ford Ash, approximately eight meters below the sod covered Quaternary surface of the table. Below the Rocky Ford Ash ledge is a sheer Brule face in the center part of the section.

At each of the four physical habitat sites selected for detailed investigation, soil pits were dug using a 3-inch diameter bucket auger and soil characteristics were described using a Truogg Field pH Kit and the Munsell Color Chart. Calcareous soils were determined by exposure to a weak HCl solution and were recorded as degree of effervescence.

Spatial analysis was also used to characterize the physical habitat where *A. barrii* was found. ESRI ArcGIS 8.3 with Spatial Analyst extension was used to identify the intersections of 109 mapped *A. barrii* populations with the native mapping units and map

polygons in the original map resolution for soils and aspect as derived from the digital elevation model described in Table 1.

The digital soils data were intersected with the geospatial data of *A. barrii* absence and presence. This intersection yielded 220 distinct soil polygons with confirmed absence and 131 distinct soil polygons with confirmed presence. These 351 polygons were then analyzed using the chi-square test for independence to compare the observed frequency with the expected frequency to determine if the relationship between soil texture and *A. barrii* presence or absence was significant. To decrease the number of cells in which the expected value was less than 5, some adjacent soil classes were combined (clay and clay loam, and fine sand and sandy loam).

The digital elevation model was used to create an aspect coverage with 8 bearings in 45° increments (N = 337-22°, NE = 22-67°, E = 67-112°...). The aspect data was intersected with the geospatial data of *A. barrii* absence and presence. This intersection yielded 7083 distinct aspect polygons of confirmed absence and 521 distinct aspect polygons of confirmed presence. These 7604 polygons were then analyzed using the circular statistics of mean bearing and degree of dispersion to determine if there was a difference between the vectors for presence and the vectors for absence.

Field notes were used to describe other surface features and geology relationships observed during this study.

## **B. Results**

Soil pits were dug in four locations in areas around where the plants occurred and profiles were described (Table 16). If seemingly identical, but currently unoccupied habitat was located nearby, soil pits were also dug in those areas to determine if there was an obvious difference in soil characteristics between the occupied and unoccupied sites. These paired pits were dug in 6 locations and no notable differences were found between the sites with *A. barrii* and those sites without *A. barrii*.

In general, the soils described during these site investigations are common in arid and semi-arid landscapes, such as the White River Badlands. Soils were slightly to strongly alkali with a pH ranging from 7.5 to 8.5. All pits revealed some amount of effervescence, either of masses or matrix or both, indicating calcareous soils. Most profiles revealed poor soil development and only the Rocky Ford Ash site, site #4, had a developed A horizon. All profiles were relatively shallow ranging from 2 cm to 39 cm before encountering a lithic or paralithic contact. Most soils were silty clay or silty clay loam with one occurrence of silt loam in a sparse grassy basin and one occurrence of sandy clay located directly below a sandstone bench.

Table 16. Soil profiles found during site investigations

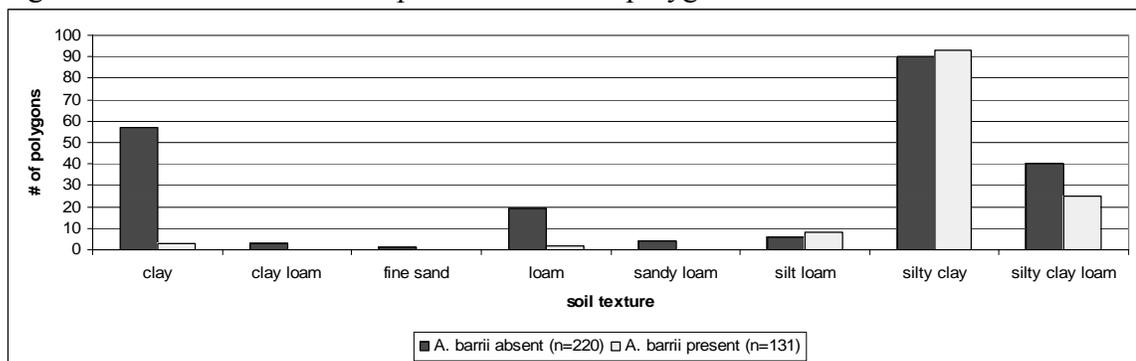
Site	Pit	Setting	Depth (cm)	Description
1	1	Sparsely vegetated, basins	0 – 7.5	4mm limestone gravel on surface, silty clay texture with about 60% clay, some structure, moderate weathering, 8.0 pH, 5YR32 color, weakly effervescent matrix
			7.5 – 39	massive with no structure, heavier in clay content than the soil above, weakly effervescent matrix
			39	dense shale layer, weakly effervescent, 7.5-8.0 pH
	2	Sparse grassy basin	0 – 2.5	Granular silt loam, lots of roots, violently effervescent
			2.5 – 8.5	Some sign of soil structure, common fine and medium roots, 15% white soft CaCO <sub>3</sub> masses up to 1 cm diameter
			8.5 – 24.5	Weakly effervescent matrix, <5% soft CaCO <sub>3</sub> masses up to 1 cm diameter
	3	Silty overwash	0 – 6	Silty clay loam, not effervescent, 8.0-8.5 pH
			6 – 13	Some rock structure, silty clay texture, 8.0 pH
			13+	Platey structure, decomposed shale, 8.0 pH
			throughout	No coarse fragments and no limey masses
2	1	slope w/ 80% chalcedony	0 – 6	Silty clay texture with fine shaley structure, violently effervescent, 8.5+ pH, possibly sodium
			6 – 30	Moderately effervescent, fine and medium shale fragments, 8.0 pH
			30+	Moderately effervescent, coarse shale, 8.0 pH
	2	Flat silty wash	0 – 8	Silty clay loam texture, massive structure, 8.2 pH
			8-18	Silty clay texture with 50% clay, platey structure, 8.0+ pH
			18+	Dense layer, silty clay texture, 60% clay, 8.0 pH
	3	Toe slope of sod table w/ 10% chalcedony	0 – 3	Silty clay loam texture, granular structure, violently effervescent
			3 – 22	Silty clay loam texture, effervescent
			22+	Dense layer, silty clay texture, effervescent
3	1	Sandstone bench, flat	0 – 2	Surface litter of 2 cm sandstone and limestone gravel
			2+	Silty clay texture, platey and massive structure, effervescent
	2	Below sandstone bench, flat	0 – 2	80% coverage of 2 cm sandstone and limestone gravel
			2+	Sandy clay texture, no roots, violently effervescent
4	1	Finger of Rocky Ford Ash, flat	0 – 10	Developed A horizon with many fine roots, weakly calcareous matrix, clay texture, granular, weak sub-angular or blocky structure, 10YR52 grayish brown color, 8.0 pH
			10 – 33	C <sub>1</sub> horizon, few coarse roots, silty clay texture that includes volcanic glass, moderately coarse platey structure with roots on plate surfaces, not effervescent, 8.0 pH
			33+	C <sub>2</sub> horizon, shale with coarse platey structure, not effervescent, 7.5 pH
	2	Near juniper trees along edge of table and above Rocky Ford Ash ledge	0 – 7	Developed A horizon, silty clay loam with 50% shale fragments, shale fragments are medium to fine platey with roots along surfaces, common fine and medium roots, 8.0 pH, matrix is effervescent, shale is not effervescent
			7 – 13	C <sub>1</sub> horizon, 80% shale fragments with 20% fine earth fragments from Quaternary surface above, few roots along shale faces
			13+	C <sub>2</sub> horizon, dark colored shale, 7.0 pH

Geospatial analysis indicates that *A. barrii* was found most frequently in silty soils as shown by its occurrence in silty clay, silty clay loam, and silt loam soil textures (Table 17; Figure 14). *A. barrii* was absent from sandy soil textures and virtually absent from clayey soil textures. *A. barrii* presence/absence was significantly related to soil texture ( $X^2 = 55.08$ ;  $p < 0.0001$ ;  $n = 6$ ;  $df = 5$ ).

Table 17. Number of *A. barrii* present and absent polygons in each soil texture class used in chi-square test for independence.

Soil Texture	Observed Absent	Observed Present	Ob. Row Total	Expected Absent	Expected Present	Ex. Row Total
clay + clay loam	60	3	63	39.49	23.51	63
fine sand + sandy loam	5	0	5	3.13	1.87	5
loam	19	2	21	13.16	7.84	21
silt loam	6	8	14	8.77	5.23	14
silty clay	90	93	183	114.70	68.30	183
silty clay loam	40	25	65	40.74	24.26	65
<b>Column Total</b>	<b>220</b>	<b>131</b>	<b>351</b>	<b>220</b>	<b>131</b>	<b>351</b>

Figure 14. Number of *A. barrii* presence/absence polygons in each soil texture class.



Geospatial analysis found that while plants were found most frequently on north aspects (Figure 15), the relationship to aspect did not appear to differ between presence and absence as indicated by the similar vector lengths and degree of dispersion (Table 18).

Schassberger (1990) also reported that populations occurred on all aspects, but went on to observe that, where overstory was lacking, populations appeared to be established more often on northern aspects. While all of the *A. barrii* populations found in our study area were lacking an overstory, we did not find a significant affinity for north-facing slopes.

Figure 15. Percent of presence cases found on each aspect.

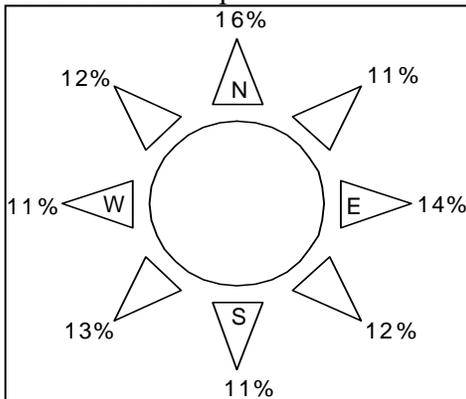


Table 18: Mean bearing and degree of dispersion for presence/absence cases based on aspect.

Measure	Presence	absence
x-y tip of mean vector	x: 0.1009 y: 0.2108	x: 0.0756 y: 0.2052
mean vector	x: 0.1010 y: 1.3584	x: 0.0757 y: 1.3641
vector length	1.3621	1.3662
dispersion	-0.3622	-0.3662
variance	-0.7244	-0.7324

Digital geology coverage for the study area is incomplete, so it was not used in geospatial analysis. Field notes indicate that most of the populations were found near the contact of the Chadron and Brule formations. The most abundant populations - those with the largest perimeter and/or plant density - were found in older Quaternary alluvium sitting on top of the Chadron formation and composed of reworked material from both the Brule and Chadron formations. Most populations were found in areas covered with chalcedony cobble and to a lesser extent coarse limestone gravel. The presence of chalcedony was so frequently associated with the presence of *A. barrii* that it became a good field marker for locating these small plants in a vast landscape.

Those populations where plants were not found in association with chalcedony or limestone were generally found in short linear distributions along the low energy deposition zone of unincised drainages where steep Brule buttes intersect relatively flat Quaternary surfaces. The plants followed along the drainage for 5 – 50 meters until either the channel began to incise or the drainage fed into a basin that was stable enough for grasses to become abundant. Once the drainage became incised or dispersed into grasslands, the *A. barrii* plants were no longer present. Where multiple unincised channels arose from the base of the butte in an embayment and converged in a shallow basin of active deposition, the populations formed a glove-shaped distribution where the basin (the “palm”) was populated with plants and the fingers of the population extended up drainages until the gradient became too steep or intersected the grass covered tops of sod tables. In some cases, the unincised drainages were interspersed with narrow interfluves covered with chalcedony that also supported widely spaced and somewhat less vigorous *A. barrii* plants. The plants occurring on interfluves were generally small and there were numerous dead plants and plants with large areas of crown dieback found in these areas.

Only three populations were found in a geologic formation other than Brule, Chadron, or Quaternary alluvium derived from those formations. All three populations were found close together in a narrow ledge of Rocky Ford Ash along the margin of Sheep Mountain Table. These populations were unusual within the study area for both the geologic

formation they were growing in as well as their growth in sites that were not covered with chalcedony cobble or limestone gravel and were not associated with unincised drainages.

Plants were found on a wide range of slopes ranging from flat to almost vertical. In some cases, populations exhibited a down slope population migration with large, dead plants found on the upper slope and a range of size classes represented by live plants on the slope below. All sites occupied by *A. barrii* were run-in sites, that is, areas of deposition of alluvium and colluvium.

All plants were found below the Badlands Wall in either the White River watershed or the Cheyenne River watershed. Although there was a great deal of habitat that appeared to be highly suitable in the Sage Creek basin above the Badlands Wall, and while several weeks were spent searching this area, no plants were found in the Cheyenne River watershed north of the Badlands Wall. The Badlands Wall is a prominent scarp that creates a watershed divide that is very steep, narrow, and completely unvegetated. The only plants found in the Cheyenne River drainage were located below the Wall along a gradual divide known as Cottonwood Pass between the Cheyenne River watershed and the White River watershed. This watershed divide is indistinct and so gradual it is easily traversed by vehicle or foot. There is no interruption of vegetation patterns, including *A. barrii*, along the Cottonwood Pass watershed. There were no populations found in the Bad River watershed located north of the Badlands Wall in the northeast portion of the study area.

## D. Discussion

Geologically, the most notable relationship was found in the occurrence of *A. barrii* where chalcedony cobble was present on the surface. During the intermittent soaking rains of spring the chalcedony cobbles adhere to the soil surface which serves to reduce evaporation and hold in soil moisture. The areas where chalcedony coverage is almost continuous are the last to dry out after rain, sometimes holding moisture up to a week after a saturating precipitation event (Gries 1996). The chalcedony also serves to reduce surface erosion as well as prevent the establishment of sod or an abundance of other vegetation. Limestone gravels also serve to reduce surface erosion and reduce competition but the spaces between gravel particles make it less effective in these functions compared to the interlocking plates of chalcedony beds. These characteristics -- increased soil moisture, reduced surface erosion, and reduced competition -- may all be important to the establishment and perpetuation of *A. barrii*.

The presence of chalcedony cobble or limestone gravel may also aid in seed scarification. The silty soils of the area generally have low erosive capacity, yet greenhouse germination studies indicate that physical seed scarification is required for germination of *A. barrii* (Locklear 1987), a common trait of the *Astragalus* genus (Baskin and Baskin 1998). Furthermore, the seed coat of *A. barrii* is very tough requiring numerous deep scratches for successful scarification. As part of this study, germination trials with seed collected in June, July, and August demonstrated that the most viable seed was collected

in early July. One reasonable hypothesis is that the ripe seed is shed in July, falling on the soil surface. The relatively high clay content of the soil creates shrink/swell conditions during the frequent afternoon thunderstorms that characterize the Badlands in late summer. This shrink/swell movement may provide friction within the soil column, moving the seeds against the abrasive edges of chalcedony cobble or limestone gravel, thus scarifying the seed. The scarified seed is then able to absorb moisture over winter and germinate near the soil surface in early spring. Additional study is needed to test this hypothesis.

Seed scarification requirements may also explain the presence of the plants along the low energy zone of unincised drainages. These seeds may have tumbled for relatively long distances, encountering various resistant surfaces and suspended solids that scarified the seed coat. This seed is then deposited in the fine silts along the margin of the drainage. The relatively narrow, linear distribution along the edges of the drainage, and its absence from the center of the drainage or where the drainage is incised, might be explained by fluvial processes. The high energy associated with a gradient steep enough to incise or within the center area of an unincised drainage may bury the seed too deeply, but the thin silts deposited along the edges provide an adequate depth for germination. Additional study is needed to test this hypothesis.

The association of *A. barrii* with the Chadron-Brule contact may be an expression of soil texture and slope associated with these formations. This contact is characterized by the

steep slopes of Brule formation terminating in the relatively flat or rounded Chadron formation creating a zone of active deposition that is sparsely unvegetated. The alluvium deposited at the base of the Brule contributes large quantities of silt and sometimes limestone gravel to the soil. The erosion of the Chadron contributes clay to the soil and serves to weather out the chalcedony veins. The result is an area of Quaternary alluvium characterized by silty soil textures with an abundance of platy chalcedony cobble or gravel and sometimes limestone gravel, a condition that seems to support abundant *A. barrii* populations. In this habitat, the plants appear to occupy the entirety of the hospitable terrain and the population margins are defined by the occurrence of inhospitable terrain, such as 1) areas of aggradation that are stable enough to support other plants, 2) the near vertical walls of the Brule formation or vertical edge cuts of Quaternary sod tables, or 3) areas of erosion where enough flow is collected and the gradient is sufficient to cause incision of the drainages.

The association with silty clays in the White River Badlands was highly significant and may be the most important soil characteristic for the presence of *A. barrii*. Sandy soils, with more than 50% sand particles, have a coarse texture. They drain rapidly after a rain and they hold water and minerals poorly. The absence of *A. barrii* in sandy soil textures may be a result of insufficient soil moisture for establishment of new seedlings (Gurevitch et al. 2002). Clayey soils contain more than 40% clay and can hold a large volume of water and they retain water and minerals exceptionally well. However, due to their low permeability, they are very slow to warm in spring (Gurevitch et al. 2002). The

absence of *A. barrii* in very clayey soils may be a result of this thermal property. *A. barrii* breaks winter dormancy in late March or early April and is presumed to germinate in early spring as well. The cold conditions associated with clayey soils may create a sub-optimal condition for early spring germination and growth. Silty soils are intermediate between clayey and sandy soil textures. A possible explanation for *A. barrii* affinity for silty clay soils may be that these soils have sufficient water retention for establishment of new plants and sufficient permeability to warm up in the early spring.

The association of *A. barrii* with silty-clay soil textures in the White River Badlands is somewhat different from the edaphic factors described for the populations in the Powder River Basin of southeastern Montana where *A. barrii* was associated with heavy clay soils from soft shale parent material (Schassberger 1990). The association of *A. barrii* with silty clay soil textures in our study area might be a reflection of the prevalence of silty soil textures found in the White River Badlands where 67,394 ha or 68% of the study area is classified as silty clay, silty clay loam, or silt loam.

## **VI. LIFE HISTORY AND DEMOGRAPHY**

### **A. Objective**

The third and final objective of this study of *A. barrii* in Badlands National Park was to characterize the life history of *A. barrii* to better understand the major life history features of this species.

### **B. Methods**

#### **1) Status of Populations**

Within six *A. barrii* populations (the population used for demographic plots and five populations found in the 2003 field inventory effort) belt transects were used to quantitatively estimate density, plant size, and flowering status. More than one transect was used in large populations. Belt transects followed the methodology of Elzinga et al. (1998). From a haphazard starting point along the population perimeter, a metric tape was laid from perimeter to perimeter of the population across the slope gradient to define the edge of a two meter wide, rectangular quadrat of variable length. All plants within the quadrat were counted and categorized as flowering if any visible form of a flower (e.g. bud or senescent) was observed. Quadrat edge effects were dealt with by counting as in any plants along quadrat edges only on the side marked by the tape and the terminal two

meter end of the quadrat. Within each transect, the diameters of all plants in the quadrat that were within one meter of the tape were measured and the flowering status of each individual plant was recorded. A total of 22 transects were used, including 817 plants counted for density, and a subset of 601 plants measured for diameter and individual flowering status.

The data were analyzed using descriptive statistics, tables, and graphs in Microsoft Excel 2003. Systat 10.2, distributed by Systat Software, Inc., was used to calculate analysis of variance (ANOVA).

Plant densities in belt transects were estimated using the following formula: [ # plants / (transect length \* transect width)]. Within these transects, plant diameter was used to calculate surface area using the formula for the area of a circle: [ $\pi * (\text{diameter}/2)^2$ ]. The results of using a single diameter and the circle formula were found to differ by less than 1% from the results obtained in the demography plots by taking two orthogonal measurements and using the formula for an ellipsoid. For expediency in field data collection during the short flowering season, the single diameter measurement was used for estimating surface area of plants found in transects.

The plant size data showed a right-skewed distribution that was normalized using a natural log transformation. A single-factor ANOVA was used to perform a simple analysis of variance on data to determine if plant size varied by population, with an F-

statistic critical value at the significance level of 0.05 ( $\alpha = 0.05$ ). Mean values reported for this data set are the back-transformed values, thus representing the geometric mean of the skewed distribution.

The proportion of plants in flower in populations was adjusted based on the date that the population was surveyed because percent flowering varies over the flowering season with fewer plants in flower early in the season. The percent flowering observed weekly in the demography plots was plotted as a curve for percent flowering from day 1 (4/28/2003) to day 50 (6/16/2003) (Figure 20). This curve was then used to interpolate percent flowering on any day from day 1 to day 50. Only 92% of the plants in the demography plots flowered during the entire flowering season, so the percent flowering observed in the plots was then adjusted for a base value of 0.92. The other populations in the study were only surveyed once during the growing season and the observed proportion flowering was adjusted with the following formula: [observed % flowering in popn / (survey day % flowering in demo plots / 0.92)].

For all 101 populations mapped during this study, population sizes were visually estimated following the methodology of Elzinga et al. (1998) where the number of plants in each population was estimated in one of the following classes: 1-3, 4-10, 11-30, 31-60, 61-100, 101-200, 201-500, 501-1000, 1001-5000, 5001-10000. Because the plants are widely spaced, spatial delineation of populations was problematic. As a primary purpose for mapping these populations was to determine spatial relationships to habitat, the

geographical delineation of populations was based on the spatial extent of continuous versus discontinuous distributions of plants. If plants became separated by topographic features such as buttes or intermittent drainage channels that would likely act as barriers to local dispersal, the discontinuous groupings were mapped as separate populations. To some extent the distinction used to define populations was artificial as it is possible that groups of plants in close proximity to each other but separated by some physical barrier to local dispersal would share the same pollinators, and thus be genetically related.

## **2) Life History**

Demographic data were collected from one *A. barrii* population. On April 29, 2003, six 1-m<sup>2</sup> plots were haphazardly placed in areas with plants over a range of site characteristics within this population. Plots were marked with a center pin, the GPS coordinate of the center point was recorded, and each plot was digitally photographed. All living plants within each plot were mapped, assigned to a plot quadrant, and assigned a number.

At the time of installation, the six demography plots included a total of 75 individual live plants. Flowering status of these plants were recorded in 2003 on April 29; May 7, 18, 25, 29; and June 5, 10, 16. Size measurements were recorded on April 29 and June 16.

The plots were revisited on May 15, 2004 during the flowering season. Each plot was again digitally photographed and plotted. Mortality, flowering status, and crown diameter of each plant in the plot was recorded and any new plants were identified and mapped.

The data were analyzed using descriptive statistics, tables, and graphs in Microsoft Excel 2003. Systat 10.2, distributed by Systat Software, Inc., was used to calculate Kruskal-Wallis statistics.

As plant crowns are generally round to ellipsoidal in shape, growth of individual plants in the demography plots was quantified by measuring the plant crown across the widest section, then orthogonally to the widest section. These two diameter measurements were used to calculate surface areas based on the formula for the area of an ellipsoid:

$[(\text{maximum diameter}/2) * (\text{minimum diameter}/2) * \pi]$ . Intra-annual growth was obtained by subtracting the size of plants on April 29, 2003 from the size on June 16, 2003. No additional growth occurred after June 16, 2003 because the plants were dormant for the rest of the year. Inter-annual growth was obtained by subtracting the sizes on June 16, 2003 from the sizes on May 15, 2004. Negative growth values reflect partial die backs that occur during the growing season where a portion of the plant appeared as a blackened crown with no green leaves.

Plants were grouped into four size classes: 0-5 cm<sup>2</sup>, 6-20 cm<sup>2</sup>, 21-100 cm<sup>2</sup>, and > 100 cm<sup>2</sup> based on the initial size measurement taken in April 2003. These size classes were used

to capture the range of plant sizes observed in a manageable number of classes that provide roughly equal sample sizes convenient for analysis.

As both the class size and percent growth variables possess non-normal distributions, the Kruskal-Wallis statistic, a non-parametric equivalent of the one-way ANOVA that is based on ranks, was calculated to determine whether growth varied with size class. Chi-square tests were conducted to determine whether the number of plants flowering varied by size class, whether mortality varied by size class, and whether the number of plants exhibiting die-back varied by size class.

### **3) Seed Germination**

Seed pods were opportunistically collected from *A. barrii* populations at various times of the growing season during 2002 and 2003. Seed pods that were collected were either still attached to or trapped within the leaves of the mother plant. The location of each mother plant was recorded using a Trimble Pathfinder 3 GPS unit in 2002 and a Trimble Pathfinder XP GPS unit in 2003. Each mother plant was defined on the basis of a geographically distinct crown and the seeds from each mother plant were kept separate. Seeds collected in 2002 and 2003 were then used in greenhouse germination trials to evaluate seed viability.

In 2002, 61 seed pods were collected on July 9 and August 6 from a total of eleven mother plants in one population. In 2003, seed pods were collected from a total of 61 mother plants in 8 populations: 2 populations each were collected on June 10, June 11, July 3, and July 11.

Seeds were separated from the dehiscent pod, inspected under a dissecting scope, scarified with sandpaper, inspected again under the dissecting scope to confirm scarification, and planted in either standard Petri dishes or greenhouse containers. Of the 61 seeds collected in 2002, 23 were observed to be severely misshapen, shrunken or shriveled and are assumed to be the aborted seed reported by Barneby (1964). The seeds collected in 2003 on June 10 and June 11 were found to be very immature as noted by the green, soft seed coat. The green seeds could not easily be separated from the pods and were too soft to be scarified, thus they were unusable. The seed collected in July was usable, and in contrast to 2002, only 5 seeds out of 300 were found to be severely misshapen, shrunken, or shriveled.

In 2002, a total of 46 seeds were planted in containers in two different trials (Trial 1: 34 seeds; Trial 3: 12 seeds). The scarified seed were planted 0.5 cm deep in standard germination potting mix, placed on racks on an automatic mister table in a temperature controlled greenhouse, and periodically treated with Pentac miticide (3 mL/gal) as required by greenhouse conditions. In three different trials, a total of 15 seeds were also planted in agar test tubes and Petri dishes so that emergence of the radicle could be

observed (Trial 2: 3 seeds in Petri dish; Trial 4: 4 seeds in Petri dish; Trial 5: 8 seeds in agar test tubes). For seeds planted in agar, the scarified seed was pressed into the agar then the container was closed, sealed, and placed in natural light at room temperature.

In trial 6, the 300 seeds were scarified, planted in germination potting mix in containers on an automatic mister table in a temperature controlled greenhouse, and a box fan on low fan speed was directed to blow across the surface of the containers 24 hours a day. Miticide as was not used during this trial as it was not warranted by greenhouse conditions.

The greenhouse data were analyzed using descriptive statistics, tables, and graphs in Microsoft Excel 2003.

## C. Results

### 1) Status of Populations

The mean plant density per population ranged from 0.23 to 1.00 plants/m<sup>2</sup>, with a mean of 0.53 plants/m<sup>2</sup> (SD = 0.27 plants/m<sup>2</sup>; Figure 16). The geometric mean plant size across all populations was 35.38 cm<sup>2</sup> (SD = 14.76 plants/m<sup>2</sup>), with the mean plant size per population ranging from 13.7 cm<sup>2</sup> to 50.9 cm<sup>2</sup> (Figure 17). Plant sizes varied significantly among populations ( $F = 19.79$ ;  $n = 6$ ;  $P < 0.0001$ ).

Figure 16. Mean plant density in six populations of *A. barrii* (error bars are +1 SE).

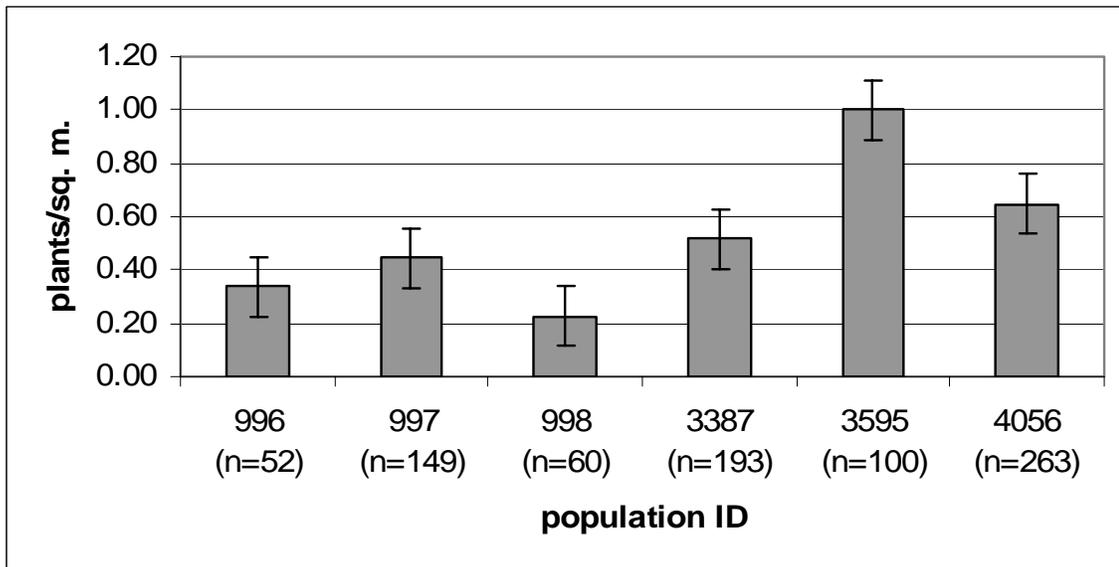
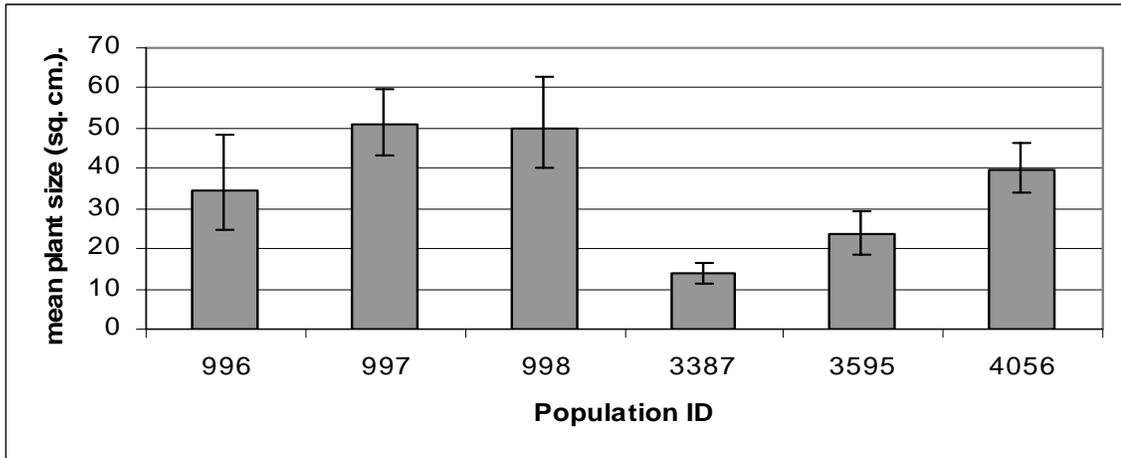
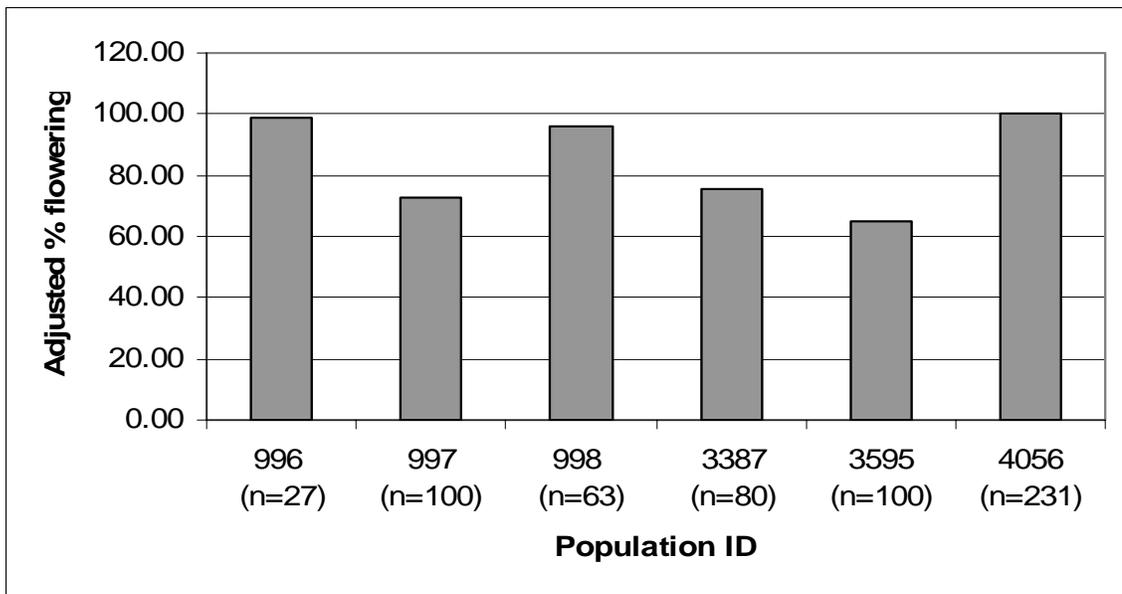


Figure 17. Mean plant size in six populations of *A. barrii* (error bars are 95% confidence intervals)



Mean percent flowering, adjusted based on sampling date, across all 6 populations was 84.8% (SD=15.4%), ranging from 65.0% to 100.0% (Figure 18). Percent flowering varied significantly among populations ( $\chi^2 = 106.3$ ;  $n = 6$ ;  $P < 0.0001$ ).

Figure 18. Mean percent flowering in six populations of *A. barrii*



Population sizes varied widely, ranging from two plants to up to 5001-10,000 plants (Table 19). There are an estimated 53,000 *A. barrii* plants in Badlands National Park.

Estimated # of plants	Number of populations
1-3	2
4-10	14
11-30	25
31-60	12
61-100	9
101-200	10
201-500	10
501-1000	11
1001-5000	5
5001-10000	3

Table 19. Estimated number of plants in each population (n=101)

## 2) Life History

### a. Growth

The mean growth per plant from April 29 to June 16, 2003 was  $-0.3 \text{ cm}^2$  (SD =  $22.0 \text{ cm}^2$ ), ranging from  $-91.1 \text{ cm}^2$  to  $94.3 \text{ cm}^2$ . Negative growth is discussed under mortality and die-back. Using only the 54 non-negative observations, the mean intra-annual growth per plant was  $7.2 \text{ cm}^2$  (SD =  $27.9 \text{ cm}^2$ ). The mean growth per plant from June 16, 2003 to May 15, 2004 was  $13.4 \text{ cm}^2$  (SD =  $23.2 \text{ cm}^2$ ), ranging from  $-26.7 \text{ cm}^2$  to  $90.3 \text{ cm}^2$ . Using only the 52 non-negative observations, the mean inter-annual growth per plant was  $18.1 \text{ cm}^2$  (SD =  $22.6 \text{ cm}^2$ ). Nineteen plants showed negative intra-annual growth and eleven

plants showed negative inter-annual growth as a result of partial die-offs in which some portion of the crown died but the plant was still alive.

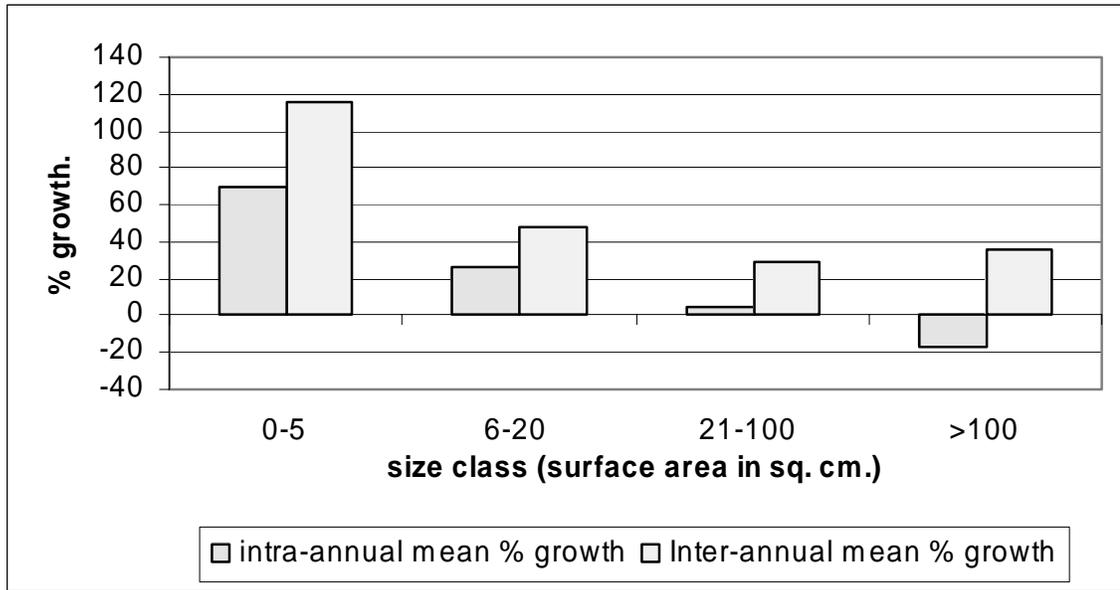
All size classes contained individuals with positive intra-annual and inter-annual maximum growth and negative intra-annual and inter-annual minimum growth. The inter-annual and intra-annual maximum growth was the greatest in plants with a surface area > 100 cm<sup>2</sup> (Table 20).

Table 20. Intra-annual and inter-annual plant growth for different size classes (n=75)

Sizeclass (cm <sup>2</sup> )	Intra-annual n	Mean intra-annual growth (cm <sup>2</sup> )	Range of intra-annual growth (cm <sup>2</sup> )	Inter-annual n	Mean inter-annual growth (cm <sup>2</sup> )	Range inter-annual growth (cm <sup>2</sup> )
<b>0-5</b>	18	2.8 (SD=2.5)	-0.8 to 13.9	13	1.7 (SD=2.5)	-4.71 to 4.71
<b>6-20</b>	22	3.6 (SD=4.6)	-3.9 to 12.6	19	6.9 (SD=6.7)	-3.9 to 21.2
<b>21-100</b>	23	2.2 (SD=13.1)	-31.4 to 22.8	21	12.9 (SD=18.6)	-18.9 to 55.0
<b>&gt;100</b>	12	-17.2 (SD=49.8)	-91.1 to 94.3	10	42.0 (SD=40.6)	-26.7 to 90.3

The smallest size classes showed the greatest mean percent growth, both inter-annually and intra-annually, and mean percent growth decreased significantly from the smallest size class to the largest size class (Figure 19; Kruskal-Wallis H = 16.01; n = 75; P < 0.0001). Inter-annual mean percent growth was greater than intra-annual growth in all size classes.

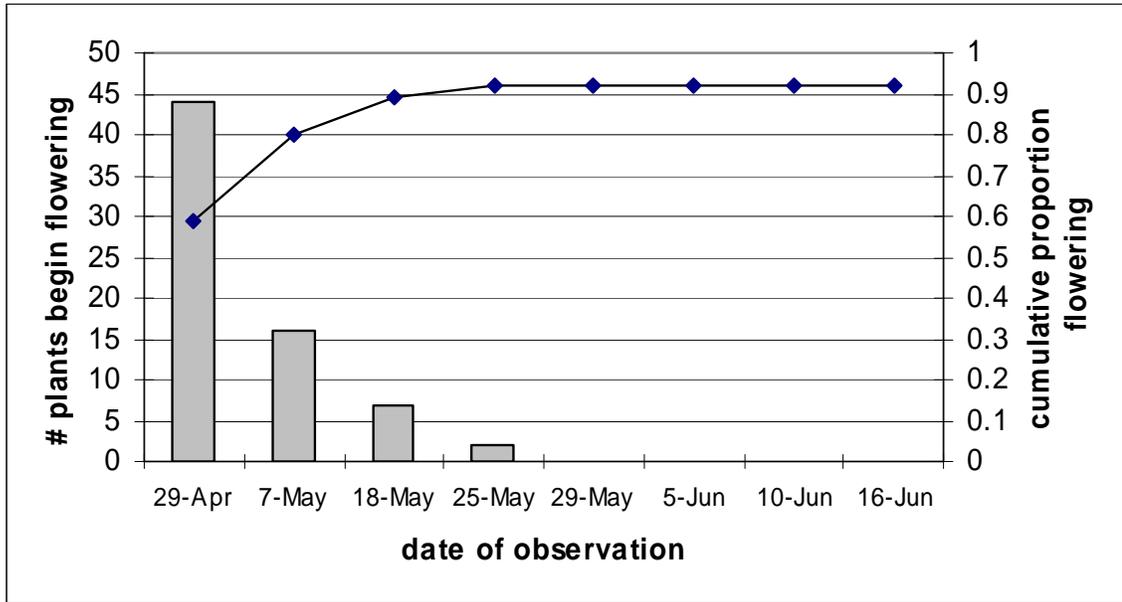
Figure 19. Intra-annual and inter-annual percent growth for different size classes (n=75).



## b. Flowering

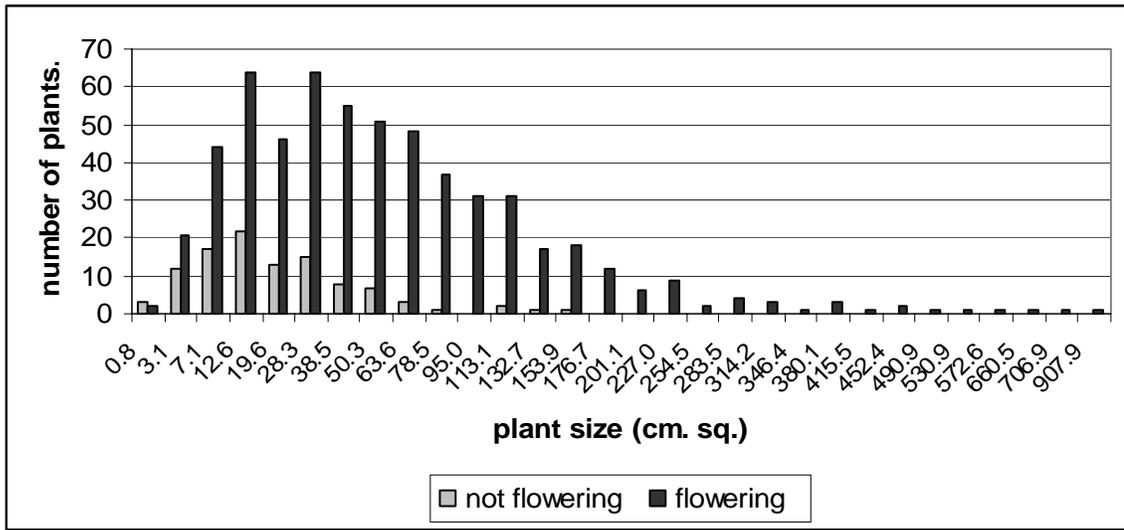
Most flowering was initiated in April and early May (Figure 20). Six of the 75 plants in the demography plots did not flower at all during 2003. Of the 69 plants that did flower, 44 were in flower at the initiation of the project on April 29 and the lack of senesced flowers indicated that flowering started no more than two weeks earlier. All 69 plants were in flower by May 25 and no plants began flowering after this date as confirmed by weekly observation until June 16, 2003. Flowering could not commence after June 16, 2003 because the plants had started losing their leaves and became dormant for the remainder of the growing season.

Figure 20. Onset of flowering and cumulative proportion flowering. (n=75)



The proportion of flowering plants increased with plant size and all plants flowered that were equal to or greater than 179 cm<sup>2</sup> surface area (Figure 21). The smallest plants showed the lowest proportion flowering (0.25) and this was the only size class where there were more non-flowering than flowering plants. The proportion of plants flowering varied significantly with plant size ( $X^2 = 51.13$ ;  $P < 0.0001$ ;  $n = 4$ ;  $df = 3$ ).

Figure 21. Flowering status of different size plants for all plants observed within the population transects as well as in the demography plots (n=682)



**c. Seed Germination**

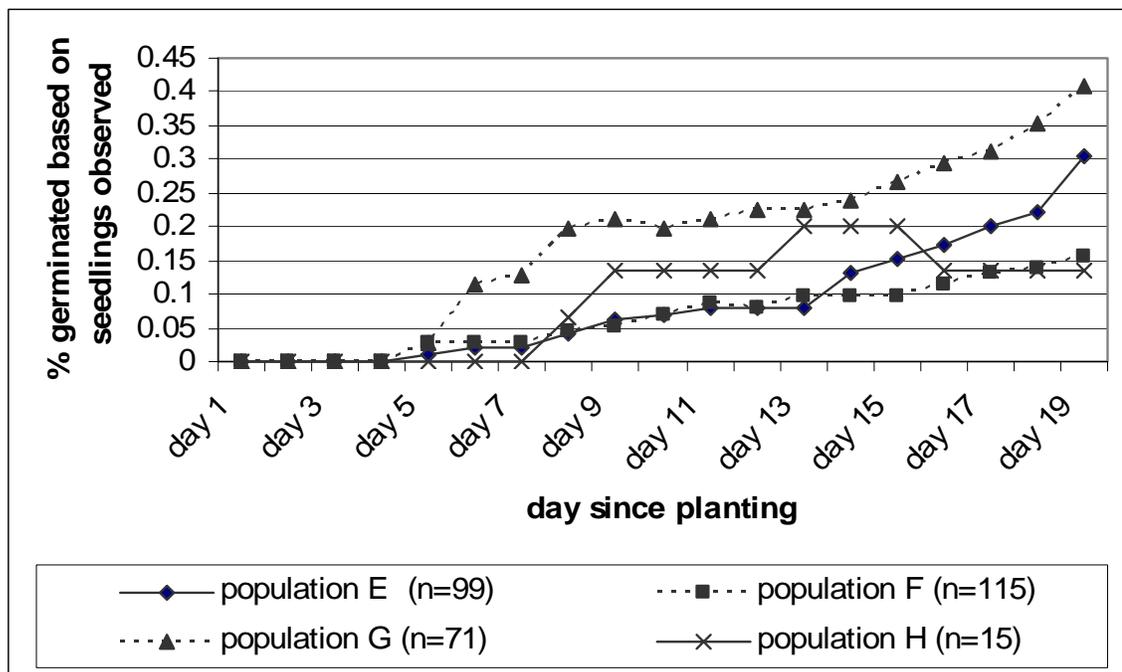
Of 61 seeds collected and planted in 2002, eight seeds germinated (13%). All eight germinated seeds were collected on July 9; none of the seed collected on August 6 germinated.

Table 21. Results of germination trials

Year	Trial: method	# seeds planted	# seeds germinated	% germination
2002	1: greenhouse containers, watered 30 secs/10 mins	34	2	5.9
2002	2: Petri dish	3	3	100.0
2002	3: greenhouse containers, watered 2 mins/1 hour	12	2	16.7
2002	4: Petri dish	4	1	25.0
2002	5: agar test tubes	8	0	0.0
2003	6: greenhouse containers, watered 45 secs/30 mins	300	79	26.0

Of the 300 seeds collected and planted in 2003, 79 had germinated by day 19 (26%). The 79 seeds represented 30 out of 99 planted from population E, 18 out of 115 planted from population F, 29 out of 71 planted from population G, and two out of 15 planted from population H. Seedlings emerged as early as five days and as late as 19 days after planting (Figure 22).

Figure 22. Results of 2003 germination trials (n=300)



The most viable seed was collected in early July, which corresponds with the timing of natural seed dispersal. Seeds collected in June were too green and soft to be scarified. Seeds collected in August appeared to be shriveled or misshapen and were likely aborted seeds left in the pod after dispersal. The aborted seeds were not viable.

#### **d. recruitment**

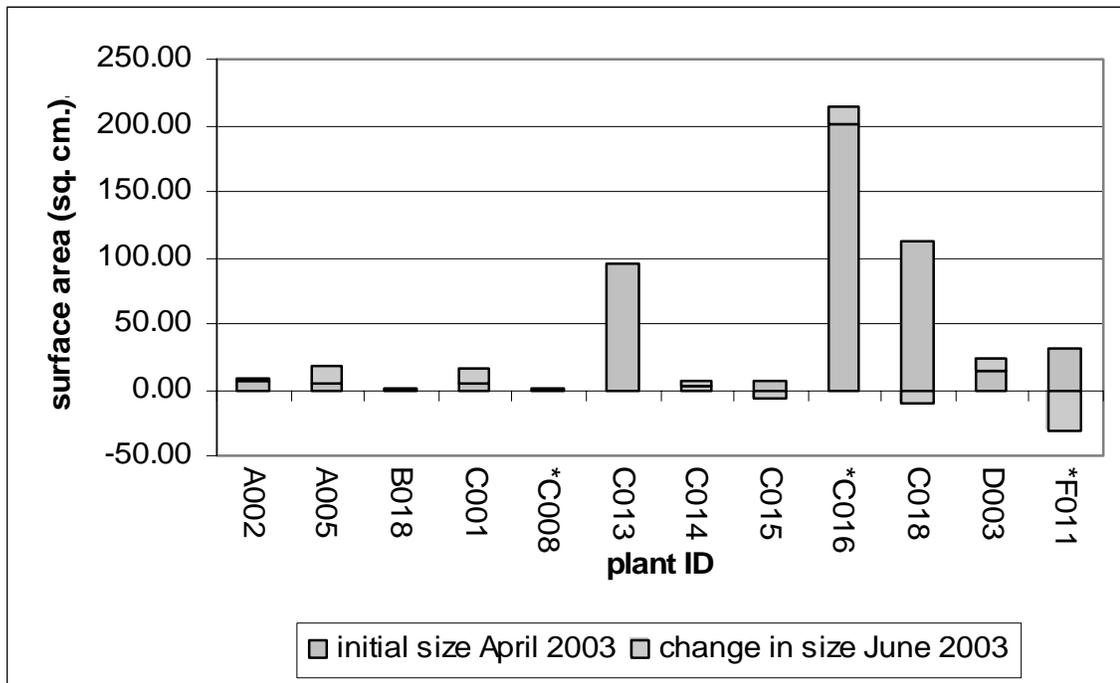
No intra-annual recruitment was observed in the demography plots. However, three new seedlings established between June 16, 2003 and May 15, 2004. Recruitment included one plant in 1-m<sup>2</sup> plot and two plants established immediately adjacent to each other in another 1-m<sup>2</sup> plot. The three new seedlings were established within 20 cm of other plants in silty soil with chalcedony gravel on the surface. Seedling size was quite variable. The lone seedling in one 1-m<sup>2</sup> plot was the largest of the three (4.71 cm<sup>2</sup>), while the two seedlings in the same 1-m<sup>2</sup> plot were 0.78 cm<sup>2</sup> and 1.96 cm<sup>2</sup> (mean seedling size = 2.49 cm<sup>2</sup>; SD= 2.02 cm<sup>2</sup>). These three new plants represent a 4% recruitment rate for the 75 plants that were alive on April 29, 2003.

#### **e. mortality and die-back**

Between April 29, 2003 and June 16, 2003, three plants died in the demography plots. Between June 16, 2003 and May 15, 2004, an additional nine plants died. The total cumulative mortality was twelve plants (16%) of the 75 plants observed over the course of this study. The cause of death for two plants can be attributed to the deposition of silt over the top of the crown but there was no obvious cause of death for the remaining ten plants. Of the plants that died, the mean size measured as surface area was 40.3 cm<sup>2</sup> (SD = 63.3 cm<sup>2</sup>) and ranged from 0.8 cm<sup>2</sup> to 201.1 cm<sup>2</sup>. There was no difference in mortality between size classes ( $X^2 = 2.87$ ;  $P = 0.4127$ ;  $n = 4$ ;  $df = 3$ ). Ten of the twelve plants that

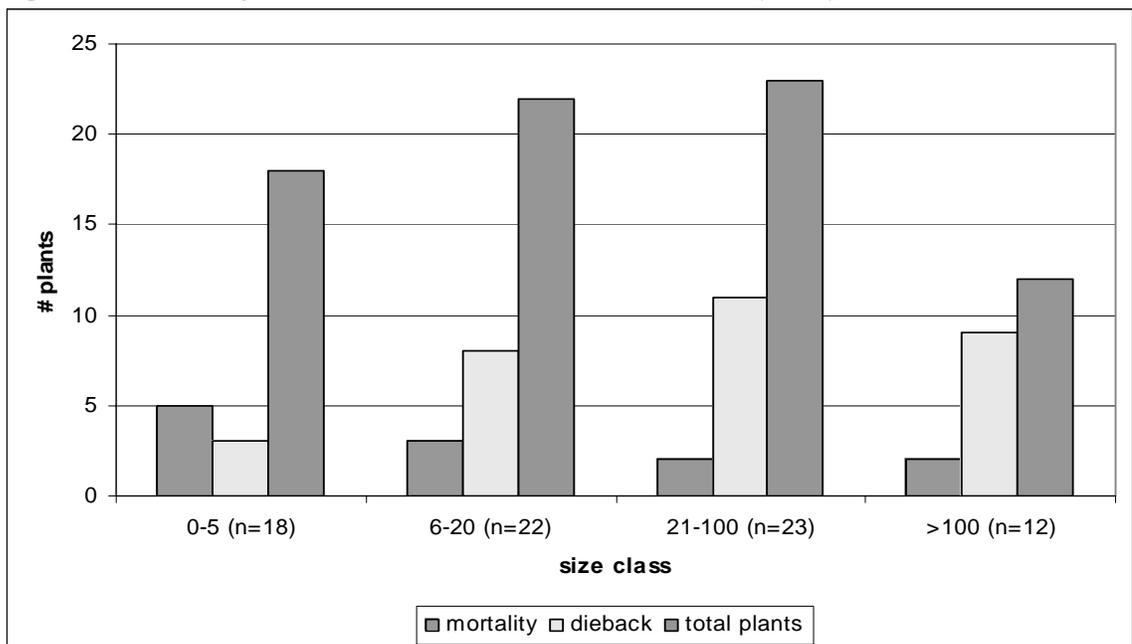
eventually died had flowered in 2003, including two out of the three plants that died in 2003 and eight out of the nine plants that died by May 15, 2004. Also, six out of the twelve plants showed positive growth in 2003 prior to death, and two plants had increased their surface area by over 200% during the 2003 growing season but had died before May 15, 2004 (Figure 23). Mortality occurred in five of the six demography plots and one plot (Plot C) showed the highest number of dead plants with two recorded in 2003 and five recorded in 2004 for a total of seven. This was the only location where dead plants were adjacent to each other, where one plant died in 2003 followed by the death of two immediately adjacent plants in 2004.

Figure 23. Growth prior to death for 12 plants that died during the study, based on initial surface area as measured on April 29, 2003 and the change in surface area measured June 16, 2003. A \* indicates mortality prior to June 16, 2003, others died before May 15, 2004.



In 2004, large area die-backs were observed in seven plants in the demography plots where approximately 50% or more of the leafy crown was dead. Die-back along the margin of the leafy crown was also detected as negative inter-annual and intra-annual growth. To account for measurement error, only those negative values greater than 1 cm<sup>2</sup> were considered die-back. Intra-annual margin dieback occurred in 16 plants between April 29 and June 16, 2003 and inter-annual margin dieback occurred in ten plants between June 16, 2003 and May 15, 2004, including two plants that exhibited both intra-annual and inter-annual dieback. In total, 31 of 75 (41%) plants showed some type of dieback during the study. The smallest size class of 0-5 cm<sup>2</sup> showed the lowest number of plants with die-back (Figure 24). The highest number plants with die-back occurred in the size class of 21-100 cm<sup>2</sup>. There was a significant relationship between size class and the occurrence of die-back ( $X^2 = 10.75$ ;  $P = 0.0132$ ;  $n = 4$ ;  $df = 3$ ).

Figure 24. Mortality and die-back for different size classes (n=75)



## **D. Discussion**

Populations differ in population size, plant density, plant size, and proportion of plants flowering. In all populations studied, the proportion of plants flowering was high, possibly because of the frequent rain that was received in April 2003. Reports regarding the status of *A. barrii* populations in the Powder River Basin indicate that drought-induced stress results in reduced vigor, higher mortality, and reduced flowering (Schassberger 1990).

Population size was highly variable and appeared to be largely controlled by the extent of contiguous suitable habitat. Where populations existed in fairly homogenous basins, the plants were distributed across the entire basin and the extent of the population was defined by major barriers such as steep buttes, sod, or incised intermittent channels. In other areas, the populations appeared to be more fragmented, with significant barriers separating small groupings of plants.

Both intra-annual and inter-annual percent growth followed a similar trend with the smallest size classes showing the largest percent growth and the largest size classes showing the smallest percent growth or even negative growth. Interestingly, the very smallest size class of 0-5 cm<sup>2</sup> showed 70% growth between April 29 and June 16, 2003 and 116% growth between June 16, 2003 and May 15, 2004, but not all plants advanced from the smallest size class in one year. As the plants were observed to drop their leaves

and become dormant in July, most growth occurred early in the growing season before the onset of flowering. Assuming similar growth rates in 2003 and 2004, the sampling period in 2003 most likely missed significant early season growth in April and this early season growth was most apparent in the smallest plants. Future studies should identify and confirm the species identity of *A. barrii* populations the year before the beginning of the study and then initiate data collection in early April to capture information regarding the entire growing season.

Estimation of plant longevity based on annual growth rate indicates that *A. barrii* can be a long-lived species. The largest plant in the demography plots was 801.1 cm<sup>2</sup> in June 2003 and given the mean inter-annual growth observed in this study, 13.4 cm<sup>2</sup>, this plant is 59 years old. Based on the maximum inter-annual growth observed in this study, 90.3 cm<sup>2</sup>, this plant could be as young as 8 years old. Of course, plant growth rates are likely to vary from year to year based on growing conditions and plant size. Using the mean inter-annual growth for each size class shown in Table 20, this plant is 18 years old. This estimate of longevity for the largest plants is consistent with ages reported for other *Orophaca Astragali*: 25 years old for *A. aretioides* and 15 years old for *A. tridactylicus* (Roberts 1977). For all plants measured in this study, the median plant size was 38.5 cm<sup>2</sup> which is estimated to be about seven years old based on the mean inter-annual growth rate for each size class. Regardless of which extrapolation is used, it is clear that some *A. barrii* plants are quite old and have managed to persist in a dynamic habitat. Such longevity is in sharp contrast to the annual and biennial species that share its habitat.

Assuming that size is correlated with age, most plants do not get the opportunity to become long-lived as indicated by one population where 16% of plants died and 41% of plants showed some sort of dieback during the course of this study. In every population, small plants far outnumbered large plants as shown by the right-skewed frequency distribution, but there were also 105 out of 610 plants (17%) greater than 100 cm<sup>2</sup>, including 13 plants (2%) that were greater than 300 cm<sup>2</sup>. Assuming seed production is proportional to plant size, these relatively few large plants might account for a disproportionately large proportion of the seeds produced in a given year. Given their likely age relative to the rest of the plants in a population, these few large plants also have a high net reproductive rate.

Given that 41% of plants showed some die-back, two possible explanations are worth consideration. First, is the common pattern of dead centers exhibited in many shrub species. In this scenario, the die-back observed in *A. barrii* is simply the partial die-back of a single plant. Second, is the possibility that what appears to be a single plant may actually be composed of more than one plant and die-back is the death of one of the component plants. *A. barrii* seeds were often observed stuck in the thick silt that had accumulated within the crown of the mother plant; if these seeds germinated in place, the daughter plants would grow within the crown of the mother plant. While it was beyond the scope of this study to intentionally destroy any live plants, on one occasion a completely dead crown was opportunistically dug up when the substrate was wet. The plant crown was found to be one medium size plant with a large woody caudex, and two

smaller plants each with a separate caudex. The difficulty in accurately distinguishing if a single crown is one or multiple plants should be considered when interpreting data collected during this study, as measurements were taken on what was assumed to be a single plant due to the continuous leafy crown.

Plants in every size class, even those plants  $< 1 \text{ cm}^2$ , were observed to flower and almost all plants over  $95.0 \text{ cm}^2$  and 100% of plants over  $177 \text{ cm}^2$  flowered. The three new recruits observed in 2004 did not flower. Flowering was not correlated with same season or next season mortality as evidenced by the flowering of nine out of the 12 plants that were observed to die in the course of this study. The lack of flowering of the new recruits may be a way to distinguish a “juvenile” stage class for future stage-based demographic studies. However, flowering status would not be useful in identifying a post-reproductive stage class as all of the largest and presumably oldest plants flowered up to the time they died. In consideration of future studies where flowering status is of interest, the best time for capturing flowering status with a single data collection effort is mid-May. All plants that were going to flower had flowered by May 25. In mid-May, most plants were in full flower and those that had flowered early in the growing season still had recognizable flowers.

Schassberger (1990) observed relatively low flowering percentage and signs of water-stress in populations studied in Montana, leading to the conclusion that flowering is depressed by drought. Also, Locklear (1986) reports that *A. barrii* produces few or no

flowers in some years even under greenhouse conditions. The abundant flowering observed in Badlands National Park might be a reflection of good growing conditions during the study or could represent regional variation in flowering frequency between diverse populations.

During the field data collection, a large solitary bee was seen visiting multiple flowers on multiple plants within one population. This was the only pollinator directly observed during the study. This observation is consistent with the pollination mechanism reported for other *Orophaca Astragali*, which indicates bumblebees, solitary bees, or herbivorous beetles are responsible for pollination of this group (Roberts 1977). However, the report of herbivorous beetles commonly seen foraging on and in the flowers and significant seed predation by the beetle larvae (Roberts 1977) was not observed in this study of *A. barrii*.

Seed germination was the focus for the greenhouse germination trials because of the potential relationships between seed germination requirements and edaphic habitat factors, a primary emphasis of this study. Study of seed production was considered but was not included in this project because *A. barrii* plants produce an abundance of flowers in a tightly packed arrangement, producing fruit in the form of dehiscent pods, and then later shedding the seed into the silty substrates in and around the mother plants. These conditions make it difficult to collect all of the ripe seed on a given plant unless the fruits are picked before they open, which could result in unripe seed that are not suitable for germination.

The largest quantity of viable seed was collected in early July. The aborted seed found in pods collected in August was what was left after the ripe seed had dispersed. This observation is generally consistent with the findings of Barneby (1964) that only one seed reaches maturity within each pod of *A. barrii*. Based on the observed onset of flowering and the condition of seeds collected in June, July, and August, the maturation period for seed is approximately seven weeks and most seed is dispersed in early July.

The life history data superficially suggest that the population studied in the demography plots is declining as evidenced by the 16% mortality rate compared with the 4% recruitment rate. However, it is likely that recruitment was under-estimated because this study did not account for establishment of new plants outside of the 1 m<sup>2</sup> plots; given that seed dispersal is primarily via gravity (Roberts 1977) aided by surface flow (S. Dingman, pers. obs.), the number of seedlings downslope and downstream of the study plots could be substantial. Conversely, mortality was likely to be unbiased since plots were placed where plants were growing. Inter-annual mortality and recruitment were probably similar.

Overall, the life history data suggest that the populations studied are at least stable and probably thriving as evidenced by the positive mean inter-annual growth observed, large percentage of plants that flowered, and good seed viability. The size class distribution showed an abundance of vigorous small and medium sized plants, indicating the potential for continued population growth. There were also many large plants that were still actively growing, indicating that plants are able to persist in the populations for years.

## VII. ECOLOGICAL AND MANAGEMENT IMPLICATIONS

*A. barrii* is a characteristic member of the *Orophaca* Phalanx of *Astragalus*, a suite of seven species that are endemic to the Northern Great Plains, an oddity in a landscape that is poor in endemic plants. A common characteristic of all of the *Orophaca Astragali* is their palmately trifoliolate leaves, low cushion growth form, and their restricted distribution to sparsely vegetated erosional habitats such as buttes, gullied slopes, thin knolls, and badlands. While morphologically distinct (Isely 1998, Wojciechowski et al. 1999), current phylogenetic studies are unable to resolve relationships between the *Orophaca* group and other *Neo-Astragalus* species which are estimated to have evolved 4-5 million years ago (Wojciechowski et al. 1999). One explanation is that the group *Orophaca* is not distinct from other *Neo-Astragalus*. Another possible explanation is that the *Orophaca* have only recently diverged, probably within the last 14,000 years following the end of the Pleistocene glaciations, and have evolved their unique morphological characteristics as an adaptation to their colonization of erosional habitats but that morphological adaptation is not yet reflected in genetic markers that can be detected with molecular techniques.

An understanding of the variables that influence the presence or absence of *A. barrii* in these erosional habitats furthers both the conservation of *A. barrii* as well as advances the understanding of factors that might influence the distribution of the *Orophaca Astragali*.

Results of habitat modeling, physical habitat properties, and life history studies indicate that *A. barrii* is an edaphic specialist. Silty clay soil texture and substrates high in chalcedony or limestone gravels were found to be important habitat characteristics, possibly providing the mechanism for physical seed scarification as well as the thermal and soil moisture properties necessary for germination. As many species of *Astragalus* are known to possess hard, impermeable seed coats that impose a strong physical germination barrier, they require physical scarification of seed in order to germinate (Baskin and Baskin 1998). This characteristic is typical of seeds that are relatively long-lived and are known to remain viable in the soil longer than seeds of most other species (Baskin and Baskin 1998) and persistent seed banks are often found in early successional communities or in communities subject to natural disturbance (Thompson 2000). It is probable that the other *Orophaca Astragalus* species possess specific habitat requirements for seed scarification and germination. Additional study is needed to determine if this relationship between presence/absence and edaphic conditions for scarification and germination is consistent across the range of *A. barrii*, including populations outside of the White River Badlands, and if similar relationships exist for the other *Orophaca Astragali*.

The occurrence of *A. barrii* on poorly developed soils that generally lack an A horizon and support few other species indicates that the species is a poor competitor. This strategy would generally preclude competition by most native species. Considering the co-occurring species reported by Schmoller (1993) and Weedon (1991) are mostly

annuals, biennials, or short-lived perennials, the persistence of *A. barrii* as a long-lived perennial in such a dynamic environment is remarkable.

Due to the lack of resolution in the geospatial data, the populations that occurred on the Rocky Ford Ash micro-sites could not be predicted using the habitat models; nonetheless, these populations do occur on microsites that possess the same edaphic characteristics associated with *A. barrii* throughout the study area. In this case, the Rocky Ford Ash weathers to a silica-rich clay that gets intermixed with fine silty loam that washes down from the Quaternary eolian deposits that cap Sheep Mountain Table. The result is a silty clay loam rich in silicates that could provide the abrasive material needed for seed scarification. The micro-sites are relatively level with steep slopes above and below and are sparsely vegetated.

*A. barrii* presence and absence in the White River Badlands showed a striking relationship to watersheds that has implications for the evolutionary history and meta-population dynamics of *A. barrii* and possibly the other *Orophaca Astragali*. *A. barrii* was completely absent north of the Badlands Wall. Roberts (1977) inferred from seed shape and the lack of other obvious dispersal mechanisms that seed dispersal for the *Orophaca Astragali* is via gravity. During this study, the opportunistic observation of seed tumbling along an unincised surface flow during a rainstorm (S. Dingman, pers. obs.) indicates that dispersal via gravity may also be aided by surface flow, at least for short distances. The influence of water dispersed seed is also supported by the

observation of plants scattered along the low energy deposition zone of unincised drainages directly downslope from abundant populations growing on interfluves. Given that these normal dispersal mechanisms limit the distance of dispersal, the steep hydrologic divide associated with the Wall may serve as an effective barrier to dispersal, thus preventing establishment north of the Badlands Wall. However, such localized dispersal mechanisms and the short time in which the species has evolved fail to account for the fact that populations in the Powder River Basin and the White River Basin are separated by hundreds of miles. One possible explanation is that there are, or were, populations located between the two basins. Another explanation is that the normal short distance dispersal mechanisms are occasionally augmented by rare long distance dispersal events. Such events might include severe wind storms that transport the seed from one area to another as eolian deposition or riverine flood events that transport seed from one drainage to another as overbank deposition.

The distribution of the species throughout its range - found in the White River and Cheyenne River drainages in South Dakota and the Powder River basin of Wyoming and Montana - may reflect the influence of topography on both evolutionary history and meta-population colonization patterns. As the *Orophaca Astragalus* species have very similar seed morphologies (Roberts 1977), evolutionary history and meta-population colonization patterns for this entire group might similarly respond to hydrologic divides, possibly giving rise to speciation of this compact and closely related suite of endemic species.

The life history traits observed in this study have implications for the design of future studies of *A. barrii*, and possibly the other endemic *Orophaca Astragalus* species of the Northern Great Plains. Based on the relatively low annual recruitment rate and the potential for a single plant to live for decades, both traits reported for other *Orophaca Astragalus* species (Roberts 1977, Locklear 1986), demographic studies should be of relatively long duration in order to capture enough inter-annual transitions to fully characterize this species. The traditional stage-based approach to plant demographic studies is unsuitable for this species because the vast majority of plants were reproductive and only a very few plants could be categorized as juveniles or senescent, resulting in very uneven class sizes that could be problematic for many statistical analyses. The age-based approach is also problematic because the only known reliable way to quantitatively age a single plant is through destructive sampling to age the plant based on growth rings in the woody caudex, an approach that is not recommended for rare species (Baskin and Baskin 1986); however, additional estimates of inter-annual growth correlated with growing conditions might provide a usable range of annual growth rates to estimate age based on size. Size-based demographic studies are the most viable option if a single cushion could accurately be ascribed to a single plant rather than a mother plant with offspring growing within the same crown. Also, the prevalence of partial die-back in the interior of the crown or around the margin of the crown has implications for size-based demographic studies and such studies would need to determine if size class is based on the entire crown or only the green portion of the crown.

The Great Plains along the eastern slope of the Rocky Mountains is an understudied and under-collected flora, coupled with a low incidence of endemism. Additional studies of *A. barrii*, or the other *Orophaca Astragali*, could further understanding of a variety of fields pertinent to conservation biology. Consequently, additional research should be encouraged in Badlands National Park and elsewhere throughout the region. Beyond those topics already discussed, potential topics include:

- genetic studies to determine patterns of paternity within and between populations;
- phylogenetic studies to examine the relationships between the *Orophaca Astragali*;
- meta-population studies to determine the rates and patterns of colonization and extinction across the range of the species; and
- comparison of distributions and meta-population dynamics of all *Orophaca Astragalus* species to further understanding of speciation and adaptation.

## **Management Recommendations**

Badlands National Park hosts numerous populations of this rare and endemic species. As such, inventory efforts should continue to the extent that funding and staffing can accommodate the workload. Inventory efforts should concentrate on the Stronghold District, Sheep Mountain Table area, and Conata Basin. The probabilities calculated using logistic regression and presented in Figure 13 can be used to further focus field inventory efforts within these prime habitat areas. Additionally, two monitoring efforts should be undertaken. First, yearly observation of the established demography plots near Highway 44 should be continued. Similar to the data collected in 2004, each plot should be visited in mid-May to record mortality and recruitment, document flowering status, and take size measurements. Over time, the minimal effort required to collect this individual-based life history data will be useful in determining the threat posed by invasive species, longevity of the species, recruitment rates, population trends, and other demographic parameters. Second, in about 10 years, all 101 known populations mapped in the course of this study should be revisited. If a population is found to have gone extinct, that information could be useful in a meta-population study and effort should be made to identify obvious causes of extinction, such as the presence of invasive species or alteration of the physical habitat. For populations that continue to persist, their perimeter should be re-mapped to determine if their extent has expanded or diminished over time.

The deductive habitat similarity map presented in Figure 12 should be used to analyze impacts to the species as well as avoid and minimize potential impacts, with consideration that exhaustive searches failed to find any populations above the Badlands Wall. Generally, impacts to *A. barrii* are not an issue for projects (e.g. construction sites, burn units, weed treatment areas) that are located above the Badlands Wall.

One of the primary risks posed to this species in Badlands National Park and other areas of the Northern Great Plains is the implementation of prescribed fire. As this species grows in relatively barren substrates with discontinuous and light fuel loads, this species is probably poorly adapted to survive fire. Similarly, fire is unlikely to naturally carry into *A. barrii* populations due to the light fuels. If possible, burn units located below the Badlands Wall that include suitable habitat should be surveyed in May of the growing season before the burn plan is completed. Where populations are found, specific measures should be incorporated into the burn plan to exclude fire from those areas. Care should be used in planning for use of imprecise firing techniques, such as aerial ignition, where populations exist in the burn unit. Additionally, vehicular access should be restricted from the populations, but the plants are likely to be fairly resistant to light volume foot traffic.

Road realignments, trails, overlooks, and new facilities should be sited to avoid known populations. For project areas located below the Badlands Wall and in suitable habitat,

the area should be surveyed for the presence of *A. barrii* in May before plans are finalized.

Weed invasion in *A. barrii* populations probably reduces the viability of the population as it does not tolerate shading. Of particular concern is the presence of annual brome grasses (*Bromus tectorum* and *Bromus japonicus*) and yellow sweet clover (*Melilotus officianalus*). These species are capable of colonizing the dynamic environment where *A. barrii* thrives. At the population along Highway 44, there is significant encroachment of these species into the *A. barrii* habitat and direct competition where these species are growing directly out of the leafy crown of *A. barrii*. As these weedy species tend to invade along disturbed areas, such as roads and trails, care should be taken to avoid bringing any new disturbances into the immediate vicinity of known *A. barrii* populations as that disturbance is likely to bring in weeds as well. There are no specific recommendations for chemical weed control where these weedy species have invaded *A. barrii* populations because any chemical applied would likely be harmful to *A. barrii* as well and because annual and biennial weed species are not easily controlled with herbicide.

The persistence and even abundance of *A. barrii* in the Stronghold District of Badlands National Park indicates that the species is apparently capable of withstanding the current levels of Tribal cattle and horse grazing and administrative vehicular use. In fact, it was observed to be growing within a tire track in one location. However, any increase in

vehicle use, particularly ATV or recreational 4x4 use, should be avoided in *A. barrii* habitat. Discussion with resource managers for Bureau of Land Management and the U.S. Forest Service indicates that recreational 4x4 use has detrimentally affected several known *A. barrii* populations within their jurisdictions in southwestern South Dakota and eastern Wyoming. As this species continues to thrive on lands used for cattle grazing in the Stronghold District of Badlands National Park and Buffalo Gap National Grasslands, it is unlikely that continuation of existing bison management practices or even moderate expansion of the bison herd or bison pasture would have a detrimental affect on the species.

There is no concern for incidental trampling by visitor or administrative foot traffic, as this species readily persists with cattle trampling. Individual plants appear to be quite resilient to the occasional foot impact. However, prolonged backcountry use, such as field camps used by researchers, should be sited to avoid *A. barrii* populations as such use might concentrate trampling on the population beyond its tolerance.

Continuation of existing prairie dog and ferret management practices as well as the natural expansion of prairie dog towns are unlikely to pose a significant impact to the persistence of *A. barrii* populations. The loamy substrates and gentle slopes that are attractive to prairie dogs are generally not suitable for *A. barrii*. Thus the occurrence of prairie dogs and *A. barrii* appear to be mutually exclusive.

In general, continuation of existing management practices are unlikely to pose significant threat to *A. barrii* in Badlands National Park and the park has an opportunity to serve as host to a rare and endemic species worthy of conservation.

## VIII. REFERENCES

- Angiosperm Phylogeny Group. 1998. An ordinal classification for the orders and families of flowering plants. *Annals of the Missouri Botanical Garden* 85:531-553.
- Ashworth, A.C., R.C. Benton, R.F. Biek, E. C. Murphy, G.W. Shurr, K.K. Stevens, and D.O. Terry. 1996. A field guide to Tertiary tectonism in the Northern Great Plains: Road Log, Field Trip 1. *In* C.J. Paterson and J.G. Kirchner, eds. *Guidebook to the Geology of the Black Hills, South Dakota*. South Dakota School of Mines and Technology Bulletin 19: 9-18.
- Barneby, R. 1956. Pugillus Astragalorum XIX: Notes on *A. sericoleucus* Gray and its immediate relatives. *The American Midland Naturalist* 55:506.
- Barneby, R. 1964. Atlas of North American *Astragalus*. *Memoirs of the New York Botanical Garden* 13: 1-1188.
- Barr, C.A. 1951. *Bulletin of the American Rock Garden Society* 9:2-4.
- Baskin, J.M. and C.C. Baskin. 1986. Some considerations in evaluating and monitoring populations of rare plants in successional environments. *Natural Areas Journal* 6(3): 26-30.
- Baskin, C.C. and J.M. Baskin. 1998. Seeds: ecology, biogeography, and evolution of dormancy and germination. New York: Academic Press. pp 388-404.
- Batt, J.E. 1991. Grassland Community Types of the Sage Creek Wilderness Area, Badlands National Park, South Dakota. M.S. Thesis. Vermillion, South Dakota: University of South Dakota. 152 pp.
- Boetsch, J.R., F.K. Van Manen, and J.D. Clark. 2003. Predicting rare plant occurrence in Great Smoky Mountains National Park, USA. *Natural Areas Journal* 23(3): 229-237.
- Boyce, M.S., P.R. Vernier, S.E. Nielsen, and F.K.A. Schmiegelow. 2002. Evaluating resource selection functions. *Ecological Modelling* 157:281-300.
- Britton, N.L. and A. Brown. 1897. *An Illustrated Flora of the northern United States, Canada and the British possessions from Newfoundland to the parallel of the southern boundary of Virginia, and from the Atlantic Ocean westward to the 102d meridian, vol. 2*. New York: C. Scribners's Sons.

- Brussard, P.F. 1991. The role of ecology in biological conservation. *Ecological Applications* 1: 6-12.
- Bump, J.D. 1956. Geographic names for members of the Brule formation of the Big Badlands of South Dakota. *American Journal of Science* 254: 429-432.
- Butler, J.L. and J.E. Batt. 1995. Final Report: Grassland Community Types of Badlands National Park, South Dakota. Vermillion, South Dakota: University of South Dakota. 133 pp.
- Cas, R.A.F. and J.V. Wright. 1988. Volcanic successions: Modern and ancient. London: Chapman and Hall. 528 pp.
- Clark, J. 1937. The stratigraphy and paleontology of the Chadron formation in the Big Badlands of South Dakota. *Carnegie Museum Annals* 25: 261-350.
- \_\_\_\_\_. 1954. Geographic designation of the members of the Chadron formation in South Dakota. *Carnegie Museum Annals* 33: 197-198.
- \_\_\_\_\_. 1975. Controls of sedimentation and provenance of sediments in the Oligocene of the central Rocky Mountains. *In* B.F. Curtis, ed. *Cenozoic history of the southern Rocky Mountains*. Geological Society of America Memoir 144: 95-117.
- Clark, J., J.R. Beerbower, and K.K. Kietzke. 1967. Oligocene sedimentation, stratigraphy, paleoecology, and paleoclimatology in the Big Badlands of South Dakota. *Fieldiana Geology Memoirs* 5. Chicago: Field Museum of Natural History. 158 pp.
- Cohen, J. 1960. A coefficient of agreement for nominal scales. *Educational and Psychological Measurement* 20:37-46.
- Easterbrook, D.J. 1999. *Surface Processes and Landforms*, second edition. New Jersey: Prentice-Hall. 546 pp.
- Elzinga, C.L., D.W. Salzer, and J.W. Willoughby. 1998. Measuring and monitoring of plant populations. U.S. Department of the Interior, Bureau of Land Management Technical Reference 1730-1. 477 pp.

- Evans, J.E., and L.C. Welzenbach. 1998. Episodes of carbonate deposition in siliciclastic-dominated fluvial sequence, Eocene-Oligocene White River Group, South Dakota and Nebraska. *In* D.O. Terry, H.E. LaGarry, and R.M. Hunt Jr., eds. *Depositional Environments, Lithostratigraphy, and Biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America)*. Geological Society of America, Inc. Special Paper 325: 93-116.
- Faber-Langendoen, D. and Midwest State Natural Heritage Program Ecologists. 1996. Terrestrial Vegetation of the Midwestern United States. *In* International Classification of Ecological Communities: Terrestrial Vegetation of the United States. The Nature Conservancy: Arlington, Virginia. 33 pp plus tables.
- Falk, D.A. and P. Olwell. 1992. Scientific and policy considerations in restoration and reintroduction of endangered species. *Rhodora* 94: 287-315.
- Fertig, W. and G. Beauvais. 1999. Wyoming Plant and Animal Species of Special Concern. Wyoming Natural Diversity Database, Laramie, WY.
- Fertig, W., C. Refsdal, and J. Whipple. 1994. Wyoming Rare Plant Field Guide. Wyoming Rare Plant Technical Committee, Cheyenne, WY.
- Fielding, A.H. and J.F. Bell. 1997. A review of methods for the assessment of predicting errors in conservation presence/absence models. *Environmental Conservation* 24(1): 38-49.
- Fielding, A.H. 2002. What are the appropriate characteristics on an accuracy measure? *In* J.M. Scott, P.J. Heglund, M.L. Morrison, J.B. Haufler, M.G. Raphael, W.A. Wall, and F.B. Samson, eds. *Predicting Species Occurrences: Issues of Scale and Accuracy*. Covello, California: Island Press. pp 271 – 280.
- Goedickemeier, I., O.Wildi, and F. Kienast. 1997. Sampling for vegetation survey: Some properties of a GIS-based stratification compared to other statistical sampling methods. *Coenoses* 12(1): 43-50.
- Gries, J.P. 1996. *Roadside Geology of South Dakota*. Missoula, Montana: Mountain Press Publishing Company. 358 pp.
- Great Plains Flora Association. 1986. *Flora of the Great Plains*. R.L. McGregor, T.M. Barkley, R.E. Brooks, and E.K Schofield, eds. Lawrence, Kansas: University Press of Kansas. 1400 pp.
- Guisan, A. and N.E. Zimmermann. 2000. Predictive habitat distribution models in ecology. *Ecological Modelling* 135: 147-186.

- Gurevitch, J., S.M. Scheiner, and G.A. Fox. 2002. *The Ecology of Plants*. Sunderland, Massachusetts: Sinauer Associates, Inc. 523 pp.
- Hanski, I. and M.E. Gilpin. 1997. *Metapopulation Biology: Ecology, Genetics, and Evolution*. San Diego, California: Academic Press. 512 pp.
- Harksen, J.C. and J.R. Macdonald. 1969. Type section for the Chadron and Brule formations of the White River Oligocene in the Big Badlands, South Dakota. South Dakota Geological Survey Report of Investigations No. 99. 23 pp.
- Harris, D.V. and E.P. Kiver. 1985. *The Geologic Story of the National Parks and Monuments*. New York: John Wiley and Sons. 464 pp.
- Horton, R. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin* 56: 275-370.
- Huston, M.A. 2002. Introductory Essay: Critical issues for improving predictions. *In* J.M. Scott, P.J. Heglund, M.L. Morrison, J.B. Haufler, M.G. Raphael, W.A. Wall, and F.B. Samson, eds. *Predicting Species Occurrences: Issues of Scale and Accuracy*. Covello, California: Island Press. pp. 7 - 21.
- Isely, D. 1983. New combinations and two new varieties in *Astragalus*, *Orophaca*, and *Oxytropis* (Leguminosae). *Systematic Botany* 8: 420-426.
- Isely, D. 1998. Native and naturalized Leguminosae (Fabaceae) of the United States. Provo, Utah: M.L. Bean Life Science Museum, Brigham Young University. pp. 753-757.
- Kruckeberg, A.R., and D. Rabinowitz. 1985. Biological aspects of endemism in higher plants. *Annual Review of Ecology and Systematics* 16:447-479.
- Larson, E.E. and E. Evanoff. 1998. Tephrostratigraphy and source of the tuffs of the White River sequence. *In* D.O. Terry, H.E. LaGarry, and R.M. Hunt Jr., eds. *Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America)*. Geological Society of America, Inc. Special Paper 325: 1-14.
- Lisenbee, A.L. and E. DeWitt. 1993. Laramide evolution of the Black Hills uplift. *In* A.W. Snoke, J.R. Steidtmann, and S.M. Roberts, eds. *Geology of Wyoming; Geological Survey of Wyoming Memoir* 5(2): 374-412.
- Locklear, J. 1986. On the trail of Barr's milkvetch. *Nebraska Statewide Arboretum. University of Nebraska – Lincoln*.

- Manel, S., J.-M. Dias, and S.J. Ormerod. 1999. Comparing discriminant analysis, neural networks and logistic regression for predicting species distributions: a case study with a Himalayan river bird. *Ecological Modelling* 120: 337-347.
- Manel, S., H.C. Williams, and S.J. Ormerod. 2001. Evaluating presence-absence models in ecology: The need to account for prevalence. *Journal of Applied Ecology* 38: 921-931.
- Montana Natural Heritage Program. 2003. Plant species of concern. 35 pp. On-line at: <http://nhp.nris.state.mt.us/plants/>
- O'Harra, C.C. 1920. The White River Badlands. South Dakota School of Mines Bulletin Number 13, Department of Geology. Stickney, South Dakota: Argus Printers. pp 31-51.
- Olden, J.D., and D.A. Jackson. 2000. Torturing data for the sake of generality: How valid are our regression models? *Ecoscience* 7(4):501-510.
- Pearce, J. and S. Ferrier. 2000. Evaluating the predictive performance of habitat models developed using logistic regression. *Ecological Modelling* 133:225-245.
- Plymate, T.G. 2004. Lecture Notes for Principles of Geology. University of Minnesota. <http://geosciences.smsu.edu/faculty/Plymate/GLG110/Lecture28-29outline.ppt>
- Raymond, W.H. and R.U. King. 1974a. Geologic Map of the Quinn Table SW and parts of the Quinn Table and Imlay Quadrangles, Pennington and Shannon Counties. Miscellaneous Field Studies Map MF-601. U.S. Department of the Interior, United States Geological Survey.
- Raymond, W.H. and R.U. King. 1974b. Geologic Map of the Quinn Table SE and parts of the Quinn Table NE and Bouquet Table Quadrangles, Pennington and Shannon Counties, South Dakota. Miscellaneous Field Studies Map MF-602. U.S. Department of the Interior, United States Geological Survey.
- Raymond, W.H. and R.U. King. 1974c. Geologic Map of the Scenic and parts of the Brennan Flat and Sheep Mountain Table Quadrangles, Pennington and Shannon Counties, South Dakota. Miscellaneous Field Studies Map MF-603. U.S. Department of the Interior, United States Geological Survey.
- Raymond, W.H. and R.U. King. 1974d. Geologic Map of the Wall SW and parts of the Wall and Conata Quadrangles, Pennington, Shannon and Washabaugh Counties, South Dakota. Miscellaneous Field Studies Map MF-615. U.S. Department of the Interior, United States Geological Survey.

- Raymond, W.H. and R.U. King. 1974e. Geologic Map of the Wall SE and Conata NE Quadrangles, Pennington, Jackson and Washabaugh Counties, South Dakota. Miscellaneous Field Studies Map MF-616. U.S. Department of the Interior, United States Geological Survey.
- Raymond, W.H. and R.U. King. 1974f. Geologic Map of the Cottonwood SW and parts of the Cottonwood and Interior y Quadrangles, Jackson County. Miscellaneous Field Studies Map MF-617. U.S. Department of the Interior, United States Geological Survey.
- Raymond, W.H. and R.U. King. 1976. Geologic Map of the Badlands National Monument and Vicinity, West-Central South Dakota. Miscellaneous Investigations Series, Map I-934. U.S. Department of the Interior, United States Geological Survey.
- Rempel, R.S. and A.P. Carr. 2003. Patch Analyst extension for ESRI ArcView: version 3. <http://flash.lakeheadu.ca/~rrempel/patch/index.html>.
- Retallack, G.J. 1983. Late Eocene and Oligocene paleosols from Badlands National Park, South Dakota. Geological Society of America Special Paper 193: 1-82.
- Ritter, R.J. and R.G. Wolff. 1958. Channel sandstones of the eastern section of the Big Badlands of South Dakota. Proceedings of the South Dakota Academy of Science 37: 184-191.
- Ritter, M.E. 2003. The Physical Environment: An Introduction to Physical Geography (on-line textbook). University of Wisconsin – Stevens Point. [http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/title\\_page.html](http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/title_page.html)
- Roberts, M.L. 1977. Systematics of the *Orophaca Astragali*. M.S. Thesis. Laramie, Wyoming: University of Wyoming. 101 pp.
- Rothrock, E.P. 1943. A geology of South Dakota, Part I: The Surface. South Dakota Geologic Survey Bulletin No. 13. 88 pp.
- Sanderson, M.J. and J.J. Doyle. 1993. Phylogenetic relationships in North American *Astragalus* (Fabaceae) based on chloroplast DNA restriction site variation. Systematic Botany 18 (3): 395-408.
- Sanderson, M.J. and M.F. Wojciechowski. 1996. Diversification rates in a temperate legume clade: Are there “so many species” of *Astragalus* (Fabaceae)? American Journal of Botany 83(11): 1488-1502.

- Schassberger, L.A. 1988. Status review of *Astragalus barrii*. Unpublished report submitted to the U.S. Department of Agriculture Forest Service, Custer National Forest, Montana. Helena, Montana: Montana Natural Heritage Program. 57 pp.
- Schassberger, L.A. 1990. Report on the conservation status of *Astragalus barrii*, a candidate threatened species. Unpublished report submitted to the U.S. Department of the Interior Fish and Wildlife Service, Denver, Colorado. Helena, Montana: Montana Natural Heritage Program. 85 pp.
- Schmoller, D. 1993. Status survey for *Astragalus barrii* in the Wall Ranger District, Buffalo Gap National Grasslands. Unpublished report submitted to the U.S. Department of Agriculture Forest Service, Buffalo Gap National Grasslands. On file with slides and field notes at the Wall District Office, Wall, South Dakota. 8 pp.
- Schumm, S.A. 1956. The role of creep and rainwash on the retreat of badland slopes. *American Journal of Science* 254: 693-706.
- Shurr, G.W., A.C. Ashworth, R. Benton, E.C. Murphy, and R.F. Biek. 1996. Regional framework for Tertiary tectonism in the Northern Great Plains. *In* C.J. Paterson and J.G. Kirchner, eds. *Guidebook to the Geology of the Black Hills, South Dakota*. South Dakota School of Mines and Technology Bulletin No. 19: 129-134.
- Seedfeldt, D.R. and M.O. Glerup. 1958. Stream channels of the Scenic member of the Brule formation, western Big Badlands, South Dakota. *Proceedings of the South Dakota Academy of Science* 37: 194-202.
- Simberloff, D. 1988. The contribution of population and community biology to conservation science. *Annual Review of Ecology and Systematics* 19: 473-511.
- Smith, K. 1958. Erosional processes and landforms in Badlands National Monument, South Dakota. *Bulletin of the Geological Society of America* No. 69: 975-1008.
- South Dakota Natural Heritage Program. 2002. Rare, threatened, and endangered plant species tracked by the South Dakota Natural Heritage Program. Pierre, South Dakota: South Dakota Department of Game, Fish and Parks. On-line at: <http://www.sdgifp.info/Wildlife/Diversity/rareplant2002.htm>
- Stoffer, P.W. and J.A. Chamberlain. 1996. The upper Pierre Shale/lower Fox Hills interval (Late Cretaceous; latest Campanian/early Maastrichtian) in Badlands National Park, South Dakota and eastern Wyoming. *Geological Society of America Abstracts with Programs* 28: 39-40.

- Store, R. and J. Jokimaki. 2003. A GIS-based multi-scale approach to habitat suitability modeling. *Ecological Modelling* 169:1-15.
- Terry, D.O. and J.E. Evans. 1994. Pedogenesis and paleoclimatic implications of the Chamberlain Pass formation, Basal White River Group, Badlands of South Dakota. *Palaeogeography, Palaeoclimatology, Palaeoecology* 110: 197-215.
- Terry, D.O. 1998. Stratigraphy, depositional environments, and fossil resources of the Chadron formation in the South Unit of Badlands National Park, South Dakota. *Dakoterra* 5:127-138.
- The Nature Conservancy and Environmental Research Systems Institute. 1994. NBS/NPS Vegetation Mapping Program: Standardized National Vegetation Classification System. Arlington, VA.
- Thompson, K. 2000. The functional ecology of soil seed banks. *In* Fenner, M., ed. *Seeds: The Ecology of Regeneration in Plant Communities*. Wallingford, England: C.A.B. International. pp. 215-235.
- USDA Natural Resources Conservation Service. 1996. Soil Survey of Custer and Pennington Counties, Prairie Parts, South Dakota. Washington, D.C. 288 pp, plus maps.
- USDA Soil Conservation Service. 1987. Soil Survey of Jackson County, Northern Part, South Dakota. Washington, D.C. 216 pp, plus maps.
- \_\_\_\_\_. 1971. Soil Survey of Shannon County, South Dakota. Washington, D.C. 92 pp, plus maps.
- USDI National Park Service. 1998. Badlands National Park Resource Management Plan. On file at Park Headquarters, Badlands National Park, Interior, South Dakota.
- \_\_\_\_\_. 2000. National Park Service Management Policies.
- USDI U.S. Geological Survey. 1999. National Elevation Dataset. EROS Data Center, Sioux Falls, South Dakota.
- Von Loh, J., Cogan, D., Faber-Langendoen, D., Crawford, D., and M.J. Pucherelli. 1999. USGS-NPS Vegetation Mapping Program Badlands National Park, South Dakota (Final Report). Technical Memorandum No. 8260-99-03. Denver, Colorado: U.S. Bureau of Reclamation Technical Service Center. 67 pp plus appendices.

- Ward, F. 1922. The geology of a portion of the Badlands. South Dakota Geological and Natural History Survey, Circular No. 8. South Dakota University Bulletin 21(7). 80 pp.
- Weedon, R.R., B.L. Muenchau, M.F. Webster, and J.P. Hardy. 1991. Final Report: Status surveys for Barr's milkvetch and Dakota buckwheat on the Fall River District, Buffalo Gap National Grasslands, South Dakota. Unpublished report submitted to the U.S. Department of Agriculture Forest Service, Nebraska National Forest. 17 pp.
- Wiser, S.K., R.K. Peet, and P.S. White. 1998. Prediction of rare-plant occurrence: A southern Appalachian example. *Ecological Applications* 8(4): 909-920.
- Wojciechowski, M.F., M.J. Sanderson, and J.M. Hu. 1999. Evidence on the monophyly of *Astragalus* (Fabaceae) and its major subgroups based on nuclear ribosomal DNA ITS and chloroplast DNA *trnL* intron data. *Systematic Botany* 24(3): 409-437.
- Wu, B. and F. Smeins. 2000. Multiple-scale habitat suitability modeling approach for rare plant conservation. *Landscape and Urban Planning* 51: 11-28.