MOJAVE DESERT NATIVE PLANTS: BIOLOGY, ECOLOGY, NATIVE PLANT MATERIALS DEVELOPMENT, AND USE IN RESTORATION

BUSH MUHLY

Muhlenbergia porteri (Scribn. ex Beal)

Poaceae - Grass family

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ORGANIZATION

NOMENCLATURE

Bush muhly (*Muhlenbergeria porteri* Scribn. ex Beal) (USDA NRCS 2022) belongs to the Poaceae or grass family. It is in the subfamily Chloridoidea which is characterized by adaptations in leaf anatomy and a C_4 photosynthetic pathway especially suited for warm and arid climates (Barkworth et al. 2007).

NRCS Plant Code.

MUPO2 (USDA NRCS 2022).

Synonyms.

Muhlenbergia texana Thurb. ex Porter & J.M. Coult., *Podosemum porteri* (Scribn.) Bush (ITIS 2023).

Common Names.

Bush muhly, zacate aparejo (Spanish), ku:kpadag (Tohono O'Odham), hoe grass, Porter's muhly, mesquite grass (Wolf 2019, SEINet 2023).

Black grama, which is now the primary common name for *Bouteloua eriopoda*, was commonly used for *M. porteri* in publications during the early- to mid-1900s (USDA 1937).

Subtaxa.

No varieties or subspecies are currently recognized by the Flora of North America (Peterson 2012) or the Integrated Taxonomic Information System (ITIS 2023).

Chromosome Number.

Reported chromosome counts for bush muhly are 2n=20, 23 ,24, and 40 (Peterson 2012, CCDB 2023).

Since bush muhly possesses intraspecific ploidy variation (differences in chromosome numbers between populations), it may be necessary to assess the cytotypes of populations prior to mixing seed sources or starting propagation. Combining incompatible cytotypes can result in loss of fitness and fertility in plantings (Kramer et al. 2018).

Hybridization.

There is no evidence of hybridization between bush muhly and other species.

DESCRIPTION

Bush muhly is a perennial, shrub-like grass that grows 25-100 cm tall (Peterson 2021; Figure 1). Bush muhly grows in dense tufts from a knotty base and is not rhizomatous (Peterson 2021, SEINet 2023). Its bushy appearance is due to many freely branching stems which diverge at sharp angles. Plants do not die back to the ground in dormant periods and can readily respond to rainfall with new growth at axial buds, creating many branching nodes that become knot-like at the base of the plant (Peterson 2012, McAuliffe 2016).

The internodes are slightly rough to the touch. Blades are 2-8 cm long and 0.5-2 mm wide and can be flat or folded with rough undersides (Peterson 2021). The truncate, toothed and membranous ligules (1-2.5 mm long) decurrently extend along the sheath margins (Peterson 2012, 2021). The open, glabrous sheaths spread away from the stems and are shorter than the internodes (SEINet 2023).

The inflorescence is a red- to purple-tinged spreading panicle, ovate in outline, 5-15 cm wide, with thread-like branches terminating in spikelets comprised of a single floret (Figures 2 and 3). The spikelets include glumes that are 2-3 mm long, taper to a point, and occasionally have short awns (<1 mm). Lemmas are 3-4.2 mm long, hairy on the lower portions of the margins and midveins, and with a 2-10 mm long delicate awn. The anthers are 1.5-2.3 mm long and can be purple to yellow (Peterson 2012). The caryopses (seeds) are 2-2.4 mm long, oblong, compressed, and yellowish-brown (Peterson 2021).

Bush muhly is a warm-season grass that utilizes the C_4 photosynthetic pathway which allows it to minimize water loss to photorespiration (Aleksoff 1999).

Figure 1: A robust bush muhly individual growing in the open. Photo: BLM SOS NM930

Figure 2: The open panicle of bush muhly. Photo: Patrick Alexander

Figure 3: Single florets and capillary awns of bush muhly Photo: Patrick Alexander

DISTRIBUTION AND HABITAT

Bush muhly occurs throughout the warm desert regions of the southwestern United States and northern Mexico (Figure 4). It is common within the central and eastern portions of the Mojave Desert—specimen records are densely clustered in the Ivanpah and Shadow Valleys near the California and Nevada border, likely due to sampling bias in and around the Mojave National Preserve (SEINet 2022; Figure 4). It is widespread and fairly common throughout the Sonoran and Chihuahuan Desert scrub and grassland communities. It is also abundant in semi-desert grasslands of the Madrean Archipelago ecoregion which bridges the Chihuahuan and Sonoran Deserts. Its distribution suggests it may do best in regions that receive some amount of summer monsoonal precipitation as opposed to the more unimodal winter precipitation patterns further west in the Mojave Desert.

Within the Arizona-New Mexico Plateau ecoregion, it occurs in the Grand Canyon of the Colorado River and its tributaries, in high desert grasslands around the Four Corners region, and along the middle Rio Grande in New Mexico.

Bush muhly is also found in the lower elevation grasslands and juniper woodlands in the Arizona-New Mexico Mountains ecoregion in areas bordering warm desert ecoregions. It becomes sporadic towards the edges of its range in the Colorado Plateau, High Plains, and Central Basin and Range ecoregions.

Perennial, warm-season grasses were historically more prevalent in portions of the Mojave and Sonoran Deserts (Chew 1982, McAuliffe 2016). Heavy cattle grazing and fire suppression during European colonization likely contributed to declines in perennial grass species, including bush muhly (Warren and Anderson 1987, Felger et al. 2014, McAuliffe 2016). The species experienced evident declines and local extirpations in response to heavy cattle grazing in the Sonoran (Warren and Anderson 1987) and Mojave Deserts (McAuliffe 2016), but populations naturally rebounded in some areas where cattle were removed following the establishment of national monuments.

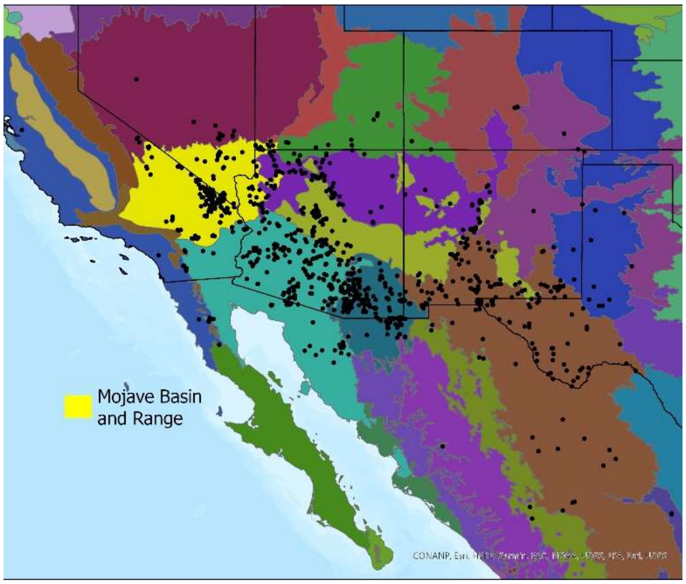

Figure 4: Distribution of bush muhly based on georeferenced herbarium specimens and verified observations (black circles, SEINet 2022) with EPA Level III Ecoregions (US EPA 2015). The Mojave Basin and Range ecoregion is shown in yellow.

Habitat and Plant Associations.

Bush muhly generally grows in dry sandy washes or stream terraces, open desert flats and bajadas, and rocky slopes among boulders and cliffs (SEINet 2022).

NatureServe recognizes one ecosystem division, one habitat group, and seven habitat associations defined by the presence of bush muhly, indicating its importance as a dominant to subdominant member of vegetation communities across the warm desert regions (NatureServe 2022). Neither the habitat group nor any of the habitat associations are within the Mojave Desert.

In areas that experience any level of livestock grazing, it is typically found beneath the protection of shrubs (SEINet 2022). However, it can occur in more open areas in the absence of livestock (McAuliffe 2016). Protective shrubs include cresosote bush (*Larrea tridentata*), desert-thorn (*Lycium* spp.), mesquite (*Prosopis* spp.), and catclaw acacia (*Acacia greggii*).

In the Chihuahuan and Sonoran Deserts, bush muhly is found in semi-desert grasslands where it grows with velvet mesquite (*Prospis velutina*), bristlegrass (*Setaria leucopila*), cane beardgrass (*Bothriochloa barbinodis*), Arizona cottontop (*Digitaria californica*), and Lehmann lovegrass (*Eragrostis lehmanniana*).

Figure 5: Bush muhly in a desert scrub habitat in California. Photo: BLM SOS CA930A

Mojave Desert.

In the Mojave Desert, bush muhly can be found in desert scrub and Joshua tree woodlands.

In addition to the protective shrub species listed above, bush muhly is associated with Mojave yucca (*Yucca schidigera*), burrobush (*Ambrosia dumosa*), Joshua tree (*Yucca brevifolia*), slim tridens (*Tridens muticus*), big galleta (*Pleuraphis* *rigida*), Jame's galleta (*Pleuraphis jamesii*), black grama grass (*Bouteloua eriopoda*), Mexican bladdersage (*Salazaria mexicana*), blackbrush (*Coleogyne ramosissima*), and Nevada joint-fir (*Ephedra nevadensis*) (BLM SOS 2022, SEINet 2022).

Figure 6: Bush muhly growing in an open desert habitat in California. Photo: BLM SOS CA930A

Climate.

The Mojave Desert is characterized by low annual precipitation (2-10 inches or 5-25 cm in valley areas), with most rainfall occurring in the winter and a smaller amount during summer thunderstorms (Randall et al. 2010). Heterogenous climate patterns across the region are influenced by large-scale patterns and regional topography and are important drivers of local adaptation and intraspecific variation (Shryock et al. 2018, Baughman et al. 2019) and phenological events (Beatley 1974). Specifically, the reproductive phenology of many desert plant species is highly responsive to pulses in rainfall over short time scales (Bowers and Dimmitt 1994, Zachmann et al. 2021).

Climate information is derived from the climate-based provisional seed transfer zones (PSZs) where bush muhly occurs (Shryock et al. 2018; Table 1). According to herbarium specimen locations, bush muhly occurs in most PSZs in the Mojave Desert ecoregion but is absent in zones 22 and 28 (Table 1). It is most abundant in zones 20 and 23 and least abundant in zone 27. Bush muhly seems to be more abundant in seed zones that have higher summer precipitation—these are also seed zones that more closely border the Sonoran Desert where monsoonal summer precipitation is more prevalent than in the western portion of the Mojave Desert. The average annual precipitation in the PSZs where bush muhly occurs in the Mojave Desert ecoregion is 16.7 cm (6.6 inches), with an average of 5.2 cm (2.0 inches) falling in the summer and an average of 11.6 cm (4.6 inches) falling in the winter. Herbarium specimen locations may not represent the full distribution and abundance of bush muhly due to sampling bias towards accessible locations.

Elevation.

Bush muhly is typically found at elevations between 2,000-6,000 ft (610-1829 m) (SEINet 2022).

Soils.

Bush muhly occurs in coarse, well-drained soils. It is often found on sandy to fine gravelly soils of young alluvial deposits and stream terraces (McAuliffe 2016). Parent materials include limestone, granite, and basalt (SEINet 2022). It can tolerate calcium carbonate, but not high salinity soils (Wolf 2019).

No associations with biological soil crusts were noted in the literature.

Table 1: Climate of the provisional seed zones (PSZ) where bush muhly occurs within the Mojave Desert ecoregion (Shryock et al. 2018).# = the number of herbarium or verified observations of bush muhly within the PSZ (SEINet 2022); MAP=mean annual precipitation; SP=summer precipitation, or the mean precipitation that falls in the summer (May-October); WP= winter precipitation, or the mean precipitation that falls in the winter (November-April); MAT=monthly average temperature; Range= Average of the monthly temperature ranges (monthly maximum minus monthly minimum).

PSZ	#	MAP (cm)	SP (cm)	WP (cm)	MAT (C)	Range (C)
20	103	25.5	10.5	14.9	15.3	34.5
23	101	15.8	5.4	10.4	16.1	35.9
25	37	16.5	6.2	10.3	18.9	34.6
21	36	15.6	6.2	9.4	18.8	38.4
29	14	25.5	4.2	21.4	13.8	31.7
24	11	10.7	2.8	7.9	18.8	38.6
26	10	14.5	2.7	11.8	16.8	34.9
27	4	9.6	3.3	6.3	20	36.7

ECOLOGY AND BIOLOGY

Bush muhly is considered a drought-tolerant climax species (Aleksoff 1999, USU Extension 2023). Its tendency to grow in the protection of shrubs is attributed to nearly complete removal by livestock of the highly palatable grass in open areas not protected by impenetrable canopies of shrubs (Aleksoff 1999, Felger et al. 2014). Bush muhly does not seem to establish readily after fire, especially fires intensified by invasive annual grasses (e.g., Bromus spp.) in desert grasslands (Aleksoff 1999).

Reproduction.

Breeding System.

No literature describing bush muhly's breeding system was found. The genus *Muhlenbergia* includes species with cleistogamous panicles where inflorescences are retained in sheaths and able to self-fertilize (Connor 1979). However, bush muhly panicles are fully open at maturity and it is likely outcrossing (Peterson 2012).

Reproductive Phenology.

Bush muhly will typically flower from August to November, following summer rains in the eastern Mojave Desert (SEINet 2022). In the northern Chihuahuan Desert, flowering may occur as early as April to May (Aleksoff 1999). Fruits mature in the late summer and early fall (BLM SOS 2022).

In a study of phenology patterns across the Mojave Desert, Browning et al. (2018) found that bush muhly exhibited annual variation in phenological timing, but was synchronous in timing of first seed set and initial growth across seven sites within each year. This indicates that within a given year, bush muhly may undergo certain phenological events at approximately the same time across sites, but the timing will vary year-to-year at a given site (Browning et al. 2018).

Pollination.

Like all grasses, bush muhly is wind-pollinated (Connor 1979).

Seed and Seedling Ecology.

Bush muhly regenerates from seeds which are dispersed by wind and animals (Aleksoff 1999). Specifically, cactus wrens (*Campylorhynchus brunneicapillusis*) are important dispersers of bush muhly seeds (Milton et al. 1998). They utilize the grass for the majority of their nest materials and viable seeds have been found in nests up to 213 feet (65 m) from source plants (Milton et al. 1998). Mature panicles also break off as a single unit and scatter in the wind, dispersing seeds in the process (Felger et al. 2014).

Generally, bush muhly seeds will germinate from February to April, as soil temperatures start to warm (Aleksoff 1999). Germination rates and seedling growth are inhibited by both extreme cold and extreme heat (Sosebee and Herbel 1969, Roundy and Biedenbender 1996).

In an experimental study of germination response to various temperature regimes, Roundy and Beidenbender (1996) found that bush muhly seeds from the Sonoran and Chihuahuan Deserts exhibited markedly low germination under winter temperatures and noted the species to be "especially sensitive to cold temperatures." They found optimum germination temperature for bush muhly to be 30 °C (86 °F) (Roundy and Biedenbender 1996).

Another experimental study of how temperature affects seed germination and seedling growth in a light chamber found that bush muhly had optimal germination (84%) when temperatures alternated between 20 °C (68 °F) at night and 35 °C (95 °F) during the day (Sosebee and Herbel 1969). They also found bush muhly seedling survivorship was highest (94%) with a maximum soil temperature of 53 °C (122 °F) (Sosebee and Herbel 1969).

In a study of factors influencing bush muhly germination in southern Arizona grasslands, researchers found that bush muhly germinated after at least three days of available soil moisture (Livingston 1992).

Using seeds sourced from southern Arizona, Cavin (1949) found that bush muhly had highest germination under temperatures of 32 °C (90 °F) to 38°C (100 °F) and that germination decreased with temperatures below 32 °C (90 °F).

Collectively, these studies support that summer temperature conditions in the warm desert regions may be optimal for bush muhly germination and emergence. However, no studies were found about bush muhly germination in the Mojave Desert. Ecotypic population patterns and local climate variation may influence germination response (Rosbakh and Poschlod 2015).

Bush muhly seeds treated with extracts of creosote bush have reduced radicle and shoot growth, indicating creosote bush may inhibit bush muhly seedling establishment due to water-soluble chemical compounds from creosote bush that can leach into the soil (Knipe and Herbel 1966).

Species Interactions.

Belowground Interactions.

No information on belowground interactions between bush muhly and soil organisms was found in literature or personal communications. However, the majority of vascular plants have some level of mutualism with mycorrhizal fungi and these relationships can be especially critical for plants in arid ecosystems (Titus et al. 2002).

Insect Herbivory.

Bush muhly is a larval host plant for the range caterpillar moth (*Hemileuca oliviae*) (Robinson et al. 2010), which occurs in grasslands primarily in New Mexico. The caterpillars, whose stinging hairs can irritate livestock, exhibit periodic outbreaks in which they feed on forage grasses and can greatly reduce grass cover, which results in less forage for livestock and can facilitate accelerated erosion (Lotts and Naberhaus 2021).

It may also be a host plant for the white-lined sphinx moth (*Hyles lineaata*) (Calscape 2023).

Wildlife and Livestock Use.

Birds and Wildlife.

Bush muhly is a preferred forage plant for the threatened Mojave desert tortoise (*Gopherus agassizii*) (Esque et al. 2021). Desert tortoises will also use the grass for cover while foraging (Felger et al., 2014).

Bush muhly can provide nest material for a variety of bird species. In an area where creosote bush has been treated with herbicides, black-throated sparrows (*Amphispiza bilineata*) and Cassin's sparrows (*Peucaea cassinii*) preferentially nested in dead shrubs surrounded by dense growth of bush muhly (Smith 1984). Bush muhly is also a dominant nest material for scaled quail (*Callipepla squamata*) in the Chihuahuan Desert in Texas (Buntyn et al. 2017).

Due to its bushy growth form, bush muhly can provide cover for small mammals (Aleksoff 1999). Although bush muhly is a diet item for jackrabbits, its cover did not differ between lagomorph excluded versus unexcluded plots over a 50-year period in the Chihuahuan Desert (Gibbens et al. 1993).

Livestock Grazing.

Bush muhly is palatable and nutritious to livestock, particularly during drought or winter when other grasses are dormant (McAuliffe 2016). This is due to its growth habit and resource allocation: bush muhly does not die back completely to the ground and instead retains living aboveground biomass where most of the plant's carbohydrate reserves are stored. The aboveground stems can quickly grow new leaves and shoots from axillary buds in response to small amounts of precipitation (McAuliffe 2016). However, its elevated apical meristems and axillary buds make the growing points vulnerable to removal, rendering bush muhly less resistant to grazing (Miller and Donart 1981). The combination of high palatability with low resistance to grazing contributes to its vulnerability to overgrazing and its tendency to grow in protection of shrubs. Plants are damaged when continuously grazed to a height of less than 10 cm (4 inches) (USU Extension 2023).

Negative impacts of grazing on bush muhly can be mitigated based on timing and frequency of grazing. Continuous and late season grazing, especially during late summer flowering and seed ripening stages, have the greatest impact on bush muhly fitness (Miller and Donart 1981, Angell and McClaran 2001). To maintain stands of bush muhly, it is best to reduce utilization to less than 65% and limit grazing until after plants have set seed (Miller and Donart 1981). Deferring grazing in late summer every second or third year can allow the plants to set seed and increase regeneration potential (Allison and Ashcroft 2010).

Bush muhly is also one of the most abundant species in feral burro diets in the Mojave Desert (Abella 2008) and in Grand Canyon National Park (Jordan et al. 1980), despite it being a minor component of the overall vegetation.

Other Notable Species Interactions.

In addition to providing protection from livestock grazing, areas beneath shrubs such as mesquite (*Prosopis* spp.) can have higher nutrient availability than open areas (Tiedemann and Klemmedson 1973). However, the relationship between bush muhly and creosote bush can be inhibitory to both species as they compete for moisture, nutrients, and sunlight while sharing a common footprint (Welsh and Beck 1976, Castellanos-Perez 2000). In a study in the

Chihuahuan Desert, researchers found that creosote bush growing without bush muhly had higher photosynthesis rates and stomatal conductance than those growing with bush muhly, suggesting that bush muhly can negatively impact the ecophysiology of creosote bush (Castellanos-Perez 2000). Similarly, they found that bush muhly growing alone had higher net assimilation rate (rate of increase of dry weight per unit of leaf area) than plants growing with creosote bush (Castellanos-Perez 2000). Bush muhly has also been shown to increase in cover when creosote bush live canopy was reduced after herbicide (dicamba) treatments, potentially due to release from competition and inhibition (Whitford et al. 1978).

Disturbance Ecology.

Bush muhly is commonly considered a climax species (Aleksoff 1999).

Generally, bush muhly can likely regenerate after fire from the seedbank, though information on regeneration is lacking in the literature (Aleksoff 1999). Recovery time will likely vary considerably based on climate and competition with more disturbance-tolerant species (Moody et al. 2010). Several studies and anecdotal observations indicate bush muhly has poor establishment after fires in desert grasslands, especially those invaded by grasses such as cheatgrass (*Bromus tectorum*), red brome (*Bromus rubens*), and Lehmann lovegrass (*Eragrostis lehmanniana*) (Biedenbender and Roundy 1996, Aleksoff 1999, Monasmith et al. 2010). Due to its dense growth form, bush muhly may contribute to fire spread (Aleksoff 1999). It may be susceptible to higher fire temperatures when growing beneath shrubs where fuel loads are typically higher (Aleksoff 1999).

Ethnobotany.

The Tohono O'odham word for bush muhly, ku:kpadag, means "plant formerly used to close water containers", suggesting that clumps of the grass were used as stoppers for water jugs (Hill and Zepeda 1974 as cited by Wolf 2019).

Early Euro-American settlers and soldiers would gather large quantities of bush muhly for feed for their animals (Allred 2005). The common name "hoe grass" comes from this manner of use. Whole plants were removed from the ground with a hoe and collected for livestock feed (Allred 2005).

Horticulture.

Bush muhly does not seem to be commonly used as a landscaping or ornamental plant, though it is available for retail purchase from a limited selection of commercial nurseries (Calscape 2023).

DEVELOPING A SEED SUPPLY

A robust and stable supply of genetically appropriate seed is needed to meet restoration demands in response to expanding environmental stressors from land degradation, invasive species, and climate change. Restoration success is, in part, predicated on applying the right seed in the right place, at the right time (PCA 2015). Developing a restoration seed supply involves coordination across many partners in all steps of the process: from conducting wildland collections to propagating materials in nurseries and agricultural fields to eventual seeding or outplanting at restoration sites. Appropriate protocols for preserving genetic diversity and adaptive capacity should be in place (Erickson and Halford 2020) and seed origin should be documented for certification purposes and other seed planning considerations.

Seed Sourcing.

Seed sourcing can influence restoration outcomes due to local adaptation (Custer et al. 2022), landscape genetic patterns (Massatti et al. 2020, Shryock et al. 2021) and differing ability to adapt to current and future climate conditions (Bucharova et al. 2019). However, there has been relatively little research evaluating seed sourcing strategies in actual restoration settings where many additional factors influence performance (Pizza et al. 2023). While non-local sources can perform well in meeting initial restoration goals such as establishment and productivity (Pizza et al. 2023), plants have coevolved with interacting organisms, such as pollinators and herbivores, that can exhibit preferential behavior for local materials (Bucharova et al. 2016, 2022). Further, evidence of local adaptation and its influence on restoration outcomes can take decades to emerge for long-lived species (Germino et al. 2019).

Empirical seed transfer zones have not been developed for bush muhly. The Desert Southwest Provisional Seed Zones (PSZs) may be used to plan seed sourcing in absence of species-specific information (Figure 7). The Desert Southwest PSZs use twelve climatic variables that drive local adaptation to define areas within which plant materials may be transferred with higher probability of successful establishment and reduced risk of introducing maladapted ecotypes (Shryock et al. 2018). Overlaying PSZs with Level III ecoregions can serve to further narrow seed transfer by identifying areas of both climate similarity inherent in the PSZs and ecological similarity captured by the ecoregion, namely vegetation and soils. Within the PSZs and ecoregion areas, further site-specific considerations such as soil, land use, species habitat and microclimate affinities, and extant plant community may be relevant to seed sourcing decisions.

The USGS Climate Distance Mapper Tool incorporates the Southwest Deserts Seed Transfer Zones with climate models and can serve to guide seed sourcing according to current and projected climate conditions.

Commercial Seed Availability and Germplasm Releases.

Limited amounts of bush muhly can be available for purchase from large-scale commercial seed vendors. However, availability may be inconsistent, and sources may be limited to a narrow range of appropriate seed zones. Commercially available seed may not be source identified, and source seed zone information may not be available. There have been no conservation plant releases of bush muhly.

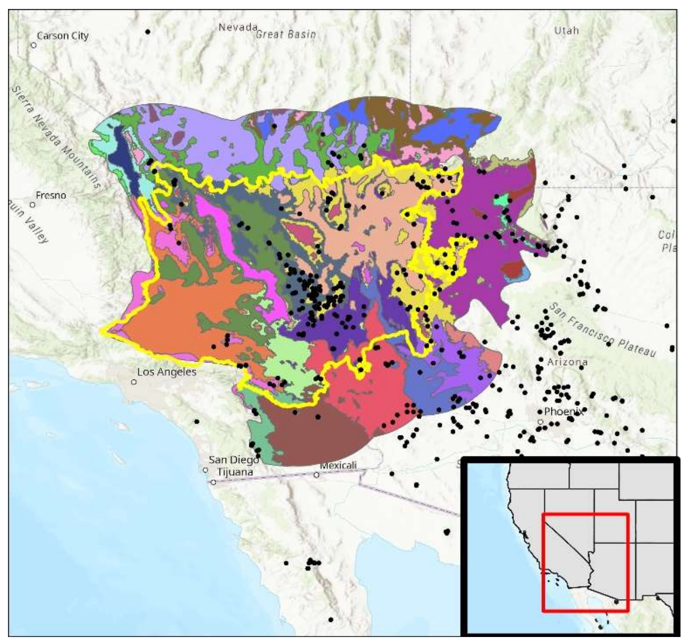

Figure 7: The distribution of bush muhly across the Desert Southwest Provisional Seed Zones (Shryock et al. 2018). Occurrences (black dots) are based on georeferenced herbarium specimens and verified observations (SEINet 2022). The Mojave Basin and Range Level III ecoregion (yellow outline) is buffered up to 100km in all directions. PSZs do not always extend a full 100km beyond the Mojave ecoregion.

Wildland Seed Collection.

Wildland seed collection involves visiting naturally occurring populations of target species to provide source seed for propagation, restoration, and research. Ethical practices are intended to prevent overharvesting by limiting harvesting no more than 20% of available seed (BLM 2021). However, in arid regions and in drought conditions, it may be best to adapt this guidance to collect no more than 10% of available seed due to limited regeneration and low-density populations (Asbell 2022, personal communication). Several practices are in place to ensure proper genetic diversity is captured from the source population. These include collecting from the entire population uniformly, sampling a diversity of phenotypes and microclimates, and collecting in various time windows to capture phenological and temporal diversity (BLM 2021).

Seed Collection Timing.

In the Mojave Desert, bush muhly is typically collected September through November with the majority of collections occurring in October (BLM SOS 2022).

Collection Methods.

In drought years, bush muhly plants may form panicles and flowers, but fail to develop seed (Kleiner 2023, personal communication). To assess seed set prior to collection, florets can be placed in the palm of the hand and rubbed with the alternate hand to break down the bracts and expose the tiny caryopses (Ashlee Wolf, personal observation). Holding the panicle up to sunlight can also give insight into the presence or absence of caryopses within the florets (Ashlee Wolf, personal observation).

Seed can be collected by hand into a paper bag, stripping florets from the panicles by running a hand upwards along the rachis or snapping whole panicles and placing them into the bag (Ashlee Wolf, personal observation).

Wild collections can include significant amounts of chaff or non-seed material (compare bulk weight to clean weight in Table 2), likely due to the small seed size and methods where whole panicles or portions of panicles are collected.

Figure 8: Collected material of bush muhly including whole panicle segments. Photo: BLM SOS NM930

Post-Collection Management.

Immediately following collection, seeds should be properly managed to avoid damage or declines in viability during transport and temporary storage. Seed should be dried and ventilated to prevent molding (Pedrini and Dixon 2020). Ventilation can be achieved by collecting and storing seed in breathable containers, such as paper or cloth bags.

To dry material before storage or processing, spread it in a single layer on trays or newspaper indoors in a well-ventilated room, or outdoors in a shaded area (BLM 2021). Collected material should be visually inspected for seed-predating insects (Pedrini and Dixon 2020). If seed predation is observed, consider fumigation with No-Pest Strips. After collection, prevent exposure to excessively hot or cold temperatures during transportation and temporary storage by keeping seed in a dry, insulated container (e.g., a cooler) in a shaded area while in the field (BLM 2021).

Figure 9: Collected florets of bush muhly; scale shown in cm. Photo: BLM SOS CA930A

Figure 10: Florets (left) and naked cariopses (right). Photo: Patrick Alexander

Seed Cleaning.

Due to its very small seeds and lightweight, abundant chaff, bush muhly is exceedingly difficult to clean, even with agricultural seed cleaning equipment (Saidnawey and Cain 2023, Dial 2023, personal communication). Bush muhly can be processed with a Westrup LA-H Lab brush machine with #10 mantel with the end open to allow stems to escape, followed by sieving to remove all large stemmy material, and then running it through an air separator at low speed to minimize seed loss (Saidnawey and Cain 2023).

It can also be cleaned using a rubbing board to break down panicles just prior to sowing (Dial 2023, personal communication).

Larger amounts of seeds, such as those harvested from a seed increase field, can be cleaned by processing with a hammermill or brush machine to break up the panicles followed by air screening (Wolf 2019).

Seed Storage.

In general, seeds should be stored in cool and dry conditions, out of direct sunlight, to maintain viability. Optimal conditions for medium-term storage of orthodox seeds (up to 5 years) are 15% relative humidity and 15° C (59° F). For long-term storage (>5 years), completely dried seeds should be stored at -18° C (0° F) (De Vitis et al. 2020, Pedrini and Dixon 2020).

Bush muhly seed is orthodox (SER SID 2023). Seeds stored under ideal conditions at the Royal Botanic Gardens Kew exhibited 100% germination in a 1% agar medium under 26 °C (79 °F), though the storage duration is not specified in this record (SER SID 2023).

Seed Testing.

After collection, a representative sample of each seed lot must be tested in an appropriate seed lab to ensure purity and germination meet minimum standards defined by the Association of Official Seed Analysts (AOSA 2016) and species standards from state-level certification programs as available. A set of “principles and standards for native seeds in ecological restoration” (Pedrini and Dixon 2020) outlines further guidelines specific to native plants, including procedures for obtaining representative samples of seed lots and incorporation of dormancy measures into seed testing and labels.

The pure seed unit—a combined unit of seed and attached structures that is classified as pure seed as opposed to inert material—for bush muhly is defined by AOSA as a "single floret…with or without awn(s), provided a caryopsis with some degree of endosperm development can be detected" (AOSA 2016).

The AOSA does not specify guidelines for testing germination, viability, or purity of bush muhly seed or congeners (AOSA 2016).

Wildland Seed Yield and Quality.

Wild-collected bush muhly seed is of fair quality, with an average of 78% fill, 85% purity and 72% viability indicated by tetrazolium tests of Seeds of Success (SOS) collections (BLM SOS 2022, Table 2). Wild collections contain an average of over 1,600,000 Pure Live Seed (PLS) per lb (BLM SOS 2022, Table 2). Bush muhly exhibits a wide range in PLS per lb, with the maximum being 4.5 times greater than the minimum, potentially due to variation in seed maturity at the time of collection.

Collectors should be careful to examine florets for developed caryopses (see Collection Methods)—two collections processed at the Bend Seed Extractory were found to have no actual seeds in the delivered materials (BLM SOS 2022), likely due to lack of examination at the time of collection.

Table 2: Seed yield and quality of bush muhly seeds collected in the Mojave Basin and Range Ecoregion, cleaned by the Bend Seed Extractory and tested by the Oregon State Seed Laboratory or the USFS National Seed Laboratory (BLM SOS 2022). Fill (%) was measured using a 100 seed X-ray test. Viability (%) was measured using a tetrazolium chloride test.

	Mean	Range	Samples
Bulk weight (lbs)	0.67	0.1-6.14	20
Clean weight (lbs)	0.01	0.0003-0.06	20
Purity (%)	85	32-99	20
Fill (%)	78	20-99	20
Viability (%)	72	24-94	16
Pure live seeds/lb	1,663,267	642,018-2,901,452	20

Wildland Seed Certification.

The Association of Official Seed Certifying Agencies (AOSCA) sets the standards for seed certification and provides guidance on production, identification, distribution, and promotion of all certified seed, including pre-varietal germplasm. Pre-varietal germplasm (PVG) refers to seed or other propagation materials that have not been released as varieties (AOSCA 2022). Pre-varietal germplasm certification programs for source-identified materials exist in several states encompassing the Mojave Desert ecoregion including California (CCIA 2022), Utah (UTCIA 2015), and Nevada (NDA 2021). Arizona does not have a PVG certification process at this time. Source-Identified (SI) germplasm refers to seed collected directly from naturally occurring stands (G0), or seed grown from wildland-collected seed in agricultural seed increase fields (G1-Gx) that have not undergone any selective breeding or trait testing. These programs facilitate certification and documentation required for wildland-collected seed to be legally eligible for direct sale or seed increase in an agricultural setting. Certified SI seed will receive a yellow tag, also referred to as an SI-label, noting key information about the lot including the species, the generation of seed (G0-Gx), source location, elevation, seed zone, etc. (UTCIA 2015, NDA 2021, CCIA 2022).

Wildland seed collectors should be aware of documentation required for seed certification. The Seeds of Success data form and protocol (BLM 2021) include all appropriate information and procedures for site documentation and species identification verification to meet certification requirements for wildland sourced seed. Seed certifying agencies may also conduct site inspections of collection locations prior to certification—specific requirements for inspections vary by state and are at the discretion of the certifying agency.

AGRICULTURAL SEED PRODUCTION

Bush muhly is rarely grown for agricultural seed production. However, the Natural Resource Conservation Service (NRCS) has grown trials of bush muhly at the Tucson Plant Materials Center (PMC) from both Sonoran and Mojave Desert sources (Wolf 2019, Dial 2023, personal communication). The lack of commercial availability may largely be due to the difficulty in processing seeds (Dial 2023, personal communication) as described in Seed Cleaning, above.

Agricultural Seed Field Certification.

As with wildland source seed (see Wildland Seed Certification section), seed grown in an agricultural seed increase field must also be certified by an official seed certifying agency, where programs exist. Field grown seed is also certified and labeled as Source-Identified (SI), as long as it has not undergone selective breeding or testing. Seed field certification includes field inspection, seed testing for purity and germination (see Seed Testing section), and proof of certification for all source or parent seed used to start the field (AOSCA 2022). The SI-label or "yellow tag" for seed from a seed increase field denotes information about source seed, field location, and generation level (G1-Gx) indicating if there is a species-specific limitation of generations allowed to be grown from the original source (e.g., in a species with a three-generation limit, G1/G3, G2/G3, G3/3) (AOSCA 2022).

There are no specified seed certification standards for bush muhly crops in the state of California. However, Table 3 outlines the pre-variety germplasm certification standards for a congeneric species, deergrass (*Muhlenbergia rigens*), with a minimum of a two-ounce sample size to be submitted for testing (CCIA 2019). The Nevada and Arizona Departments of Agriculture do not specify standards for PVG crops. The Utah Crop Improvement Association does not specify standards for PVG crops, but may apply standards of similar species or crop groupings (UCIA 2023).

Figure 11: Bush muhly growing at the Tucson PMC. Photo: Heather Dial

Table 3: Pre-varietal Germplasm (PVG) standards for seed analysis results of the related species, deergrass, in California.

Factor	G1	G2	G3 to G10
Pure Seed (minimum)	80%	80%	80%
Inert Matter (maximum)	20%	20%	20%
Total Other Crop Seed (maximum)	0.2%	0.3%	0.5%
Weed Seed (maximum)	0.2%	0.3%	0.5%
Noxious Weed	None	None	None
Germination and Hard Seed (minimum)	65%	65%	65%

Isolation Distances.

Sufficient isolation distances are required to prevent cross-pollination across seed production crops of bush muhly from different sources or other *Muhlenbergia* species. Table 4 summarizes the isolation distances required for PVG certification in both Utah and California. Because there are no specified seed certification standards for bush muhly crops in the state of California, the isolation distances are those required for the related species, deergrass (CCIA 2019). The Utah standards are general for outcrossing perennial species (UCIA 2023). Nevada and Arizona do not specify these standards for Source Identified PVG seed. The distances recommended by California (15-60 feet) are likely insufficient to prevent gene flow between different Source Identified bush muhly crops, especially considering it is a wind-pollinated species.

Table 4: Crop years and isolation distance requirements for pre-varietal germplasm crops of the related species, deergrass. CY= crop years, or the time that must elapse between removal of a species and replanting a different germplasm entity of the same species on the same land. I= isolation distance, or the required distance (in feet) between any potential contaminating sources of pollen.

State	G1		G2		G3+	
	CY	I	CY	I	CY	I
Utah	3	900-600	2	450-300	1	330-165
California	5	60	5	30	2	15

Site Preparation.

Fields should be as weed-free as possible prior to planting. Site preparation to reduce undesirable vegetation should be planned and implemented well in advance of field establishment (USDA NRCS 2004). If fields are uncultivated or fallow and have perennial or annual weeds, one or more years of intensive cultivation (i.e. cover cropping) and herbicide treatment may be necessary (USDA NRCS 2004). After managing undesirable species, final seedbed preparation can include shallow tilling followed by packing to promote a finely granulated, yet firm seedbed that allows soil to seed contact, as well as facilitation of capillary movement of soil moisture to support seedling development (USDA NRCS 2004).

Seed Pre-treatments.

Bush muhly seeds are non-dormant and can germinate readily under appropriate temperature conditions (Ashby and Hellmers 1955, Baskin and Baskin 2002). See Seed and Seedling Ecology for a discussion of temperature ranges for germination in wildland settings.

Cold stratification is not recommended for bush muhly. Prechilling seeds sourced from southern Arizona at 1.6 °C (35 °F) on moistened filter paper in petri dishes reduced germination rates of bush muhly by 16% to 22% (Cavin 1949).

Seeding Techniques.

Seeds can be sown in the early spring at a depth of ¼ inch with a seeding rate of 0.45 pure live seed (PLS) lbs per acre if using a drill and 0.9 PLS lbs per acre if seed is broadcast (Wolf 2019).

The Tucson Plant Materials Center (PMC) has grown bush muhly trial fields by transplanting containerized plants (plugs) grown from both Mojave and Sonoran Desert sources (Dial 2023, personal communication). Plugs were seeded in a nursery greenhouse in January to February and transplanted into the field in the summer. The plants established easily after transplanting with no noticeable mortality issues (Dial 2023, personal communication). Plugs can be planted with 40-48 inches spacing between rows, and 36-40 inches within rows (Wolf 2019).

Establishment and Growth.

Bush muhly planted from plugs in the summer may be able to produce seed within the same year, but waiting until the next season to harvest seed crops can allow the plants to mature and produce a full crop (Dial 2023, personal communication).

Weed Control.

Weeds can be manually removed or carefully spot-sprayed with an appropriate herbicide, after bush muhly plants have developed at least 3-5 leaves (Wolf 2019).

There are limited number of herbicides registered and labeled for use on native plant crops. See the Native Seed Production guide from the Tucson Plant Materials Center (USDA NRCS 2004) for further details on weed management in native seed production fields.

Pest Management.

No pests were reported from the Tucson PMC fields (Dial 2023, personal communication). No other examples of pests or pest management in bush muhly seed increase were found in the literature or through personal communications.

See Insect Herbivory for information on the range caterpillar which may have potential to impact seed increase fields.

Pollination Management.

Since bush muhly is wind pollinated, plants should be able to readily exchange pollen within a seed production field without employing management strategies.

Irrigation.

After seeding, fields should be irrigated to maintain a moist soil surface and avoid soil crusting that would interfere with germination (Wolf 2019). Once plants are established, the Tucson Plant Materials Center has used flood irrigation applied approximately every four weeks during the growing season (Wolf 2019). Irrigation frequency will depend on heat and precipitation levels and may be as frequent as every two weeks during the hottest part of the year to avoid stressing plants and lowering seed yield (Dial 2023, personal communication).

Drip irrigation may also be effective, though no examples were found specific to bush muhly in the literature or through personal communications.

Seed Harvesting.

Flowering and seed set is fairly uniform in bush muhly crops (Dial 2023, personal communication). Seed can be harvested with a flail vac, seed stripper or combine (Wolf 2019, Dial 2023, personal communication). The whole inflorescence will be included in harvest material when using this machinery (Dial 2023, personal communication). Collecting by hand using techniques described in Collection Methods may be appropriate in smaller fields.

Seed Yields and Stand Life.

No information on seed yields was found in the literature or through personal communications. Yields are difficult to quantify since the seeds are rarely processed down to a pure seed unit (Dial 2023, personal communication).

No information on stand life was found in the literature or through personal communications. Bush muhly fields have not been grown long enough at the Tucson PMC to see declines in productivity (Dial 2023, personal communication).

NURSERY PRACTICE

Bush muhly is considered a "sow and go" species in nursery practice since it does not require treatments to break dormancy (Plath 2023, personal communication; Dial 2023, personal communication).

No nursery practices unique to bush muhly were described in the literature or through personal communications.

REVEGETATION AND RESTORATION

Bush muhly is a desirable restoration plant due to its myriad benefits to wildlife, including the endangered desert tortoise (see Birds and Wildlife). Its palatability and nutrition for livestock during winter and drought make it of interest for rangeland revegetation, though it seems to be difficult to establish from common seeding and planting methods (McClaran et al. 2003). Lack of commercial seed availability may limit its widespread application in revegetation and restoration.

Wildland Seeding and Planting.

Wildland Seedings.

For dense stands, bush muhly can be seeded at a depth of ¼ inch with a seeding rate of 0.45 pure live seed (PLS) lbs per acre if using a drill and 0.9 PLS lbs per acre if seed is broadcast (Wolf 2019). Bush muhly can germinate quickly when seeding coincides with consistent rainfall (Abbott and Roundy 2003), but seedlings can be vulnerable to desiccation if rainfall does not persist (Flory 1942). Planting when rain is likely to be more consistent following germination (i.e. late June to mid-July in regions with monsoonal summer rainfall patterns) can increase recruitment and establishment (Abbott and Roundy 2003).

When seeded into stands of the invasive perennial grass, Lehman lovegrass (*Eragrostis lehmanniana*) in southeastern Arizona, bush muhly had limited or no establishment (Biedenbender and Roundy 1996). Seeds were collected in southern New Mexico and applied in southern Arizona under similar climate conditions, but approximately 300 miles from the seed source. Seeding occurred in three different events from early to late summer and seeds were applied in experimental plots where Lehman lovegrass stands had been either mowed, burned, treated with herbicide and left as standing dead, or left standing alive. The authors do not discuss why bush muhly failed to establish under all treatments (Biedenbender and Roundy 1996).

In the Sonoran Desert, bush muhly was seeded in trial plots using a variety of methods in June of 1946 (Judd 1966, Judd and Judd 1976). The seed sourcing for this project was not specified. Bush muhly emerged in plots that were disked and cultipacked but did not persist after the first year of monitoring. However, bush muhly emerged and persisted in plots with brush mulch (scattered whole branches of local woody species) for nearly twenty years after the original seeding (Judd 1966, Judd and Judd 1976). Brush mulch has more recently been indicated to improve vegetation establishment in drylands (Leger et al. 2022).

Wildland Plantings.

There are no examples of success with transplanting container stock of bush muhly in wildland restoration.

Bush muhly plants grown in small conetainer plugs from local seed sources at the Lake Mead National Recreation Area (NRA) nursery were transplanted into a burned area in the eastern Mojave Desert (Abella 2010). The planting included treatments to assess strategies for boosting establishment such as supplemental water via slow-release irrigation, shelter from herbivory, a combination of water and shelter, and no treatment. Bush muhly exhibited poor survival across all treatments--only 2 of 40 plants survived. The surviving plants had received the combination of supplemental water and herbivory shelter (Abella 2010). The author notes that other species transplanted from small conetainer plugs had poor establishment compared to species transplanted from one-gallon pots and that the container size may have contributed to establishment failure (Abella 2010).

Bush muhly was also included in another study in Lake Mead NRA to test the persistence of perennial species outplanted from container stock at a disturbed site in the eastern Mojave Desert (Abella 2017). Seed was sourced locally, with most from within 30 km (18.7 miles) of the restoration site. Seedlings were grown in a greenhouse for one year in four-liter (one gallon) round, plastic pots. Plants were transplanted into experimental plots which received 0.2 cm (0.08 inches) per week of supplemental irrigation for the first 18 months after outplanting. Researchers monitored the plants 18 months and 6 years after planting and found none of the bush muhly plants persisted (Abella 2017).

Seventy mature bush muhly plants in Sonoran Desert grasslands were dug up and transplanted with supplemental irrigation applied for three weeks. Only 4% survived (McClaran et al. 2003).

One source suggests bush muhly may be propagated vegetatively via divisions, where portions of a mature plant in the wild are dug up by the root and transplanted to a new location (Newton and Claassen 2003). Success rates for this method are not indicated.

ACKNOWLEDGEMENTS

Funding for *Mojave Desert Native Plants* was provided by the Bureau of Land Management, Mojave Native Plant Program. The conceptual framework and design of the Mojave Native Plant Guide was developed by Corey Gucker and Nancy Shaw in [Western Forbs: Biology, Ecology, and Use in Restoration]. Cierra Dawson and Brooke Morrow developed maps and summarized data for climate, seed collection, and seed certification sections. Scott Harris (IAE), Jay Goodwin (NPS), and Joe McAuliffe (Desert Botanical Garden) provided content review. The following individuals provided information on their first-hand experience working with bush muhly: Heather Dial (NRCS), Ed Kleiner (Comstock Seed), and Steve Plath (Desert Seed Resource Center). Thank you to Judy Perkins (BLM) for coordination, content review, and initiating this project.

LITERATURE CITED

Abbott, L. B., and B. Roundy. 2003. Available Water Influences Field Germination and Recruitment of Seeded Grasses. Journal of Range Management 56:56–64.

Abella, S. R. 2008. A Systematic Review of Wild Burro Grazing Effects on Mojave Desert Vegetation, USA. Environmental Management 41:809–819.

Abella, S. R. 2010. Revegetating Burned Arid Lands: Identifying Successful Native Species Using Trait and Competition Analysis: Final Report. Final Report.

Abella, S. R. 2017. Persistent Establishment of Outplanted Seedlings in the Mojave Desert. Ecological Restoration 35:16–19.

Aleksoff, K. 1999. Muhlenbergia porteri. https://www.fs.usda.gov/database/feis/plants/graminoid/muhpor/all.html#7.

Allison, C., and N. Ashcroft. 2010. New Mexico Range Plants. https://pubs.nmsu.edu/_circulars/CR374/.

Allred, K. W. 2005. A Field Guide to the Grasses of New Mexico. Third edition. New Mexico State University.

Angell, D. L., and M. P. McClaran. 2001. Long-term influences of livestock management and a non-native grass on grass dynamics in the Desert Grassland. Journal of Arid Environments 49:507–520.

AOSA. 2016. AOSA Rules for Testing Seeds, Volume 1. Principles and Procedures. Association of Official Seed Analysts, Wichita, KS.

AOSCA. 2022. How AOSCA tracks wildland sourced seed and other plant propagating materials. Association of Official Seed Certifying Agencies, Moline, IL.

Asbell, M. 2022, November 17. Director of Plant Conservation Programs, Mojave Desert Land Trust. Phone call about Encelia actoni and Encelia farinosa.

Ashby, W. C., and H. Hellmers. 1955. Temperature Requirements for Germination in Relation to Wild-Land Seeding. Journal of Range Management 8:80.

Barkworth, M. E., L. K. Anderton, K. M. Capels, S. Long, and M. B. Piep. 2007. Manual of Grasses for North America. University Press of Colorado.

Baskin, J., and C. Baskin. 2002. Propagation protocol for production of Container (plug) Muhlenbergia porteri Scribn. https://npn.rngr.net/renderNPNProtocolDetails?selectedProtocolIds=poaceae-muhlenbergia-1749.

Baughman, O. W., A. C. Agneray, M. L. Forister, F. F. Kilkenny, E. K. Espeland, R. Fiegener, M. E. Horning, R. C. Johnson, T. N. Kaye, J. Ott, J. B. St. Clair, and E. A. Leger. 2019. Strong patterns of intraspecific variation and local adaptation in Great Basin plants revealed through a review of 75 years of experiments. Ecology and Evolution 9:6259–6275.

Beatley, J. C. 1974. Phenological Events and Their Environmental Triggers in Mojave

Desert Ecosystems. Ecology 55:856–863.

Biedenbender, S. H., and B. A. Roundy. 1996. Establishment of Native Semidesert Grasses into Existing Stands of Eragrostis lehmanniana in Southeastern Arizona. Restoration Ecology 4:155–162.

BLM. 2021. Bureau of Land Management technical protocol for the collection, study, and conservation of seeds from native plant species for Seeds of Success. U.S. Department of the Interior, Bureau of Land Management.

BLM SOS. 2022. USDI Bureau of Land Management, Seeds of Success. Seeds of Success collection data.

Bowers, J. E., and M. A. Dimmitt. 1994. Flowering phenology of six woody plants in the northern Sonoran Desert. Bulletin of the Torrey Botanical Club 121:215–229.

Browning, D. M., T. M. Crimmins, D. K. James, S. Spiegal, M. R. Levi, J. P. Anderson, and D. P. C. Peters. 2018. Synchronous species responses reveal phenological guilds: implications for management. Ecosphere 9:e02395.

Bucharova, A., O. Bossdorf, N. Hölzel, J. Kollmann, R. Prasse, and W. Durka. 2019. Mix and match: regional admixture provenancing strikes a balance among different seed-sourcing strategies for ecological restoration. Conservation Genetics 20:7–17.

Bucharova, A., M. Frenzel, K. Mody, M. Parepa, W. Durka, and O. Bossdorf. 2016. Plant ecotype affects interacting organisms across multiple trophic levels. Basic and Applied Ecology 17:688–695.

Bucharova, A., C. Lampei, M. Conrady, E. May, J. Matheja, M. Meyer, and D. Ott. 2022. Plant provenance affects pollinator network: Implications for ecological restoration. Journal of Applied Ecology 59:373–383.

Buntyn, R. J., E. K. Lyons, D. Rollins, and K. A. Cearley. 2017. Scaled Quail Reproduction in the Trans-Pecos Region of Texas. National Quail Symposium Proceedings 7.

Calscape. 2023. Porter’s Muhly, Muhlenbergia porteri. https://calscape.org/loc-California/Muhlenbergia%20porteri%20(Porter's%20Muhly)?newsearch=1.

Castellanos-Perez, E. 2000. Ecophysiological relationship of creosotebush (Larrea tridentata) and bush muhly (Muhlenbergia porteri) when growing alone and in common. New Mexico State University, ProQuest Dissertations Publishing.

Cavin, W. C. 1949. Increasing Germination in Some Important Arizona Forage Species. University of Arizona.

CCDB. 2023. Chromosome Counts Database. http://ccdb.tau.ac.il/Angiosperms/Malvaceae/Sphaeralcea/Sphaeralcea%20ambigua%20A.%20Gray/.

CCIA. 2019, December 17. Deergrass Standards. https://ccia.ucdavis.edu/quality-assurance-programs/pre-variety-germplasm/deergrass-standards.

CCIA. 2022. Pre-Variety Germplasm Program. California Crop Improvement

Association. University of California, Davis, CA. https://ccia.ucdavis.edu/quality-assurance-programs/pre-variety-germplasm.

Chew, R. M. 1982. Changes in Herbaceous and Suffrutescent Perennials in Grazed and Ungrazed Desertified Grassland in Southeastern Arizona, 1958-1978. The American Midland Naturalist 108:159–169.

Connor, H. E. 1979. Breeding systems in the grasses: a survey. New Zealand Journal of Botany 17:547–574.

Custer, N. A., S. Schwinning, L. A. DeFalco, and T. C. Esque. 2022. Local climate adaptations in two ubiquitous Mojave Desert shrub species, Ambrosia dumosa and Larrea tridentata. Journal of Ecology 110:1072–1089.

De Vitis, M., F. R. Hay, J. B. Dickie, C. Trivedi, J. Choi, and R. Fiegener. 2020. Seed storage: maintaining seed viability and vigor for restoration use. Restoration Ecology 28:S249–S255.

Dial, H. 2023, May 10. Phone call with Heather Dial (USDA NRCS) about bush muhly growing practices.

Erickson, V. J., and A. Halford. 2020. Seed planning, sourcing, and procurement. Restoration Ecology 28:S219–S227.

Esque, T. C., L. A. DeFalco, G. L. Tyree, K. K. Drake, K. E. Nussear, and J. S. Wilson. 2021. Priority Species Lists to Restore Desert Tortoise and Pollinator Habitats in Mojave Desert Shrublands. Natural Areas Journal 41.

Faber-Langendoen, D., J. Drake, M. Hall, G. Kittel, S. Menard, C. Nordman, M. Pyne, M. Reid, M. Russo, L. Schulz, L. Sneddon, K. Snow, and J. Teaugue. 2018. Sphaeralcea ambigua - Sphaeralcea coccinea - Sphaeralcea parvifolia Dry Meadow Alliance | NatureServe Explorer. https://explorer.natureserve.org/Taxon/ELEMENT_GLOBAL.2.958434/Sphaeralcea_ambigua_-_Sphaeralcea_coccinea_-_Sphaeralcea_parvifolia_Dry_Meadow_Alliance.

Felger, R. S., S. Rutman, and J. Malusa. 2014. Ajo Peak To Tinajas Altas: A Flora Of Southwestern Arizona Part 6. Poaceae – Grass Family. Phytoneuron 35:1–139.

Flory, E. L. 1942. Regrassing for Soil Protection in the Southwest. U.S. Department of Agriculture.

Germino, M. J., A. M. Moser, and A. R. Sands. 2019. Adaptive variation, including local adaptation, requires decades to become evident in common gardens. Ecological Applications 29:e01842.

Gibbens, R., K. Havstad, D. Billheimer, and C. Herbel. 1993. Creosotebush vegetation after 50 years of lagomorph exclusion. Oecologia 94:210–217.

ITIS. 2023. Integrated Taxonomic Information System. https://www.itis.gov/.

Jordan, J. W., G. A. Ruffner, S. W. Carothers, A. M. I. Phillips, and H. S. Colton. 1980. Summer diets of feral burros (Equus asinus) in Grand Canyon National Park, Arizona. Symposium on the Ecology and Behavior of Wild and Feral Equids :

University of Wyoming, Laramie, September 6-8, 1979.

Judd, B. I. 1966. Range Reseeding Success on the Tonto National Forest, Arizona. Journal of Range Management 19:296–301.

Judd, B. I., and L. W. Judd. 1976. Plant Survival in the Arid Southwest 30 Years after Seeding. Journal of Range Management 29:248.

Kleiner, E. 2023, January 13. Comstock Seeds: Conversation about Growing Mojave Desert Native Plants (video call).

Knipe, D., and C. H. Herbel. 1966. Germination and Growth of Some Semidesert Grassland Species Treated with Aqueous Extract from Creosotebush. Ecology 47:775–781.

Kramer, A. T., T. E. Wood, S. Frischie, and K. Havens. 2018. Considering ploidy when producing and using mixed-source native plant materials for restoration. Restoration Ecology 26:13–19.

Leger, A., K. Ball, S. Rathke, and J. Blankinship. 2022. Mulch more so than compost improves soil health to reestablish vegetation in a semiarid rangeland. Restoration Ecology 30.

Livingston, M. 1992. Factors influencing germination and establishment of Arizona cottontop, bush muhly, and plains lovegrass in southern Arizona - ProQuest. The University of Arizona, ProQuest Dissertations Publishing.

Lotts, K., and T. Naberhaus. 2021. Range caterpillar moth Hemileuca oliviae T.D.A. Cockerell, 1898 | Butterflies and Moths of North America. https://www.butterfliesandmoths.org/species/Hemileuca-oliviae.

Massatti, R., R. K. Shriver, D. E. Winkler, B. A. Richardson, and J. B. Bradford. 2020. Assessment of population genetics and climatic variability can refine climate-informed seed transfer guidelines. Restoration Ecology 28:485–493.

McAuliffe, J. R. 2016. Perennial Grass-dominated Plant Communities of the Eastern Mojave Desert Region. Desert Plants 32.

McClaran, M. P., P. F. Ffolliott, and C. B. Edminster. 2003. Santa Rita Experimental Range--100 Years (1903 to 2003) of Accomplishments and Contributions: Conference Proceedings, October 30-November 1, 2003, Tucson, AZ. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Miller, R. F., and G. B. Donart. 1981. Response of Muhlenbergia porteri Scribn. to Season of Defoliation. Journal of Range Management 34:91–94.

Milton, S. J., W. R. J. Dean, G. I. H. Kerley, M. T. Hoffman, and W. G. Whitford. 1998. Dispersal of Seeds as Nest Material by the Cactus Wren. The Southwestern Naturalist 43:449–452.

Monasmith, T. J., S. Demarais, J. J. Root, and C. M. Britton. 2010. Short-Term Fire Effects on Small Mammal Populations and Vegetation of the Northern Chihuahuan Desert. International Journal of Ecology 2010:e189271.

Moody, A., C. Scilacci, and P. Novak-Echenique. 2010, February. Techincal Note: Plant

Characteristics (MLRA 30). U.S. Department of Agriculture, Natural Resource Conservation Service, Nevada.

NatureServe. 2022. Gutierrezia sarothrae / Pleuraphis rigida - Sphaeralcea ambigua Shrub Grassland | NatureServe Explorer. https://explorer.natureserve.org/Taxon/ELEMENT_GLOBAL.2.689383/Gutierrezia_sarothrae_-_Pleuraphis_rigida_-_Sphaeralcea_ambigua_Shrub_Grassland.

NDA. 2021. Certified Seed Program. Nevada Department of Agriculture. Sparks, NV. https://agri.nv.gov/Plant/Seed_Certification/Certified_Seeds/.

Newton, G. A., and V. P. Claassen. 2003. Rehabilitation of Disturbed Lands in California: A Manual for Decision-Making. California Department of Conservation, California Geological Survey.

Omernik, J. M. 1987. Ecoregions of the Conterminous United States. Annals of the Association of American Geographers 77:118–125.

PCA. 2015. National seed strategy for rehabilitation and restoration, 2015-2020. Plant Conservation Alliance. U.S. Department of the Interior, Bureau of Land Management, Washington, D.C.

Pedrini, S., and K. W. Dixon. 2020. International principles and standards for native seeds in ecological restoration. Restoration Ecology 28:S286–S303.

Peterson. 2012. Muhlenbergia porteri. https://ucjeps.berkeley.edu/eflora/eflora_display.php?tid=34110.

Peterson, P. M. 2021. Muhlenbergia porteri - FNA. http://floranorthamerica.org/Muhlenbergia_porteri.

Pizza, R. B., J. Foster, and L. A. Brudvig. 2023. Where should they come from? Where should they go? Several measures of seed source locality fail to predict plant establishment in early prairie restorations. Ecological Solutions and Evidence 4:e12223.

Plath, S. 2023, March 1. Desert Seeds Resource Center: Conversation about nursery propagation and restoration practices for Mojave native plants (video call).

Randall, J. M., S. S. Parker, J. Moore, B. Cohen, L. Crane, B. Christian, D. Cameron, J. B. Mackenzie, K. Klausmeyer, and S. Morrison. 2010. Mojave Desert Ecoregional Assessment. The Nature Conservancy of California:210.

Robinson, G. S., P. R. Ackery, I. J. Kitching, G. W. Beccaloni, and L. M. Hernandez. 2010. HOSTS- a database of the world’s Lepidopteran hostplants. https://www.nhm.ac.uk/our-science/data/hostplants/.

Rosbakh, S., and P. Poschlod. 2015. Initial temperature of seed germination as related to species occurrence along a temperature gradient. Functional Ecology 29:5–14.

Roundy, B. A., and S. H. Biedenbender. 1996. Germination of Warm-Season Grasses under Constant and Dynamic

Temperatures. Journal of Range Management 49:425.

Saidnawey, L., and T. Cain. 2023. Seed Cleaning Manual. Southwest Seed Partnership.

SEINet. 2022. SEINet Portal Network. http//:swbiodiversity.org/seinet/index.php.

SEINet. 2023. SEINet Portal Network. http//:swbiodiversity.org/seinet/index.php.

SER SID. 2023. Seed Information Database. https://ser-sid.org/.

Shryock, D. F., L. A. DeFalco, and T. C. Esque. 2018. Spatial decision-support tools to guide restoration and seed-sourcing in the Desert Southwest. Ecosphere 9:e02453.

Shryock, D. F., L. K. Washburn, L. A. DeFalco, and T. C. Esque. 2021. Harnessing landscape genomics to identify future climate resilient genotypes in a desert annual. Molecular Ecology 30:698–717.

Smith, B. H. 1984. Avian Habitat Selection in a Mixed Creosotebush-Grassland Community. University of Arizona.

Sosebee, R. E., and C. H. Herbel. 1969. Effects of High Temperatures on Emergence and Initial Growth of Range Plants1. Agronomy Journal 61:621–624.

Tiedemann, A. R., and J. O. Klemmedson. 1973. Nutrient Availability in Desert Grassland Soils Under Mesquite (Prosopis juliflora) Trees and Adjacent Open Areas. Soil Science Society of America Journal 37:107–111.

Titus, J. H., P. J. Titus, R. S. Nowak, and S. D. Smith. 2002. Arbuscular Mycorrhizae of Mojave Desert Plants. Western North American Naturalist 62:327–334.

UCIA. 2023. REQUIREMENTS AND STANDARDS | Utah Crop Improvement Association.

US EPA, O. 2015, November 25. Ecoregions of North America. Data and Tools. https://www.epa.gov/eco-research/ecoregions-north-america.

USDA. 1937. Range Plant Handbook. U.S. Government Printing Office.

USDA NRCS. 2004, September. Native Seed Production, Tucson Plant Materials Center. Tucson Plant Materials Center.

USDA NRCS. 2022. The PLANTS Database. Natural Resources Conservation Service, National Plant Data Team, Greensboro, NC USA. https://plants.usda.gov/home.

USU Extension, U. S. 2023. Bush Muhly. https://extension.usu.edu/rangeplants/grasses-and-grasslikes/bush-muhly.

UTCIA. 2015. Certified wildland. Utah Crop Improvement Association, Logan, UT. https://www.utahcrop.org/certified-wildland/.

Warren, P. L., and L. S. Anderson. 1987. Vegetation Recovery Following Livestock Removal Near Quitobaquito Spring, Organ Pipe National Monument. Cooperative National Park Resources Studies Unit.

Welsh, R. G., and R. F. Beck. 1976. Some Ecological Relationships Between Creosotebush and Bush Muhly. 29.

Whitford, W. G., S. Dick-Peddie, D. Walters, and J. A. Ludwig. 1978. Effects of shrub defoliation on grass cover and rodent species in a Chihuahuan desert ecosystem. Journal of Arid Environments 1:237–242.

Wolf, M. 2019, June. Bush muhly (Muhlenbergia porteri) Plant Guide. USDA- Natural Resources Conservation Service, Tucson Plant Materials Center. Tucson AZ 85705.

Zachmann, L. J., J. F. Wiens, K. Franklin, S. D. Crausbay, V. A. Landau, and S. M. Munson. 2021. Dominant Sonoran Desert plant species have divergent phenological responses to climate change. Madroño 68.

RESOURCES

AOSCA NATIVE PLANT CONNECTION

https://www.aosca.org/wp-content/uploads/Documents/AOSCANativePlantConnectionBrochure_AddressUpdated_27Mar2017.pdf

BLM SEED COLLECTION MANUAL

https://www.blm.gov/sites/default/files/docs/2021-12/SOS%20Technical%20Protocol.pdf

OMERNIK LEVEL III ECOREGIONS

https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states

CLIMATE SMART RESTORATION TOOL

https://climaterestorationtool.org/csrt/

MOJAVE SEED TRANSFER ZONES

https://www.sciencebase.gov/catalog/item/5ea88c8482cefae35a1faf16

MOJAVE SEED MENUS

https://rconnect.usgs.gov/MojaveSeedMenu/

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Ashlee Wolf; Molly S. Wiebush. 2023. Bush muhly (*Muhlenbergia porteri*). In: Mojave Desert Native Plants: Biology, Ecology, Native Plant Materials Development, And Use in Restoration. Corvallis, OR: Institute for Applied Ecology. Online: https://www.blm.gov/programs/natural-resources/native-plant-communities/native-plant-and-seed-material-development/ecoregional-programs

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