Geologic Associations of Arizona Willow in the White Mountains, Arizona

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ABSTRACT: The Arizona willow (*Salix arizonica* Dorn) is a rare species growing in isolated populations at the margins of the Colorado Plateau. Although its habitat in the White Mountains of Arizona has been mischaracterized as basaltic, the area is actually a complex mixture of felsic, basaltic and epiclastic formations. Comparing the distribution of the Arizona willow to mapped geologic formations revealed that occupied sites are strongly associated with felsic, coarse-textured Mount Baldy formations. The most robust subpopulations are located in three glaciated reaches, but about half occur in exposures of the Sheep Crossing Formation. Other sites occur in areas mapped as Quaternary basalt, but these lie either downstream from Mount Baldy formations or where basalt and porous cinders form a relatively thin mantle over the Mount Baldy formations. Glacial deposits, the Sheep Crossing Formation, and large alluvial deposits have high hydrologic conductivity that may favor the willow. Despite its affinity for the Mount Baldy formations, the Arizona willow is not a strict substrate specialist, since it has survived when transplanted into basaltic areas in Arizona and it grows in different substrates in New Mexico and Utah. Nonetheless, understanding the geologic associations of this rare plant can help to explain its distribution and to design appropriate conservation measures.

INTRODUCTION

Mount Baldy stands out at the second highest mountain in Arizona (3476 m) and as a refuge for rare species. The mountain represents the only known habitat in Arizona and the southernmost habitat overall for the Arizona willow (*Salix arizonica* Dorn). Because geology has tremendous influence over climate, topography, hydrology, and soil chemistry, it is essential to interpreting plant biogeography. However, many ecologists trying to explain the distribution of plants in the White Mountains have discounted or misrepresented the geologic variation of the area. For example, Sivinski and Knight (1996) concluded that substrate specialization was not an important factor governing plant endemism in the Mogollon Province, which extends from New Mexico to the White Mountains, because the area was "almost entirely volcanic in origin." The conservation agreement for the Arizona willow asserted that all but one population of this plant in New Mexico and Arizona occur on "basaltic (volcanic) soils" (AWITT 1995). Similarly, a conservation assessment characterized the habitat of the Mogollon Paintbrush (*Castilleja mogollonica* Pennell), which co-occurs with Arizona willow, as “basalt-derived” (Bainbridge and Warren 1992). Failure to recognize the potential confounding effects of geologic variation can result in faulty inferences concerning the distribution and status of species.

STUDY AREA

Mount Baldy has been studied and mapped by geologists beginning well over a century ago, when G. K. Gilbert described Mount Baldy as “massive eruptions of trachyte,” from which, “stretch, in every direction, long slopes of sanidin-dolerite

[basalt]" (Gilbert 1875). Gilbert's description of two distinctive lithologies has remained accurate to the present day, yet one of the first regional maps lumped the two types into "Quaternary-Tertiary basalt" (Wilson and Moore 1960). Melton (1961) was the first to describe numerous glacial deposits on Mount Baldy, while Finnell et al. (1967) observed that the volcano was composed of three major groups of volcanic rocks with different compositions. However, Merrill's dissertation (1974) was the first work to map various felsic volcanic, mafic volcanic, and epiclastic formations around the entire mountain.

A variety of volcanic and epiclastic flows created the White Mountains of Arizona. Between 23 to 12 million years ago, volcanic and volcaniclastic eruptions of predominantly andesitic to basaltic-andesitic petrology flowed across a wide area in east-central Arizona (Berry 1976). Atop this surface, felsic lava flows built the Mount Baldy volcano to an elevation of nearly 4000 m (Merrill 1974; Nealey 1989). The Sheep Crossing Formation resulted from volcaniclastic processes that caused colluvium and tuff to accumulate in the valleys at the base of the volcano (Merrill 1974). Starting approximately nine million years ago and continuing into the Quaternary, basaltic flows partially covered the older volcanic deposits (Merrill 1974; Condit 1984).

During the Quaternary Ice Ages, four distinct glacial events sculpted the two major peaks of the volcano, Mount Baldy and Mount Ord (Merrill 1974). The earliest glaciation was the most extensive, shaping five valleys that flowed in directions to the north, west, and east. The glaciers sculpted out U-shaped valleys and deposited small amounts of till on the slopes of the two peaks. Most of the material loosened by the glaciers was transported far away from the mountains where the streams were less steep (Merrill 1974). A very small glacier occurred on Mount Ord within the past 3000 years, while periglacial activity formed talus deposits in northeastern drainages of the Mount Baldy volcano and also shaped south-facing slopes (Merrill 1974).

METHODS

We prepared a composite geology map of the Mount Baldy area based on the maps by Merrill (1974), Wrucke and Hibpshman (1981), Condit (1984), and Nealey (1989). Onto this map, we plotted the reported locations of Arizona willow subpopulation (fig. 1). We identified subpopulations based on groups that occurred on separate drainages, or that occurred on the same drainage but were separated by at least 500 meters of apparently unoccupied habitat. For each subpopulation, we identified the geologic formations at the site. We also determined whether the watershed above the site was derived from felsic Mount Baldy formations or from basaltic formations. To compare the association between the Arizona willow and particular formations, we summed both the number of populations on each type and the estimated total numbers of Arizona willow on each type.

This overlay approach has several limitations. First, while all large stands of Arizona willow have probably been identified, small plants may have been missed. Consequently some subpopulations may not have been identified in small side drainages. Second, recent human impacts such as reservoir construction has altered plant distributions. However, in the dammed drainages where it occurs, the plant is still found above and below the reservoirs. Third, the geologic maps available for the area may be inexact, especially in describing drainage bottoms. Maps sometimes overrepresent younger formations that may

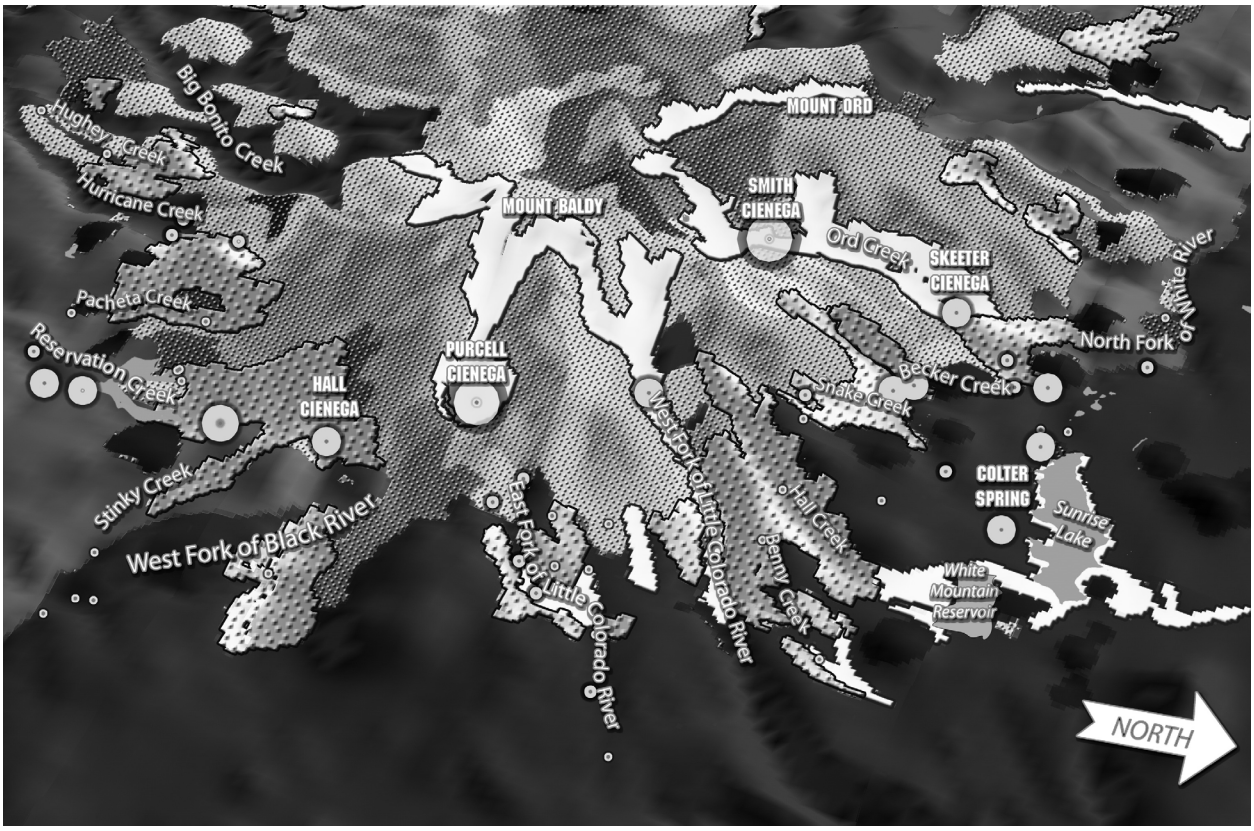

FIGURE 1: Three-dimensional view of geologic formations on the eastern face of Mount Baldy, overlaid by subpopulations of Arizona willow (outlined circles in proportion to estimated size). Fine stippling designates felsic volcanic rocks, coarse stippling designates the Sheep Crossing Formation, white designates glacial and alluvial formations, and dark gray and black designate older and younger basaltic formations, respectively.

have been eroded and replaced with alluvium from older, upstream formations. Despite the limitations of the approach, the results offer valuable insights into relationships between plants and the rocks beneath them.

Enumerating subpopulations of Arizona willow is difficult because individual plants are hard to separate. We used the estimates in the Arizona Willow Conservation Agreement (AWITT 1995) and the White Mountain Apache Tribe's Ecosystem Management plan for Arizona willow habitat (WMAT 1995). Both approaches applied a rule of counting plants separately where their stems were spaced more than 1 meter apart. However, estimated sizes of the largest subpopulations are likely to have large error terms due to the difficulty in counting the prostate form of this clonal species. The enumerations of both subpopulations and individual plants are used only to demonstrate geologic associations of the plant in relative terms.

RESULTS

Subpopulations occur in a 500 m elevation range, with the highest subpopulation in Smith Cienega (3050 m) and the lowest subpopulation in Hughey Creek (2550 m). Subpopulations are found between 2600 m and 2900 m in all three major watersheds draining Mount Baldy (White River, Black River, and Little Colorado River). Sub-populations occur in drainages that flow north, south, and east, but not in any drainages that flow primarily westward, except for a single plant on a slope above the North Fork of the White River (fig. 1).

The subpopulations are concentrated on landforms derived from the Mount Baldy volcanics (fig. 2), and most of the estimated individuals occur in glaciated reaches (fig. 3). The three largest and densest populations are located in large glaciated meadows (fig. 1 and fig. 3). These populations have been estimated in the hundreds to thousands (AWITT 1995). Large populations also occur in the glaciated valley of the West Fork of the Little Colorado River and in the extensive alluvial deposits along the East Fork of the Little Colorado River.

Nearly half of the populations occur in exposures of the Sheep Crossing Formation (fig. 2), primarily in the upper member of that formation. The Sheep Crossing Formation is texturally indistinguishable from glacial tills in the area, although it was deposited millions of years earlier from debris fans and mudflows from Mount Baldy (Merrill 1974). The only extensive outcrops of the Campground Member that are not associated with the Arizona willow are all located on the western half of Mount Baldy. Several other populations occur in areas mapped as basaltic, but in valleys downstream from Mount Baldy formations where the felsic substrates naturally deposit. All of these are located within 3.8 kilometers downstream from exposures of the Sheep Crossing Formation.

A few populations occur in areas mapped as basalt and are not downstream of exposures of Mount Baldy formations (fig. 3). These populations occur in the Snake Creek watershed and an adjacent tributary that flows into White Mountain Reservoir. This area has a more complex geology than superficial mapping suggests. The younger basalts, including highly porous cinders, form a relatively thin mantle over the older formations, including the Sheep Crossing Formation, as shown in cross-sections by Merrill (1974). Colter Spring (fig. 1), the location of the holotype specimen of Arizona willow, is a prominent example of one of the many springs in this area.

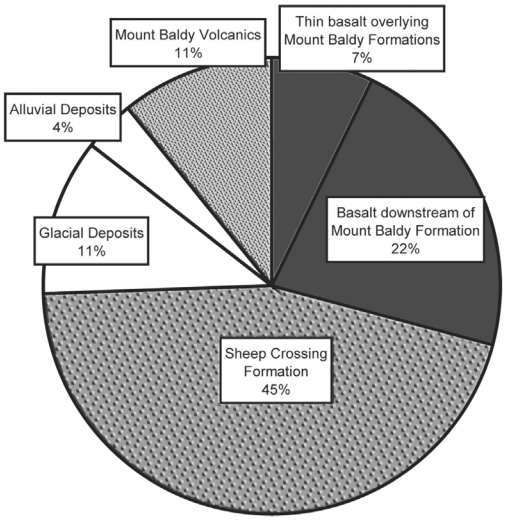

FIGURE 2: Percentage of estimated total Arizona willow subpopulations located on particular geologic formations.

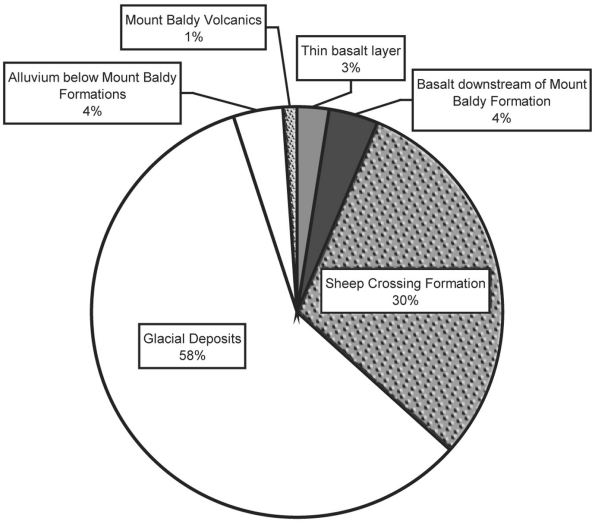

FIGURE 3: Percentages of estimated total Arizona willow individuals located on particular geologic formations

DISCUSSION

Many factors, including elevation, temperature, aspect, soil texture, soil chemistry, and past glaciation, could constrain the distribution of Arizona willow. Due to the evolutionary history of Mount Baldy, most of these factors are inherently correlated and therefore difficult to separate (Long et al. 2003). However, a combination of lithology and topography, or a "lithotopo type" (Montgomery 1999), is largely sufficient to explain the distribution of the species. Specifically, the willow inhabits areas where deposits of felsic Mount Baldy rocks have collected in wide valleys on the lower flanks of the volcano. Climatic regimes may further constrain the downstream and upstream limits of Arizona willow habitat, since there are alluvial deposits further downstream and at least one glacial deposit (Bull Cienega on Ord Creek) that are not inhabited by the plant. However, the distribution is not determined simply by elevation, because streams with spring flows at suitable elevations in basaltic areas have no evidence of Arizona willow, including Soldier Creek to the north, Big Bonito Creek to the Southwest, and Burro Creek to the east.

Influence of Geology on Edaphic Conditions

Differences in geology exert a variety of influences on soils that could account for differences in the suitability of habitat for Arizona willow. However, the most basic difference is soil texture. In Arizona, the substrates occupied by Arizona willow are derived from Mount Baldy formations, which are felsic rocks with greater than 50% silica content (Merrill 1974; Nealey 1989). As such silica-rich volcanics weather, they form relatively deep, acidic soils with low clay content and low organic matter content (Freeman and Dick-Peddie 1970). Riparian meadow soils derived from the Mount Baldy formations generally have more sand, less clay, less silt, and lower pH than soils derived from basaltic formations (Long et al. 2003). In Utah, all but one of eighteen Arizona willow populations sampled by Mead (1996) had over 30% sand in the uppermost mineral soil horizon (excluding sites that lacked mineral soils due to thick cover of peat). Coarse-textured soils may create more favorable habitat for the Arizona willow by increasing hydrologic conductivity and aeration.

Botanists have noted associations between soil aeration and growth of many willow species. Tall-growing willows of many species are associated with well-aerated mineral soils, while prostrate forms often occur in poorly-drained bogs with abundant fine organic matter (Brinkman 1974). In some cases (e.g., *Salix myrtillifolia* Anderss.), the tall- and low-growing forms of a single willow species have been so distinctive that the two forms were even classified as subspecies (Dorn 1975). For the Arizona willow, taller specimens were observed in microsites where they were sheltered from ungulate grazing (AWITT 1995). However, the occurrence of the prostrate growth form in lightly grazed areas was hypothesized to reflect the influence of finer-textured, less aerobic soils (AWITT 1995). Examining sites in Utah, Mead (1996) concluded that the tallest Arizona willows, and 75% of all stands with an average height greater than 100 cm, grew on Tertiary volcanic parent materials in alluvial flood plains with mineral soils. He also found that peat depth was negatively associated with Arizona willow height. Wetland successional processes such as the accumulation of fine sediments and decomposition of organic matter may reduce gas exchange and stimulate growth of bacteria, both of which

promote anaerobic conditions (AWITT 1995).

More complex differences in soil chemistry also could affect the physiology of the willow, yet it demonstrates considerable tolerance. Soil analyses revealed that Arizona willow sites in Utah are highly variable in chemical constituents, none of which seem to be constraining the species (Mead 1996). An isolated subpopulation has persisted at a site with high surface soil pH and low nutrient concentrations on the East Fork of the Sevier River (Mead 1996), demonstrating the species has the capacity to colonize a wide range of coarse substrates. Consequently, substrate preferences of the willow are more likely to be attributable to hydrologic properties than to chemical differences, although it is impracticable to entirely separate these attributes. Furthermore, while most transplants of Arizona willow into purely basaltic areas in the White Mountains apparently died (AWITT 1995), some have survived in Burro Creek (Granfelt 2003). Thus, available evidence suggests that the Arizona willow prefers coarse-textured soils, but it is not a strict substrate specialist.

Topography may reinforce lithology in maintaining favorable hydrologic conditions for Arizona willow. While basalt flows are typically flat, felsic volcanics form steep domes (Stokes 1986). Glaciers, mudflows, and landslides sculpt such steep landforms to form extensive deposits of gravels, sands, and boulders. Rinne (2000) reported that streams draining the Mount Baldy volcano, including glaciated drainages and those below the Sheep Crossing Formation, had higher concentrations of fine gravels than streams in areas of younger basalts. High permeability of the Sheep Crossing Formation relative to the surrounding volcanic formations enables it to serve as a thin aquifer (Merrill 1974), storing and conducting shallow groundwater to seeps and springs at the base of the mountain where the willows congregate. The Arizona willow most likely draws its water from the hyporheic zone rather than from runoff, as has been shown for its cousin and common associate, the serviceberry willow (*Salix monticola* Bebb) (Alstad et al. 1999).

Drainage Connections

Lithology and topography are not sufficient to explain the distribution of the plant, however, because there are extensive exposures of felsic rocks, glacial deposits, and Sheep Crossing Formation on the western slopes of Mount Baldy that are unoccupied. Aspect may partly explain this pattern, since the last major glaciation formed only a small glacier on the west-facing slope (at the head of the East Fork of the White River), while large glaciers occurred in three north- and east-facing drainages. This pattern suggests that north- and east-facing drainages were colder and/or moister. However, Arizona willow occurs in several south-facing drainages (e.g., Hurricance, Hughey, and Pacheta Creeks, fig. 1), indicating that the plant can tolerate warmer, drier aspects. Consequently, topographic barriers and drainage connections may explain why the plant does not occur on the western slopes of Mount Baldy. Subpopulations along Ord Creek are blocked from drainages to the west by the 300 m tall ridge extending from Mount Ord (fig. 1). Similar topographic obstacles may explain the southwestward limit on Arizona willow populations. The next drainage west of Hughey Creek is Big Bonito Creek, whose canyon has incised about 150 meters below the Mount Baldy formations into pre-Mount Baldy volcanic rocks.

We hypothesize that Arizona willow came to the White Mountains via the Little Colorado River, and that low drainage

divides and headwater stream transfers facilitated extension to the White and Black River watersheds. The drainage divides between the North Fork of the White River and the Little Colorado River and between the Little Colorado River and the West Fork of the Black River are both very low (<30 m), as are most of the divides between smaller tributaries in that area. Consequently, the eastern flank of Mount Baldy is a relatively gentle landform with shallowly incised streams. The steeper canyons of the North Fork of the White River and Big Bonito Creek may have captured streams on the edge of this plateau after the Arizona willow had become established there. Snake Creek and Becker Creek turn abruptly west to meet the North Fork of the White River, which has incised 150 m over the past 1.5 million years (Condit 1984). Behnke (1979) presumed that headwater transfers were important mechanisms in distributing fish species in the White Mountains.

The Role of Glaciation in Forming Arizona Willow Habitat

Some ecologists have argued that Pleistocene glaciation was a primary factor controlling the distribution of *Salix arizonica* and other willow species in the Southwest (Price et al. 1996). However, alpine conditions such as high elevation, cold temperatures, and increased precipitation not only are associated with past glaciation, but are also intrinsic to the volcanic formations that cap many of the plateaus and peaks of the Southwest. Given this inherent correlation and the limited fossil evidence of pre-glacial conditions, it is difficult to determine the role of glaciation in distributing the modern flora. Glaciation directly affected only five drainages in the White Mountains (Merrill 1974), and Arizona willow occurs in only three of the five. However, the climatic effects of glacial periods are evident well beyond these drainages. During the last glacial maximum, which ended about 14,000 years ago, temperatures were at least 5° C lower, precipitation may have been 20 to 25% higher, and tree-line was at least 800 m lower (Merrill 1974). Conditions were even colder during the previous two glacial periods (Merrill 1974). Consequently, almost all of the present habitat occupied by Arizona willow would have been above tree-line during the three major glacial episodes.

The environmental conditions associated with glaciation interacted with the pre-glacial landscape to produce the habitats presently occupied by the willow. For many willow species, factors that promote early seral conditions such as an open canopy and mineral soils may provide the best opportunity for seedling establishment. Consequently, the retreat of glaciers would have created optimal habitat for the Arizona willow within the occupied drainages, while periglacial activity such as frost action and rock glaciers formed talus piles in other drainages, notably Becker Creek (Merrill 1974). Heavy snows and rock slides rejuvenate willow shrubs and promote a more stable age structure of ramets (Price et al. 1996). Extensive reworking of these glacial and proglacial deposits would have created good habitat for willow colonization, as demonstrated by the strong correlations between willow pollen and influxes of sediment in Holocene records of willows reported from the San Juan Mountains of Colorado (Andrews et al. 1975).

Implications for Sustainability of Arizona willow subpopulations

In the White Mountains, Arizona willow is presently well-distributed throughout the glacial tills and exposed Sheep Crossing Formation except on the

western slopes of Mount Baldy and Mount Ord. The distribution does not suggest that Arizona willow habitat has been eliminated from a broader area that includes purely basaltic drainages, as some other researchers have suggested (AWITT 1995). Researchers have reported death of individual plants and extirpation of small populations following severe infections of a fungus (*Melamspora epitea*) (AWITT 1995). Differences in habitat quality associated with geologic variation may influence the vulnerability of particular subpopulations. The White Mountains have experienced significant warming and drying in the past decade, resulting in severe defoliation of spruce trees in high-elevation forests (Lynch 2004). This period coincides with the reports of deteriorating Arizona willow habitat. Lower elevation subpopulations more commonly assume the tall growth form, which is associated with lower water tables (AWITT 1995; Mead 1996). Consequently, subpopulations that occur at lower elevations in basaltic areas may more vulnerable to drought, disease, insects, and ungulate impacts due to naturally warmer and drier conditions. The glacial deposits that harbor the largest subpopulations of Arizona willow are colder and wetter. These subpopulations are mostly in the prostrate form, similar to low-growing willow species that are accustomed to alpine environments. Because they occur at higher elevations, these populations may be better buffered from the impacts of warming.

Other ecologists have observed that extensive coarse-textured alluvial and colluvial deposits may have special biological significance because they maintain extensive hyporheic exchange zones (Jensen and Goodman 2001). This association may help to understand the distribution of the Arizona willow and the Mogollon paintbrush. However, consideration of other rare plants in the White Mountains demonstrates that rare plant-geology associations are often individualistic. For example, the Bebb willow (*Salix bebbiana* Sarg.) is most commonly found in basaltic meadows (Long et al. 2003), and it overlaps with Arizona willow only at the lower edge of the latter's range (Granfelt 2004). While the conservation agreement for the Arizona willow (AWITT 1995) states that the willow "occurs in the same ecosystem" as the endemic Mogollon clover (*Trifolium neurophyllum* Greene), others have observed the clover only in association with basaltic soils (Ladyman 1996). On the other hand, the Mogollon clover's close relative, the pygmy clover (*Trifolium longipes* Nutt. var. *pygmaeum* (Gray) J. Gillett), does co-occur with Arizona willow in both Arizona (JWL, personal observation) and in Utah (Mead 1996). Gillet (1969) suggested that because the two closely related clovers are both found in the White Mountains, they would be likely to hybridize. However, geologic segregation might reduce the potential for interbreeding.

The Arizona willow's association with epiclastic formations on the flanks of Mount Baldy has important implications for conservation of the species. Monitoring of the species' status should distinguish between subpopulations in marginal habitats at low elevations in basaltic areas and subpopulations in the preferred lithotopo type. Low elevation populations will probably continue to suffer under a warmer, drier climate, while the glaciated meadows will serve as refugia for this ancient species. Efforts to stimulate reproduction or expand populations of this plant will be more likely to succeed in areas with sandy-gravelly substrates and abundant groundwater supplies. Efforts to conserve the biodiversity of the White Mountains and other high-

elevation landscapes of the Southwest should consider fine-scale geology variation on the distribution and demographics of rare species.

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