Society for Range Management

A History of Plant Improvement by the USDA-ARS Forage and Range Research Laboratory for Rehabilitation of Degraded Western U.S. Rangelands

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On the Ground

- Climate change models for the western United States predict warmer winters in the Great Basin and hotter, drier summers in the Mojave Desert, increasing the already high rate of rangeland and pasture degradation, which in turn will increase annual grass invasion, escalate wildfire frequency, and reduce forage production.
- These changes in western U.S. rangelands will continue to result in the emergence of novel ecosystems that will require different and/or improved plant materials for successful revegetation.
- Traditional plant improvement of native and non-native rangeland plant species by the USDA, ARS Forage and Range Research Laboratory (FRRL, Logan, Utah) has been accomplished through rigorous evaluation of seed collections followed by recurrent selection and hybridization of unique plant types within selected populations to identify plants with superior establishment and performance characteristics. After such plant types have been selected, they are further evaluated in multiple ecologically diverse locations to identify broadly adapted superior germplasm for public release.
- Plant improvement of perennial grasses, legumes, and forbs by the FRRL has provided and will continue to deliver plant materials that support sustainable rangeland management efforts to service productive and functionally diverse rangelands.

Keywords: plant materials, restoration, novel ecosystems, plant breeding, abiotic stress tolerance, resilience.

Rangelands 38(5):233–240

doi: 10.1016/j.rala.2016.08.004

The semi-arid and arid rangelands of the western United States provide a broad array of ecosystem services, including wildlife/livestock forage, a diversity of native plants, pollinators, wildlife, and recreational activities.[1] However, disturbances by wildfire, livestock, wildlife (e.g., undomesticated mammals), and humans (including recreational activities) have contributed to degraded conditions on much of America's 800 million acres of rangeland.[2] Many of these regions have been classified as severely disturbed and non-productive,[3] resulting in the emergence of novel ecosystems (i.e., the emergence of species that occur in combinations and relative abundances that have not occurred previously within a given biome).[4] Moreover, based on predicted climate change models for semi-arid regions, seasonal weather patterns of several environments in the western United States will likely change (e.g., warmer winters in the Great Basin and hotter, drier summers in the Mojave Desert), increasing the already high rate of rangeland and pasture degradation and resulting in the spread and dominance of invasive annual grass species, more frequent wildfires, and reduced forage productivity.[5] In fact, currently available plant materials do not often display the degree/type of traits required to persist in novel ecosystems.[6,7] Thus, in water-limited environments of the western United States, there is a need to develop grasses, legumes, and forbs that will establish under drought, compete with invasive weeds, and persist with adequate productivity and quality to meet the needs of wildlife populations and livestock throughout the year.

The U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), Forage and Range Research Laboratory (FRRL[i]) in Logan, Utah[ii] has historically provided improved

[i] For more information on the FRRL, see http://www.ars.usda.gov/main/site_main.htm?modecode=20-80-10-00.

[ii] The 70th Annual Society of Range Management Annual Meeting will be held in St. George, Utah 29 January–2 February 2017. This article highlights Utah range science and management. For more information on SRM Red Rock & Rangelands 2017 see http://rangelands.org/srm17/.

plant materials and management alternatives for sustainable stewardship of rangelands and pastures in the western United States. Research by the FRRL is performed at 38 field locations in the greater Intermountain West from the Mojave Desert north to the Scablands of Washington state, west to central Nevada, and east to the western edge of the short grass prairie of the United States. Through evaluation and breeding of native and non-native species, the FRRL has developed over 50 plant materials that are used broadly on western rangelands and pastures. The development of these improved grass, legume, and forb plant materials as pre-variety germplasms and cultivars has been accomplished through a multidisciplinary team of geneticists (breeding and genomics) and ecologists/plant physiologists (ecological applications). When combined with best-management practices, these plant materials have and will continue to provide rangeland practitioners with flexible strategies for sustainable rangeland stewardship. What follows describes the evolution of the FRRL as an international research organization, its germplasm collection contributions, ecological research to improve rangeland rehabilitation strategies, and future prospects. Research efforts by the FRRL have resulted in plant materials that improve the resilience of rangelands and pastures to environmental and anthropogenic stresses.[8]

Rangeland Management in the Great Basin of the Intermountain West

There were historic interactions between ranchers and federal and state governments that led to the emergence of strategies for rangeland improvement in the Great Basin and the concomitant creation of the FRRL. During the early 1900s, many citizens shared concerns about the degradation of public lands in the western United States. Private producers and public institutions (e.g., U.S. government, universities) concluded that concerted and sustained efforts were necessary to improve plant cover and reduce soil erosion. Through the efforts of Gifford Pinchot (U.S. forester and politician) and Albert F. Potter (Chief of Grazing-Division of Forestry), President Theodore Roosevelt traveled to Salt Lake City in 1903 to create the Logan Forest Reserve in Utah. Subsequently, cooperative studies among the USDA (established in 1862), the Bureau of Plant Industry (established in 1901), and the U.S. Forest Service (established in 1905) were initiated in 1907 with the goal of improving range and forestland conditions. These and other actions in 1912 led to the creation of the USDA Utah Experiment Station located near Ephraim in Sanpete County (central Utah) to conduct research on Great Basin rangelands. In 1930, the Intermountain Forest and Range Experimental Station was created in Ogden, UT to re-establish native grasses found on U.S. rangelands during its early settlement by explorers and pioneers. However, early revegetation efforts using native plants to seed arid and semiarid rangelands frequently failed. Non-native crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.) and Russian wildrye grass (*Psathyrostachys juncea* [Fisch.] Nevski) nevertheless proved to establish well, especially in revegetation efforts during 1930 to 1950.[7,8]

Research Relationships Between the USDA, ARS, and Utah State University in Logan, Utah

Cooperative relationships between the U.S. government and Utah State University (named in 1957) had their origins very early in the history of the university, which was first established as the Agricultural College of Utah in 1888 through Hatch Act appropriations. In fact, several USDA employees (e.g., William M. Jardine, P.V. Cardon, and Gerald Thorne) were associated with the Agricultural College of Utah (UAC) shortly after the college was established. In the 1920s, the USDA and UAC began collaborative efforts to reduce soil erosion, which continue to the present. Subsequently, in the middle 1930s cooperative work commenced on rangelands and forage grasses as a complement to ongoing research in water, irrigation, and soils. A key cooperative relationship between the Utah Agricultural Experiment Station and the U.S. government during that time up to the present involved the Intermountain Herbarium (established in 1931) at USU. By 1938, there were 17 USDA collaborators (e.g., John W. Carlson, Dean F. Ferdinand, A.C. Hull, and Wesley Keller) associated with the college. Research focused on drought resistance and mineral nutrition of cereals, vegetables, sugar beets, and legume seed production, as well as soils and irrigation-related problems.

In 1960, ARS completed construction of a research complex on the USU campus named the USDA, ARS Crops Research Laboratory, which was renamed the FRRL in 1987. Through the late 1970s and early 1980s, increasing emphasis at FRRL was placed on forage breeding and genetics research, which was led initially by Douglas R. Dewey. This work focused on the cytogenetics and reproductive mechanisms of range grasses. Since the late 1980s, substantial emphasis has been placed on improving rangeland, pasture, and turf grass species for drought, heat, and salinity tolerance, with emphasis placed on seedling establishment (germination and emergence) and plant persistence. More recently, efforts have been made to characterize the genetic nature of economically important traits using DNA technologies.

Historic, Current, and Future Research at the FRRL

Historically, plant improvement at the FRRL involved the collection of unique domestic (native) and foreign (non-native) germplasm followed by the evaluation of their potential for rangeland rehabilitation of degraded western landscapes (Figure 1). If domestic germplasm is deemed to have immediate economic potential, it typically is released as pre-variety germplasm with (manipulated track) or without (natural track) trait selection.[9] In addition to morphological evaluation, recent FRRL pre-variety germplasm releases have been described using DNA-based technologies that define their genetic identity and relationships to other accessions of the same species. If native or non-native germplasm has potential (e.g., possesses drought, heat, and/or salinity tolerances), but is lacking in important agronomic attributes (e.g., adequate seed production, seedling establishment, or

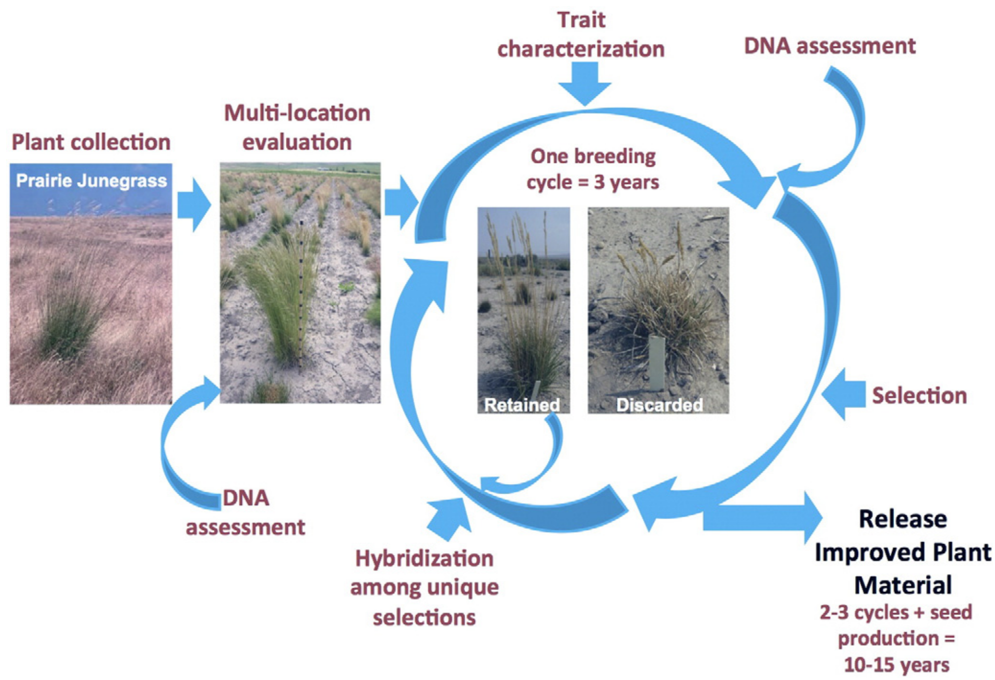

Figure 1. A schematic representation of breeding (plant evaluation, selection, and recurrent selection) leading to the development of improved plant materials.

persistence) to allow for its immediate commercialization, it typically undergoes recurrent selection for desirable traits to improve its genetic potential under growing environments of western rangelands. After repeated cycles of selection and evaluation in harsh environments, this enhanced germplasm is normally released as a cultivar. Traditionally, distribution of FRRL plant releases to the public has been accomplished through the Utah Crop Improvement Association as certified seed. More recently, plant materials have also been licensed via private entities (e.g., seed companies) as a result of research agreements (e.g., Material Transfer Research Agreement, Cooperative Research and Development Agreement) and cooperative research.

Plant Collection and Use of DNA Technologies for Plant Improvement

Plant collection consists of making seed collections across the distributional range where a target species occurs. This first step is essential to capture the broadest possible genetic variation for plant improvement. Since 1977, FRRL scientists have made more than 10,000 overseas and domestic seed collections. Overseas collections have come from 17 countries (mainly in Central Asia), while domestic collections have focused primarily on germplasm resources in the 11 western states, and Alberta and British Columbia, Canada. These collections are evaluated by the FRRL in multiple locations for plant improvement potential in observational and replicated trials (Figure 1). Remnant seed of the original collections are sent to the U.S. National Plant Germplasm System (NPGS). The NPGS repository maintains seed collections and is located at an ARS facility in Pullman, Washington. These collections provide the genetic material for selection and release of rangeland germplasm with enhanced tolerance of abiotic stresses (e.g., drought and salinity) and successful rehabilitation of novel ecosystems, where distinct changes in ecological functioning are commonplace.

The FRRL uses molecular markers to assess genetic diversity, identify species (i.e., DNA fingerprinting), and construct genetic maps to identify and elucidate genes and genetic mechanisms that control trait expression. Morphological and DNA-based genetic assessment of collections is used to identify geographically significant ecotypes, races, or meta-populations (i.e., collections often originating from diverse geographic regions) within species. Molecular analyses are conducted to determine the genetic identity and diversity within and between species. These analyses have been particularly important in the FRRL pre-variety germplasm releases of basalt milkvetch (*Astragalus filipes* Torr. Ex A. Gray) and western prairie clover (*Dalea ornata* [Douglas] Eaton & Wright). For instance, although DNA marker analysis detected extensive genetic diversity and gene flow (cross pollination) among native basalt milkvetch collections made in Washington, Oregon, Nevada, California, Idaho, and Utah, a genetically differentiated group was identified in central Nevada. Genetic similarity within these collections was, however, maximal in north-central Oregon and decreased radially from that region, which suggested that this was a center of diversity for basalt milkvetch.[10] In the case of western prairie clover, 22 native collections were found to be distributed into two meta-populations by DNA marker analysis: one along the Deschutes River drainage in central Oregon and the second encompassing the remaining collections in eastern Oregon and Idaho.[11]

Visual identification of different grass varieties within species in many cases is virtually impossible. However, as DNA technologies rapidly evolved during the past two decades, FRRL researchers used various molecular marker techniques to ensure correct species and variety identification during breeding, as well as documenting the genetic diversity and identity of potential releases. For example, native grass cultivars Joseph and Nezpurs have been widely grown and used as the only commercially available cultivars of Idaho fescue (*Festuca idahoensis* Elmer). However, DNA fingerprinting and DNA sequencing of these cultivars by the FRRL revealed that they were derived from mixed collections of two recognized species, Idaho fescue and Roemer's fescue (*Festuca roemerii* [Pavlick] S. Aike).[12] Likewise, DNA markers were used to identify a previously unrecognized subspecies of bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey) that subsequently assisted in the selection and release of FRRL germplasms Antelope Creek and Pleasant Valley.[13]

Genetic maps have been constructed for basin wildrye[14] and are now being constructed for intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D.R. Dewey) and a fine-leaved *Festuca* species (*F. valesiaca* Schleich. ex Gaudin; Volga fescue) to identify genes for economically important traits (e.g., rooting and flowering characteristics, biomass). The identification and genetic characterization of such genes will allow for the elucidation of genetic mechanisms, which, in turn, will provide potential for improving breeding efficiency. Recently for instance, DNA-based genetic structure analysis along with morphological assessment has facilitated the selection of diverse *Festuca* grass genotypes and the development of breeding strategies for plant improvement in specific populations.[15]

Improvement of Non-Native and Native Plant Materials

Efforts by the FRRL to improve non-native plant materials for western rangelands date back to 1936, but initial improvement progress was relatively slow. Even though there were a relatively large number of species being considered for plant improvement, knowledge of underlying trait heritability and species reproduction was very limited. Thus, much of the early effort focused on revegetation and management strategies for improving the success of rangeland seedings. Beginning in the 1950s and 1960s, a new focus on the cytogenetics (chromosome structure and behavior) of wheatgrasses and wildrye germplasms provided knowledge that facilitated breeding efforts and the subsequent release of a broad array of improved rangeland grass cultivars. From its inception, however, the FRRL has released both native and non-native plant materials to improve rangeland productivity and ecological function, and to increase biological diversity.

In 1984, the FRRL released its first non-native perennial grass cultivar, 'Hycrest' crested wheatgrass, which has been used extensively to revegetate degraded western rangelands. Hycrest possessed improved stand establishment when compared with older crested wheatgrass cultivars. Moreover, its high seedling vigor allowed Hycrest to compete more effectively with annual weeds, such as cheatgrass (*Bromus tectorum* L.), than previously available non-native and native grasses. Hycrest proved to be so successful in improving rangeland productivity that for several years it was the second most widely produced cool-season grass, behind only Kentucky bluegrass. Hycrest and other non-native FRRL grass cultivars (Table 1) establish rapidly, stabilize soil, and compete with annual weeds (Figure 2), and, thus, have been widely used in western rangeland revegetation efforts.

The release of 'Bozoisky-Select' Russian wildrye (1985) rapidly followed that of Hycrest. During the next 25 years, other FRRL non-native perennial grass cultivars included 'NewHy' RS hybrid wheatgrass (1989), 'Vavilov' Siberian wheatgrass (*Agropyron fragile* [Roth] Candargy; 1995), 'Douglas' crested wheatgrass (1995), 'CD-II' crested wheatgrass (1996), 'RoadCrest' crested wheatgrass (1998), 'Mustang' Altai wildrye (*Leymus angustus* [Trin.] Pilg.; 2004), 'Bozoisky-II' Russian wildrye (2005), 'Hycrest-II' crested wheatgrass (2008), 'Vavilov-II' Siberian wheatgrass (2009), 'Stabilizer' Siberian wheatgrass (2011), and 'Arsenal' meadow bromegrass (*Bromus biedersteinii* Roem. & Schult. [excluded]; 2015). In addition to these grasses, the sub-shrub 'Snowstorm' forage kochia (*Bassia prostrata* [L.] A.J. Scott; 2014) was released for its persistent, tall-statured, and highly nutritious qualities and for its ability to extend livestock and wildlife grazing season into fall and winter. Likewise, 'Don' falcata-type alfalfa (*Medicago sativa* subsp. *falcata* L.) was released in 2008 for its persistence under harsh semi-arid rangeland conditions.

Rangeland practitioners have recently emphasized the use of native plant species in landscape restoration. Selecting the most appropriate plant materials for a restoration project, however, can be difficult and one must consider practical limitations (e.g., the restoration gene pool concept).[16] Native plant materials development at the FRRL encompasses the broad range of restoration needs resulting in both pre-variety germplasm and cultivars. This effort is dedicated to increasing species diversity and genetic diversity within species through pre-variety germplasm releases, and improving seedling establishment, persistence, biomass, and seed yield in cultivar releases. In particular, to facilitate successful restoration within novel ecosystems, the FRRL has focused on developing native plant cultivars with greater adaptation to degraded landscapes through genetic selection for improved characteristics to establish and persist.[16] In fact, the use of native species cultivars, and even non-invasive introduced plant materials, may be the most suitable options when local plant material is no longer present or is poorly adapted to the highly-altered conditions of novel ecosystems.

Even though native plant materials development at the FRRL began in 1986, germplasm of several wildland grass populations had previously been collected and evaluated to allow for the identification of target grass species for initial improvement (i.e., Indian ricegrass [*Achnatherum hymenoides* {Roem. & Schult.} Barkworth], Snake River wheatgrass [*Elymus wawawaiensis* J. Carlson & Barkworth], bluebunch wheatgrass [*Pseudoroegneria spicata* {Pursh} Á. Löve], and basin wildrye [*Leymus cinereus* {Scribn. & Merr.}

Table 1. Estimates of foundation seed acres planted of some rangeland cultivars developed and released through 2015 by the USDA-ARS Forage and Range Research Laboratory, Logan, Utah

Cultivar and release year	Foundation seed sold (lbs)*	Acres of certified seed planted (4 lbs/acre)	Average seed yield per acre	Certified seed produced annually (lbs)	Seed per acre planted (lbs)	Estimated acres planted annually
Siberian wheatgrass						
Vavilov (1995)	15,757	3,939	800	3,151,200	10	315,120
Vavilov II (2008)	5,287	1,322	800	1,057,400	10	105,740
Stabilizer (2012)	300	75	800	60,000	10	6,000
Crested wheatgrass						
Hycrest (1985)	4,909	1,227	1,000	1,227,250	10	122,725
Douglas (1995)	3,001	750	800	600,200	10	60,020
RoadCrest (2001)	2,400	600	600	360,000	10	36,000
CDII (2001)	4,540	1,135	1,000	1,135,000	10	113,500
Hycrest II (2008)	5,154	1,289	1,000	1,288,500	10	128,850
Russian wildrye						
Bozoisky (1985)	7,674	1,919	350	671,475	10	67,148
Bozoisky II (2008)	3,035	759	350	265,563	10	26,556
Bottlebrush squirreltail						
Sand Hollow (1996)	51	13	150	1,913	10	191
Toe Jam Creek (2003)	162	41	150	6,075	10	608
Fish Creek (2003)	322	81	150	12,075	10	1,208
Rattlesnake (2007)	6	2	150	225	10	23
Indian ricegrass						
Rimrock (1996)	4,575	1,144	600	686,250	10	68,625
Altai wildrye						
Mustang (2005)	35	9	600	5,250	10	525
Western yarrow						
Yakima WY (2005)	11	3	20	55	2	28
RS hybrid						
NewHy (2003)	7,887	1,972	600	1,183,050	10	118,305
AC Saltlander (RS-H) (2006)						1,000

(continued on next page)

Table 1 (*continued*)

Cultivar and release year	Foundation seed sold (lbs)*	Acres of certified seed planted (4 lbs/acre)	Average seed yield per acre	Certified seed produced annually (lbs)	Seed per acre planted (lbs)	Estimated acres planted annually
Bluebunch wheatgrass						
P7 (2001)	1,332	333	350	116,550	10	11,655
Columbia (2015)						
Meadow brome						
Cache (2004)	10,167	2,542	1,000	2,541,750	15	169,450
Arsenal (2014)	300	75	1,000	75,000	15	5,000
Slender wheatgrass						
FirstStrike (2006)	2,337	584	350	204,488	10	20,449
Western wheatgrass						
Recovery (2009)	1,060	265	400	106,000	10	10,600
Falcata alfalfa						
Don (2009)	120	30	600	18,000	2	9,000
Forage kochia						
Snowstorm (2012)	221	55	250	13,813	2	6,906
Snake River wheatgrass						
Discovery (2008)	565	141	350	49,438	10	4,944
Western prarie clover						
Spectrum (2011)	4	2	200	300		
Majestic (2011)	10	3	250	800		
Basalt milkvetch						
NBR-1 (2008)	30	10	300	2,880		
					Total	**1,410,174**

*** Estimated from gross seed sales.**

Á. Löve]). Parallel to these early grass improvement efforts, evaluation and breeding of globemallow species (*Sphaeralcea* ssp.) and Utah sweetvetch (*Hedysarum boreale* Nutt.) was also being initiated. These and other early breeding efforts resulted in the release of ARS 2936 (Scarlet globemallow; *S. coccinea* [Nutt.] Rydb; 1992), ARS (Munroe globemallow; *S. munroana* [Douglas] Spach; 1992), 'Timp' Utah sweetvetch (1994), 'Rimrock' Indian ricegrass (1996), and Sand Hollow big squirreltail germplasm (*E. multisetus* M.E. Jones; 1996). Plant releases made in the early 2000s included pre-variety germplasms of P-7 bluebunch wheatgrass; Cucharas and Fowler green needlegrass (*Nassella viridula* [Trin.] Barkworth); Star Lake, Blue Powder, and White River Indian ricegrass; Toe Jam Creek, Fish Creek, Wapiti, Pueblo, Rattlesnake, Antelope Creek, and Pleasant Valley bottlebrush squirreltail (*E. elymoides* ssp.); Yakima western yarrow (*Achillea millefolium* L. var. *occidentalis* DC.); FirstStrike slender wheatgrass (*E. trachycaulus* [Link] Gould ex Shinners); Discovery Snake River wheatgrass, Recovery western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve); Majestic and Spectrum western prairie clover, and NBR-1 basalt milkvetch. Between 2015 and 2016, FRRL plant material releases included Bannock II thickspike wheatgrass (*E. lanceolatus* [Scribn. & J.G. Sm] Gould); Fanny, Bonneville, and Carmel Searls' prairie

Figure 2. Siberian wheatgrass successfully excludes cheatgrass on the northern edge of the Great Salt Lake in Tooele County, Utah.

clover (*D. searlsiae* [A. Gray] Barneby); Columbia bluebunch wheatgrass; Turkey Lake bottlebrush squirreltail; Trailhead II basin wildrye; Princeton Thurber's needlegrass (*Achnatherum thurberianum* [Piper] Barkworth); and Charleston Peak slender wheatgrass.

Native and non-native FRRL plant material releases have often been the result of long-term collaborative research with public and private partnerships. Such partnerships have included Utah State University, the University of Idaho, U.S. Department of Interior Bureau of Land Management, U.S. Department of Agriculture Forest Service, U.S. Department of Defense Army Corps of Engineers (ACE), and private landowners across the western United States. For example, during the late 1990s and early 2000s, the FRRL developed a partnership with the ACE to identify non-native and native perennial grasses for rapid revegetation of degraded semi-arid and arid sites following military training exercises with heavy machinery. In cooperation with the ACE, the FRRL evaluated plant materials on military sites at Ft. Carson, Colorado; Guernsey, Wyoming; and Yakima, Washington. This research resulted in the publication of the Intermountain West Military Training Lands Planting Guide

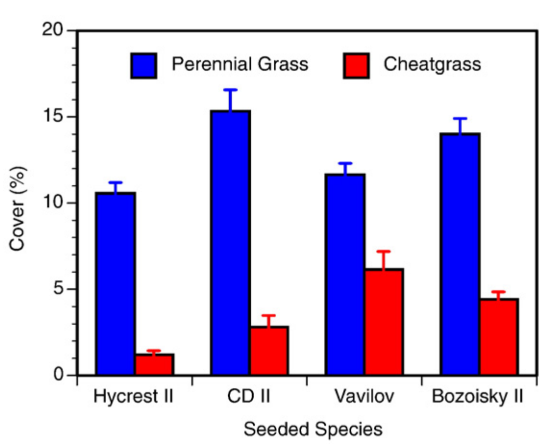

Figure 3. Average percentage cover (± 1 standard error) of four non-native perennial grass species planted in replicated four, 10-acre cheatgrass infested parcels in Park Valley, Utah six years after sowing.

in 2009, and the release of several perennial cool-season grasses (i.e., 'Bozoisky-II', 'Vavilov-II', 'FirstStrike' slender wheatgrass [*Agropyron trachycaulum* {Link} Malte ex H.F. Lewis], Reliable sandberg bluegrass [*Poa secunda* J. Presl], and 'Recovery' western wheatgrass [*Pascopyrum smithii* {Rydb.} Á. Löve]) for use by the military and public land managers. More recently, FRRL has partnered with other ARS research units, private and public institutions, and state and federal agencies in similar efforts to recover degraded rangelands using its improved plant materials in the scabland region of western Washington, central Montana and Nevada, and northeastern Mojave Desert.

Development of Management Strategies for Ecological Restoration

A primary goal of ecological restoration is to reverse the degradation of landscapes and promote sustainable human–nature relationships. Improved plant materials play a key role in rangeland restoration because they function as a building block to support numerous ecological services, including soil stabilization, feed for wildlife and livestock, and replacement of invasive plants.

In the western United States and numerous dryland ecosystems worldwide, disturbances associated with past land uses and invasive plants (e.g., cheatgrass) present a compounding challenge to the sustainable use of rangelands. For example, many lower-elevation basins in the Intermountain West that were once dominated by big sagebrush (*Artemisia tridentata* Nutt.) or salt desert shrub ecosystems are currently threatened by annual grass invasion. Recognizing the need for science-based solutions to combat these invasions and their impact on sustainable rangeland use, land managers have made substantial efforts to address this problem. However, successes have been relatively infrequent, and mounting evidence suggests that annual grasses continue to spread into new regions beyond the Intermountain West.[17] To address this threat, FRRL joined a region-wide ARS effort initiated in 2008 to use ecological principles, processes, and practices to determine the underlying causes of annual grass invasion (see Ecologically-Based Invasive Plant Management at www.EBIPM.org). The FRRL directed three team-oriented studies in northwestern Utah (i.e., Park Valley; elevation = 7,000 ft and annual precipitation = 12 in) where annual grass invasion has diminished the capacity of shrubland ecosystems to provide suitable forage for livestock production and habitat for wildlife.

The first study assessed the impact of historical cultivation and dryland grain production on soils and plant establishment in a cooperative effort with four private landowners. Research revealed that vegetation, soils, and plant growth in cultivated areas were fundamentally different than areas not influenced by this land-use legacy.[18] Consequently, because lands in this region were generally considered highly modified (i.e., novel ecosystems) and in need of repair,[19] a second study was then initiated to identify differences among four improved FRRL perennial grass cultivars (Hycrest II, CD II, Vavilov, and Bozoisky II) that establish well under harsh environmental conditions and interrupt the dominance of annual grasses. These grasses were seeded individually on 10-acre replicated plots within a working cattle ranch, and their ability to replace the invasive annual species cheatgrass (*Bromus tectorum* L.) and persist was assessed after six years. Results demonstrated that while these genetically improved perennial grasses varied in both persistence and in their ability to suppress cheatgrass, all have potential for use in efficacious revegetation in that region (Figure 3). Consequently, a third study was initiated to identify environmental factors most closely associated with cheatgrass dominance and to evaluate how combinations of herbicide, seed removal by mowing, and prescribed fire influence cheatgrass dominance and assist in the establishment of perennial grasses. Assessment of large-scale treatment areas within two working cattle ranches (i.e., more than 200-acre replicated plots) indicated that cheatgrass abundance was strongly associated with soil water and nitrogen concentrations, and that the combination of burning and herbicide was most effective at reducing cheatgrass cover and supporting the establishment of perennial grasses.[20]

Given the increasing number of novel ecosystems on western rangelands, emphasis at the FRRL is presently being placed on the development of native and non-native plant materials that can re-initiate ecological processes to restore disturbed rangelands using "ecologically appropriate" plant materials that assist in the restoration process of degraded landscapes.[6,21] To address these opportunities, plant improvement of the native legumes Utah trefoil (*Lotus utahensis* Ottley), rushy milkvetch (*Astragalus* lonchocarpus Torr.), and Lewis flax (*Linum lewisii* Pursh.) and the grasses prairie Junegrass [*Koeleria macrantha* (Ledeb.) Schult.], bluebunch wheatgrass, Snake River wheatgrass, and basalt milkvetch are currently underway. Likewise, non-native perennial grasses such as crested wheatgrass, tall wheatgrass (*Thinopyrum ponticum* [Podp.] Z.-W. Liu & R.-C. Wang), intermediate wheatgrass, and meadow bromegrass are being improved to support sustainable rangeland management efforts to ensure productive, biologically diverse rangelands.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rala.2016.08.004.

References

1. Booth, M.S., M.M. Caldwell, and J.M. Stark. 2003. Overlapping resource use in three Great Basin species: implications for community invasibility and vegetation dynamics. *Journal of Ecology* 91:36-48.
2. Davison, J. 1996. Livestock grazing in wildland fuel management programs. *Rangelands* 18:242-245.
3. Abella, S.R. 2010. Disturbance and plant succession in the Mojave and Sonoran Deserts in the American Southwest. *International Journal of Environmental Research & Public Health* 7:1248-1284.
4. Hobbs, R.J., E. Higgs, and J.A. Harris. 2009. Novel ecosystems: implications for conservation and restoration. *Trends in Ecology & Evolution* 24:599-605.
5. Munson, S.M., J Belnap, C.D. Schelz, M. Moran, and T.W. Carolin. 2011. On the brink of change: plant responses to climate on the Colorado Plateau. *Ecosphere* 2:1-15.
6. Jones, T.A. 2013. Ecologically appropriate plant materials for restoration applications. *BioScience* 63:211-219.
7. Asay, K.H., W.H. Horton, and A.J. Palazzo. 2001. Merits of native and introduced triticeae grasses on semiarid rangelands. *Canadian Journal of Plant Science* 81:45-52.
8. Hull Jr., A.C. 1974. Species for seeding arid rangelands in southern Idaho. *Journal of Range Management* 27:216-218.
9. Chivers, I.H., T.A. Jones, L.M. Broadhurst, S.R. Larson, and I.W. Mott. 2016. The merits of artificial selection for the development of restoration-ready plant materials of native perennial grasses. *Restoration Ecology* 24:174-183.
10. Bushman, B.S., K. Bhattarai, and D.A. Johnson. 2010. Population structures of *Astragalus filipes* collections from western North America. *Botany* 88:565-574.
11. Bhattarai, K., B.S. Bushman, D.A. Johnson, and J.G. Carman. 2010. Phenotypic and genetic characterization of Western Prairie Clover collections from the Western United States. *Rangeland Ecology & Management* 63:696-706.
12. Jones, T.A., S.R. Larson, and B.L. Wilson. 2008. Genetic differentiation and admixture among *Festuca idahoensis, F. roemerii*, and *F. ovina* detected in AFLP, ITS, and chloroplast DNA. *Botany* 86:422-434.
13. Larson, S.R., TA Jones, C.L. McCracken, and K.B. Jensen. 2003. Amplified fragment length polymorphism in *Elymus elymoides*, *Elymus multisetus*, and other *Elymus* taxa. *Canadian Journal of Botany* 81:789-804.
14. Larson, S.R., and H.F. Mayland. 2007. Comparative mapping of fiber, protein, and mineral content QTLs in two interspecific *Leymus* wildrye full-sib families. *Molecular Breeding* 20:331-347.
15. Robbins, M.D., J.E. Staub, and B.S. Bushman. 2016. Development of fine-leaved *Festuca* grass populations identifies genetic resources having improved forage production with potential for wildfire control in the western United States. *Euphytica*, http://dx.doi.org/10.1007/s10681-016-1644-z.
16. Jones, T.A. 2003. *debate*. *Restoration Ecology* 11:281-290.
17. Mack, R.N. 2011. *Fifty years of 'waging war on cheatgrass': research advances, while meaningful control languishes*. *In:* Richardson DM, editor. *Fifty years of invasion ecology: the legacy of Charles Elton. Oxford, UK: Wiley-Blackwell. p. 253-265.*
18. Morris, L.R., T.A. Monaco, and R.L. Sheley. 2014. *in Great Basin shrublands*. *Rangeland Ecology & Management* 67:285-291.
19. Monaco, T.A., C.A. Call, M.C. Hirsch, and B. Fowers. 2012. *Repairing ecological processes to direct ecosystem state changes*. *Rangelands* 34:23-26.
20. Hirsch-Schantz, M.C., T.A. Monaco, C.A. Call, and R.L. Sheley. 2014. *relationships and promote perennial grasses in salt desert shrublands*. *Rangeland Ecology & Management* 67:255-265.
21. Jones, T.A., and T.A. Monaco. 2009. *A role for assisted evolution in designing native plant materials for domesticated landscapes*. *Frontiers in Ecology & the Environment* 7:541-547.

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