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Cold Regions Research
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Improved Native Grasses and Establishment Methods for Use on Military Training Lands

Antonio J. Palazzo, Susan E. Hardy, and Kevin B. Jensen

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Prepared for STRATEGIC ENVIRONMENTAL RESEARCH AND DEVELOPMENT PROGRAM

ABSTRACT

The objective of this project was to develop more wear-resistant plants and evaluate the relationships between military training and plant injury, regrowth, and wear resistance. Through plant breeding, we were able to improve traits related to resiliency and establishment in introduced and native species of range-land grasses. We selected for early spring growth, increased seedling vigor, improved tiller and rhizome development after disturbance, and resistance to abiotic and biotic stresses. Our improved plant materials will be ecologically compatible at the military sites because they were developed from collections of species native to or previously seeded at these sites. We made advances in relating molecular markers to plant characteristics and in using DNA fingerprinting techniques to characterize genetic diversity. We used markers to identify species and plants that can grow better at low temperatures. We now have the tools to assess the genetic differences and similarities in commercial and natural seed sources, enabling land managers to select seed sources that will ensure genetic compatibility with existing populations. Our tank traffic studies showed that naturalized, introduced species are more tolerant and recover more rapidly under repeated tracking than native plants. However, two improved native species, western wheatgrass and Snake River wheatgrass, showed promise as stabilization species because of their ability to colonize damaged areas. Our studies on what we call "ecological bridges" confirm that we can select seed mixtures that will establish more rapidly than all-native mixes and will ultimately lead to healthy and persistent stands of native plants. The species in the seed mixtures and the equipment needed are readily available, and the seeding can be done in one application, thus saving money. Our improved germplasm will make these seeding mixes even more desirable.

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TERMINOLOGY

Apomictic. Apomixis is a complex form of asexual reproduction that occurs extensively in *Poa* (bluegrass) species. In an apomictic species, the seed produced is genetically identical to the seed-bearing parent.

Breeder's, foundation, and certified seed. *Breeder's* seed is produced from the last cycle of selection. This seed is used to produce *foundation* seed, which, in turn, is used to establish *certified* seed fields from which seed is produced for commercial sale.

Cultivar vs. germplasm vs. selected class germplasm. Plant materials developed in this project will be released as *cultivars*, *germplasms*, or *selected-class germplasms*. *Selected-class germplasm* refers to a native species that has not been tested prior to formal release; it may be selected for a certain trait (such as germination), or it may be a multiple-origin population that has not undergone any selection. A *germplasm* (pre-cultivar) can be a single genotype or a collection of multiple genotypes from multiple origins that are unique for a given character. A *cultivar* (sometimes called a variety) is a population that is unique for selected traits and that has undergone multiple cycles of selection and extensive testing in multiple locations. A cycle refers to a complete generation from seed to plant (selection) to seed. Cultivars are genetically stable.

Full sib and half sib. In breeding, when you can control both parents, the offspring are *full sibs*. When only one of the parents is known, the offspring are *half sibs*.

Introduced vs. naturalized vs. native species. In this report, we use the term *introduced* to represent species not indigenous to North America. Many of the introduced plant materials on western rangelands, including those in this project, originated in Central Asia, where they occur in very diverse ecosystems. The superior stand establishment characteristics, hardiness, adaptability, persistence under grazing, seed availability, seed cost, and productivity of introduced perennial species compared with indigenous *native* species have been documented in many regions (Barker et al. 1977, Vallentine 1978, Kilcher and Looman 1983, Lawrence and Ratzlaff 1989). Like their native counterparts, introduced grasses have the capacity to sort by natural selection and improve their adaptation to the environmental conditions on sites where they are seeded. As a result, many of the introduced species included in the project are *naturalized*, having existed in stands for over 50 years. These naturalized species have co-existed with native flora on North American rangeland (both private and public) for years. Within this report, we use only the terms *introduced* and *native*, based on the species' origin.

Invasive. For the purposes of this study, we define an *invasive* species as an introduced species that will spread beyond the areas it currently inhabits and prevent the establishment of desired perennial plants. We do not agree with definitions of invasive that equate it to any introduced or exotic species. Tiller and rhizome development and seedling encroachment through seed dispersal are indicators of potential invasiveness. Except for RoadCrest crested wheatgrass, which is moderately rhizomatous and is best suited for cantonments and roadsides, we did not use any introduced species displaying these characteristics. On the other hand, rhizome development is valuable in desired native species for land stabilization and reclamation of disturbed lands. We worked with some rhizomatous natives to improve the establishment and persistence of desired species.

SCIENTIFIC NAMES

Common name	Scientific name	Range relative to U.S.
Alfalfa	*Medicago sativa*	Introduced
Basin wildrye	*Leymus cinereus* (Scribn. & Merr.) Á. Löve	Native (western U.S.)
Beardless wildrye	*Leymus triticoides* (Buckley) Pilg.	Native (western U.S.)
Big sagebrush	*Artemisia tridentata*	Native
Bluebunch wheatgrass	*Pseudoroegneria spicata* (Pursh) A. Löve	Native (western U.S.)
Cheatgrass	*Bromus tectorum* L.	Introduced invasive weed
Crested wheatgrass (Fairway type)	*Agropyron cristatum* (L.) Gaertn.	Introduced
Crested wheatgrass (Standard type)	*Agropyron desertorum* (Fisch. ex Link) Schult.	Introduced
Forage kochia	*Kochia prostrata* sp. *virescens*	Introduced shrub
Hard fescue	*Festuca brevipila* R. Tracey	Introduced
Kentucky bluegrass	*Poa pratensis* L.	Native (northern U.S.)
Little bluestem	*Schizachyrium scoparium* (Michx.) Nash var. *scoparium*]	Native
Medusahead rye	*Taeniatherum asperum* (Simonk.) Nevski	Introduced invasive weed
Purple needlegrass	*Nassella pulchra* (Hitchc.) Barkworth	Native (California)
Russian wildrye	*Psathyrostachys juncea* (Fisch.) Nevski	Introduced
Sandberg bluegrass	*Poa sandbergii* Vasey or *Poa secunda* J. Presl	Native (western U.S.)
Sheep fescue	*Festuca ovina* L.	Introduced
Siberian crested wheatgrass	*Agropyron fragile* (Roth) P. Candargy	Introduced
Slender wheatgrass	*Elymus trachycaulus* (Link) Gould ex Shinners	Native
Snake River wheatgrass	*Elymus wawawaiensis* ined.	Native (northwestern U.S.)
Switchgrass	*Panicum vergatum* L.	Native
Tall fescue	*Festuca arundinacea* Schreb.	Introduced
Thickspike wheatgrass	*Elymus lanceolatus* (Scribn. & J. G. Sm.) Gould	Native
Weeping lovegrass	*Eragrostis curvula* (Schad.) Nees	Introduced
Western wheatgrass	*Pascopyrum smithii* (Rydb.) Á. Löve	Native (western U.S.)
Western yarrow	*Achillea millefolium* L.	Native forb

PREFACE

This report was prepared by Antonio J. Palazzo, Research Agronomist, and Susan E. Hardy, Research Program Specialist, Environmental Sciences Branch, U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire, and by Dr. Kevin B. Jensen, Research Geneticist, U.S. Department of Agriculture – Agricultural Research Service (USDA–ARS) in Logan, Utah.

This project was a cooperative effort primarily with the USDA–ARS in Logan, Utah, including research geneticists Dr. Kay Asay (retired) and Dr. Steve Larson, plant breeding specialist Dr. Blair L. Waldron, and rangeland specialists W. Howard Horton and R. Deane Harrison. The principal investigator at ERDC-CRREL was Antonio J. Palazzo, with supporting work by Timothy J. Cary and Susan E. Hardy. Nancy Perron and Troy Arnold provided technical support. James Wuebben, CRREL Acting Director, and J.-C. Tatinclaux, Chief, Environmental Sciences Branch, also helped with field work.

Supporting work was also performed by Dr. David Huff, a specialist in plant genetics and root growth at Pennsylvania State University, and by Alan Anderson and Dr. Richard Gebhart, specialists in land capability models at the Construction Engineering Research Laboratory (ERDC-CERL) in Champaign, Illinois. Field work was assisted by George Savoy, Jeff Linn, and James Kulbeth from Fort Carson; Pete Nissan, Clark Reames, and Brian Cochran from Yakima Training Center; and Tom Lent and Ian Warden at Fort Drum. Dr. Kay Asay, USDA-ARS, Logon, Utah (retired), and Dr. C. Richard Lee, ERDC Environmental Laboratory (retired), reviewed the manuscript.

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The Commander and Executive Director of ERDC is Colonel James R. Rowan, EN. The Director is Dr. James R. Houston.

Improved Native Grasses and Establishment Methods for Use on Military Training Lands

ANTONIO J. PALAZZO, SUSAN E. HARDY, AND KEVIN B. JENSEN

1 PROJECT BACKGROUND

DoD Relevance

The Department of Defense (DoD) must constantly balance its military mission and its commitment to stewardship on millions of hectares of federal land. These military training lands are some of the most intensely used public lands in the United States. The military mission requires that vegetation, primarily grasses, be as resilient as possible to military training exercises to maintain realism and control soil erosion.

Throughout the DoD, land stewardship and management of natural resources fall under the Sikes Act of 1960, which promotes "effective planning, development, maintenance, and coordination of wildlife, fish, and game conservation and rehabilitation in military reservations on military lands." The Army implements the Sikes Act through the Integrated Training Area Management (ITAM) program in place at over 60 installations. Through the ITAM, consideration of natural resources management objectives are integrated with land warfare training requirements. Today, all of the military departments are completing biological inventories on their lands, building on efforts that were initially driven by the National Environmental Policy Act and the Endangered Species Act. Integrated Natural Resources Management Plans (INRMPs)—the tool for implementing ecosystem management—provide balanced and coordinated consideration of various perspectives, including forestry, agronomy, soil science, pest management, livestock grazing, and fish and wildlife management (Gibb 2002).

In the future the military faces increasingly difficult land management challenges. Proposed weapons systems will be longer-range, requiring more land for training exercises. As technology improves, training and testing requirements change. Complicating this challenge is the impact of continuing development, especially urbanization, outside the boundaries of military installations. As population growth and urban expansion continue, landscapes around facilities will be further degraded, and additional pressures are likely to be brought to bear on native species, biological communities, and the ecological processes that sustain them. In some cases this growing pressure is likely to intensify demands that military installations and other federal lands take on even greater responsibilities for biodiversity conservation (Keystone Center 1996).

The DoD has approximately 10 million hectares (25 million acres) of land to manage in the continental United States (CONUS). Within this area the Army has 4.5 million hectares (11 million acres) of training lands under the ITAM program, and the greatest expense in the ITAM budget is Land Repair and Maintenance (LRAM). The Air Force has over 3.8 million hectares (9.5 million acres) of land in CONUS. While each DoD organization produces its own unique impacts to the land related to its mission, all federal land managers (military and others) need to consider threatened and endangered habitats and follow Executive Orders on native plants and invasive weed control.

The goal of this project is to increase the efficiency of lands for military use by understanding the effects of training on plant establishment and growth and by enhancing plant resiliency through improved selective breeding programs to develop new plant materials.

Benefits

We anticipate that this work will improve the return on the military's investment in the ITAM Program, which is budgeted at about $50 million annually.[*] Along with guidance for mitigation methods and improved seedling establishment, this work will provide more-resilient plants that will help increase training opportunities on existing training areas while protecting environmental resources and wildlife habitat. These plant materials will be ecologically compatible with the various areas because they were developed on and from collections made near the sites. Lower costs in land maintenance are anticipated because of increased persistence and less frequent seedings. Thus, we will increase the value and use of current training areas, offer reduced unit training costs, and enhance DoD mission-related environmental activities.

Within the range of distribution for the new germplasms (Fig. 1), we identified 42 DoD facilities, including over 525,000 hectares (1.3 million acres) of Army and Air Force land. The new germplasms are also appropriate for other federal, state, or local agencies; highway rights-of-way; mine spoils; rangelands; and other disturbed areas.

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[*] Personal communication with T. Macia, Team Leader for Training Lands at Chief of Staff Army, G3 Training Support Division, August 2002.

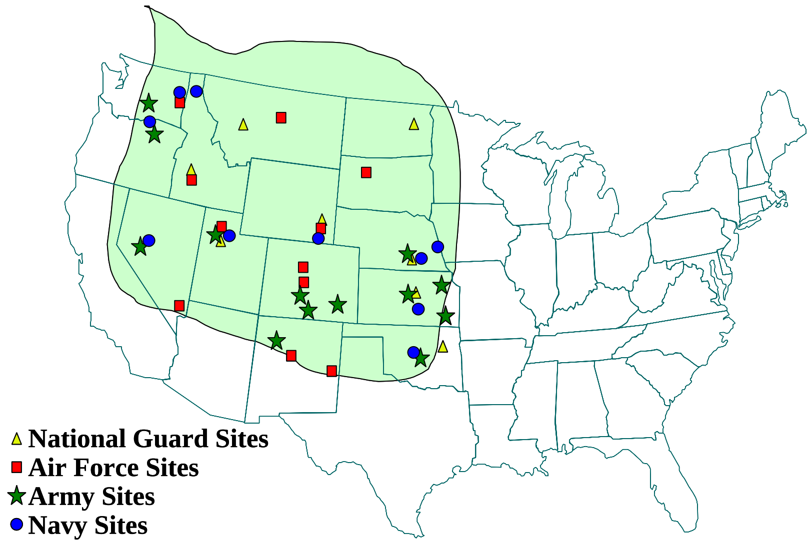


Figure 1. Adapted area for SERDP-select germplasms. All plant materials were collected within this area.

Scientific Background

There is limited knowledge on the relationships between military training and plant injury, regrowth, and wear resistance. Before this study, no plant breeding or selection had been conducted to increase the wear resistance of plants for military training-land rehabilitation.

Resilience is defined as the ability of a vegetative system to recover after disturbance and return to its original state (Doe et al. 1999). Military training exercises often destroy the vegetation, which leads to soil erosion (Halvorson et al. 2001). Based on ecological studies conducted in the shortgrass prairie, Shaw and Diersing (1990) reported that a two-year rotation might not be long enough for adequate plant recovery. Hinchman et al. (1990) concluded that it took up to three years after seeding to return shortgrass-prairie land to a condition suitable for resuming training.

Training by tracked vehicles disaggregates and compacts soil, which increases the effects of erosive forces (Diersing et al. 1988). Shaw and Diersing (1990) found that tracking decreased plant basal and litter cover. Ayers et al. (1990) noted that the greatest soil compaction occurred in the upper 15 cm of the soil profile.

Shaw and Diersing (1990) concluded that increased training intensity was correlated to the frequency of noxious weeds. A common weed problem on western military lands is cheatgrass, which was introduced to North America at the end of the 19th century and has become a major threat to the ecological balance across much of the western rangelands (Young and McLain 1997). This noxious weed, as well as others, fuels recurrent fires that increase seed production for cheatgrass and eventually remove native plant materials from plant communities. Limited progress has been made in rehabilitating land infested with cheatgrass and other noxious weeds (Asay et al. 2001).

Seeding perennial, cool-season grasses on rangelands is a valuable tool for restoring burned and disturbed areas and managing noxious weeds (Vallentine 1971). The use of introduced perennial grasses, however, has been the focus of considerable debate among environmental, political, research, and user groups. Some contend that introduced grasses reduce biodiversity by displacing native species and disrupt the ecology and aesthetics of the plant community. This rationale has gained considerable support and has led to policies restricting the use of introduced plant materials on public lands. In particular, introduced Triticeae grasses have fallen into disfavor because many early seedings were made as large-scale monocultures that were unappealing and had limited biological diversity (Marlette and Anderson 1986). Despite this disfavor, the superior stand establishment characteristics, hardiness, adaptability, seed availability, seed cost, and productivity of introduced perennial species compared to native species have been documented for many regions (Barker et al. 1977, Kilcher and Looman 1983, Lawrence and Ratzlaff 1989, Vallentine 1978). Like their native counterparts, introduced grasses have the capacity to sort by natural selection and improve their adaptation to environmental conditions. Indeed many introduced grasses are more tolerant of frequent defoliation and disturbances because they have been subjected to similar conditions longer than our natives. These advantages have led to continued use of Triticeae grasses such as crested wheatgrass, intermediate wheatgrass, and Russian wildrye on federal lands (Richards et al. 1997). Introduced cool-season perennial grasses have proven effective in competing with annual weedy grasses (Whitson and Koch 1998, Hull and Stewart 1948) and forbs (Cronin and Williams 1966). More recently they have been found to compete favorably with some of the perennial invasive noxious weeds (Bottoms and Whitson 1998, Ferrell et al. 1998, Borman et al. 1991, Hubbard 1975, Larson and McInnis 1989).

The success of native plant establishment is partially related to root growth in a competitive environment. In our earlier studies (Palazzo and Brar 1997, Palazzo and Lee 1997, Brar and Palazzo 1995a, 1995b), we reported that plant root and leaf growth and plant resiliency were influenced by differences in soil texture, soil moisture, cultivars and species, and zinc-contaminated soil. Root growth is closely associated with plant resiliency. We postulated that if we could identify populations possessing improved root growth and other traits promoting resiliency to military activities, we could selectively breed improved populations that would withstand the stresses on DoD training lands more successfully. Such improved plant materials should have wide adaptability to other areas with low-maintenance vegetation needs, such as roadsides, dams, embankments, and other conservation projects.

2 OBJECTIVES

The overall objectives of this project were to:

(a) Breed improved native and introduced plant germplasms that have increased persistence and establishment characteristics under conditions created by military training activities;

(b) Understand the effects of training on soil compaction, plant injury, and regrowth; and

(c) Evaluate seeding methodology to better establish native and introduced grasses in mixed stands and still control invasive weeds.

By combining plant and soil data, we can enhance existing land management models to include the effects of training on soil compaction, plant injury, and regrowth, which will provide methods for mitigation and rehabilitation. Land users will be able to make knowledgeable choices concerning plant selection and site rehabilitation procedures to reduce soil erosion.

The project began with evaluation trials to identify the most promising species and with basic research on genetic markers for traits associated with resiliency on low-maintenance, high-use military training areas. The applied research phase took the identified species through several cycles of selection to develop germplasms that possess the desired traits. In the demonstration phase of the project, the resiliency of new plant materials is being evaluated through controlled tests on military training lands at Yakima Training Center, Washington, and Camp Guernsey, Wyoming.

Objective (a): Breeding Resilient Plants

Our main goal was to develop improved, training-resilient plants, especially grasses, that would be adapted to a wide range of environmental conditions in the semiarid, temperate regions of the U.S. Our intention was to improve existing plant materials through standard selection processes enhanced by identification of genetic markers. We would not use species that were not already on the site nor would we perform any genetic engineering.

We worked with both native species and introduced species that had become naturalized on the training areas. Our goal was to help land managers satisfy the requirements for native plants, while also cost-effectively restoring training land as rapidly as possible to prevent erosion and reduce downtime. We included the introduced species in the program because they establish more rapidly and we believed that they could serve as a nurse crop for the establishment of the slower-developing natives. As the project progressed, we placed increased emphasis on improving native germplasms to address changing regulatory decisions.

The desired characteristics of the new germplasms were early spring growth, rapid seedling establishment, improved tiller and rhizome development after disturbance, and resistance to abiotic and biotic stresses. At the same time, we wanted to ensure that newly developed germplasms would not themselves become invasive and move beyond the target habitats.

Our new native plant germplasms should provide improved plant persistence on military lands at a reduced environmental risk with respect to habitat loss and soil erosion. These plant materials will be ecologically compatible with the areas where they will be used, as well as with similar climatic areas, because they were developed from collections made from these sites.

Objective (b): Soil Compaction and Root Studies

The second objective was to conduct field and greenhouse studies to quantify the degree of soil compaction that occurs during training and relate this soil condition to root injury in plants with known resilience. The most critical variable is the effect of soil compaction on root growth. Increased soil compaction leads to reduced soil aeration and shallow root growth, which reduces the capability of the plants to regrow after injury. Knowledge of the effects of soil compaction on plant growth will help us provide better habitats with less soil erosion.

Objective (c): Establishment Techniques

As we placed increasing emphasis on native species, we added a third objective of developing cost-effective seeding techniques to establish viable stands of natives. Native species are generally much slower to establish than are introduced species. Before a native grass can become established, erosion or noxious weeds often become costly problems to land managers. Our goal was to find cost-effective methods that would rapidly protect the soil and permit the eventual establishment of resilient native species. We want to reduce the costs of land repair and maintenance while simultaneously reducing downtime on military training areas.

3 TECHNICAL APPROACH

For the three main objectives, the general approach was as follows:

(a) For plant breeding and germplasm development, we surveyed existing plants on military facilities and selected the most promising species. The most promising populations of these species were either used directly for seed increase without selection or included in the breeding program, where they underwent two cycles of selection for desired characteristics such as improved seed germination, seedling vigor, rhizome development, persistence, drought tolerance, and weed suppression. Simultaneously, genetic markers associated with desired traits were identified for future breeding programs. The final steps in this part of the approach were the testing and release of the new germplasms.

(b) For plant root growth and tracking, we studied root growth in the greenhouse and established tracking studies on existing grasses in the field.

(c) To improve establishment and inhibit invasive weeds, we evaluated the use of seed mixtures at three field locations.

In our final technology transfer phase of the project, we have provided data for several land management models, demonstrated the new germplasms and our seeding mixtures on three military facilities, and begun to implement a business plan that will ultimately make the improved seeds available to land users.

Approach (a): Breeding Resilient Plants

Assessment

The first step was to assemble a broad genetic base and select the best accessions and clonal lines for the desired characteristics. We surveyed representative DoD installations to identify the most promising introduced and native species as well as the characteristics associated with resiliency in those species. Through research funded by Army Forces Command (FORSCOM), we had already identified resilient plant species at several training sites using field surveys and the data generated by the ERDC-CERL Integrated Training Area Management (ITAM)–Land Condition Trend Analysis (LCTA) program. The LCTA program, which includes monitoring of vegetation dominance on lands subjected to military training, provided information on the resiliency, persistence, and adaptation of plant species. While making field collections, we identified plant characteristics that are critical to soil conservation, plant survival, and training resiliency. These traits included a vigorous ground cover; a deep, fibrous root system; tiller and rhizome development; initiation of growth early in the spring; persistence under environmental extremes (temperature and drought); and rapid seedling and plant establishment.

To assemble the best lines for the introduced breeding populations, we looked for the desired characteristics among the plant materials already assembled in nurseries at USDA-ARS and Pennsylvania State University. To assemble native breeding populations, we collected plants with the desired traits from training sites and other conservation lands.

We planted the assembled promising species in seeded evaluation trials at Yakima Training Center and Fort Carson during the fall of 1994 and 1996. More than 60 cultivars, breeding lines, and plant accessions directly from the training sites were included in the Yakima trials. Over 40 cultivars, breeding lines, and material indigenous to the training sites were included at Fort Carson. Visual percent stand and vigor ratings were taken throughout 1995, 1996, 1997, and 1998. From the nurseries and the seeded evaluation trials, we selected the most promising species for the breeding process.

Development

The next step was to make crosses among the best lines to produce progeny, conduct parent–progeny tests to initiate the second breeding cycle, and continue the breeding cycle as necessary. We used traditional plant-breeding techniques to combine desired traits into breeding populations. Figure 2 shows a typical

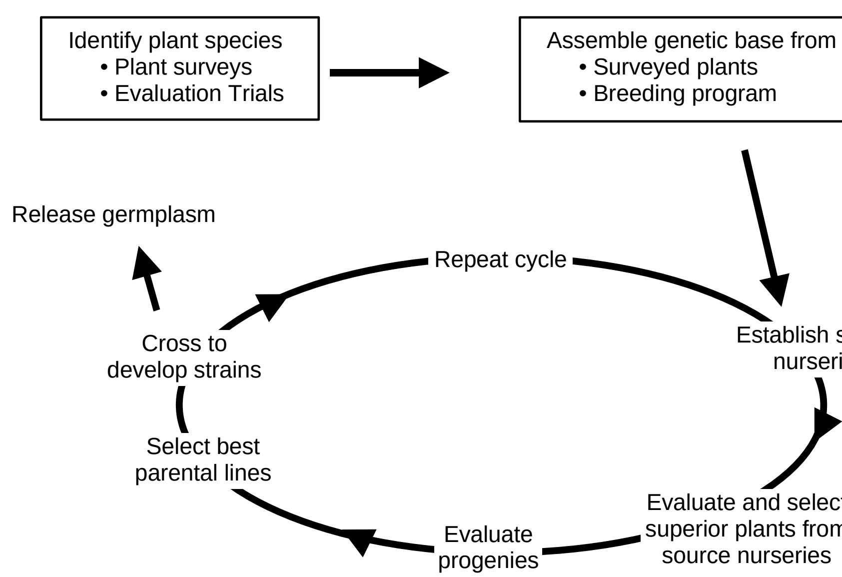


Figure 2. Plant breeding cycle.

breeding program from plant surveys to germplasm release. Under normal conditions, it takes two to three years to complete one cycle of selection. The first year is a field establishment year with no selection. The second and third years are for selecting traits and harvesting seed. If hybridization between selected clones is desired, it can take an additional year to isolate the hybrid and increase seed. With the exception of conducting plant surveys and assembling a broad genetic base (the boxes at the top of Figure 2), the breeding cycle is repeated until the population has become genetically stable for the improved traits; each cycle increases the frequency of genes conditioning increased adaptation or specific traits. At some point after selection, the population is genetically stable for the desired traits from one generation to the next and may be released as a germplasm or, with more intense testing, as a cultivar.

We typically took plants through two cycles of selection. We selected parental lines by analyzing measurable traits such as stand establishment vigor, rate of tillering and rhizome development, vegetative vigor, and seed yield potential. Native grasses with seed dormancy problems were screened for more rapid germination. For future use we used Random Amplified Polymorphic DNA (RAPD) or Amplified Fragment Length Polymorphic (AFLP) DNA analyses to identify genetic markers for desirable traits in some of the species.

Some new germplasms were not subjected to selection pressure. Instead, they were assembled from broad ecological ranges, resulting in a broader genetic base than in any of the individual populations and the potential to be better adapted to a wide range of different ecotypes.

Test and evaluation

We then tested new strains in replicated seeded trials and in soil compaction trials in the field. We also evaluated the new strains to ensure that they would not become invasive, and we analyzed the genetic diversity of the new strains.

Prior to formal release, cycle-2 breeding populations are established in seeded trials under a range of environmental conditions. Data obtained from these trials are used to write up the formal release notices, which include areas of adaptation. Seed from cycle-2 populations—breeder's seed—is also used to establish foundation seed-increase fields. Seed from those fields will be released commercially as certified seed.

We established an Independent Review Panel to assess whether the introduced species of interest are a threat to invade habitats other than those currently occupied by the species. For this review we evaluated older sites at Yakima Training Center (YTC) that contained the same species as those in the breeding program. We evaluated the species for spread (through either vegetative tillering or reseeding) after 4–19 years of growth by counting plants growing outside the plots where they were planted. The Independent Review Panel met at YTC to view the sites, discuss their findings, and make a definitive statement on the potential invasiveness of the plant materials.

We used both RAPD and AFLP DNA analyses to compare the genetic diversity of several of the new strains to their currently available counterparts.

Approach (b): Soil Compaction and Root Studies

Assessment

We used cone penetrometers to assess the degree of soil compaction that occurs on training lands at three facilities: Yakima Training Center, Fort Carson, and Fort Drum. A variety of lands were assessed, including training areas, lightly used dirt roads, and bivouac areas. We also used the cone penetrometer to study the influence of frost on alleviating soil compaction.

Development

We conducted controlled studies to support the field tracking studies. In the greenhouse we compressed soil inside rhizotron tubes using compaction rates taken from the field measurements in the assessment step above, and we evaluated the root growth of plants grown in the compressed soil. In environmental chambers we used growth pouches to study the effect of various temperatures on early growth and root elongation of military-important species.

Test and evaluation

We conducted simulated tracking exercises at Yakima Training Center on our original evaluation plots, four years after they were established. The plots were tracked with a tank making no, one, two, or four passes. We used the cone penetrometer to record soil compaction values before and immediately after tracking and then again a year later. We used point-frame techniques to analyze the different species for resiliency evaluated after the tank passes, measuring gaps between target species, percent target species, dry matter yield, bluegrass encroachment, percent bare ground, and cheatgrass invasion on and off the tracked area.

Approach (c): Establishment Techniques

Native grasses are usually more difficult to establish than their introduced counterparts because of seed dormancy, poor seedling vigor, and reduced tolerance to defoliation, grazing, and traffic. While improving these traits in our SERDP-select natives, we also investigated seeding methods to further enhance their establishment and prevent the encroachment of invasive weeds. We are using non-invasive introduced grasses as what we call an "ecological bridge" to the establishment of native grasses.

At Fort Drum we tested and demonstrated a seed mixture of introduced and native species to obtain a native meadow on sandy (92% sand), infertile soils.

At Yakima Training Center we evaluated the establishment of native grasses using a mixture of native and introduced wheatgrasses. We seeded various combinations of the native 'Secar' Snake River and 'Goldar' Bluebunch wheatgrasses with the introduced 'Vavilov' Siberian wheatgrass, which has been shown to inhibit growth of the noxious weed cheatgrass (Asay et al. 2001). Each grass was planted alone, in a mixture with one or two other grasses, or in alternating rows with one of the other grasses. Plots were evaluated for the percent cheatgrass growing after one and two years.

At Fort Carson we evaluated a native grass mix planted with one of five introduced grass add-ons. We compared those mixes with the standard Fort Carson seed mix. The stands were evaluated after two, three, and four years for species composition and percent ground cover.

4 PLANT BREEDING ACCOMPLISHMENTS

Plant Surveys and Collections

We conducted vegetation surveys at Fort Carson, Yakima Training Center (YTC), and Fort Drum to identify the most promising native and introduced species and to determine plant characteristics that are important for adaptability in a training land environment. To identify specific collection sites, we reviewed soil and ecological site data from the USDA Natural Resources Conservation Service (USDA-NRCS).

For the native grasses of interest, we collected seeds and clonal materials from a broad ecological range at Yakima Training Center, Fort Carson, and Fort Drum. At Yakima Training Center we made 134 collections of native species in 1994 and 1995, including the grasses bluebunch wheatgrass, Sandberg bluegrass, and basin wildrye, and the forb western yarrow. At Fort Carson we made 166 collections of natives including western wheatgrass, blue grama, sideoats grama, and Indian ricegrass. At Fort Drum we collected fine fescues, hairgrass, little bluestem, and switchgrass.

For the introduced species we used known germplasm lines in collections at space-planted nurseries at the Utah State University Blue Creek Experimental Farm in Box Elder County, Utah, approximately 80 km northwest of Logan, Utah. We also collected related species from Asia. We did some preliminary testing and selection at a space-planted nursery at Exit 11 at Yakima Training Center. Table 1 gives the annual precipitation and soil types at the two nursery sites.

Table 1. Precipitation and soil type at breeding nursery sites.

Location	Site	Annual precipitation (mm)	Soil type
Yakima, Washington	Exit 11	200–250	Benwy series
Blue Creek, Utah		200–375	Parley’s silt loam

We identified the important characteristics to be seedling vigor, tiller and rhizome development, resistance to drought and plant pests, and growth at low temperatures. Seedling vigor was identified as the most important of the these desired characteristics for returning land to training as soon as possible and for fighting invasive weeds.

Preliminary Evaluation Trials to Identify Promising Species

At the beginning of the program, many more species were examined and eventually dropped based on adaptive characteristics as the most promising species became apparent. We began with evaluation trials at two U.S. Army sites to help identify promising germplasm. The evaluation trials to assess stand establishment were conducted at Fort Carson in south-central Colorado and at the Yakima Training Center (YTC) in south-central Washington. The trials were established during the fall of 1994 and 1996. The seeded evaluation sites at the facilities differed in soil type and precipitation, which allowed for evaluation of germplasm over different environmental regimes (Table 2).

Table 2. Precipitation and soil types at species evaluation sites.

Location	Site	Annual precipitation (mm)	Soil type
Yakima, Washington	Snake A and B	200–250	Benwy series
Fort Carson, Colorado	Turkey Creek	300–350	Rizozo-Neville Complex
	South Boundary	175–225	Minnequa-Manvel loams

Two evaluation trials were conducted at Fort Carson: Turkey Creek and South Boundary. Both sites received less than normal precipitation during our trials, especially in the latter years. Turkey Creek receives 325 mm of average annual precipitation; however, there were only 265, 159, 274, and 120 mm in 1999, 2000, 2001, and 2002, respectively. South Boundary receives 200 mm of average annual precipitation, but only 134, 141, 197, and 115 mm were received in 1999, 2000, 2001, and 2002, respectively. The soil type at Turkey Creek is a Rizozo-Neville Complex [fine-loamy, mixed (calcareous), mesic Ustic Torriorthent], and the area is dominated by piñon pine, juniper, blue grama, and western wheatgrass. At South Boundary the soils are Minnequa-Manvel loams [fine silty, mixed (calcareous), mesic Ustic Torriorthents], and the dominant vegetation is blue grama and galletta.

At YTC, evaluation trials were conducted on adjacent Snake River sites A and B. The YTC location received 353, 375, 175, and 193 mm in 1995, 1996, 1997, and 1998, respectively. The soil type is a Benwy series (fine-loamy, mixed superactive, mesic Calciargidic Argixerolls), and the area is dominated by bluebunch wheatgrass and Sandberg bluegrass, with some basin wildrye in low areas.

The Fort Carson plots were seeded as dormant seedings during late October 1994 at Turkey Creek and in early August 1996 at South Boundary. Native and introduced grasses were evaluated on Turkey Creek and South Boundary. At YTC, plots were seeded during late October 1994 as a dormant seeding; native and introduced grasses were evaluated on Site A and natives on Site B.

Seeding was accomplished on mechanically prepared, weed-free seedbeds with a drill equipped with double-disk furrow openers and depth band regulators. Seeds were placed from 1.25 to 2.0 cm below the soil surface at a rate of approximately one seed per centimeter. Individual plots consisted of drilled rows spaced 30 cm apart. Plot sizes were 1.5 by 15 m. Plots were arranged in a randomized complete block with four replications at each of the two sites. The seeding procedures are fully described by Asay et al. (2001).

The percent stand establishment was determined annually on a visual basis at all sites; however, stand data in 1997 were determined on the basis of plant counts in two 1-m^2 sampling areas per plot. Seedling vigor was also determined at the YTC sites using ratings of 1 to 9, with 1 for the worst plot and 9 for the best plot. All data were subject to analysis of variance using ANOVA and General Linear Model (GLM) procedures, and mean separations were made on the basis of a least significant difference (LSD) test at the 0.05 probability level (SAS Institute Inc. 1994).

Table 3 shows the species used in the evaluation trials. Over 60 cultivars, breeding lines, and material collected from the training sites were included in the Yakima trials. Over 40 cultivars, breeding lines, and material indigenous to the training sites were included at Fort Carson.

Table 3. Plant species used in evaluation trials.

	Native grasses		**Introduced grasses**
Bluebunch wheatgrass	Thurbers needle grass	Lovegrass	Crested wheatgrass
Snake River wheatgrass	Green needle grass	Blue grama	Siberian wheatgrass
Wheatgrass hybrid	Idaho fescue	Side oats grama	Intermediate wheatgrass
Western wheatgrass	Sheep fescue	Buffalograss	Russian wildrye
Slender wheatgrass	Sandberg bluegrass	Prairie sandreed grass	Giant wildrye
Thickspike wheatgrass	Canby bluegrass	Little bluestem	
Bottlebrush squirreltail	Indian ricegrass	Sand dropseed	
Basin wildrye	Needle and thread grass	Galleta grass	
	Native forbs and legumes		**Introduced forbs, legumes, and shrubs**
Western yarrow	Spiny hopsage	Bitterbrush	Forage kochia
Small burnett	Fourwing saltbrush	Globemallow	Cicer milk vetch
			Alfalfa

Results at Turkey Creek, Fort Carson

The Turkey Creek site has fertile soils, and most of the introduced species established well (Table 4). In the first year the three Russian wildrye cultivars did not establish as well as Siberian or crested wheatgrass cultivars; stands of all introduced entries were similar after the first year. ‘Rosana’ western wheatgrass and the two thickspike wheatgrass cultivars established better than the other native plant entries but initially not as well as all but two of the introduced

Table 4. Stand establishment of perennial grasses at the Fort Carson Turkey Creek site, seeded in the fall of 1994.

Entry	1997	1998	1999	2000	2001
	Mean % stand				
Introduced entries					
Crested wheatgrass					
CD-II crested wheatgrass	100	97	94	89	99
RoadCrest crested wheatgrass	91	100	100	92	93
Siberian wheatgrass					
P27 Siberian wheatgrass	84	100	94	91	90
Vavilov Siberian wheatgrass	83	97	88	80	95
Kazakhstan Siberian wheatgrass	73	94	78	69	83
Russian wildrye					
Tetraploid Russian wildrye	68	94	91	78	93
Mankota Russian wildrye	46	91	88	72	89
Bozoisky Russian wildrye	30	84	81	64	86
Native entries					
Rosana western wheatgrass	54	81	100	97	100
Thickspike wheatgrass					
Sodar thickspike wheatgrass	55	91	84	80	93
E27 thickspike wheatgrass	52	81	75	66	77
Indian ricegrass					
Paloma Indian ricegrass	31	56	47	30	28
T593 Indian ricegrass	13	38	31	19	28
Nezpar Indian ricegrass	26	25	19	23	12
CSU10 Indian ricegrass	9	22	16	16	25
Needle and thread grass	5	31	47	45	51
Alma blue grama	0	0	31	22	15
Vaughan sideoats grama	0	0	19	19	15
LSD (0.05) entries	8	16	18	16	14

entries. The stand increase of those three natives was due to rhizome development. In the remaining years those three leading native plant entries had stand values similar to the introduced species. None of the other native entries attained a stand greater than 50%.

Results at South Boundary, Fort Carson

The soils at South Boundary are shallower, much drier, and less fertile than those at the Turkey Creek site. Except for the two intermediate wheatgrass entries, the introduced species had high percent stand values after one year (Table 5). The percent stand values for the intermediate wheatgrasses never improved over the next four years. The best-performing introduced species were the four entries of Russian wildrye, 'RoadCrest' crested wheatgrass, and Vavilov Siberian wheatgrass. For native plant entries, 'Barton' and 'Rodan' western wheatgrass and 'Pryor' slender wheatgrass had the best initial stand values. In the final two years the three western wheatgrass entries were the only native entries with stand values greater than 14%. With its strong early establishment, Pryor slender wheatgrass may prove useful in mixes with other slower-establishing natives such as the western wheatgrasses. Pryor may be a possible ecological bridge providing cover and protecting the soil, giving the other natives time to establish (for discussion of the ecological bridge concept, see the later section on "Methods for Establishing Natives and Fighting Invasive Weeds").

Results at Yakima Training Center

Annual precipitation during stand establishment (353 mm in 1995 and 375 mm in 1996) was substantially above normal, and good stands were obtained for all of the introduced and native wheatgrasses. Differences between introduced and native Triticeae grasses were less definite at this site, which is dominated by bluebunch wheatgrass (Table 6). Vavilov and P-27 Siberian wheatgrass demonstrated the best stand establishment of the introduced grasses. Among the native grasses the Snake River and bluebunch wheatgrasses, bluegrasses, Bannock thickspike wheatgrass, and most of the thickspike wheatgrass hybrids established well and maintained their stands for the duration of the trial. Secar Snake River wheatgrass was particularly well adapted to this site, and in 1998 this cultivar had stands equivalent to or significantly better than any other entry at the location.

At the Snake A site, good stands were generally obtained for all introduced grasses during the year of establishment in 1995, and stands were maintained during subsequent years through 1998 (Table 6a). Vavilov Siberian wheatgrass established faster than other grasses evaluated. In 1998, stands of Vavilov Siberian wheatgrass were similar to P-27 ($P>0.05$); however, stands of all introduced

Table 5. Stand establishment of perennial native and introduced grasses at the Fort Carson South Boundary site, seeded in the fall of 1996.

Entry	1997	1998	1999	2000	2001
	Mean % stand				
Introduced entries					
Russian wildrye					
Bozoisky	63	93	94	81	91
Tetraploid	59	88	78	70	88
Syn A	66	88	84	78	86
Mankota	72	78	88	80	85
Crested wheatgrass					
CD-II	69	41	47	37	30
RoadCrest	88	94	91	83	91
Siberian wheatgrass					
Vavilov	81	81	78	64	78
Kazak	56	69	63	52	55
Intermediate wheatgrass					
Luna	28	9	16	7	3
Rush	34	6	13	1	1
Native entries					
Western wheatgrass					
Barton	63	50	72	69	88
Rodan	63	44	53	42	58
Rosana	41	34	53	50	78
Bottlebrush squirreltail	34	6	3	4	2
Sandhollow	25	9	9	4	3
Thickspike wheatgrass					
E-27	25	3	6	3	4
Sodar	28	13	3	8	14
Pryor slender wheatgrass	72	38	31	7	0
Sand lovegrass	31	3	16	0	0
Mean	53	45	47	39	44
LSD (0.05)	18	23	20	15	18

Table 6a. Seeding vigor ratings and percent stand of native and introduced perennial Triticeae grasses during stand establishment (1995) and subsequent years on Snake A site at Yakima Training Center. (This site was used for the tracking study in 1999; subsequent data are included in the tracking section of this report.)

Entry	Seedling vigor [z] May 1995	% Stand[y] 1995	% Stand 1996	% Stand 1997	% Stand 1998
Snake A introduced entries					
Siberian wheatgrass					
Vavilov Siberian wheatgrass [T]	9	99	100	100	100
P-27 Siberian wheatgrass [T]	9	96	82	83	88
Kazak Siberian wheatgrass [T]	7	75	66	80	72
Mean	8	90	83	88	87
Crested wheatgrass					
Hycrest [T]	7	94	82	69	79
Ephraim [T]	8	77	69	71	75
Mean	7	85	75	70	77
Russian wildrye					
Bozoisky [T]	5	67	57	55	63
Tetraploid [T]	4	50	25	38	38
Mean	4	59	41	46	50
Intermediate wheatgrass (cv. Luna)[T]	4	61	72	77	78
Snake A native entries					
Wildryes					
Leymus-1 hybrid	1	8	0	3	7
Basin wildrye (Yakima) [T]	3	35	13	34	38
Mean	1	21	7	19	22
Bluegrasses					
Canby bluegrass [T]	8	69	70	60	82
Sandberg bluegrass	7	49	50	51	54
Mean	7	59	53	32	68
Indian ricegrass					
Nezpar Indian ricegrass	6	60	10	0	10
T553 Indian ricegrass	1	11	3	0	16
Mean	3	35	7	0	13
Western wheatgrass (cv. Rosana)[T]	3	33	35	32	41
Bottlebrush					
Squirrel tail 87	3	41	41	0	0
Squirrel tail 89	6	55	47	0	0
Mean	4	48	44	0	0
Miscellaneous species					
Needle and thread grass	2	14	0	8	6
SL hybrid (thickspike X bluebunch)	4	46	57	34	50
Mean	2	30	28	21	28
LSD (0.05)–Entries	1	19	14	12	14
LSD (0.05)–Species	2	20	18	17	17

[z] Seedling vigor ratings 9 May 1995, following a dormant fall seeding in 1994; 1=poor, 9=best seedling vigor.
[y] Percent stand based on visual ratings.
[T] Entries included in the tracking study.

Table 6b. Seeding vigor ratings and percent stand of native and introduced perennial Triticeae grasses during stand establishment (1995) and subsequent years on Snake B site at Yakima Training Center. (This site was used for the tracking study in 1999; subsequent data are included in the tracking section of this report.)

Entry	Seedling vigor [z] May 1995	% Stand[y] 1995	% Stand 1996	% Stand 1997	% Stand 1998
Snake B native entries					
Bluebunch wheatgrass					
Goldar [T]	7.0	67	56	49	75
Whitmar [T]	6.3	66	72	62	75
ACC-238 [T]	6.0	70	53	53	75
Yakima collection [T]	6.5	59	38	45	69
Mean	6.4	66	55	52	73
Snake River wheatgrass					
Secar [T]	7.3	69	94	92	97
ACC-707 [T]	7.0	75	88	75	91
EVT-572 [T]	7.5	73	91	87	100
Mean	7.3	72	91	85	96
Thickspike wheatgrass and hybrids					
Bannock [T]	7.3	73	72	53	75
Sodar	6.5	64	41	35	41
E-20 (thickspike X Snake River) [T]	7.0	72	78	80	88
E-27 (thickspike X Snake River) [T]	6.5	70	81	69	81
SL hybrid (thickspike X bluebunch)	4.3	52	22	23	28
Mean	6.3	66	59	52	63
LSD (0.05)–Entries	1	14	16	11	10
LSD (0.05)–Species	0.6	8	15	12	13

[z] Seedling vigor ratings 9 May 1995, following a dormant fall seeding in 1994; 1=poor, 9=best seedling vigor.

[y] Percent stand based on visual ratings.

[T] Entries included in the tracking study.

grasses were greater than 70% with the exception of Bozoisky-Select and Tetraploid (Table 6a). Vavilov Siberian wheatgrass, 'Ephraim' crested wheatgrass, and 'Luna' intermediate wheatgrass maintained their stands throughout the study.

Of the native grasses at the Snake A site, the bluegrasses, especially the 'Canby' cultivar, maintained or increased in percent stand from 1995 to 1998. The SL hybrid (thickspike wheatgrass × bluegrass) also did about as well as Canby bluegrass, which was the poorest performer of the bluegrasses. Seedlings of 'Nezpar' Indian ricegrass established relatively well during 1995 following the late-fall seeding; however, stands of this caespitose species declined from 60% in 1995 to 10% in 1998. All other native grasses at the Snake A site were difficult to establish and subsequently had relatively poor stands throughout the study (Table 6a).

At the Snake B site, seedlings of Snake River wheatgrass had significantly ($P<0.05$) higher vigor ratings in 1995 than did bluebunch wheatgrass and thickspike wheatgrass (Table 6b). With the exception of wildland-collected bluebunch wheatgrass from the Yakima Training Center (69%), Sodar thickspike wheatgrass (41%), and the SL hybrid (28%), all native grasses had stands in excess of 70% by 1998. Stands of the rhizomatous native grasses (Bannock thickspike and hybrids between thickspike and Snake River wheatgrass) were maintained at an acceptable level during the study.

Evaluation Trial Conclusions

These evaluation trials helped us identify the most promising species for germplasm improvement, and they supported our hypothesis that mixed seedings of introduced and native species might provide the best method for establishing natives and preventing encroachment by invasive weeds. Most of the introduced species established better than did the native species at both facilities. Any differences between entries of the introduced species lasted only one year, while the native grass entries usually took two to three years to attain a stand greater than 50%.

On sites with severe water limitations (<300 mm per year) or infertile soils, the native grasses were more difficult to establish, less vigorous, and less persistent than their introduced counterparts (Siberian and crested wheatgrass and Russian wildrye). At Yakima, where moisture conditions were more favorable, the native grasses established and persisted relatively well compared to the introduced entries. Although difficult to establish, stands of the rhizomatous native western wheatgrass increased each season after establishment. Most wheatgrasses are bunchgrasses, but western wheatgrass has rhizomes and the ability to develop an excellent ground cover. With its hard seed coat and persistency, western wheatgrass looked like a good candidate for selective breeding for improved rhizome or tiller characteristics.

These findings suggest that adapted introduced grasses be considered along with native grasses as a component of seed mixtures on environmentally harsh sites that have been burned, infested with competitive weedy species, or otherwise degraded. An improper choice of plant materials would perpetuate degradation of soil resources, especially on sites that are dominated by weedy annual species such as cheatgrass and medusahead rye. Because introduced grasses generally establish better than natives in such conditions, the best choice may be to begin by planting introduced grasses or a mixture of introduced and native grasses (Asay et al. 2001).

All introduced grasses in these trials exist in biologically diverse ecosystems in their native habitats, and rarely, if ever, are they invasive. On the Palouse rangelands near Yakima, bluebunch wheatgrass has successfully co-existed with Siberian wheatgrass on sites that were seeded more than 15 years ago (Asay et al. 2001). At the Snake A and B sites in these trials, the fully established native grasses will be competitive with and may largely replace the introduced grasses.

Non-grasses that looked promising included the introduced shrub forage kochia and the native forb western yarrow. Forage kochia is a good candidate for use as a firebreak and on ranges. Western yarrow will add diversity to seed mixtures of grasses.

Non-Invasiveness of Introduced Species

While our current emphasis is on improving the resilience of native species on training lands, the research program began by looking primarily at introduced or naturalized species. Our first three releases are introduced species, and in-progress program reviewers were concerned about the effects of introducing these germplasms in native ecosystems. The reviewers wanted assurance that the introduced germplasms we develop will not dominate lands currently inhabited by native species or prevent the return of native plants in the future. Similarly the training-land managers want to avoid any potential regulatory problems (invasive plants, soil erosion, etc.) that might interfere with their training needs.

To address this concern we invited a panel of independent reviewers from the U.S. Environmental Protection Agency, The Nature Conservancy, the USDA-NRCS, and another USDA-ARS office to review the materials we were evaluating at Yakima Training Center (Appendix B; Palazzo et al. 1999). We asked the review panel to assess whether the germplasms used to develop the new cultivars have the potential to invade habitats other than those currently occupied by the species. This group met in May 1999 and evaluated the mature Snake River A and B sites (described in the previous section), examined several sites previously seeded to introduced grasses, and reviewed our data.

The Invasiveness Question

We believe that extensive invasion (through seed dispersal or vegetative growth) by the new plant materials we are developing is unlikely because we limited our breeding studies to bunch-type species, all of which are already present on the training lands. Most of our work has been with natives; the three introduced species we have worked with—crested wheatgrass, Siberian wheatgrass, and Russian wildrye—were most likely originally introduced on the property before it became a military installation.

For the purposes of this study we defined an invasive species as an introduced species that will spread substantially beyond the areas it currently inhabits. The characteristics we were concerned about as indicators of potential invasiveness in introduced species are tiller and rhizome development and seedling encroachment through seed dispersal. (This study was concerned with the potential invasiveness of our introduced germplasms. Rhizome development is valuable in desired native species for land stabilization and reclamation of disturbed lands.)

Summary of Data on the Spread of Introduced Species

We evaluated the spread of the introduced species we used to develop new cultivars. We did not see any obvious vegetative spread by the introduced species, which are predominantly bunch-type grasses. For spread via escaped seeds, we measured seven sites: two four-year-old research sites and five areas seeded 13–19 years earlier. We found very few plants of crested or Siberian wheatgrass outside of the areas where they were planted, and after 19 years the greatest spread was only two plants found 12 m (40 ft) from the seeded plot. In one research site (Snake A) the native bluebunch wheatgrass was successfully invading the stands of introduced and native plants sown there four years ago. In the old seeding sites, Sandberg bluegrass (another native) was found to be invading the seedings of the wheatgrasses. Sandberg bluegrass is an understory plant that adds to the biological diversity of the site, and it is part of our breeding program (Palazzo et al. 1999; see Appendix B for the data collected for the review meeting).

Discussion and Conclusions on the Spread of Introduced Species

There is a great difference between the introduced, naturalized species that have been present on Yakima Training Center since ranchers used the land and the aggressive, exotic species that invade and exclude existing species from the community. Although some of the introduced grasses at Yakima appeared to be outside the area where they were originally sown, there was a greater movement of surrounding native vegetation into the sown plots. The introduced species were not forming monocultures nor did they appear to be “invading” new habitats. It was evident that native grasses such as bluebunch wheatgrass and Sandberg bluegrass were moving into the seeded introduced areas.

Participants on the review panel discussed the relative merits and disadvantages of native species compared to non-natives. Many also looked for assurance that the introduced species, which did not cause problems in the intended habitat, would not escape to other habitats and become noxious invaders. It was agreed that crested and Siberian wheatgrass had not established monocultures, nor were they invading other habitats in the area. With that in mind, participants weighed the other options available (such as the exclusive use of natives) and found those options would not be as successful in achieving all the goals of the project, primarily due to the slow establishment rate of the native plants. Introduced species are important to the ecosystem because they prevent the loss of fertile topsoil and help keep weeds out of disturbed areas until the natives can re-establish in those areas. There are no rapidly establishing native species that can provide the same degree of soil protection and weed prevention in the more arid areas around Yakima.

Crested and Siberian wheatgrass appear to be excellent choices for rehabilitating areas subject to recurrent disturbance by providing soil protection and invasive weed suppression. Where the species volunteered outside seeded areas, they appeared to be filling in gaps rather than displacing native grasses. Crested and Siberian wheatgrass tend to appear early in the succession in low-disturbance areas. Late-seral native species were actively colonizing such sites where a seed source was available and disturbance was infrequent and of limited severity.

The Independent Review Panel concluded that the plants we are using to develop wear-resistant cultivars for military training lands were not encroaching on other plant communities and were not establishing monocultures. The panel felt that continued long-term monitoring of some of the sites would be valuable, both to monitor the spread of the introduced plants and to investigate the competitiveness of crested and Siberian wheatgrasses planted with native species such as Snake River, western, and bluebunch wheatgrass and Sandberg bluegrass.

We were encouraged that our work with seeding mixtures of native and introduced plants may lead to grass stands that are dominated by native species. The later section on “Methods for Establishing Natives and Fighting Invasive Weeds” describes how we are continuing to evaluate seeding mixtures so that we can find the best combination to maximize the establishment of natives and diminish the need for persistent non-natives.

Breeding Program

Based on data from our field surveys, the LCTA program, and the seeded evaluation trials, we selected the following species to carry forward in our breeding program to develop the new germplasms; the right-hand column shows the current status of each species in our breeding program.

Introduced

Crested wheatgrass	(SERDP-select RoadCrest and CD-II commercial releases)
Siberian wheatgrass	(SERDP-select)
Russian wildrye	(SERDP-select Tetra-1 public release)

Native

Bluebunch wheatgrass	(P-7 multi-line public release and SERDP-select)
Snake River wheatgrass	(SERDP-select)
Basin wildrye	(SERDP-select)
Western wheatgrass	(two SERDP-select populations)
Slender wheatgrass	(two SERDP-select populations)
Sandberg bluegrass	(SERDP multi-line)
Western yarrow	(SERDP multi-line)

The basic breeding process was described earlier in this report and illustrated in Figure 2. We used the following selection process for most of the species we developed in this program:

Cycle 0

1. Transplant a broad range of materials to the field.
2. Evaluate plants for desired traits, such as stand establishment vigor, rate of tillering and rhizome development, vegetative vigor, and seed yield potential, and mark the best plants.
3. Allow selected plants to open pollinate with all plants or control pollination so that only the selected plants cross with each other.
4. Harvest seed from the selected plants.

Cycle 1

1. Plant seeds harvested from selected clones 5 cm (2 in.) deep in cones in the greenhouse.

2. Monitor germination and select the seedlings that emerge first and are the most vigorous.
3. Plant selected seedlings in the field to produce seed for the next cycle of selection.
4. Evaluate plants for vigor, etc. and mark the best plants (this may take two to three years).
5. Harvest seed from selected plants.

This example includes one cycle of selection for vegetative vigor and other morphological traits in the field and one cycle for seedling vigor, as monitored in the greenhouse. With each cycle of selection, we assume we are accumulating favorable alleles (genes) that promote improved seedling vigor. Because emergence from a deep planting is a greenhouse test of seedling vigor, field testing is also necessary to validate that progress is being made from the selection process. Subsequent cycles repeat Cycle 1 until we have produced populations that show improvements over the original populations and that are genetically stable for the desired traits from one generation to the next. In our program, breeding populations were typically subjected to two cycles of selection. Table 7 illustrates how we were able to demonstrate improvements in certain traits when the original populations of known cultivars were compared with those of the selected populations.

Table 7. Mean values of desired traits for four SERDP-select native germplasms compared to the "original" populations of known cultivars.

	Seedling emergence rate/day (mean)		Seed weight (mean g/50 seeds)		Total seed yield (mean g/plant)	
	Original	Selected	Original	Selected	Original	Selected
Bluebunch wheatgrass	1.2	2.6	0.2	0.3	5.9	8.3
Western wheatgrass	2.3	3.9				
Snake River wheatgrass	2.3	3.9			11.8	16.3
Basin wildrye	0.9	1.3				

Some new native germplasms were not subjected to selective pressure. Instead they were assembled from a range of ecotypes, resulting in a broader genetic base than in any of the individual populations and creating populations that should more readily adapt to changing stresses. Broad-based germplasms of Sandberg bluegrass, bluebunch wheatgrass (P-7), and western yarrow were developed by assembling seed collected from plant populations found on representative ecosystems throughout the training bases. To maintain the broad genetic base within each germplasm, we did not subject these populations to intentional selection. Therefore, these germplasms are not specifically adapted to any given site on the base, but they are widely adapted to the training base as a whole. This type of germplasm may not be the most vigorous or the most productive for a given environment, but it is more likely to result in a successful seeding after military disturbance throughout the training base. Because these native species are important for recolonization or understory growth of disturbed sites, it is imperative that reseeding is successful.

A second population of bluebunch wheatgrass (Yakima collections) also originated from a broad-based population that was then selected for seed germination, seedling and plant vigor, and emergence from a deep seeding depth. Similarly one of our two populations of slender wheatgrass seed originated as a broad-based population from several Fort Carson sites and was then selected for improved seed germination, seedling vigor, and plant vigor.

Once the cycles are completed so that a genetically and morphologically stable germplasm is developed, our research phase is complete. In the next phase, we begin the seed increase process, and we register the new germplasm in the journal *Crop Science*. The registration communicates to others that we have a new source-identified or selected-class germplasm or a new cultivar. The seed increase, accomplished in production fields in Utah, is done both to produce seed for large-scale demonstrations (the seed harvest shown in Table 8 below) and to produce breeder's seed. The seed harvested for large-scale demonstration usually amounts to about 150–200 kg/year (330–440 lb/year). The "Transition Plan" section of this report describes our large-scale demonstrations. We also increase seed to produce breeder's seed to begin the initial production of seed for the newly released germplasms or cultivars. For breeder's seed, seed is produced in large enough quantity (25 kg; 50–60 lb) to provide seed for sale. The typical process is for a middleman, such as a crop improvement association, to acquire the breeder's seed from the researcher and use that seed to produce larger quantities of foundation seed. That foundation seed is, in turn, sold to commercial seed companies, who use it to produce certified seed for sale directly to users.

Improved Species

Table 8 summarizes the new traits developed in each new germplasm. Details for each species are given in the sections below.

Table 8. Improved traits and current status of SERDP-select germplasms.

Introduced selections	Original traits	Traits of improved populations	Seed harvest	Release date
Russian wildrye	Poor seedling vigor			
RWR-Tetra-1		Selected for improved seed germination and seedling vigor, increased plant height, longer and wider leaves, increased seedling emergence, heavier seeds, improved water-use efficiency		1997
Crested wheatgrass	Moderate growth in low temperatures; few rhizomes			
CD-II		Selected for increased growth under low temperatures, drought resistance, easy establishment		1996
RoadCrest		Selected for low-maintenance turf with moderate rhizome development; suitable for gunnery ranges and roadside plantings; early spring growth		1998
Siberian wheatgrass	Moderate seedling vigor	Selected for seedling vigor, plant color, vegetative vigor, seed yield, drought tolerance, early spring green-up	2003–2004	2004
Native selections	**Original traits**	**Traits of improved populations**	**Seed harvest**	**Release date**
Bluebunch wheatgrass	Hard to establish; sensitive to grazing			
P-7 Bluebunch wheatgrass		A broad-based multi-line population with no selection pressure applied		2001
Bluebunch wheatgrass		A broad-based population selected for seed germination; seedling and plant vigor; emergence from a deep seeding	2004	2004
Western wheatgrass	Strongly rhizomatous			
Turkey Creek population		Selected for plant and seedling vigor, increased germination, seed yield	2002–2004	2003
South Boundary population		Selected for plant and seedling vigor, increased germination, seed yield	2002–2004	2003
Snake River wheatgrass	Seedling vigor	Selected for increased seedling vigor and seed yield	2003–2004	2004
Basin wildrye	Poor seedling vigor	Selected for improved seed germination and seedling vigor	2003–2004	2003
Slender wheatgrass	Poor persistence			
Bunch-type population		Broad-based population selected for emergence from a deep planting depth; improved plant vigor	2002–2004	2004
Rhizomatous population		Selected for same as above plus rhizome development	2003–2004	2004
Sandberg bluegrass	Early establishment after a disturbance	A broad-based multi-line population with no selection pressure applied	2003–2004	2004
Western yarrow (a forb)		A broad-based multi-line population with no selection pressure applied	2002–2004	2003

*Russian Wildrye (*Psathyrostachys juncea*; Introduced)*

Introduction. Russian wildrye is a long-lived bunchgrass that is exceptionally tolerant of cold and drought. Most of the forage produced is contained in the basal leaves, which grow rapidly in the spring as long as soil moisture is available. In North America it has been seeded most often on arid and semiarid rangelands of the Northern Great Plains and Intermountain regions in areas receiving between 150 and 300 mm of precipitation annually. It is better adapted to grazing than most grasses and is equal to crested wheatgrass in its ability to withstand drought. Because of its dense and vigorous growth, Russian wildrye competes effectively against undesirable plants within stands once it is established. Within the Great Basin, Russian wildrye is adapted to sagebrush, mountain brush, and juniper piñon sites, and it is useful on soils too alkaline for crested wheatgrass. The diploid cultivar Bozoisky is an excellent dryland bunchgrass that is drought resistant.

Limitations. The use of Russian wildrye is often limited by its relatively slow seedling growth and development. Stands are often difficult to obtain, particularly under severe soil-water stress and where seeds have been planted too deeply. Russian wildrye does not tolerate spring flooding and is generally not well adapted to moist cool areas in the Great Basin.

SERPD Russian wildrye. Asay et al. (1996) showed that by doubling the chromosome number in Russian wildrye from $2n = 14$ to $2n = 28$, the plants will have larger seeds and better seedling vigor than the currently used diploids. In the SERDP program, we developed a 28-chromosome tetraploid from Bozoisky Russian wildrye that has improved seed germination and seedling vigor.

Registration of RWR-Tetra-1 Tetraploid ($2n = 28$). RWR-Tetra-1 Russian wildrye [*Psathyrostachys juncea* (Fisch.) Nevski] germplasm (Reg. no. GP-75, PI 599302) was released in 1997 (Jensen et al. 1998). This 26-line composite was released as source material for genetic studies and for the development of improved cultivars of tetraploid ($2n = 4x = 28$) Russian wildrye. Most Russian wildryes found in natural populations are diploids ($2n = 2x = 14$) (Asay et al. 1996).

RWR-Tetra-1 traces to ten parental accessions that were initially obtained by K.H. Asay, D.A. Johnson, and M.D. Casler during a collecting expedition to Kazakhstan in 1988. Four of these accessions (AJC538, AJC539, AJC540, and AJC601) were identified as natural tetraploids, and the remaining lines (AJC595, AJC596, AJC597, AJC598, AJC599, and AJC600) were described as induced tetraploids. The ten parental tetraploid accessions of Russian wildrye were donated by the N.I. Vavilov Institute of Plant Industry (VIR), St. Petersburg, Russia. The accessions have been entered in the National Plant Germplasm System (NPGS) as PI numbers 565063 to 565072.

The ten parental accessions (Cycle-0) were evaluated from 1989 to 1992 at the Utah State University (USU) Evans Experimental Farm in Logan, Utah, (330–558 mm annual precipitation) and at the USU Blue Creek Experimental Farm (mean annual precipitation of 369 mm) in northwestern Utah. The parental accessions have significantly heavier seeds, greater seedling vigor, taller stature, and longer and wider leaves than standard diploid Russian wildrye cultivars and the tetraploid cultivar Tetracan. The parental accessions also have better water use efficiency than the diploid cultivars as determined by C-isotope discrimination measurement.

At the Blue Creek Experimental Farm, open-pollinated seed from selected clones of the parental accessions was screened for seedling emergence from deep (7.6-cm) plantings in the greenhouse. The Cycle-1 population consisted of 20 half-sib families (a total of 2160 plants) that traced to open-pollinated seed of selected accessions AJC538, AJC539, AJC540, AJC596, AJC597, AJC598, AJC599, AJC600, and AJC601. The Cycle-1 population was established in 1992 as a space-planted nursery at the Evans Experimental Farm. Selection for vegetative vigor, seed yield, 100-seed weight, and seedling emergence from deep (7.6-cm) seedings in the greenhouse was practiced among and within half-sib families. Seed was harvested only from selected plants to create the Cycle-2 population. Undesirable plant types were culled prior to pollination. The Cycle-2 population consisting of 40 half-sib families was established in nurseries on semiarid sites (annual precipitation 340 mm) near Nephi, Utah, and on the Curlew Grasslands in northwestern Utah (annual precipitation 150–250 mm) to initiate the third cycle of selection.

The 40 half-sib families from the Cycle-2 population were evaluated for 100-seed weight and rate of emergence from a 7.6-cm-deep planting. The half-sib families were significantly greater ($P < 0.05$) for both characteristics than were the diploid cultivars tested. Using a selection index that included forage yield, total seed weight, and individual seed weight (double weighted), equal amounts of open-pollinated seed from 26 selected half-sib families were combined to generate the broad-based RWR-Tetra-1 germplasm.

RWR-Tetra-1 is highly cross-pollinated and behaves meiotically as an autotetraploid ($2n = 4x = 28$) (genome constitution NsNsNsNs) with a high frequency of multivalents typical of those observed in artificially induced tetraploids of Russian wildrye (Wang and Berdahl 1990). It is the first release of tetraploid Russian wildrye germplasm that includes naturally occurring tetraploid plants in its parentage. Previous work, including that conducted with the cultivar Tetracan

(Dhindsa and Slinkard 1963, Lawrence et al. 1990), has been limited to tetraploids artificially induced from diploids. Morphologically, RWR-Tetra-1 is taller than the Vinall, Cabree, and Tetracan cultivars and has longer leaves than Vinall. RWR-Tetra-1 has heavier seeds than existing diploid cultivars. Spike characteristics are similar to diploid Russian wildrye.

*Crested Wheatgrass (*Agropyron cristatum *and* A. desertorum*; Introduced)*

Introduction. Crested wheatgrass is an extremely long-lived, drought-tolerant, bunch to moderately rhizomatous range grass that is adapted to a wide range of ecological sites and zones receiving as little as 200–250 mm of annual precipitation. In North America it is particularly well adapted to the northern and central Great Plains and the more arid intermountain region. It is very winter hardy and has an extensive root system that gives it excellent drought resistance. Vegetative growth is greater from mid-April to mid-June and declines rapidly by early July. It has very vigorous seedlings, making it relatively easy to establish under harsh environmental conditions. With seedling vigor and times of rapid growth coinciding with those of invasive annual weeds, crested wheatgrass is a natural competitor. Crested wheatgrass does well on most fertile soils, including heavy clay soils, and it is fairly tolerant of highly alkaline soils.

There are three recognized morphological types of crested wheatgrass: fairway (*A. cristatum*), standard (*A. desertorum*), and Siberian (*A. fragile*). The fairway type has short, broad spikes that taper at the top, and, compared to the standard type, it has smaller seeds, grows shorter, and has finer leaves and stems. The spikes on the standard type are longer than on the fairway type, but they vary in shape from comb-like to oblong. The spikes of the Siberian type are longer and much narrower than on the standard and fairway types. (Throughout this document we have grouped the Siberian crested wheatgrasses separately from the fairway- and standard-type crested wheatgrasses.)

Limitations. In general, crested wheatgrass is not adapted to moist soils and cool, short growing days with high humidity. It will tolerate short periods of spring flooding that do not exceed 7–10 days, but it is intolerant of soils with high water tables. Crested wheatgrass is less tolerant of soil salinity than tall wheatgrass, western wheatgrass, and quackgrass. Reduced plant vigor and poor stands are likely at elevations above 1980 m (6500 ft) in the Great Basin.

SERPD crested wheatgrass. We have released two new crested wheatgrass cultivars: CD-II and RoadCrest.

Registration of CD-II Crested Wheatgrass. CD-II (Reg. no. CV-24, PI 594024) crested wheatgrass is a 10-clone synthetic derived from the cultivar

Hycrest, which is a hybrid between the induced tetraploid *Agropyron cristatum* (L.) Gaertner and the natural tetraploid *Agropyron desertorum* (Fisch. ex Link) Schultes. CD-II was released on 25 January 1996 (Asay et al. 1997).

A breeding program was initiated in 1985 to improve the Hycrest breeding population. The base population was derived from 100 clonal lines, which were selected from a Hycrest foundation seed-increase block consisting of 40,000 spaced plants. Selection was based primarily on vegetative vigor and the absence of purple leaves during the early spring, tolerance to diseases and insects, and leafiness.

The 100 clonal lines were evaluated a second time in a 10-replicate crossing block for the same vegetative characters as well as for individual seed weight and emergence of polycross seedlots from deep seedings. Polycross progenies from 30 selected clonal lines were bulked in equal quantities to form a breeding population, which was advanced through two additional breeding cycles of selection for leafiness, vegetative vigor, and seedling vigor. Polycross seed from 10 clonal lines selected from the final breeding cycle was bulked to form breeder's seed.

CD-II produces significantly more forage at low temperatures in the growth chamber than Hycrest (Table 9). The seedling vigor of CD-II on a field site near Logan, Utah, was significantly greater than Hycrest (Table 10). CD-II has been distinguished from Hycrest on the basis of Random Amplified Polymorphic DNA (RAPD) fingerprinting profiles (Hu et al. 2001) (see the section on "Molecular Marker Development: Markers for Cold Tolerance and Early Spring Growth" later in this report).

Table 9. Growth of CD-II and Hycrest seedlings at low temperature in a growth chamber.

Cultivar	Grams / plot 10°C (50°F)	Grams / plot 5°C (41°F)
Hycrest	3.34	4.94
CD-II	5.39	6.17

Table 10. Growth of CD-II and Hycrest seedlings at a field site near Logan, Utah.

	Seedling height at 6 weeks (cm)	Vigor rating (1 to 9)	Stand rating (1 to 9)	Dry weight (g)
Hycrest	5.7	6.5	7.5	104
CD-II	10.4	8.5	8.5	117
LSD (0.05)	1.0	0.6	1.2	23

The CD-II cultivar produces from 670 to 900 kg seed/ha on sites receiving 400–450 mm of annual precipitation with no supplemental irrigation. CD-II produces abundant forage during the spring and early summer, and it is recommended for semiarid range sites in the Intermountain Region and Great Plains receiving 200–450 mm of annual precipitation at altitudes up to 2200 m. When drilled under dryland range conditions, a seeding rate of 7–9 kg/ha is recommended.

Registration of RoadCrest Crested Wheatgrass. RoadCrest crested wheatgrass (Reg. no. CV-25, PI 606546), a rhizomatous cultivar of crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.], was released on 2 June 1998 (Asay et al. 1999). It was derived from two accessions originally collected at Dikmen Ankara and Güvercinlik Ankara, Turkey, and provided to the USDA-ARS Forage and Range Research Unit by Dr. Esvet Acikgoz of Turkey. Rhizomatous plants, observed in these accessions during their initial evaluation on a semiarid range site in central Utah, were selected and established in a crossing block to develop the parental germplasm. These plant materials were then subjected to two cycles of selection based largely on progeny evaluation for increased rhizome development, fine leaf texture, short growth stature, and improved seedling vigor. Breeder's seed was compounded from selected polycross seedlots in the final breeding cycle.

RoadCrest is long-lived and is significantly more rhizomatous than any other crested wheatgrass included in evaluation trials, including the cultivar Ephraim, which is the only other rhizomatous cultivar of crested wheatgrass to be released. RoadCrest produces less biomass and is 15–25% shorter in stature than forage-type crested wheatgrass cultivars (Table 11). The cultivar has been evaluated on roadsides and in turf trials in Utah, Colorado, and Washington. Seedling vigor and drought resistance of RoadCrest compares favorably with other crested wheatgrasses cultivars, including Hycrest, CD-II, Fairway, and Nordan. RoadCrest is significantly easier to establish and initiates growth earlier in the spring than other turf and low-maintenance turf grasses, including Kentucky bluegrass, 'Sodar' thickspike wheatgrass, tall fescue, and hard fescue. Leaf color intensity and turf quality of RoadCrest are not as good as Kentucky bluegrass, tall fescue, and perennial ryegrass when the latter grasses are grown under optimum conditions. RoadCrest greens up early in the spring and remains green until midsummer on temperate sites similar to Logan, Utah. Plants then go dormant until temperatures decline in the fall. This characteristic varies according to summer temperatures and annual precipitation. Summer dormancy is much less prominent at elevations above 1500 m.

Table 11. Growth of RoadCrest and Ephraim crested wheatgrass in a greenhouse study. The differences between the two grasses were significant at the 0.01 probability level for both plant height and crown width.

	Plant height (cm)	Crown width (cm)
RoadCrest	72	66
Ephraim	85	59

RoadCrest has good potential as a low-maintenance turf grass on semiarid sites (250–500 mm of annual precipitation) such as roadsides, low-use playing fields, walking trails, lawns, and other non-irrigated cantonment areas, as well as on ammunition storage bunkers in training areas. As with other crested wheatgrass cultivars, supplemental irrigation can be detrimental if the total water application (precipitation plus irrigation) exceeds 550 mm annually. RoadCrest was a top performer in the dry conditions at the South Boundary site at Fort Carson.

RoadCrest is a natural tetraploid ($2n = 4x = 28$) and is fully interfertile with tetraploid cultivars of crested wheatgrass (*Agropyron cristatum* and *A. desertorum*), Siberian crested wheatgrass (*A. fragile*), and the crested wheatgrass hybrid cultivars Hycrest and CD-II. Established isolation distances from these cultivars must be maintained in certified seed fields. The cultivar produced 560 kg of seed/ha when grown in rows 0.9 m apart with moderate supplemental irrigation and 50 kg N/ha applied in the fall. At 100% purity, there are approximately 530,000 seeds/kg.

*Siberian Wheatgrass (*Agropyron fragile*; Introduced)*

Introduction. The Siberian type of crested wheatgrass occupies sites where standard crested wheatgrass will grow, but it is particularly noted for its ability to establish quickly on drier, sandy soils (200–260 mm annual precipitation). The Siberian type of crested wheatgrass is awnless, has finer leaves, and retains its greenness and palatability later into the summer than standard- and fairway-type crested wheatgrasses discussed in the previous section.

Limitations. Siberian wheatgrass has poor seedling vigor along with the same limitations as the other crested wheatgrasses (see the previous section).

SERDP-select Siberian wheatgrass. This germplasm originated from the cultivar Vavilov (Asay et al. 1995) and from collections from western Kazakhstan. The parental germplasm for Vavilov was derived from accessions originally received from the N.I. Vavilov Institute of Plant Industry (VIR); the

Stavropol Botanical Garden, Stavropol, Russia; the Eskisehir Plant Breeding Station, Eskisehir, Turkey; and selections from the cultivar P-27. In addition, it included selected lines from Kazakhstan that were originally evaluated under the SERDP program for seed yield, seed weight, seedling vigor, forage yield, and military suitability (Jensen et al. 2000).

Cycle-0 was initiated by screening seedlings of Vavilov and Kazakhstan collections for emergence from a 6.7-cm-deep seeding (an estimate of seedling vigor). These plants were established at Yakima Training Center (832 plants), Lakeside, Utah (600 plants), and Snowville, Utah (600 plants), in 1999. Based on plant vigor, total seed weight (g/plant), 100-seed weight (g), and rate of seedling emergence from a 7.6-cm-deep planting, 50 plants (15 Yakima, 29 Lakeside, and 6 Snowville) were selected for generation advance. Table 12 compares the performance of the selected plants (50; Cycle-1) with the average of the entire breeding population for the above characteristics.

Table 12. Characteristics of the Siberian wheatgrass selections compared to the entire original breeding population.

	Original population mean	Selected population mean
Seedling emergence rate (seedlings/day)	2.2	3.1
Seed weight (g/100 seeds)	0.29	0.33
Total seed yield (g/plant)	26	25

Clones from the Cycle-1 polycross block (50) were established in a seed increase block at the Blue Creek Research Station in northern Utah in 2000. Bulk seed, which is available to the Army for seed increase, was harvested for testing in 2001 and 2002. In addition, 10 clones from Cycle-1 were selected based on performance and polycrossed in the greenhouse winter of 2001-02 to initiate Cycle-2. Cycle-2 progeny were screened for their ability to emerge from a 7.6-cm-deep planting. Superior genotypes (1800 plants) were established at the Nephi Research Station (Nephi, Utah) in 2002 for further selection for seedling vigor and plant vigor. This is an excellent-looking population with good seedling and plant vigor. A formal release of Cycle-2 is expected in 2004. SERDP-select Siberian wheatgrass Cycle-2 was established in three demonstration nurseries in Colorado, Washington, and Utah during the fall of 2002.

*Bluebunch Wheatgrass (*Pseudoroegneria spicata*; Native)*

Introduction. Bluebunch wheatgrass is a cross-pollinated, predominantly diploid species widely distributed in the Intermountain West. It is a long-lived, drought-tolerant native bunchgrass that begins growth early in the spring and again with the onset of fall rains. It is an important native grass on Palouse Prairie and Intermountain sagebrush sites, and it is widely adapted geographically from high elevations in the Sonoran Desert north to Washington. It is adapted to dry mountain slopes, sagebrush, ponderosa pine, mountain-brush, and juniper-piñon ranges receiving 250–350 mm of precipitation annually. Bluebunch wheatgrass is adapted to coarse-textured soils, but it will establish and persist on deep, well-drained loamy soils. In the Palouse Prairie of eastern Washington, bluebunch wheatgrass is often associated with Idaho fescue on deeper soils and Sandberg bluegrass on shallower soils. In the Great Basin, bluebunch wheatgrass occurs as a co-dominant species with big sagebrush on arid sites that receive 120–400 mm of annual precipitation. At Yakima Training Center we have observed it to be a natural invader of lands sown to introduced species (see Table B1 in Appendix B, "Background Data for Non-Invasiveness of Introduced Species").

Limitations. Even though bluebunch wheatgrass recovers rapidly after limited grazing, it is not tolerant of heavy or repeated grazing or military training during the growing season. Because of its poor seedling vigor, bluebunch wheatgrass requires several years for stands to reach full productivity.

SERDP bluebunch wheatgrass. To improve the genetic diversity and adaptability of bluebunch wheatgrass, we have developed two new germplasms (P-7 and SERDP-select) from polycrosses of multiple collections. The P-7 release is a multiple-origin polycross with no selection pressure applied. The SERDP-select germplasm originated from a multiple-origin polycross, and we are selectively breeding in that population for improved seed germination, seedling and plant vigor, and emergence from a deep seeding.

Registration of P-7 Bluebunch Wheatgrass Germplasm. P-7 bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve] germplasm (Reg. no. GP-7, PI 619629) was released on 28 February 2001 as a Selected Class Germplasm (Jones et al. 2002). This class of prevariety germplasm is eligible for seed certification under guidelines developed by the Association of Official Seed Certifying Agencies (2001).

P-7 is a multiple-origin polycross generated by intermating two cultivars and 23 open-pollinated, native-site collections from Washington, Oregon, Nevada, Utah, Idaho, Montana, and British Columbia. The two cultivar populations were Whitmar and Goldar, which both originated in southeastern Washington. Whitmar is an awnless cultivar developed from a population collected near Colton, Whitman County, Washington, and Goldar is an awned cultivar developed from a population collected near Anatone, Asotin County, Washington; they were released by the USDA-NRCS in 1946 and 1989, respectively (Hein 1958, Gibbs et al. 1991). Nine of the remaining populations were collected by T.A. Jones (PI 537368, Pollock, Idaho; PI 537370, Riggins, Idaho; PI 598821, Wawawai Park, Washington; PI 537374, Steptoe Butte, Washington; PI 537375, Durkee, Oregon; PI 537378, Lone Mountain Junction, Nevada; PI 516185, Seneca, Oregon; PI 537388, Dayton, Washington; PI 563870, Green Canyon, Utah), seven were collected by K.H. Asay (PI 563872, New Meadows, Idaho; PI 563867, Colton, Washington; PI 563868, Wawawai Road, Washington; PI 563874, Wawawai Park, Washington; PI 562050, Wawawai Park, Washington; PI 598816, Connell, Washington; PI 562056, Lind, Washington), and seven were obtained from miscellaneous sources (PI 595192, Wawawai Road, Washington; PI 595193, Almota Road, Washington; PI 595196, Darby, Montana; PI 236670, Slocan, British Columbia; P-3, Grande Ronde River, Oregon; P-5, unknown; KJ-10, Salina Canyon, Utah). Twenty-four of the constituent populations are diploid ($2n = 2x = 14$) and one (PI 537374) is tetraploid ($2n = 4x = 28$). The inclusion of the tetraploid PI 537374 in the polycross was inadvertent. The representation of this tetraploid is expected to decline dramatically through generations of seed increase. Therefore, P-7 can be considered to be predominately diploid—the dominant ploidy level of bluebunch wheatgrass.

Sixteen of the P-7's 25 component populations are predominately awned and nine are predominately awnless. Because the awnless state is dominant and the awned state is recessive in bluebunch wheatgrass and its relatives, P-7 individuals are predominately awnless.

P-7 is intended to provide genetic diversity within a single germplasm for semiarid to mesic sites where bluebunch wheatgrass was an original component of the vegetation. Our genetic studies confirm that P-7 displays greater genetic variation than the Goldar or Whitmar cultivars (Larson et al. 2000; see the section on "Molecular Marker Development: Genetic Variation" later in this report).

Breeder's seed of P-7 was bulked across the 25 populations in direct proportion to their seed yield in 1995 in a replicated test at the Blue Creek Experimental Farm in northwestern Utah. Generation-0 (the separate 25 populations), G-1 (first intermating), and G-2 (second intermating) will be maintained by the USDA-ARS Forage and Range Research Laboratory, Logan, Utah. G-2 seed will be made available to growers for production of G-3 and G-4 generations of seed (third and fourth intermating) by the Utah Crop Improvement Association. To limit genetic shift, the sale of P-7 seed beyond generation G-4 is expressly prohibited.

SERDP-Select Bluebunch Wheatgrass. A second SERDP-select bluebunch population was derived from approximately 22 collections near Yakima, Washington. The original collections were evaluated at Yakima Training Center (Exit 11) in a space-planted nursery (3750 plants). This base population was screened for vegetative vigor, and seed from 78 superior clones was harvested in 1996 (Cycle-1). Forty of these progeny lines were subsequently selected on the basis of total seed yield (g/plant), 50-seed weight (g), and emergence from a 7.6-cm-deep seeding. These lines were then established in a 1600-plant nursery (four replications) at the Blue Creek Research Station in 1997 to initiate the next cycle of field screening. Open-pollinated seed was harvested from 53 clones selected from this nursery on the basis of superior plant vigor. Subsequent screening for total seed weight (g/plant), 50-seed weight (g), and emergence from a 7.6-cm-deep seeding reduced the 53 plants to five for generation advance (Table 13). Open-pollinated seed from the five selected lines was screened for seedling vigor, with superior genotypes being established in a seed increase field in northern Utah in 2001. Seed for demonstrations was harvested in 2002. A Selected Class Germplasm release is expected in 2004.

Table 13. Characteristics of bluebunch wheatgrass selections compared to the original breeding population.

	Original population mean	Selected population mean
Seedling emergence rate (seedlings/day)	1.24	2.58
Seed weight (g/50 seeds)	0.23	0.30
Total seed yield (g/plant)	5.91	8.32

*Western Wheatgrass (*Pascopyrum smithii*; Native)*

Introduction. Western wheatgrass is native to North America and is distributed throughout the western two-thirds of the United States and Canada. It is an important rangeland and pasture grass in the central and northern Great Plains and Intermountain Region. It is a long-lived, late-maturing, rhizomatous, cool-season grass with coarse, blue-green leaves. Because of its sod-forming characteristics, western wheatgrass is well adapted for stabilizing soils on sites subject to excessive erosion as well as on rangelands disturbed by military training activities, surface-mining operations, construction, overgrazing, brush control, and fires. Western wheatgrass is winter hardy and can survive drought. It is adapted to a wide range of soils, but it prefers the heavy and somewhat alkaline soils characteristic of shallow lakebeds or intermittent watercourses that receive excess surface drainage. It requires moderate to high soil moisture content and is most adapted to regions receiving 250–350 mm of annual precipitation. When the annual precipitation exceeds 500 mm, western wheatgrass usually becomes very aggressive. Western wheatgrass is commonly associated with blue grama and the needlegrasses of the Great Plains and with bluebunch and thickspike wheatgrasses and various shrubs of the Great Basin, where it is an important constituent of spring, summer, and early fall ranges. At arid and semiarid sites, western wheatgrass is often confused morphologically with thickspike wheatgrass. Its elevation range is 300–2750 m (1000–9000 ft).

Limitations. Western wheatgrass germinates poorly, has a high rate of seed dormancy, has low seedling vigor, and often requires two or three years to reach well-established stands. As a result, plants are initially scattered in stands, but because of its aggressive rhizome development, it may eventually dominate the site within three to four years. Western wheatgrass is a poor seed producer.

SERDP-Select Western Wheatgrass. This population originated from collections near and on Fort Carson, Colorado, from germplasm accessions, and from already existing cultivars commonly used in reseeding projects. We are developing two populations: one each from the Turkey Creek and South Boundary areas of Fort Carson.

The Turkey Creek germplasm includes parental material collected from Fort Carson (WW117FC), germplasm related to the cultivar Rodan (D2945), and Rosana, a well-proven cultivar. The current population has undergone one cycle of selection for seed yield, plant vigor, and general adaptation to the Turkey Creek area; and two cycles of selection for increased germination and seedling vigor. Initially, individual plants of a large number of germplasm collections and cultivars were evaluated at the Turkey Creek Recreation Area for two years. In 1998, open-pollinated seed was harvested from the best plants that were selected for adaptation to the area, moderate spread, vigorous growth, and abundant seed production. The harvested seed was planted in a Logan, Utah, greenhouse 6.3 cm deep and evaluated for rate of emergence (Table 14). The 50 fastest-emerging seedlings of the top four plants were transplanted to containers and, in 1999, transplanted into a field-crossing block near Logan, Utah. In 2001, seed was harvested from the crossing block and screened a second time for the ability to emerge from a deep planting. Two thousand seedlings with the fastest emergence were selected (500 from each parental source) and used to establish a seed increase field in 2001. Seed was harvested in 2002 and used for test plantings and for evaluating the gain from selection for improved seedling vigor.

Table 14. Seedling emergence rate of western wheatgrass from a 6.3-cm-deep planting.

	Original population mean	Selected population mean
Seedling emergence rate (seedlings/day)	2.3	3.9
Total seedling emergence	31.6	52.9

The South Boundary germplasm was selected for improved seedling vigor and adaptation to the South Boundary area. It initially comprised a selection of seven original plants that survived the harsh, dry conditions found at the South Boundary evaluation plot area. These plants originated from the cultivars Arriba and Rosana and from the D2945 germplasm described above. The seven plants were selected from a large evaluation nursery as being the most vigorous plants of the few surviving entries. Clones of each selected plant were transplanted to a field crossing block near Logan, Utah, in 1999. In 2001, seed was harvested from the crossing block and screened as described above for the ability to emerge from a deep planting, demonstrating improved germination and seedling vigor. Two thousand seedlings with the fastest emergence were selected (approximately 300 from each parental source) and used to establish a seed increase field in 2001. Seed was harvested in 2002 and used for test plantings and for evaluating the gain from selection for improved persistence and seedling vigor.

*Snake River Wheatgrass (*Elymus wawawaiensis*; Native)*

Introduction. Snake River wheatgrass is very well adapted in the northwest, especially at Yakima Training Center. It is a long-lived, perennial bunchgrass that is native to the valleys of the Snake River and its tributaries in Washington and northern Idaho. Morphologically this taxon is almost identical to bluebunch wheatgrass, but genetically it is similar to thickspike wheatgrass. It is adaptable to most areas suitable for bluebunch wheatgrass but is more vigorous and productive. Snake River wheatgrass has been successfully established on sites that receive as little as 200 mm of annual precipitation. At many sites, Snake River wheatgrass grows in grass mixtures with unawned forms of bluebunch wheatgrass. At such sites, Snake River wheatgrass is easily distinguished by its awns.

Limitations. Limitations for Snake River wheatgrass are similar to those for bluebunch wheatgrass. Because of its poor seedling vigor, Snake River wheatgrass requires several years for stands to reach full productivity. During seedling establishment, plants should be allowed to reach maturity before being subjected to grazing or military training activities.

SERDP-Select Snake River Wheatgrass. The SERDP-select Snake River wheatgrass population originated from 'Secar' and two native collections near Yakima, Washington. Based on results from the evaluation trials in 1998, the cultivar Secar accessions Acc:707 and T572 were selected and established in a 3096-plant space-planted source nursery. Space plants of Secar, Acc:707, and T572 had previously been screened for rate of emergence from a 7.6-cm-deep planting. Based on increased plant vigor, open-pollinated seed from 302 plants (10% selection), which included plants from all three accessions, were harvested in 1999 (Cycle-1). Based on total seed weight (g/plant) and emergence rate from a 7.6-cm-deep seeding, 36 lines were selected and clones removed from the Yakima Training Nursery in November 1999 (Table 15).

Table 15. SERDP-select Snake River wheatgrass Cycle-1 compared to the mean of the base population.

	Beginning population mean	SERDP-selected population mean
Seedling emergence rate (seedlings/day)	2.3	3.9
Total seed yield (g/plant)	11.75	16.25

Cycle-1 clones were established (1080 space plants) in a seed increase block at the Blue Creek Research Station in northern Utah in 2000. Bulk seed, which is available to the Army for seed increase, was harvested for testing in 2001 and 2002. In addition, eight clones selected from Cycle-1 were polycrossed in the greenhouse during the winter of 2001-02 to initiate Cycle-2. Cycle-2 progeny were screened for their ability to emerge from a 7.6-cm-deep planting. Superior genotypes (2200 plants) were established at the Nephi Research Station in 2002 to facilitate further selection for seedling and plant vigor. This is an excellent-looking population with good seedling and plant vigor. A formal release is expected in 2004. SERDP-select Snake River Cycle-1 was established in three demonstration nurseries in Colorado, Washington, and Utah during the fall of 2002. A release as a Selected Class Germplasm is expected in 2004.

*Basin Wildrye (*Leymus cinereus*; Native)*

Introduction. Basin wildrye is a hardy, robust, long-lived perennial bunchgrass that is native throughout the western United States. It is tall and coarse, and it is highly palatable early in the spring but becomes very unpalatable with maturity. It is used as forage by livestock and wildlife. Poor seedling vigor usually results in sparse stands, but it is one of the highest-producing grasses once established. It can be used as a component in mixtures with other adapted plants to reseed rangelands, mine spoils, highway rights-of-way, or other disturbed areas.

Basin wildrye is widely distributed throughout British Columbia to Saskatchewan, south to California, and east to Arizona and Colorado. It is adapted to the fine-textured soils in valley bottoms, along roadsides and streams, and in gullies. In sagebrush ecosystems it is often found on riverbanks or waterways, in ravines, and on other sites with a high water table. It is adapted to areas with an average annual precipitation of more than 350 mm. It is moderately tolerant of alkaline and saline soils. Basin wildrye is often associated with other wheatgrasses, rabbitbrush, and sagebrush.

Limitations. As with other wildrye species, Basin wildrye is usually difficult to establish. Poor seed development along with low germination and seedling survival has limited its usefulness for range revegetation. New seedlings should not be grazed or harvested until the late summer or fall of the second growing season.

Genetic marker studies. Inheritance studies with Basin and beardless wildrye hybrids found markers associated with leaf growth and carbohydrate content, suggesting that these two traits associated with early spring growth could be simultaneously improved (Larson et al. 1999; see the section on "Molecular Marker Development: Markers for Cold Tolerance and Early Spring Growth" later in this report).

SERDP-Select Basin Wildrye. This germplasm originated from 14 collections made on the Yakima Training Center, Washington. The original collections were evaluated at the Exit 11 site at Yakima Training Center in a space-planted nursery (700 plants). Based on increased plant vigor, open-pollinated seed from 118 plants, which included all 14 collections, was harvested in 1996 (Cycle-1). Based on total seed weight (g/plant), 50-seed weight (g), and emergence from a 7.6-cm-deep seeding, seed from 40 plants was selected and established at the Blue Creek Research Station in northern Utah (1600 space plants/four replications) in 1997. Open-pollinated seed of 53 Cycle-2 plants was selected from the Blue Creek Nursery based on superior plant vigor. Subsequent screening for total seed weight (g/plant) and emergence rate from a 7.6-cm-deep seeding reduced the 118 plants to 18 for generation advance. Open-pollinated seed from the 18 selected plants was screened for seedling vigor (Cycle-2), with superior genotypes being established in a seed increase field in northern Utah in 2002. Seed will be available for the Army and demonstration nurseries by 2003. A Selected Class Germplasm release is expected in 2004.

*Slender Wheatgrass (*Elymus trachycaulus*; Native)*

Introduction. Slender wheatgrass is a short-lived, native bunchgrass with good seedling vigor and moderate palatability. It is widely adapted throughout the western United States and Canada, where it is found growing at elevations of 1370–3660 m (4,500–12,000 ft) along dry to moderately wet roadsides, streambanks, meadows, and woodlands from the valley bottoms to subalpine and alpine elevations in aspen and open coniferous forests. It is most common in Montana and Wyoming, where it has been reported between 900 and 2135 m (3000 and 7000 ft). The salinity tolerance of slender wheatgrass is similar to that of Russian wildrye and less than that of tall wheatgrass. The seed is larger than most wheatgrasses and is easily seeded with conventional seed drills.

This self-fertilizing bunchgrass was the first native grass to be widely used in revegetation programs in the western United States and Canada. Slender wheatgrass tolerates a wide range of conditions and adapts well to high-altitude ranges and more favorable sites on aspen and tall-mountain brush regions. Because of its rapid seedling germination and establishment, moderate salt tolerance, and compatibility with other species, slender wheatgrass is a valuable component in erosion-control and mine-land reclamation seed mixes. Slender wheatgrass is most commonly used as a component of a mix in burned or disturbed-site rehabilitation, where it serves as a cover crop, eventually giving way to longer-lived perennials.

Limitations. Slender wheatgrass is less drought tolerant than most of the wheatgrasses, including crested and bluebunch wheatgrass. It prefers loams and sandy loams in areas receiving at least 350 mm of annual precipitation, but it does not tolerate waterlogged soils. Slender wheatgrass is relatively short lived. It yields well for the first three to four years, but then the stand density decreases rapidly. It is not as competitive with weeds as other wheatgrasses, but it is shade tolerant. Slender wheatgrass is highly susceptible to the grass billbug (*Sphenophorus* spp.), which can severely reduce stands. Slender wheatgrass is not resistant to close grazing, and continual heavy grazing reduces stands quickly.

SERDP-Select Slender Wheatgrass. We are developing two populations, a bunch type and a rhizomatous type. The bunch-type population originated from seven collections made on Fort Carson, Colorado, in 1994. An initial space-planted nursery (560 plants) was established at the South Boundary site at Fort Carson in 1995. Based on visible plant vigor, 210 plants were selected in 1997. These were established as clones at Snowville, Utah, in 1998, and seed was harvested in 1999 to generate a multi-line germplasm. A seed increase field of this multi-line composite was established in 2000, and large-scale seed harvests were completed in 2001 and 2002; we established three demonstration nurseries in

Colorado, Washington, and Utah during the fall of 2002. We currently have several hundred pounds of this germplasm available for the DoD demonstrations. This bunch-type germplasm is an excellent-looking population with good seedling and plant vigor. A Selected Class Germplasm release is expected in 2004.

The rhizomatous population originated from a multi-plant collection near Pike's Peak in Colorado. This collection is unique in that it exhibited a limited degree of rhizome development. Early in the 1990s, we cycled this population for persistence and rhizome development. As part of the SERDP project, we established a space-planted nursery (2250 plants), which had been screened for emergence from a 7.6-cm-deep planting in 2000. In 2001, 34 plants were selected based on rhizome development (Fig. 3), persistence, and seed production. In 2002, self-pollinated seed of these 34 plants were once again screened for rate of emergence from a 7.6-cm-deep planting and established at two locations in southern and northern Utah. A Cycle-2 seed increase with increased seedling vigor and germination was established in the spring of 2002. The development of a rhizomatous native that has the ability to establish quickly, reduce erosion, and allow for the establishment of more-persistent natives is important in the restoration process. A Selected Class Germplasm release is expected in 2004.

Figure 3. Comparison of populations of slender wheatgrass. The selected population on the left has rhizomes and the unselected population on the right lacks rhizomes.

*Sandberg Bluegrass (*Poa sandbergii*; Native)*

Introduction. Sandberg bluegrass is an apomictic native grass and is an important understory plant of the sagebrush–bluebunch wheatgrass communities found on the Yakima Training Center. It is a perennial bunchgrass that grows in small tufts no more than 0.3 m (1 ft) in diameter. It is widely distributed throughout the western range where annual precipitation is 350–500 mm, and it is somewhat tolerant of heavy trampling. Once established, Sandberg bluegrass is perhaps the most drought tolerant of the bluegrasses. It is adapted to mountains, uplands, and semi-deserts on lighter-textured and stony loam soils. It inhabits a wide range in elevations, being found as low as 300 m (1,000 ft) in Washington and as high as 3,660 m (12,000 ft) in the mountains of northern New Mexico.

Limitations. The seed viability of Sandberg bluegrass is poor, and forage quality declines rapidly as it matures. It reproduces apomictically (the progeny can be exactly like the mother plant), suggesting that, over time, populations may become genetically distinct and be adapted only to specific environments.

SERDP Sandberg Bluegrass. This germplasm originated from 28 ecotypes from 26 locations at the Yakima Training Center. The plants were transplanted to a field near Logan, Utah. Seed was harvested from those plants and used to establish a seed-increase block near Logan. Because we combined the germplasm from the different ecotypes, this broad-based mix of apomictic genotypes should be better adapted to a wider range of environments. Molecular DNA tests (Larson et al. 2001; see the section on “Molecular Marker Development: Genetic Variation” later in this report) confirmed that a similar broad-based collection of Sandberg bluegrass has a large amount of genetic diversity but that it is still 30% different from Sandberg bluegrass germplasm originating near Boise, Idaho. Seed was being increased in 2002 and 2003, and a Selected Class Germplasm release is expected in 2004.

*Western Yarrow (*Achillea millefolium*; Native)*

Introduction. In addition to the grasses, we also have western yarrow in the improved breeding program. It is a drought-tolerant, native forb that provides a good complement to grass stands. In areas of natural plant disturbance, western yarrow establishes readily and increases over time. Western yarrow is one of the most widely distributed herbaceous species in the western United States, and it grows in a wide variety of habitats ranging from aspens and open forests to sagebrush zones. It avoids dense shade, is comparatively drought resistant, and flourishes in sandy and gravelly loam soils.

Limitations. Sources of commercial seed are limited, although this may become less of a problem, as it is gaining in popularity as a revegetation species.

SERDP Western Yarrow. This germplasm originated from 28 collections made within Yakima Training Center. It is a broad-based population with no selection pressure having been applied. Our early trials at the Yakima Training Center suggested that western yarrow collected there outperformed commercially available western yarrow (Table 16). After these tests, we collected western yarrow seed from 26 Yakima Training Center locations representing six ecological sites. Plants were started from the collected seed and established in a seed-increase field. A formal release as a Selected Class Germplasm is expected by 2004.

Table 16. Results of trials comparing the percent stand of Yakima populations with the commercial variety of western yarrow.

% stand of western yarrow	1995	1996	1997	1998
Commercial variety	38	25	4	0
Yakima ecotype	21	44	44	56

Molecular Marker Development

We leveraged SERDP funding with a research project funded under the BT-25 Program “Genetic Characterization of Native Plants in Cold Regions” to identify genetic markers that relate to plant characteristics necessary for resiliency and to analyze the genetic diversity of the new germplasms. Using genetic markers can save time, since potential plants produced during the breeding process can be selected for desired genes rather than having to be grown over a two-year period to identify and select the desired traits.

In our earlier work we used the Random Amplified Polymorphic DNA (RAPD) technique to identify the markers (Huff et al. 1998). We found four markers for early spring growth in Hycrest crested wheatgrass (Hu et al. 2001) and a marker for fast seed germination in western wheatgrass (Liu et al. 1997). This latter species, which is a widely distributed, long-lived, sod-forming grass, has strong rhizomatous growth in sandy soil, an important characteristic for plant resiliency on military training lands (Asay and Knowles 1985).

We used flow cytometry to differentiate and identify fine fescue (*Festuca*) species (Huff and Palazzo 1998). Fine fescues comprise a group of plants that are morphologically similar and have fine to very fine leaf texture. Identification and classification is very difficult in such species, which creates problems for programs such as the LCTA monitoring system. We found that we can separate morphologically similar fine fescue species using flow cytometry, which essentially counts the number of chromosomes in plant tissue. The DNA content among the ten species we examined was highly positively correlated with observed or reported chromosome numbers.

As part of this SERDP project we continued to identify markers for important characters, including growth at low temperatures and early spring growth. As the project progressed, we updated our analysis techniques from RAPD and flow cytometry to the Amplified Fragment Length Polymorphic (AFLP) procedure. AFLP is much more reproducible than is the RAPD technique. For the genetic variance studies, we also used analysis of molecular variance (AMOVA) to determine the significance in genetic differences between populations (Excoffier et al. 1992).

Markers for Cold Tolerance and Early Spring Growth

We used AFLP techniques to find relationships between genetic markers and early spring growth in wildrye (*Leymus* sp.) and crested wheatgrass—two cool-season grasses used widely on military lands in the west. Early spring growth is important because most of the soil erosion on military bases occurs in the early spring prior to a plant's active growth stage. A plant usually initiates early spring growth by using the stored soluble carbohydrates (CHO) that were produced the previous fall and were carried over during the winter or dormant months. CHO compounds can also be used as cryoprotectants to protect plants against winterkill. Therefore, CHO compounds including anthocyanins are useful phenotypic markers for genetic and molecular studies of plant gene expression during cold stress and acclimation (Christie et al. 1994) and may facilitate the selection of genotypes with higher concentrations of soluble CHO (Chatterton et al. 1989, 1990). We found genetic relationships between low-temperature soluble CHO accumulations, anthocyanin coloration, and plant growth and development traits in wildrye (*Leymus* sp.) (Larson et al. 1999) and crested wheatgrass (Hu et al. 2000, 2001).

Wildrye. This grass has a circumpolar distribution. A total of 870 mapped AFLP markers were used to detect quantitative trait loci (QTL) controlling soluble carbohydrate accumulations, anthocyanin coloration, and growth characteristics in a segregating population derived from open-pollinated Basin wildrye (*Leymus cinereus*) × beardless wildrye (*L. triticoides*) hybrids. Positive trait correlations and pleiotropic gene effects were detected for soluble carbohydrate accumulations and anthocyanin coloration. Findings suggest that genetic manipulations in five QTL regions on linkage groups 1A, 1B, 2A, 4Xm, and 5Ns could improve fructan and anthocyanin synthesis (Larson et al. 1999).

In further inheritance studies on an F3 population (132 replicated clones) of the same basin wildrye × beardless wildrye hybrids, we examined three traits: leaf growth, leaf carbohydrate abundance, and anthocyanin expression. Using AFLP markers, we found one DNA marker negatively associated with all three traits, one marker positively associated with growth and carbohydrate, one marker positively associated with carbohydrate and anthocyanin, and at least four unique DNA marker groups for each trait. The results suggest that leaf growth and carbohydrate content can be simultaneously improved, extending the growing season and improving the resilience of these plants.

Crested Wheatgrass. For this plant we identified AFLP markers associated with anthocyanin coloration and upright vs. prostrate growth. Crested wheatgrass is well adapted to many semiarid steppe and prairie environments and was widely planted on military lands. The SERDP-select CD-II crested wheatgrass cultivar was selected from the cultivar Hycrest on the basis of vigorous vegetative growth and green leaf coloration during the early spring. Using AFLP markers we found that the two cultivars are distinguishable, although they remain closely related. CD-II plants have lower anthocyanin coloration (greater green leaf coloration), more upright growth, wider leaves, and earlier spring vegetative growth than Hycrest plants. It is possible to make further gains in the CD-II line for early spring growth with the aid of marker-assisted selection (Hu et al. 2000, 2001).

Genetic Variation

We studied the genetic variation of several grasses to help classify and confirm the improved characteristics or increased diversity of the SERDP-select germplasms. At the same time we looked at the diversity of commercially available plants to answer questions on the genetic diversity of purchased seeds and to help land managers make seeding decisions. A greater diversity enables a species to be more resilient or more adaptable to various environmental stresses, and our intent, especially in the selected-class germplasms, was to increase the genetic diversity in the improved germplasms. Some ecologists, however, may be concerned that the agronomic approach of cultivar development to select or breed plants with specific characteristics creates plant materials that may lack the genetic diversity to maintain their adaptation in dynamic environments. They believe that non-local seed sources may not have adapted genomes, or that non-local sources may result in genetic pollution. To put these concerns to rest, we examined the genetic diversity of natural populations and known cultivars of bluebunch wheatgrass, bluegrass, little bluestem, and western wheatgrass.

Bluebunch Wheatgrass. This cool-season, perennial grass is native to semiarid regions of western North America. During our review of the invasiveness of the introduced species under development, we found that bluebunch wheatgrass was successfully moving into seeded stands of introduced species (Palazzo et al. 1999; see Table B1 in Appendix B). One of the two new bluebunch wheatgrass germplasms we developed, P-7, is the result of multiple collections and is intended to provide genetic diversity within a single germplasm for semiarid to mesic sites where bluebunch wheatgrass was an original component of the vegetation. P-7 is a multiple-origin polycross generated by intermating 23 open-pollinated, native-site collections from Washington, Oregon, Nevada, Utah, Idaho, Montana, and British Columbia, along with the only cultivars currently available for purchase, Whitmar and Goldar. Although they are morphologically distinct—Goldar has awns and Whitmar does not—the commercially available cultivars originate from collections of populations less than 83 km apart in southeastern Washington.

We used the AFLP method to quantify and compare genetic variation within and between the Goldar and Whitmar cultivars and the SERDP P-7 multiple-origin polycross. More AFLP alleles (99) were found to be unique to P-7—present in P-7 but absent in Goldar and Whitmar—than were found to be unique to Whitmar (59) or Goldar (49). P-7 also had fewer fixed loci (233) than Whitmar (385) or Goldar (318). Overall within-population variation as shown by nucleotide-sequence diversity [$\pi \pm$ SE(1000)] was greater for P-7 (38.7 ± 1.6) than for Whitmar (34.2 ± 1.5) or Goldar (33.9 ± 1.5). Between-population variation as shown by the average net nucleotide-sequence divergence (d_A) was 0.3 ± 0.2 between P-7 and Goldar, 1.3 ± 0.2 between P-7 and Whitmar, and 2.6 ± 0.3 between Goldar and Whitmar. Therefore, P-7 is genetically intermediate between the two cultivars but more similar to Goldar than to Whitmar. Figure 4 illustrates these relationships among the P-7, Goldar, and Whitmar populations. We also found that the genetic diversity of the two named cultivars, collected more than 50 years ago, is stable, indicating that it is likely that our multi-origin cross will maintain its greater genetic diversity (Larson et al. 2000).

Bluegrasses. Bluegrasses are dominant perennial grasses in the understory steppe vegetation of western North America and are important for creating biological and genetic diversity and plant resiliency on military training lands. We used the AFLP method to measure nucleotide sequence variation within and between four commonly recognized forms of *Poa secunda* grasses: two cultivars, ‘Sherman’ big bluegrass and ‘Canbar’ canby bluegrass, and two broad-based Sandberg bluegrass sources, one collected from 19 sites at Yakima Training Center (YTC) and one collected from Mountain Home (MH) near Boise, Idaho (Larson et al. 2001). The Canbar and Sherman plants were grown from

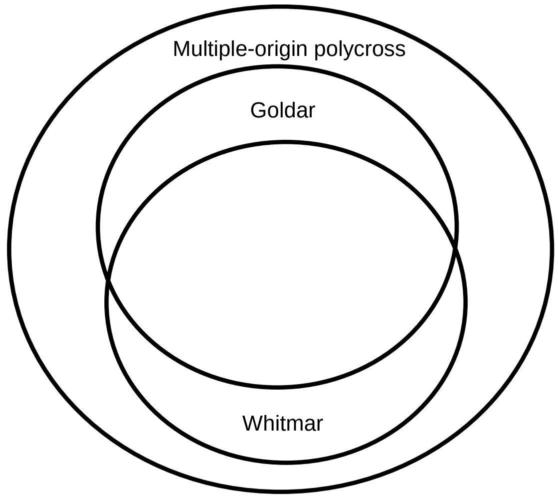


Figure 4. Genetic variation in bluebunch wheatgrass cultivars and a multiple-origin polycross (Larson et al. 2000).

seed obtained from the USDA-NRCS Plant Materials Center in Pullman, Washington. Relative DNA contents were compared between individual plants within and between populations, DNA fingerprinting was conducted using the AFLP technique, and the degree of polymorphism within populations was quantified using the Shannon–Weaver diversity index (Larson et al. 2001). Relationships between individual genotypes were analyzed by cluster analysis using the unweighted pair-group (UPGMA) procedure in NTSYS-PC (Rohlf 1992).

Of the 22 plants analyzed from each cultivar, one fixed genotype was detected in the Sherman big bluegrass and only three genotypes were detected in Canbar canby bluegrass. Although several identical genotypes were also detected with the YTC and MH Sandberg bluegrass populations, genetic diversity within these natural Sandberg populations is much greater than within Sherman or Canbar, as represented in Figures 5 and 6. These results show a high degree of variation within, but little divergence between, the two natural Sandberg bluegrass populations collected from sites nearly 600 km apart. If these populations have similar adaptation potential, then efforts to develop genetically diverse, natural germplasm sources for Sandberg bluegrass might be streamlined (Larson et al. 2001).

Western Wheatgrass. This grass is an ecologically dominant, native, perennial range grass in the northern Great Plains (Hart et al. 1996) that extends throughout much of temperate North America (Hitchcock 1951). We used AFLP

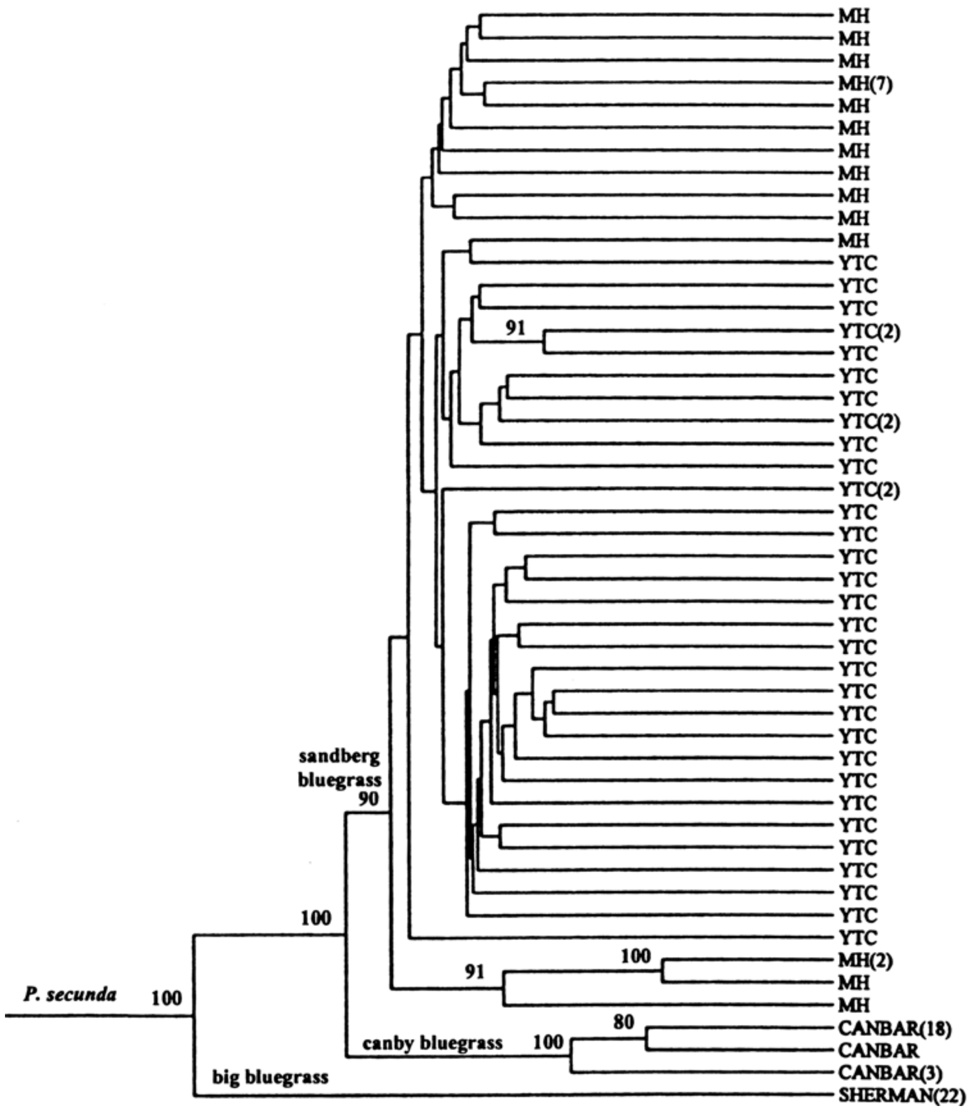


Figure 5. UPGMA analysis of AFLP variation within and among Sandberg bluegrass populations collected near Mountain Home (MH), Idaho, and Yakima Training Center (YTC), and the cultivars Canbar canby bluegrass and Sherman big bluegrass. The numbers in parentheses indicate identical genotypes. (From Larson et al. 2001.)

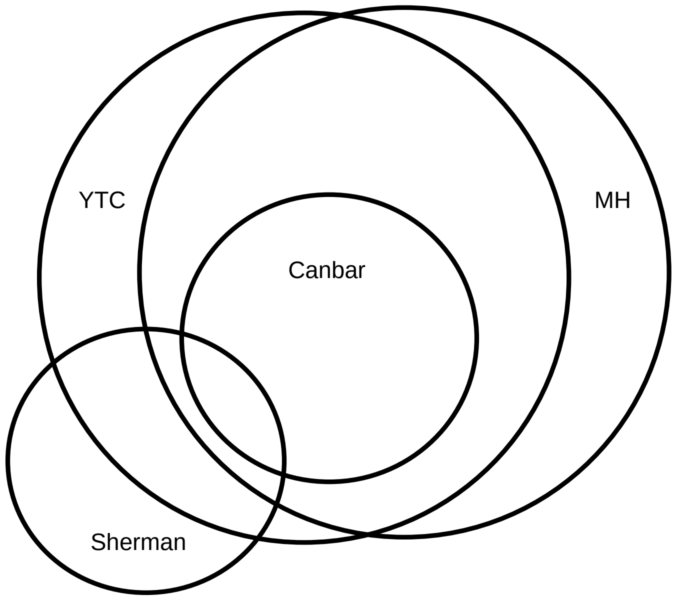


Figure 6. Venn diagram representation of genetic variation in Sandberg bluegrass populations collected near Mountain Home (MH), Idaho, and Yakima Training Center (YTC), and the cultivars Canbar canby bluegrass and Sherman big bluegrass.

techniques to look at the genotypic identification of this species. The populations analyzed were either source-identified single-origin accessions obtained from the National Plant Germplasm System or multiple-origin germplasms. We tested the similarity among individual accessions, which had come from different geographic locations, and we compared rates of DNA variation between single-origin accessions and the multiple-origin germplasms. Individual plants from 36 of 39 source-identified single-origin germplasm were different from each other; in other words, there was little genetic similarity among the single-origin populations. Three of the four multiple-origin accessions did not cluster by accession and displayed higher rates of DNA variation than the single-origin accessions; these populations show genetic variation greater than that found in any one geographic area (Larson et al. 2003). These results suggest that it might not be wise to use a single-origin source from outside the area being revegetated. The multiple-origin accessions, however, with their wider genetic variations, would be better able to adapt and survive when used in a broader range of areas.

Little Bluestem. We also studied the genetic variability of plants important in the eastern United States, especially those relevant to Fort Drum in their LRAM Program. Little bluestem is a native, warm-season, perennial bunchgrass that ranges throughout much of central and eastern North America, from Canada to Mexico. As a native species, little bluestem is increasingly being used for restoration projects to enhance the biodiversity of locally disturbed sites. We used RAPD markers to estimate the comparative genetic variation within and among four native populations of little bluestem. Genotypes were collected from high- and low-fertility sites in both New Jersey (forest biome) and Oklahoma (grassland biome) and propagated in the greenhouse. We used AMOVA to estimate variance components for the RAPD phenotypes, partitioning the total variation among individuals within populations, between populations within a biome, and between biomes. Even though most genetic variation resided within populations, significant differences were detected between sites within each biome. Furthermore, genetic distances between high- and low-fertility sites within biomes were equal to or greater than biome distances. Therefore, in this wide-ranging and highly variable species, analysis suggests that extreme local site differences in fertility and ecological history promote genetic differentiation equal to or greater than geographic differentiation (Huff et al. 1998).

5 SOIL COMPACTION AND ROOT STUDIES ACCOMPLISHMENTS

During maneuvers on training lands, military vehicles damage vegetation and compact soil. Vegetation damage includes shearing of leaves and damage to plant crowns and roots. While all three are related to plant regrowth and resiliency, crown and root damage are directly related to plant persistence and adaptation. Soil compaction changes the soil surface and reduces infiltration, which increases the volume and period of surface water runoff and increases soil erodibility. To understand the effects of training on soil compaction, plant injury, and regrowth, we measured soil compaction on several training lands subjected to various training events, and we examined plants in a controlled greenhouse environment and after simulated training exercises in the field. We also examined the resiliency after tracking of several of the species we are working with.

Measuring Soil Compaction: Preliminary Soil Penetrometer Studies

To select realistic soil compaction rates to use in our greenhouse study, we surveyed various areas on three military facilities. We used two types of cone penetrometers to measure the degree of soil compaction that occurs after land use at Yakima Training Center and Forts Carson and Drum. For most of the measurements, we used a Rimik CP20 cone penetrometer (Fig. 7), which measures compaction as a unit of resistance, MPa; the higher the MPa value, the higher the compaction of the soil. For some measurements at YTC, we used a different

Figure 7. Using the Rimik CP20 cone penetrometer in the field.

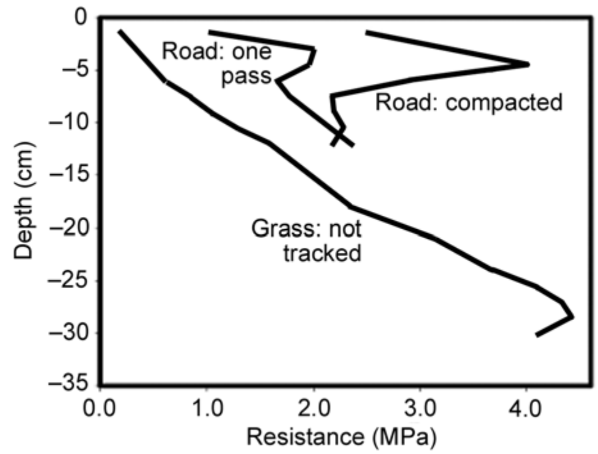


Figure 8. Soil compaction measurements at Fort Drum. Higher resistance values indicate greater compaction.

penetrometer that measures compaction as g cm^{-3}; again, the higher the value, the greater the compaction. Both of these instruments can measure compaction continuously below the surface of the soil. The areas at each location were selected for various degrees of training intensity and included high- and low-use areas and bivouac sites. At each facility, we sampled two predominant soil types: sandy or silty texture.

At Fort Drum we measured a grassy training area and lightly and heavily used travel corridors (Fig. 8). We found that land use was directly related to soil compaction at the soil surface to a depth of 5 cm (Cary et al. 2001, Palazzo et al. 2001). The more the land was traveled on, the greater the compaction of soil near the surface.

Our data on untracked sandy soils in the grassy areas at Fort Drum showed that as soil depth increases, the soil becomes more compacted and therefore has a greater water-holding capacity (Fig. 8). This is the opposite of what is normally described in the literature (Halvorson et al. 2001), which says that soil compaction decreases with depth. It is very hard to establish plants on sandy soils, such as those at Fort Drum with an average of 92% sand content, because of the low moisture-holding capacity of sandy soils. Plants sown on sandy soils begin to grow and then dry out and die, and the area then has to be reseeded. Our data suggest that we could establish plants on the Fort Drum sandy soils if we could find plants that root quickly and can extend their roots down to the moister areas in the soil at 10–15 cm deep (Fig. 9). We examined potential grasses in the greenhouse (see next section) and then developed an appropriate seed mixture for

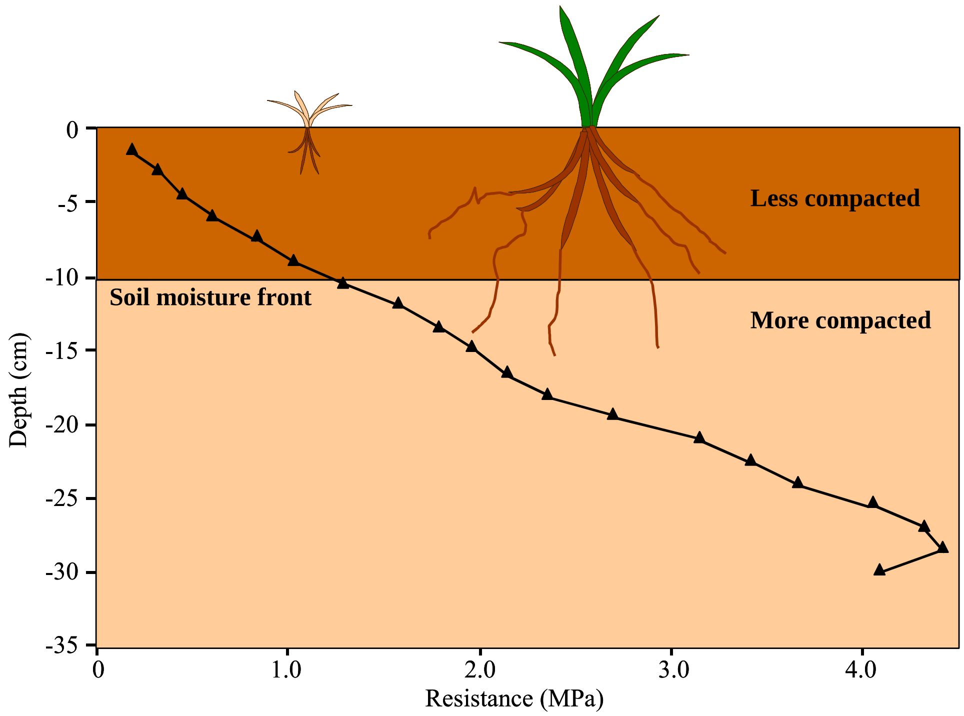


Figure 9. Effect of the compaction–depth relationship on soil moisture and plant growth. As the soil depth increases at Fort Drum, the soil becomes more compacted and therefore has a greater water-holding capacity. To establish plants on the sandy soils at Fort Drum, we need to use plants that root quickly and can extend their roots down to the moister areas in the soil.

use at Fort Drum (see "Methods for Establishing Natives and Fighting Invasive Weeds" section of this report).

At Fort Carson we measured soil compaction under various military land uses. The Fort Carson results agreed with those found at Fort Drum, where land use increased soil compaction on fine-textured soils (Fig. 10).

At YTC we looked at the effect of land use and soil moisture content on soil compaction and the effect of freeze–thaw cycling on soil compaction alleviation. Soil compaction increased in the more heavily used areas, especially in moist soils. The greater the soil moisture, the greater the increase in soil compaction when military vehicles are driven across the soils (Fig. 11). At YTC we also looked at soil compaction and the resiliency of plant species after one to four tank passes (see the "Tracking Study" section below).

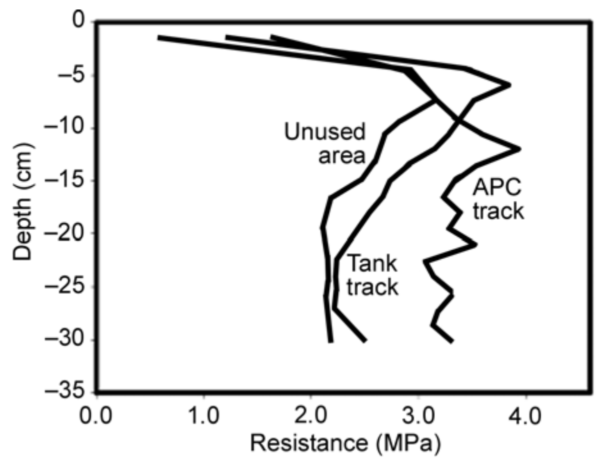


Figure 10. Soil compaction measurements at Fort Carson. Higher resistance values indicate greater compaction.

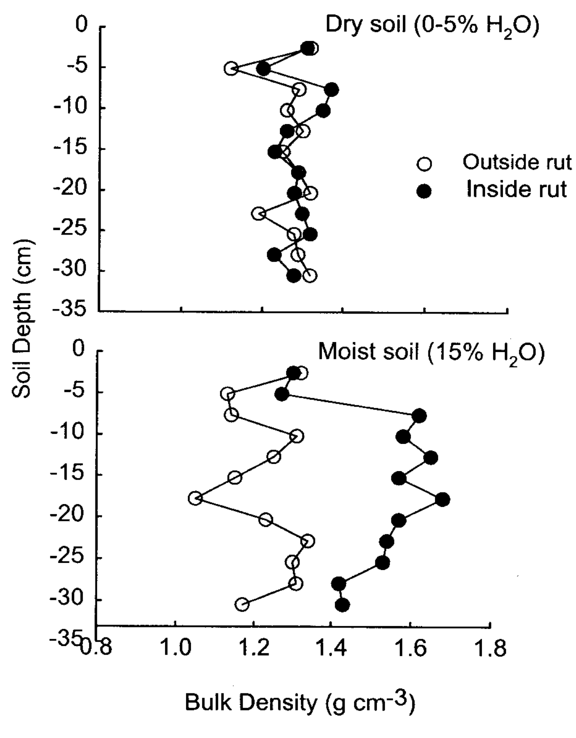


Figure 11. Soil compaction measurements on dry and moist soils at Yakima Training Center. Higher bulk density values indicate greater compaction.

We prepared a literature review on soil freeze–thaw cycling and its effect on soil compaction published in a book chapter by the Army Research Office (Gatto et al. 2001). The manuscript described the importance of incorporating the effects of freeze–thaw on soil compaction and strength, runoff, and erosion into soil erosion models. It also reports that soil freeze–thaw cycling reduces soil compaction and soil strength, increases infiltration, and changes the geometry of vehicle ruts and natural rills.

Greenhouse Root Studies

In 1998 we began a series of greenhouse studies. The first greenhouse studies evaluated how compaction affects the root growth of species in soils originating from three military bases. In two other greenhouse studies, we evaluated the differences between SERDP-select germplasms and existing cultivars. The compaction studies and the first germplasm evaluation, which examined root and stem growth, were carried out in rhizotron tubes. The second germplasm evaluation examined early root growth in growth pouches. The SERDP-select germplasms we used in these studies were in the early development stage.

Soil Compaction Study

For this study we compacted soils in rhizotrons where the amount of root growth of the grasses can be measured and observed. The rhizotrons are clear acrylic tubes (4.8-cm i.d., 60-cm long, 6-mm wall thickness) closed at the base with an aluminum cap containing holes for drainage and tightened with a steel clamp. The tubes were placed at a 15˚ angle in an enclosed wooden box (Brar et al. 1990). The sides, bottom, and top of the wooden box were covered with 2.5-cm-thick polystyrene sheets to decrease temperature fluctuations and to prevent exposure of roots to direct sunlight in the greenhouse.

We used four soils from two facilities (YTC and Fort Drum) with three compaction rates for each soil. We used a sandy soil and a silty soil from each of the facilities; the compaction rates (high, medium, and low) were based on the measurements made in the field (Table 17). The grasses used were hard fescue (introduced) and switchgrass (native).

Table 17. Soil compaction rates selected for this study. These rates were based on field measurements.

	Compaction rates (MPa)		
Installation	**High**	**Medium**	**Low**
Fort Drum	4.0	2.0	1.0
Yakima Training Center	4.0	3.0	1.5

The soils were steam-sterilized for 24 hours to kill any viable seed before they were placed in the tubes. The soil compaction levels were attained by filling each tube incrementally with equal volumes of soil and compressing the soil with a wooden dowel having a diameter that matched the inside of the tube. The level of compaction of the soil in the tube was measured with the Rimik CP20 cone penetrometer, and the compression was continued until the desired level of compaction was obtained.

The grasses were sown, two plants per tube, on 10 December 1999 and harvested on 15 February 2000, 67 days after planting. We cut the plants at the root and shoot interface and washed them with distilled water, using a paper towel to remove excess surface water from the shoots. The roots were washed free of soil over a screen by both spraying and immersion in water as described by Brar and Palazzo (1995a). The total root length was measured with an AgVision root and leaf imaging system (Decagon Devices, Inc., Pullman, Washington). Analyses of variance of the data were conducted using SAS version 8.0 (SAS Institute, Cary, North Carolina), and the means were separated using least significant differences at the 0.05 level of probability.

We anticipated that an increase in soil compaction would restrict root growth in each of the soil types. However, we did not have any consistent root growth patterns for any of the soil types. The only consistent difference was that the Fort Drum soils produced the lowest amounts of leaf and root growth in terms of length at all compaction levels (Table 18). No consistent differences were found between the soil types from the various locations; we think the lack of correlation between root growth and soil compaction is due to the stronger influence of optimal plant growth conditions in the greenhouse.

Table 18. Stem and root length measurements of hard fescue grown in rhizotrons containing either a sandy or silty soil originating from Fort Drum, New York, and Yakima Training Center, Washington.

Soil type	Compaction level	Fort Drum soils		YTC soils	
		Stem length (cm)	Root length (cm)	Stem length (cm)	Root length (cm)
Sand					
	Low	86	700	953	2013
	Medium	119	846	1279	2700
	High	94	456	1501	3002
Silt					
	Low	456	2030	1959	4479
	Medium	478	1941	3269	6563
	High	911	3293	3332	6162

Shoot and Root Growth Study

To evaluate shoot and root growth of grasses adapted to arid, western areas of the United States, we again used slant-tube rhizotrons. Each tube was filled incrementally with a Plainfield sandy soil (mixed, mesic Typic Udipsamments). The soil was settled by applying 200 mL of distilled water and tapping the tube.

We used three native SERDP-select germplasms available as of 1998 along with a standard cultivar for each. The grasses studied were: ‘Goldar’ and Yakima bluebunch wheatgrass, ‘Magnar’ and Yakima basin wildrye, and ‘Secar’ and Yakima Snake River wheatgrass. The seeds were primed in distilled water for four days. Five seeds of each grass type were planted about 10 mm deep in each tube.

The SERDP-select germplasms responded similarly to or slightly better than the commercially available cultivars (Table 19). An added benefit of the SERDP-select germplasms is that they have a wider genetic base without any loss of growth rate (see section on “Molecular Marker Development”).

Table 19. Length, surface area, and diameter of roots and length and surface area of leaves of six native plants grown in rhizotron tubes containing a Plainfield sandy soil.

	Root data			Leaf data	
Species and variety	Length (cm)	Surface area (cm^2)	Average diameter (mm)	Length (cm)	Surface area (cm^2)
Snake River wheatgrass					
SERDP-select (Yakima)	278.4	20.7	0.2352	79.3	17.5
Secar	271.3	19.9	0.2335	52.6	10.8
Bluebunch wheatgrass					
SERDP-select (Yakima)	119.3	18.1	0.4779	119.3	18.1
Goldar	120.8	23.9	0.6800	120.8	23.9
Basin wildrye					
SERDP-select (Yakima)	471.6	44.3	0.2989	139.3	37.0
Magnar	268.9	24.6	0.2905	7.28	20.8

Early Root Growth Study

We compared early root growth of five SERDP-select germplasms available as of 1998 to currently available cultivars using a growth-pouch technique (Brar et al. 1990). The grasses studied were: ‘Goldar’ and SERDP-select Yakima bluebunch wheatgrass, ‘Vavilov’ and SERDP-select P-27 and Yakima Siberian wheatgrass, ‘Magnar’ and SERDP-select Yakima basin wildrye, ‘Secar’ and

SERDP-select Yakima Snake River wheatgrass, and ‘Bottlebrush’ and SERDP-select Yakima squirreltail. We also studied cheatgrass to compare this invasive species with the SERDP-select species under development. The SERDP-select grasses studied were still in the early stages of the selection process.

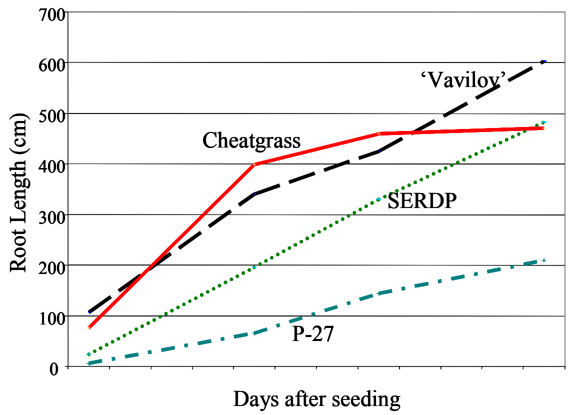
The seeds were primed in distilled water for four days. Ten seeds of each entry were selected randomly and placed in the growth pouches. The growth pouches were placed in the dark in environmental chambers at 20ºC for 16 days. Root lengths were measured on days 5, 8, 11, and 16 after seeding with an AgVision root and leaf imaging system (Decagon Devices, Inc., Pullman, Washington). Analyses of variance (ANOVA) of the data were conducted using SAS version 8.0 (SAS Institute, Cary, North Carolina), and the means were separated using least significant differences at the 0.05 level of probability.

For the introduced species the SERDP Siberian wheatgrass entries had slower root elongation than did the known cultivar (Fig. 12a). For the native species under development, SERDP basin wildrye had faster root elongation than its known cultivar (Fig. 12b), but the SERDP Snake River wheatgrass, bluebunch wheatgrass, and bottlebrush squirreltail entries did not (Fig. 12c–e). The two native wheatgrasses were similar to the commercially available cultivars. Bottlebrush squirreltail was dropped from the breeding program shortly after this study as it did not perform well here or in field evaluations.

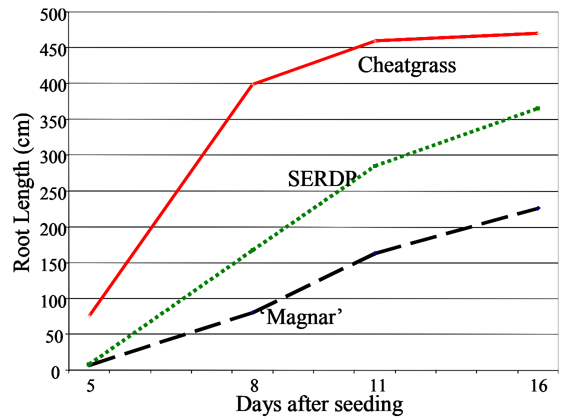
Tracking Study

In May 1999 we conducted tank traffic studies to determine plant resiliency in our evaluation plots at Yakima Training Center. We worked with Colorado State University and ERDC-CERL to determine the resiliency of the species we are breeding using the Tracked Vehicle Impact Miles (TVIM) approach.

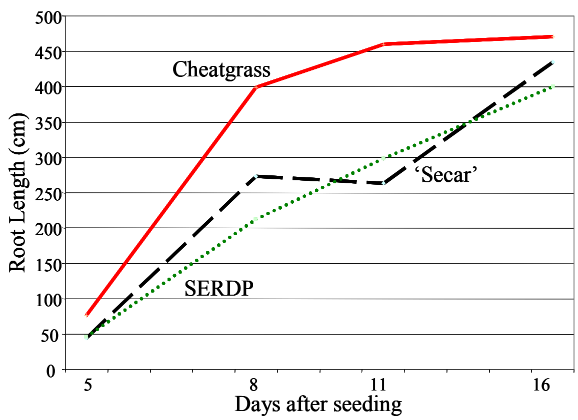
For the tracking we used the evaluation plots at the Yakima Snake River Sites A and B (Table 6) four years after the plots were seeded. Because of poor stands, only 21 of the 30 entries were included in the tracking study. On 19 May 1999 the plots were subjected to traffic using an M1A1 tank to make zero, one, two, and four passes that were perpendicular to the species plots (Fig. 13). The control was designated as the 1-m-wide area adjacent to the track. The tracking techniques we used at YTC were developed in TVIM studies conducted by ERDC-CERL and the Center for the Ecological Management of Military Lands (CEMML). All of the tank passes in our study occurred on the same day, which was intended to represent different training intensities for a single training event. We focused on a single event since one of the goals of the Army Strategic Planning ATTACC model (Anderson et al. 2001) is to place a monetary value on the degradation occurring after a training activity.



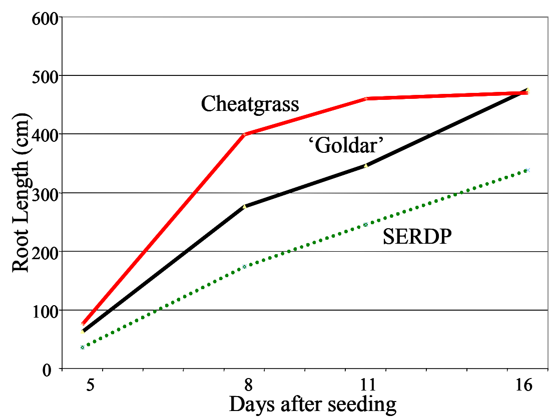
a. Siberian wheatgrass (introduced)



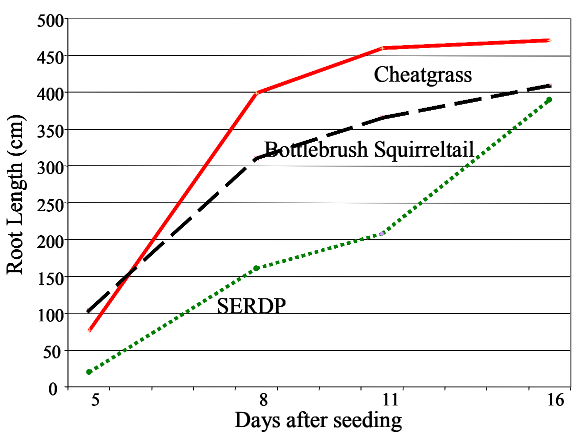
b. Basin wildrye (native)



c. Snake River wheatgrass (native)



d. Bluebunch wheatgrass (native)



e. Bottlebrush Squirreltail (native)

Figure 12. Elongation of roots after germination in growth pouches for five species compared to the invasive weed cheatgrass. For each species, we tested seeds from the early development of the SERDP-select germplasm (as of 1998) along with seeds of a known cultivar.

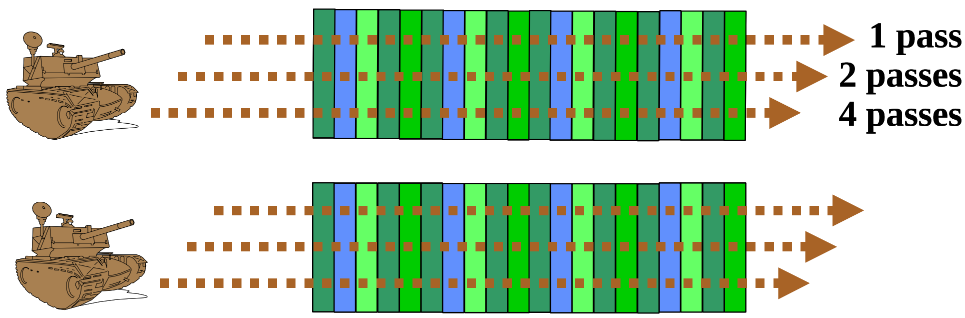


Figure 13. Layout of the tracking study. The tracking passes by the M1A1 tank were perpendicular to the direction of the seeded plots.

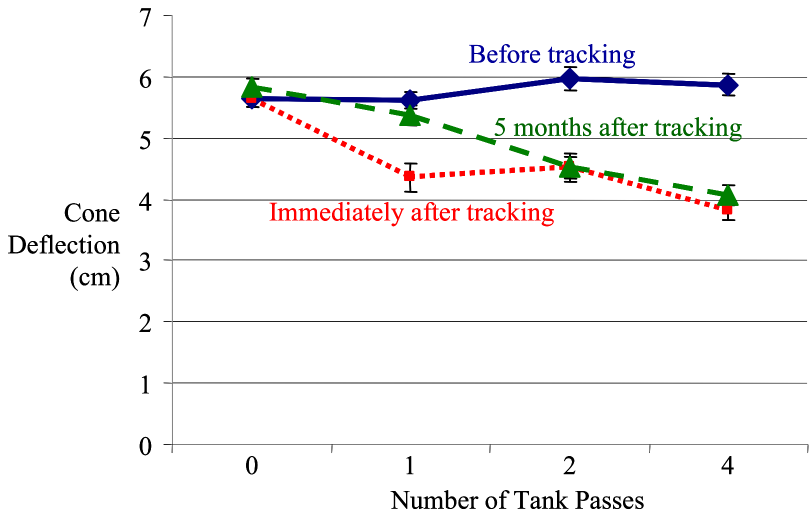
Compaction data were recorded with a cone resistance penetrometer before tracking, immediately after tracking, and five months later in October 1999. The cone resistance penetrometer measures compaction at the surface in centimeters of deflection. Lower readings indicate a greater degree of resistance to penetration and, therefore, more compaction.

Plant resiliency data were collected on September 2001, two years after the tracking. The degree of resiliency was measured by comparing the differences between treatments. Variables measured along a 3-m transect within the plot include the length of gaps that lacked the target species (species seeded), the percent target species, the forage yield, the percent encroachment of Sandberg bluegrass, the percent bare ground, and cheatgrass invasion. Forage yield was determined in September 2001 by harvesting 1 m^2 from the control and the tracked area. The percent dry matter was determined from plot samples, and forage yields expressed as grams per plot. All other variables were visually estimated.

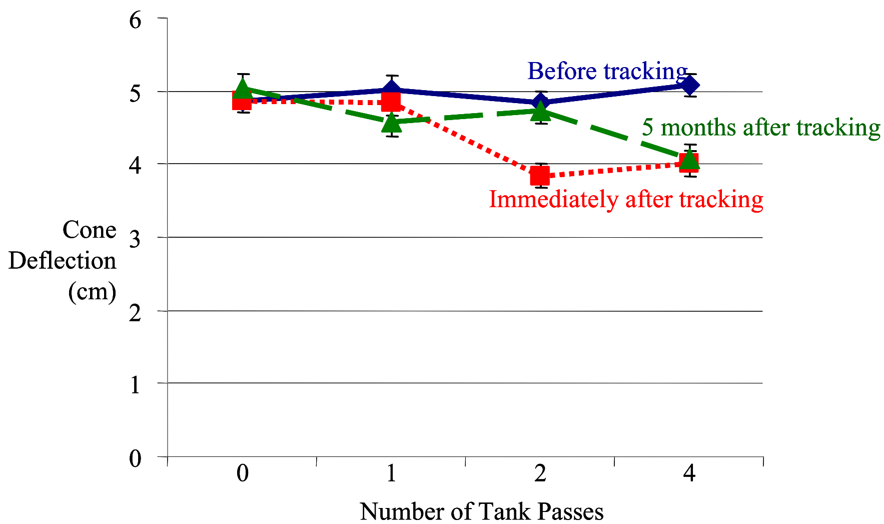
Variable means across tracks were analyzed as a randomized complete block design. F-tests of main effects and interactions were made, considering all main effects as fixed. All data were subjected to analyses of variance using GLM procedures (SAS Institute Inc. 1994), and mean separations were made on the basis of least significant differences at the 0.05 probability level (SAS Institute Inc. 1994).

Compaction Results

The data recorded immediately after tracking show that the two- and four-pass treatments resulted in the greatest soil compaction near the soil surface (Table 20, Fig. 14). Five months after tracking, the compaction measurements were similar to those taken immediately after tracking in two of the three tracking treatments in each plot. Compaction was reduced over the summer months in



a. Snake A plots.



b. Snake B plots.

Figure 14. Soil compaction measured before and immediately after zero, one, two, and four passes of an M1A1 tank on the Yakima Training Center Snake A and B plots on 19 May 1999. An additional measurement was made in October 1999. Higher cone deflections indicate less compaction.

Table 20. Cone resistance measurements on Yakima Training Center plots subjected to zero, one, two, or four passes of an M1A1 tank.

	Deflection (cm)			
	0 passes (control)	1 pass	2 passes	4 passes
Snake A				
Before tracking	5.64	5.61	5.97	5.87
Immediately after tracking	5.64	4.36	4.52	3.83
Five months later	5.82	5.37	4.52	4.07
Snake B				
Before tracking	4.86	5.02	4.84	5.08
Immediately after tracking	4.86	4.85	3.84	4.01
Five months later	5.04	4.57	4.73	4.08

the one-pass treatment in Snake A and the two-pass treatment in Snake B. Alan Anderson, ERDC-CERL, used this compaction data in his SERDP Project "Improved Units of Measure For Training and Testing Area Carrying Capacity Estimation (CS1102)" to add parameters to equations for developing the ATTACC model on management of military lands (Anderson et al. 2001).

Plant Resiliency Results

Gaps Between Sown Species. The gaps in the rows of plants were measured to obtain information on plant density. The greater the number of gaps, the lower the density of plants present.

At the Snake A site, with the exception of Vavilov and Kazakhstan Siberian wheatgrass and Rosana western wheatgrass, the number of track passes had little effect on the length of gaps between the target species within the plot (Table 21). However, even though not significant in most entries, there was a general trend towards reduced stands as the number of track passes increased. The rhizomatous, native Rosanna western wheatgrass expressed moderate tolerance to repeated tracking, showing a significant increase in gap length only at the one-pass treatment. The wildryes had the greatest gaps in all tracking treatments compared to the other grasses. This was in part due to their poorer stand establishment and their inability to tolerate any level of tracking.

Of the native species studied at Snake B, only Yakima bluebunch wheatgrass and E-27 hybrid were affected by the different number of track passes (Table 21). In addition to establishing better, Snake River wheatgrasses, especially Secar and EVT-572, persisted better under repeated tracking than bluebunch and thickspike wheatgrasses. The bluebunch wheatgrass cultivar Whitmar was the most persis-

Table 21. Mean gap between any sown plants in seeded rows of vegetation on adjacent sites (Snake A and B) at Yakima Training Center.

Entry	Length (cm)				LSD (0.05)
	Control	1 Pass	2 Passes	4 Passes	
Snake A: Introduced					
Crested wheatgrass					
Hycrest	4.6	6.5	5.8	6.5	ns
Ephraim	3.8	6.0	4.3	5.3	ns
Mean	4.2	6.3	5.1	5.9	
Siberian wheatgrass					
Vavilov	2.6	2.5	4.8	4.8	2.1
P-27	2.8	3.8	3.8	6.3	ns
Kazakhstan	3.3	3.0	6.0	8.3	4.2
Mean	2.9	3.1	4.9	6.5	
Russian wildrye					
Bozoisky	9.2	11.3	8.8	10.3	ns
Tetra-1	10.1	11.5	9.8	11.8	ns
Mean	9.7	11.4	9.3	11.1	
Intermediate wheatgrass (cv. Luna)	5.6	7.8	7.0	7.0	ns
LSD (0.05) Introduced	1.5	4.7	4.1	2.8	
Snake A: Native					
Basin wildrye (Yakima)	10.3	12.5	12.0	12.8	ns
Canby bluegrass	3.8	4.8	3.3	3.0	ns
Western wheatgrass (cv. Rosana)	4.1	8.7	5.5	4.5	3.6
LSD (0.05) Native	1.7	5.5	4.8	1.1	
Snake B: Native					
Bluebunch wheatgrass					
Goldar	4.9	7.8	7.3	7.0	ns
Whitmar	4.8	8.3	7.5	4.8	ns
ACC-238	5.4	8.0	7.3	10.8	ns
Yakima	6.0	10.8	6.8	8.5	4.0
Mean	5.3	8.7	7.2	7.8	
Snake River wheatgrass					
Secar	2.8	7.5	4.5	4.3	ns
ACC-707	3.2	6.8	5.3	6.5	ns
EVT-572	2.5	4.5	3.8	4.5	ns
Mean	2.8	6.3	4.5	5.1	
Thickspike wheatgrass and hybrids					
Bannock	4.3	7.8	6.0	7.0	ns
E-20 (Snake River × thickspike wheatgrass)	3.8	6.0	6.3	6.0	ns
E-27 (Snake River × thickspike wheatgrass)	3.5	5.0	3.5	6.8	1.6
Mean	3.9	6.3	5.3	6.6	
LSD (0.05) Native entries	1.7	3.2	ns	ns	
LSD (0.05) Native species	1.6	ns	1.4	1.3	

tent under tracking of the bluebunch wheatgrasses. There were significant differences between entries, but differences were greater between the species than within.

Percent target species. When we measured the percent target (sown) species in each plot, there was a general trend towards a decline in target species from the control to the four-pass treatment for all entries and species (Table 22).

At the Snake A site, however, that trend was significant only for the Siberian wheatgrass entries, Ephraim crested wheatgrass, and intermediate wheatgrass (Table 22). There were no significant declines among the three native entries, and both Canby bluegrass and Rosana western wheatgrass were among the most persistent at the four-pass treatment. In fact, Rosana western wheatgrass was equal to or significantly better than all the entries for all treatment passes. This persistence of western wheatgrass is likely the result of aggressive rhizome development, particularly after disturbance, in western wheatgrass. Among the introduced entries there were no significant changes in composition across all treatments for Hycrest crested wheatgrass and the two Russian wildryes (Table 22). At each tracking treatment there were significant differences between the entries and species. As previously reported, the wildryes were the poorest to establish and subsequently had the lowest percent target entries in the study.

Although western wheatgrass and canby bluegrass fared well at the Snake A site, the native grasses at Snake B were generally less persistent under repeated tracking. The entries least affected by multiple tracking were Goldar and ACC-238 bluebunch wheatgrass and E-20 hybrid wheatgrass (Table 22). Within each treatment, entries differed significantly ($P<0.05$) in the percent target entries within each plot, but differences among species were significant only at the four-pass treatment. At the four-pass treatment only, the percent target species for the Snake River wheatgrasses was significantly better than bluebunch wheatgrasses (Table 22).

There appears to be an association between the original stand establishment and the degree to which plants recover after tracking. In nearly all cases, those with increased stands at the time of tracking had recovery or persistence rates higher than those with reduced stands. The exception was western wheatgrass, which has the ability through rhizome development to colonize disturbed areas without the use of seeds (Jensen et al. 2001). The data suggest that a plant's ability to germinate quickly with strong seedlings and become established is perhaps the most critical characteristic in selecting plants for resiliency after tracking.

Table 22. Percent target species in seeded rows of vegetation on adjacent sites (Snake A and B) at Yakima Training Center.

Entry	% sown species				LSD (0.05)
	Control	1 Pass	2 Passes	4 Passes	
Snake A: Introduced					
Crested wheatgrass					
Hycrest	17.5	17.5	18.0	13.5	ns
Ephraim	19.5	18.0	16.3	11.5	6.7
Mean	18.5	17.8	17.1	12.5	
Siberian wheatgrass					
Vavilov	22.8	23.8	17.8	15.0	4.9
P-27	21.6	20.8	18.5	12.5	5.6
Kazakhstan	19.5	20.0	13.0	9.3	5.7
Mean	21.3	21.5	16.4	12.3	
Russian wildrye					
Bozoisky	11.8	9.8	12.3	7.3	ns
Tetra-1	9.7	9.5	9.3	4.3	ns
Mean	10.7	9.6	10.8	5.8	
Intermediate wheatgrass (cv. Luna)	17.2	12.5	14.0	12.3	2.3
Snake A: Native					
Basin wildrye (Yakima)	12.5	8.5	7.5	4.8	ns
Canby bluegrass	16.0	20.5	15.0	11.5	ns
Western wheatgrass (cv. Rosana)	16.0	17.3	16.3	16.8	ns
LSD (0.05) Entries	2.6	9.8	8.2	3.6	
LSD (0.05) Species	2.8	9.7	9.2	3.7	
Snake B: Native					
Bluebunch wheatgrass					
Goldar	15.2	9.3	10.8	7.5	ns
Whitmar	18.0	8.5	10.3	7.3	6.9
ACC-238	17.5	11.5	10.8	5.8	ns
Yakima	15.9	6.5	11.3	9.0	5.5
Mean	16.6	8.9	10.8	7.4	
Snake River wheatgrass					
Secar	22.4	9.8	15.8	14.3	5.2
ACC-707	17.7	10.0	13.3	7.0	10.3
EVT-572	21.4	12.0	18.3	9.5	8.1
Mean	20.5	10.6	15.8	10.3	
Thickspike wheatgrass and hybrids					
Bannock	16.9	11.0	13.0	5.0	2.0
E-20 (Snake River × thickspike wheatgrass)	17.2	10.0	12.0	10.3	ns
E-27 (Snake River × thickspike wheatgrass)	20.8	14.8	17.3	8.8	8.1
Mean	19.0	12.4	14.6	9.5	
LSD (0.05) Native entries	4.8	4.7	6.9	7.1	
LSD (0.05) Native species	ns	ns	ns	2.2	

Forage Yield. As an estimate of plant vigor after tracking, forage yield is important, but it should not be solely related to the ability of plants to reduce soil erosion. There was a general decline in forage yield of all entries and species with repeated tracking (Table 23).

Although forage yield decreased with tracking for all species at Snake A, the effects were significant only for Siberian wheatgrasses, Ephraim crested wheatgrass, and Rosana western wheatgrass (Table 23). All three Siberian wheatgrasses had statistically significant declines in forage yield across tracking treatments, with the Kazakhstan cultivar having significantly poorer yield (77% reduction) than the other two Siberian wheatgrass cultivars (Table 23). The four-pass treatments of Vavilov Siberian wheatgrass and Rosana western wheatgrass (the native) had less than 40% difference in forage yield when compared to the control. Within each pass treatment and the control, there were significant differences between entries and species for forage yield (Table 23). The forage yield of Hycrest crested wheatgrass had no significant decline across treatments, and it was significantly better than or equal to the yield of all other entries.

The effects of tracking were more severe on native entries at the Snake B site than on introduced entries at Snake A. The most significant declines in forage yield occurred at the one-pass treatment at this site (Table 23). Entries showing significant (greater than 60%) declines in forage yield from the control to the four-pass treatment were Goldar and ACC-238 bluebunch wheatgrass, EVT-572 Snake River wheatgrass, and E-27 Snake River × thickspike wheatgrass crosses (Table 23). Regardless of the treatment, there were no differences between species means for bluebunch wheatgrasses, Snake River wheatgrasses, and thickspike wheatgrasses in forage yield (Table 23). Despite having higher forage yields on the control plots at the Snake B, the native grasses were more adversely affected by tracking pressure than the introduced grasses at Snake A.

Sandberg Bluegrass Invasion. We measured Sandberg bluegrass invasion in each of the sown rows to see if a native bluegrass would be able to move into the plots. Sandberg bluegrass is a relatively low-producing perennial bunchgrass that grows as small tufts no more than 0.3 m (1 ft) in diameter. It is widely distributed throughout the western range, where it is considered an important range grass for soil stabilization and forage for wildlife and livestock. Once established, Sandberg bluegrass is perhaps the most drought tolerant of the bluegrasses. If seeded species will allow the invasion of Sandberg bluegrass into disturbed sites, it will increase desirable ground cover and reduce erosion. Encroachment of Sandberg bluegrass into existing plots was estimated as a percentage of the total ground cover within the plot.

Table 23. Forage yield as shown by mean dry weight (g) of sown species on adjacent sites (Snake A and B) at Yakima Training Center.

Entry	Dry weight (g)				LSD (0.05)
	Control	1 Pass	2 Passes	4 Passes	
Snake A: Introduced					
Crested wheatgrass					
Hycrest	44.3	37.3	42.3	36.3	ns
Ephraim	30.2	19.8	17.8	12.3	4.0
Mean	37.2	28.5	30.0	25.3	
Siberian wheatgrass					
Vavilov	46.5	33.8	31.8	30.3	11.6
P-27	45.2	44.0	41.5	25.5	18.3
Kazakhstan	37.0	22.3	23.8	8.5	19.3
Mean	43.9	33.3	32.3	21.4	
Russian wildrye					
Bozoisky	17.8	12.3	16.8	7.3	ns
Tetra-1	17.5	17.5	14.0	5.8	ns
Mean	17.7	14.9	15.4	6.5	
Intermediate wheatgrass (cv. Luna)	25.4	13.5	21.0	18.3	ns
Snake A: Native					
Basin wildrye (Yakima)	41.6	18.5	22.5	11.3	ns
Canby bluegrass	2.9	3.3	2.0	1.8	ns
Western wheatgrass (cv. Rosana)	14.5	7.0	9.0	8.8	6.4
LSD (0.05) Entries	15.5	21.2	12.1	7.6	
LSD (0.05) Species	16.7	20.2	14.0	8.1	
Snake B: Native					
Bluebunch wheatgrass					
Goldar	59.1	30.0	28.8	18.8	25.9
Whitmar	69.9	38.5	29.3	24.8	ns
ACC-238	74.5	33.8	32.8	14.8	33.5
Yakima	68.6	27.3	38.0	29.0	ns
Mean	68.1	32.4	32.2	21.8	
Snake River wheatgrass					
Secar	65.2	28.3	40.3	33.3	ns
ACC-707	65.8	36.0	38.5	29.0	ns
EVT-572	75.6	30.8	51.5	20.5	14.8
Mean	68.9	31.7	43.4	27.6	
Thickspike wheatgrass and hybrids					
Bannock	24.8	18.3	12.8	8.5	ns
E-20 (Snake River × thickspike wheatgrass)	55.6	29.0	37.5	31.5	22.3
E-27 (Snake River × thickspike wheatgrass)	93.8	38.3	56.0	35.5	31.6
Mean	56.6	26.9	31.6	21.1	
LSD (0.05) Native entries	23.7	18.3	25.5	23.5	
LSD (0.05) Native species	ns	ns	ns	ns	

The one-pass treatment at the Snake A site resulted in a significant increase in the frequency of Sandberg bluegrass observed in the seeded plots of P-27 Siberian wheatgrass, Bozoisky Russian wildrye, and Rosana western wheatgrass (Table 24). However, by the four-pass treatment, invasion of Sandberg bluegrass declined below or were the same as the control observations. Western wheatgrass spreads by rhizome development, thereby controlling erosion; however, as it grows, it creates an open or loose sod that allows for the invasion of bluegrass regardless of the tracking activity.

At the control treatment on the Snake B site, differences in percent Sandberg bluegrass encroachment among entries and species were not significant, and the one- and two-pass treatments had little or no effect on the level of Sandberg with the plots (Table 24). By the four-pass treatment the invasion of Sandberg had increased in most plots, which corresponds to a decline in target entry species at the four-pass treatment. The largest significant percentages of Sandberg bluegrass occurred at the four-pass treatment with the entries Goldar (4.8%) and ACC-238 (4.3%) bluebunch wheatgrass and Bannock (4.3%) thickspike wheatgrass. The level of tracking had little effect on Sandberg bluegrass invasion in plots of Whitmar and Yakima bluebunch wheatgrass, Secar Snake River wheatgrass, and E-27 thickspike × Snake River wheatgrass hybrid.

There was very little difference between species within tracking treatments for Sandberg bluegrass invasion. The average invasion of Sandberg bluegrass was 3.9% of the total stand for the introduced species and 2.4% for the natives. Thus, the native Sandberg bluegrass is able to invade introduced grass stands as readily as it does stands of native grasses.

Percent Bare Ground. At Snake A, species differed significantly in percent bare ground only at the four-pass treatment. Rosana western wheatgrass, which spreads by rhizomes, had the lowest levels of bare ground compared to the control with the four-pass treatment (Table 25). Five of the eight introduced entries, including all the Siberian wheatgrass entries, had significant increases in bare ground after tracking by the two- and four-pass treatments. Of the remaining introduced entries, all the Russian wildrye entries and Hycrest crested wheatgrass showed no significant differences in percentage of bare ground at any level of tracking (Table 25). Among the natives at Snake A, Rosana western wheatgrass and Yakima basin wildrye showed significant increases in bare ground at the two- and four-pass treatments, respectively, while Canby bluegrass had no significant increases in bare ground at any treatment.

At Snake B, half of the native entries had significant increases in bare ground by the two- or four-pass treatments and half did not. There were significant increases in bare ground for all of the bluebunch wheatgrasses except ACC-238,

Table 24. Mean percent Sandberg bluegrass in sown species on adjacent sites (Snake A and B) at Yakima Training Center.

Entry	% Sandberg bluegrass				LSD (0.05)
	Control	1 Pass	2 Passes	4 Passes	
Snake A: Introduced					
Crested wheatgrass					
Hycrest	2.3	3.8	3.3	1.8	ns
Ephraim	3.8	5.0	3.8	2.5	ns
Mean	3.0	4.4	2.5	2.1	
Siberian wheatgrass					
Vavilov	3.3	3.3	2.8	2.3	ns
P-27	3.5	5.0	3.8	1.8	2.1
Kazakhstan	4.3	4.8	3.0	2.8	ns
Mean	3.7	4.3	3.2	2.3	
Russian wildrye					
Bozoisky	5.1	9.0	4.3	2.0	1.6
Tetra-1	4.1	6.3	4.0	3.5	ns
Mean	4.6	7.6	4.1	2.8	
Intermediate wheatgrass (cv. Luna)	4.0	6.5	4.8	3.3	ns
Snake A: Native					
Basin wildrye (Yakima)	4.5	5.5	3.3	2.8	ns
Canby bluegrass	1.9	1.3	1.3	1.0	ns
Western wheatgrass (cv. Rosana)	2.9	6.7	3.8	2.9	2.9
LSD (0.05) Entries	2.4	4.9	2.7	2.0	
LSD (0.05) Species	2.1	ns	2.8	ns	
Snake B: Native					
Bluebunch wheatgrass					
Goldar	2.3	1.3	1.8	4.8	3.1
Whitmar	1.8	1.5	2.0	2.0	ns
ACC-238	2.3	0.6	2.5	4.3	0.7
Yakima	2.3	2.3	2.0	2.3	ns
Mean	2.2	1.5	2.1	3.3	
Snake River wheatgrass					
Secar	1.5	1.1	2.0	1.8	ns
ACC-707	2.7	1.8	1.8	3.5	1.0
EVT-572	1.8	1.3	1.3	3.0	1.6
Mean	2.0	1.5	1.7	2.8	
Thickspike wheatgrass and hybrids					
Bannock	1.8	1.3	1.8	4.3	1.0
E-20 (Snake River × thickspike wheatgrass)	1.9	1.0	2.0	3.3	1.9
E-27 (Snake River × thickspike wheatgrass)	2.0	2.0	1.8	2.8	ns
Mean	2.0	1.5	1.8	3.4	
LSD (0.05) Native entries	ns	1.3	ns	1.4	
LSD (0.05) Native species	ns	ns	ns	0.6	

Table 25. Percent bare ground in plots of sown species on adjacent sites (Snake A and B) at Yakima Training Center.

Entry	% bare ground				LSD (0.05)
	Control	1 Pass	2 Passes	4 Passes	
Snake A: Introduced					
Crested wheatgrass					
Hycrest	55.8	67.5	58.0	69.0	ns
Ephraim	56.2	63.0	62.5	75.5	14.7
Mean	56.0	65.2	60.2	72.2	
Siberian wheatgrass					
Vavilov	57.2	58.2	67.0	74.3	7.5
P-27	53.8	57.5	60.0	71.0	15.6
Kazakhstan	52.5	55.5	66.2	72.5	3.0
Mean	54.5	57.1	64.4	72.6	
Russian wildrye					
Bozoisky	60.7	61.0	66.0	76.3	ns
Tetra-1	61.8	62.0	69.5	77.2	ns
Mean	61.2	61.5	67.7	76.7	
Intermediate wheatgrass (cv. Luna)	52.0	62.0	63.3	67.5	13.4
Snake A: Native					
Basin wildrye (Yakima)	58.3	66.0	67.5	78.2	13.8
Canby bluegrass	55.8	55.3	57.0	72.3	ns
Western wheatgrass (cv. Rosana)	53.7	54.0	63.8	63.0	6.2
LSD (0.05) Entries	8.4	ns	9.7	6.9	
LSD (0.05) Species	ns	ns	ns	7.1	
Snake B: Native					
Bluebunch wheatgrass					
Goldar	63.9	77.7	73.8	77.5	11.4
Whitmar	64.7	76.9	76.5	86.2	15.3
ACC-238	62.9	78.9	75.9	79.4	ns
Yakima	63.3	75.2	74.0	82.8	19.4
Mean	63.8	77.8	75.4	81.0	
Snake River wheatgrass					
Secar	60.3	73.9	70.2	73.9	7.4
ACC-707	59.3	71.5	72.0	79.2	ns
EVT-572	57.3	69.9	62.2	78.3	ns
Mean	59.8	72.7	71.1	76.6	
Thickspike wheatgrass and hybrids					
Bannock	56.5	64.8	64.3	68.5	ns
E-20 (Snake River × thickspike wheatgrass)	60.7	74.0	70.7	75.7	ns
E-27 (Snake River × thickspike wheatgrass)	57.9	66.7	66.0	84.0	13.7
Mean	58.6	69.4	67.5	72.1	
LSD (0.05) Native entries	ns	12.3	12.5	11.0	
LSD (0.05) Native species					

Secar Snake River wheatgrass, and the E-27 Snake River × thickspike wheatgrass hybrid (Table 25). The remaining Snake River wheatgrasses, Bannock thickspike wheatgrass, and the E-20 Snake River × thickspike wheatgrass hybrid had no significant increases in bare ground.

Cheatgrass Invasion. Cheatgrass has become a major threat to the ecological balance, resource conservation, and productivity of western rangelands (Young and McLain 1997). This noxious weed fuels recurrent fires that eventually remove all of the native woody plant components of plant communities and, hence, perpetuate cheatgrass dominance and continued burning (Asay et al. 2001). Therefore, we examined cheatgrass encroachment to see how it was affected by tracking across the different sown species.

At both Snake A and B sites among all entries, cheatgrass invasion was low—never more than 2.3% and usually lower than 1%—and there were few significant differences among entries or species or level of tracking (Table 26).

Tracking Study Conclusions

Tracking generally increased the size of gaps between plants, increased the amount of bare ground, and reduced the number of sown plants. The reduction of forage yield due to tracking was greater for the native species than for the introduced species; however, the actual weights of plants were similar between the two types of species in the tracking treatments. The introduced species had lower reductions in gaps and weights than did the natives, suggesting that, in most cases, the introduced species were more tolerant or recovered more rapidly under repeated tracking. The entries that showed the greatest resiliency to tracking appear to be those with the best establishment rate prior to tracking or those that possess rhizomes. In most cases the more rapidly establishing introduced species (Table 6) were more tolerant to or recovered more rapidly after repeated tracking. For the wildryes, which are introduced species that did not establish well, tracking reduced the number of plants, caused lower yields, and increased the gaps between species. Among the natives, Snake River wheatgrasses and western wheatgrass exhibited the most resiliency across the different measurements. The presence of rhizomes in the native western wheatgrass appeared to aid resiliency by helping plants spread into damaged areas.

The native species Sandberg bluegrass successfully invaded both the native and introduced sites after tracking. Invasion of this early colonizing species can help promote native plant stands, satisfy federal requirements, reduce soil erosion, and provide ground cover while the slower-growing perennials are establishing.

Table 26. Percent cheatgrass encroachment on adjacent sites (Snake A and B) at Yakima Training Center.

Entry	% cheatgrass Control	1 Pass	2 Passes	4 Passes	LSD (0.05)
Snake A: Introduced					
Crested wheatgrass					
Hycrest	0.8	0.0	0.8	1.0	0.5
Ephraim	0.9	0.5	1.3	0.5	ns
Mean	0.9	0.3	1.0	0.8	
Siberian wheatgrass					
Vavilov	0.0	0.0	0.3	0.3	ns
P-27	0.6	0.5	0.3	1.5	0.9
Kazakhstan	0.7	2.3	0.3	1.0	ns
Mean	0.4	0.9	0.3	0.9	
Russian wildrye					
Bozoisky	1.4	2.3	1.0	1.0	ns
Tetra-1	1.8	2.0	0.8	1.0	ns
Mean	1.6	2.1	0.9	1.0	
Intermediate wheatgrass (cv. Luna)	0.6	1.0	0.5	0.8	ns
Snake A: Native					
Basin wildrye (Yakima)	1.3	1.3	1.8	1.5	ns
Canby bluegrass	0.8	1.3	0.0	0.3	ns
Western wheatgrass (cv. Rosana)	1.1	0.0	1.8	1.3	ns
LSD (0.05) Entries	1.5	ns	1.2	ns	
LSD (0.05) Species	ns	ns	0.7	ns	
Snake B: Native					
Bluebunch wheatgrass					
Goldar	0.6	0.8	1.0	0.5	ns
Whitmar	0.5	0.5	0.6	0.5	ns
ACC-238	0.2	0.4	0.5	1.0	0.6
Yakima	0.5	0.8	1.0	0.3	ns
Mean	0.4	0.6	0.8	0.6	
Snake River wheatgrass					
Secar	0.3	0.6	0.4	0.5	0.1
ACC-707	0.3	0.8	1.1	0.6	0.7
EVT-572	0.2	0.4	0.6	0.4	ns
Mean	0.3	0.6	0.7	0.5	
Thickspike wheatgrass and hybrids					
Bannock	1.2	1.8	1.8	1.3	ns
E-20 (Snake River × thickspike wheatgrass)	0.5	0.8	1.1	0.6	ns
E-27 (Snake River × thickspike wheatgrass)	0.4	0.6	0.8	0.4	ns
Mean	0.7	1.1	1.2	0.8	ns
LSD (0.05) Native entries	0.5	0.7	1.1	ns	
LSD (0.05) Native species	0.3	0.4	ns	ns	

The greater yields by the natives in the controls, the apparent resiliency of some of the natives such as Snake River and western wheatgrass, and the ability of Sandberg bluegrass to invade introduced grass stands suggest that natives can be used successfully on military training lands. The success of natives on tracked lands can likely be improved by mixed seedings of appropriate native entries and rapidly establishing introduced species.

6 METHODS FOR ESTABLISHING NATIVES AND FIGHTING INVASIVE WEEDS

To maintain good land stewardship, we need to establish stands of native plants. With their rapid growth rate soon after germination, annual invasive or noxious weeds often prevent native plants from establishing. We believe that native plants can be established if they can initiate root growth more quickly after germination or if they can be protected from the competitive or allelopathic mechanisms of the noxious weeds. Along with the genetic improvements in the SERDP-select natives for establishment and seedling vigor, we investigated seeding methods to further enhance the ability of our improved germplasms to establish viable native plant stands as rapidly as possible.

Introduced grasses establish more quickly, but where we have established strong native grass stands at both Yakima Training Center and Fort Drum, we have seen the natives moving into adjacent non-native grass swards. For this reason, we believe it is cost-effective to seed a mixture of non-natives with natives. The non-natives can provide quick, interim protection until the natives become sufficiently established. This use of non-natives to serve as a short-term ecological bridge to help establish healthy native stands should, ultimately, lead to a decrease in the need for non-native stands to provide protection for soil and wind erosion in moderately used training areas.

This section reports on three studies in three climatic areas to test our hypothesis about using introduced plants as ecological bridges to establish native plants. We also discuss our work with forage kochia, which, with its potential for fire suppression, may also serve as an ecological bridge to allow non-fire-tolerant natives to become established. A potential native ecological bridge in some geographic areas is Pryor slender wheatgrass, which did well in the first year of our early evaluation studies at South Boundary, Fort Carson, and then died out (Table 5).

Establishment of Natives on Sandy Soils at Fort Drum

On sandy soils at Fort Drum we planted mixed seedings of weeping lovegrass and fine fescues with the desired native switchgrass. Sandy soils are a problem on many northeastern DoD lands, including Fort Drum, New York, and numerous U.S. Army Corps of Engineers civil works sites with dam embankments, mine tailing sites, borrow pit areas, and roadsides. These soils are difficult to rehabilitate because of their low moisture- and nutrient-holding capacities, the short growing season, and the drying effects of winds.

We wanted to develop a cost-effective native vegetative cover for sandy soils that is quick to establish, long lasting, and low maintenance. Suitable species are available for reseeding these soils, but there are restrictions in terms of seeding season, time required for establishment, and length of persistence. Studies in plant establishment have shown that both warm- and cool-season grasses have a place in rehabilitating sandy soils (Schwendiman and Hawk 1975, Gaffney and Dickerson 1987). Cool-season grasses are easier to establish than warm-season grasses, they withstand some traffic, and they do not produce as much biomass as warm-season grasses, thus reducing the fire hazard. Their disadvantages are that they do better when seeded in the fall and their persistence is suspect after five years without additional care such as fertilization. With their long-term survival, native warm-season grasses are the species of choice for revegetating sandy, infertile soils. However, they can be sown only in the spring, and they can be very slow to establish, sometimes taking several years to reach a suitable cover to prevent soil erosion. At Fort Drum we explored methods of establishing an ecological bridge that will allow training within one year after seeding and also will allow the establishment of warm-season native plants over time.

We first looked at the factors that will optimize the success of native plants on sandy soil, including soil compaction and early root growth of native and introduced plants (Brar and Palazzo 1995a,b, Palazzo 1994), which will ease plant establishment by allowing plants to exploit moisture at greater soil depths. We then established a large research site at Fort Drum where we applied varying rates of liquid cow manure and tested seeding mixtures. In the seeding mixtures we used varying rates of weeping lovegrass along with fescues and the desired warm-season native switchgrass. Weeping lovegrass is a tropical perennial that establishes very quickly but is not winter hardy this far north. We hypothesized that weeping lovegrass and the fescues (introduced species) would provide sufficient soil cover to allow the switchgrass to establish successfully.

Fort Drum soil is a Plainfield sandy loam (92% sand, 6% silt, and 2% clay). Random sampling of soils throughout the site yielded a mean pH of 5.5, medium to low phosphorus, and low potassium. Before beginning our study, we amended the soil with fertilizer nutrients N applied at 56 kg/ha (50 lb/acre) and P_2O_5 and K_2O applied at 112 kg/ha (100 lb/acre) each. Dolomitic limestone was applied at 2240 kg/ha (2000 lb/acre).

For treatments we applied liquid cow manure at rates of 0, 22,400, 44,800, and 89,600 kg/ha (0, 10, 20, and 40 tons/acre), and we seeded the weeping lovegrass at 1.12, 3.36, and 5.6 kg/ha (1, 3, and 5 lb/acre). The species used in the mixtures with weeping lovegrass were the native 'Blackwell' switchgrass and the introduced 'Reliant' hard fescue and 'Azure' sheep fescue. The sites were seeded the day after the manure application at a depth of about 1.3 cm (0.5 in.) with a no-till seeder. The site was divided into four large plots, each measuring 13.7 by 106.7 m, or about 441 m^2 (45 by 350 ft, or 15,750 ft^2), and there were four replications within each treatment. Using permanent transects and a point-frame sampler, we recorded the percent total vegetative cover, dead vegetative cover, live introduced cover, and native vegetative cover.

The manure slurry provided a mulching effect that prevented drying of the newly established plants, allowing time for them to develop roots long enough to reach into the deeper soil layers. All grass species appeared to grow better where the cow manure was applied, and good soil cover was obtained over the entire area in the initial season through the strong growth of weeping lovegrass. The weeping lovegrass established quickly at all three rates sown, providing rapid control of wind and water erosion and allowing the land to be opened for training in about one year. The seeding provided a vegetative cover of greater than 85% in the first year with the manure applications, quickly protecting the soil and moisture. Establishment was not as quick where manure was not applied, but it eventually established a good cover in the first year. As a warm-climate annual, the lovegrass died back after the first year, allowing the fescues to come in. After four years, switchgrass dominated the stand (Fig. 15).

Weeping lovegrass shows promise as a nurse crop for improving the establishment of slow-growing native species and for short-term rehabilitation of sites that receive intensive use, such as airborne drop zones and bivouac areas. This technique of planting natives and non-natives together for a transition into a native stand is now an accepted practice at Fort Drum.

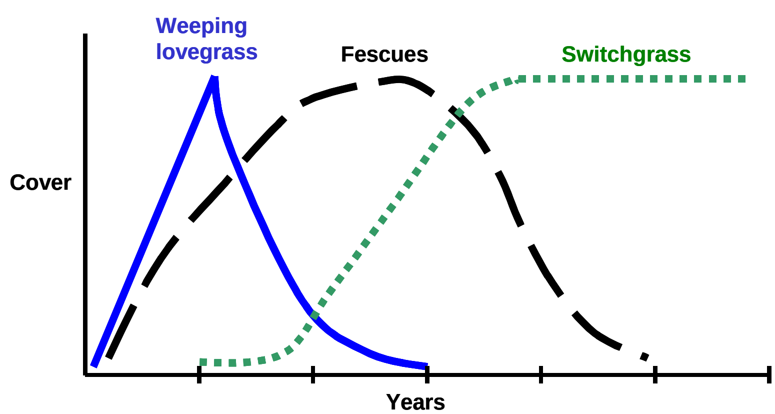


Figure 15. Ecological bridge concept. Weeping lovegrass acts as a nurse crop on sandy soils at Fort Drum, allowing fescues and eventually the desired native grass, switchgrass, to become established.

Native Wheatgrass Establishment in Cheatgrass-Infested Areas at Yakima

At Yakima Training Center we tested the hypothesis that introduced Siberian wheatgrass could act as an ecological bridge to the establishment of the native bluebunch wheatgrass in a cheatgrass-infested area. As previously mentioned, cheatgrass is a major threat to ecological balance, resource conservation, and productivity. It forms a closed system and fuels recurrent fires, which enhances the production of seed by cheatgrass and further perpetuates its dominance. A logical means of controlling cheatgrass is to replace it with a perennial grass, but there has been limited success replacing the cheatgrass with native grasses. The introduced crested and Siberian wheatgrasses have shown potential in inhibiting cheatgrass growth and may be used as an ecological bridge to reduce the amount of cheatgrass, allowing the establishment of natives.

Disturbed sites at Yakima Training Center were seeded in November 1998. We used a drill equipped with double-disk furrow openers and depth-band regulators to seed on mechanically prepared, weed-free seedbeds. Seeds were placed from 1.25 to 2.0 cm below the soil surface at a rate of 100 pure live seeds per linear meter. Individual plots consisted of four drilled rows with either 25- or 35-cm row spacings. We used Snake River wheatgrass (native), bluebunch wheatgrass (native), and Vavilov Siberian wheatgrass (introduced) in the following treatments, with four replications of each treatment:

- A monoculture of each of the three grasses;
- A binary seed mixture of Vavilov with each native grass; and
- Alternating rows of Vavilov with each native grass.

Table 27 shows percent of cheatgrass in each plot in 2000. Plots with Vavilov had lower amounts of cheatgrass. For instance, significant reductions in cheatgrass occurred when Vavilov was planted in alternating rows with bluebunch or Snake River wheatgrass, compared to each of those natives planted without Vavilov. In the Vavilov and bluebunch combinations, Vavilov allowed bluebunch to get established. The next step is to see if Vavilov will allow bluebunch to persist, especially through drought (Asay et al. 2001).

Mixed Native and Introduced Seedings at Fort Carson

In the second study we evaluated mixtures of native and introduced grasses in plantings at Turkey Creek, Fort Carson, Colorado. This study was dormant-seeded in the fall of 1997. The treatments involved a core mix of native grasses plus one of five introduced grasses. The core native mix is shown in Table 28; the introduced species was either Bozoisky Russian wildrye, SERDP-select Tetra-1 Russian wildrye, SERDP-select RoadCrest crested wheatgrass, Vavilov

Table 27. Percent cheatgrass in establishment study plots with two row spacings at Yakima Training Center in 2000 (two years after establishment).

	% Cheatgrass		
Grasses	**25-cm spacing**	**35-cm spacing**	**Mean**
Bluebunch wheatgrass	53	65	59
Snake River wheatgrass	35	78	57
Vavilov Siberian wheatgrass	7	30	19
Bluebunch/Snake River Mix	57	70	64
Bluebunch/Snake River alternating rows	30	52	41
Bluebunch/Vavilov mix	17	47	32
Bluebunch/Vavilov alternating rows	30	52	41
Snake River/Vavilov mix	25	48	36
Snake River/Vavilov alternating rows	25	48	36
Bluebunch/Snake River/Vavilov mix	16	50	33
Mean	32	56	44
LSD (0.05)	23	19	15

Table 28. Core native mix plus introduced species for mixed seedings at Fort Carson.

Species	kg/ha	lb/acre	% of mix
Core native mix			
Barton western wheatgrass	4.5	4	26
Pryor slender wheatgrass	2.2	2	14
Nezpar Indian ricegrass	1.1	1	6
Vaughan sideoats grama	1.1	1	6
Critana thickspike wheatgrass	2.2	2	13
Lovegrass	0.6	0.5	3
Blue grama	1.1	1	6
Introduced grass	4.5	4	26
Total	17.3	15.5	100

Siberian wheatgrass, or SERDP-select CD-II crested wheatgrass. For comparison the Fort Carson standard mix (Table 29) was also seeded at increased rates to match the above treatments. The plots were evaluated in 1999, 2000, and 2001 for species composition, percent ground cover, percent annual and biennial weeds, percent introduced grasses, and percent natives.

Table 29. Fort Carson standard mix at seeding rate increased to match the core-mix-plus-introduced-species treatment.

Species	kg/ha	lb/acre	% of mix
Barton western wheatgrass (native)	8.8	7.9	51
Vaughan sideoats grama (native)	4.9	4.4	28
Alkali sacaton (native)	0.5	0.4	3
Sand dropseed (native)	0.3	0.3	2
Nordan crested wheatgrass (introduced)	2.0	1.8	11
Ladak alfalfa (introduced)	0.8	0.7	5
Total	17.3	15.5	100

After three years all mixes resulted in stands with less than 5% weeds. In all three years the mixes with the crested or Siberian wheatgrasses had the fewest weeds, with less than 15% of the stand each year of the study (Fig. 16). The weeds in the plots containing the Russian wildryes decreased with time: after the first year, the Bozoisky plot had about 19% weeds and the Tetra-1 plot had 32% weeds, with both decreasing to about 3% after three years. The Fort Carson mix plot had over 60% weeds after the first year, but it also decreased to about 5% after three years.

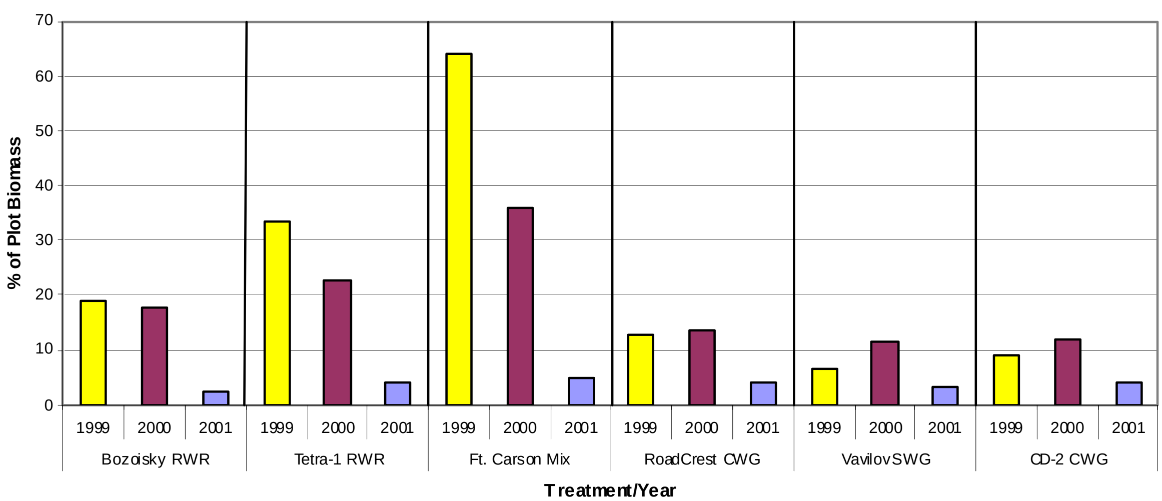


Figure 16. Percent annual and biennial weeds in Turkey Creek plots planted with the standard Fort Carson mix or with a core native mix plus an introduced grass (as named on the treatment axis). RWR = Russian wildrye, CWG = crested wheatgrass, SWG = Siberian wheatgrass.

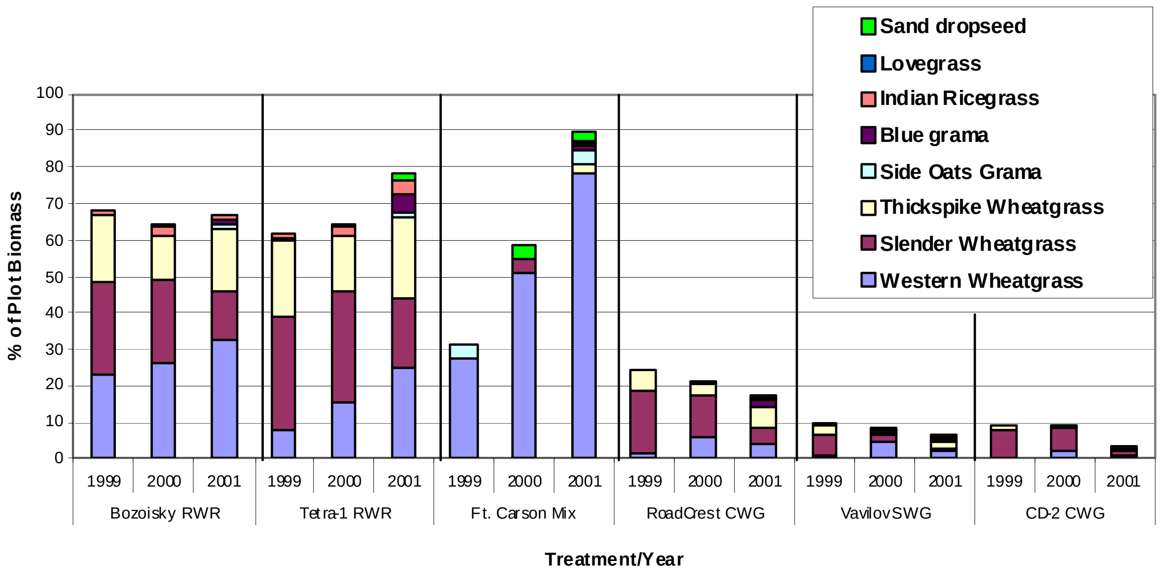


Figure 17. Percent native grasses in Turkey Creek plots planted with the standard Fort Carson mix or with a core native mix plus an introduced grass (as named on the treatment axis). RWR = Russian wildrye, CWG = crested wheatgrass, SWG = Siberian wheatgrass.

After three years, native grasses predominated in the plots with the Fort Carson mix and the core mix with Russian wildrye, while the introduced wheatgrasses predominated with the core mixes containing the crested or Siberian wheatgrass (Fig. 17). Thus, the mixes that inhibited the weedy species in the first year or two—the core mixes with crested or Siberian wheatgrass—resulted in the lowest establishment of native plants. Core mixtures containing either Bozoisky or Tetra-1 Russian wildrye had at least 60% natives in the stand from the first year on, and those stands had three native species present in nearly equal numbers. The Fort Carson mix resulted in the greatest number of natives after three years, but the natives established more slowly, from about 30% to 90% over the three years, and the mix produced much less diversity among the natives species, with western wheatgrass as the only prominent native. The Fort Carson mix contained some crested wheatgrass but at a lower rate (11%) than for the core mix with crested wheatgrass (26%). It might be interesting to try different rates of crested wheatgrass to find the optimum inhibition of weeds while ultimately producing a diverse native stand.

From these results, there appears to be several options depending on the objective:

- If the objective is rapid control of soil erosion and weeds in areas with frequent disturbance, then the core mix plus crested wheatgrass is the best choice. Although fewer natives become established with this mix, it establishes rapidly and provides the most complete weed control and soil stabilization.

- If there are four or more years between disturbances (or if disturbances are light) and erosion and weeds are not problems, then the Fort Carson mix with western wheatgrass predominating is the optimum choice. There is the opportunity for noxious weed invasion during the first two years when the Fort Carson mix is used, but after four years it results in a stand predominantly of the native western wheatgrass.
- For control of soil erosion and weeds while allowing general buildup of diverse native grasses, then the best choice is the core mix plus Russian wildrye.

Forage Kochia as an Ecological Bridge

Forage kochia is an introduced, perennial shrub that has the potential for fire suppression. We evaluated forage kochia accessions for vigor and greenness at several sites in Utah. We initially had this species in the improved breeding program but eventually dropped it because we were not successful in selecting for improved seed viability. Forage kochia remains of interest in our program for its possible role in fire suppression and, hence, its potential as an ecological bridge.

Many scientists and rangeland managers consider forage kochia to be a prime candidate for use in western range rehabilitation and fire prevention (Harrison et al. 2002). By stopping the fire cycle, forage kochia may act as an ecological bridge to fight invasive weeds and support native plant establishment. Fire is associated with increased invasion of cheatgrass by reducing and eliminating native perennial plant communities and increasing seed set in cheatgrass. Forage kochia can be used in “green strips” to contain wildfires, and it is competitive enough to help stop the spread of invasive weeds such as cheatgrass. Forage kochia seeded at 1.1 kg/ha (1 lb/acre) with a mix of grasses provides good forage and habitat for wildlife and livestock; however, forage kochia seeded as a monoculture at 3.4–6.7 kg/ha (3–6 lb/acre) can rapidly provide a good firebreak. Firebreaks can be established using lower rates, such as 1.1 kg/ha, but it may take six or more years to become fully established to the point where it can stop fires.

While controlling fires is a major effort at many western military facilities, there is concern that this non-native species will invade native stands of perennial grasses. We surveyed the dominance of this species in its native land of Kazakhstan and included discussions with Russian and Kazakhstan scientists (Harrison et al. 2000). Forage kochia was never observed to be dominant in the major plant communities of sagebrush, saltbush, winterfat, crested and Siberian wheatgrass, and needlegrass. Nowhere did this species invade from disturbed sites into adjacent perennial plant communities on the Kazakhstan steppes. We found that, many years after planting, forage kochia had not spread into perennial plant communities. However, it will recruit into disturbed sites and alkali slick spots and stabilize these areas, which is a better choice over cheatgrass and other invasive weeds (Harrison et al. 2000). Forage kochia is good for insects and wildlife such as sage grouse and other birds, deer, and elk, whereas cheatgrass creates a relatively barren and closed ecosystem. Soil is the most important commodity, and its loss through erosion is irreplaceable; therefore, it may be beneficial to use an introduced species such as forage kochia to preserve the soil for future restoration to more desired natives.

7 CONCLUSIONS

We developed more wear-resistant plants and a knowledge base of the relationships between military training and plant injury, regrowth, and wear resistance to help land managers make knowledgeable choices concerning plant selection and site rehabilitation procedures to reduce soil erosion, promote training, and protect environmentally sensitive areas. Although our original work was with introduced plants, we adapted our approach to include more native species in response to Presidential Order 13148 on using native species and to increased interest in using native species to prevent encroachment of invasive weeds.

Improved Plant Materials

Using plant breeding techniques we were able to improve traits related to resiliency and establishment in introduced and native species of rangeland grasses. In our improved plant materials, we were able to select for early spring growth, increased seedling vigor, improved tiller and rhizome development after disturbance, and resistance to abiotic and biotic stresses. We have made four releases to date, and our latest release, the native P-7 bluebunch wheatgrass, has been widely accepted by other federal land managers because of its increased genetic diversity.

An Independent Review Panel, convened to address concerns about the invasiveness of the introduced plants we used to develop wear-resistant cultivars for military training lands, found that those plants were not a threat to diverse, native ecosystems. The introduced germplasms we worked with did not encroach into other plant communities and did not establish monocultures. Our improved plant materials are ecologically compatible to the military sites because they were developed on and from collections of species existing at these sites. Military installations and other federal landowners can use both our introduced and native germplasms with no fears of adverse effects on ecosystem diversity.

We made significant advances in relating molecular markers to both plant characteristics and genetic diversity. We used markers to identify species and individual plants that can grow better at low temperatures. For genetic diversity we now have the tools to assess the genetic differences and similarities in commercial and natural seed sources. Land managers will be able to confidently select the most cost-effective seed sources that will ensure genetic compatibility with existing populations.

Tracking Studies

Our improved species show promise for better resilience on training lands. Our tank traffic studies showed that introduced species are more tolerant and recover more rapidly under repeated tracking than native plants. However, two of the natives we are working with, western wheatgrass and Snake River wheatgrass, showed promise as stabilization species since they are able to spread into damaged areas. We also observed that the native species Sandberg bluegrass, another of the species we are improving, successfully invaded sites containing introduced species after tracking. The greater yields by the natives in the controls indicates that, as native plants are developed with improved training resilience, they can be used successfully in combination with introduced species to obtain native plant swards. The tracking study data suggest that a plant's ability to germinate quickly with strong seedlings and become established is perhaps the most critical character in selecting plants for resiliency after tracking, and that is, indeed, one of the traits that we emphasized in the breeding program.

Establishment of Natives

Our studies on ecological bridges show that we can make intelligent choices on selecting seed mixtures that will allow for earlier land use for training and still end up in the out years with a native plant stand. The species in the seed mixtures and the equipment used are readily available, and the seeding is accomplished in one application, thus saving money. Our improved germplasms will make these seeding mixes even more desirable. This ecological bridge concept has been very well received at several invited technical presentations. Our methods can be further enhanced to provide greater cost-effective benefits by combining our findings with those of other SERDP projects on invasive weed control: "Application of Hyperspectral Techniques To Monitoring and Management of Invasive Weed Infestation" (Ustin, CS-1143), "Exotic Annual Grasses in Western Rangelands: Predicting Resistance and Resilience of Native Ecosystems to Invasion" (Belnap, CS-1144), and "Integrated Control and Assessment of Knapweed and Cheatgrass on Department of Defense Installations" (Paschke, CS-1145).

Benefits

Our work is already providing a better return on the military investment in the ITAM program, through seed mixtures in use at three installations. Our new plant materials and seeding techniques can already provide improved plant persistence on all military lands at a reduced environmental risk with respect to habitat loss and soil erosion. As native grass stands are established more quickly and at lower seeding costs, training lands will have decreasing downtime, further adding to cost savings for facilities. The various facets of this project are already increasing the value and use of current training areas, offering reduced unit-training costs, and enhancing DoD mission-related environmental activities.

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APPENDIX A. PUBLICATIONS AND PRESENTATIONS ORIGINATING FROM SERDP PROJECT

The following publications relate to research funded by the Strategic Environmental Research and Development Program (SERDP) project, CS-1103, "Identify Resilient Plant Characteristics and Develop Wear-Resistant Plant Cultivars for Use on Military Training Lands."

Peer-reviewed Journals or Papers

Asay, K.H., N.J. Chatterton, K.B. Jensen, R.R.-C. Wang, D.A. Johnson, W.H. Horton, A.J. Palazzo, and S.A. Young (1997) Registration of 'CD-II' crested wheatgrass. *Crop Science,* **37:** 1023.

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APPENDIX B. DATA ON NON-INVASIVENESS OF INTRODUCED SPECIES

The following data are from our "Report of Independent Review Panel Meeting: Evaluation of Naturalized Species Being Used for New Cultivar Development" (Palazzo et al. 1999) held at Yakima Training Center in May 1999.

To analyze the spread of introduced species, we sampled our research plots and areas previously seeded at the Yakima Training Center (YTC) in western Washington. These sites included an area to evaluate new germplasm (Snake A and B sites), sites that were sown 13–19 years earlier by YTC personnel, and a plant breeding site (Exit 11).

Snake A and B Sites

The Snake A site contained 1.5- by 15-m (5- by 50-ft) plots of 28 cultivars (17 natives and 11 introduced), and the Snake B site contained rows of 12 native cultivars. Borders were planted with Hycrest crested wheatgrass (an introduced species) (Table B1). All plots were allowed to grow to seed maturity each year.

The main goal of this review was to evaluate the invasive potential of plants in the Snake A and B plots that are being used in the breeding program to develop new cultivars. The species being used in the breeding program include natives—bluebunch wheatgrass, Snake River wheatgrass, Basin wildrye, and Sandberg bluegrass—and three introduced species—crested wheatgrass, Siberian wheatgrass, and Russian wildrye. In December 1998 we evaluated the spread of the trial plants at the Snake A and B sites by assessing vegetative tillering and natural reseeding.

We examined vegetative spread by observing the plants along the borders of the sown areas of the Snake A plots (Snake B plots contained only native species). We did not observe any vegetative tillering by the introduced species outside the sown plots. Vegetative spread did not occur because the plant materials we are developing are bunch-type or only moderately rhizomatous species.

To determine reproductive spread by natural reseeding of an introduced species, we counted the number of crested wheatgrass plants that moved into the plot area from the border around the plots. Within each plot we surveyed an area 0–3 m (0–10 ft) and 3–6 m (10–20 ft) away from the outside border, for a total of 224 counting locations and a total area of 1650 m^2 (18,000 ft^2).

At the Snake A site we counted 14 plants in the 0- to 3-m zone and 15 plants in the 3- to 6-m zone, or a total of 29 plants—which was a very small number of plants moving outside of areas where they were planted (Table B1). Interestingly

Table B1. Number of crested wheatgrass (CWG) and bluebunch wheatgrass (BWG) plants found inside the Snake A and B evaluation plots. Numbers are totals of eight replications.

Common Name	Origin	CWG 0–3 m in	CWG 3–6 m in	BWG
Snake A Entries				
Sandberg bluegrass	Native	1	0	3
Bottlebrush squirreltail	Native	2	1	6
Ephraim crested wheatgrass	Introduced	—	—	0
Vavilov Siberian crested wheatgrass	Introduced	—	—	0
Russian wildrye	Introduced	0	0	3
Four-wing saltbush	Native	0	0	3
Alfalfa	Introduced	0	1	1
Russian wildrye	Introduced	0	0	1
Basin wildrye - Yakima collection	Native	0	1	9
Canby bluegrass	Native	2	2	0
P27 Siberian crested wheatgrass	Introduced	—	—	0
Small burnett	Native	0	0	2
Western yarrow - Yakima collection	Native	0	0	0
Forage kochia	Introduced	1	2	2
Spinihop sage	Native	0	3	0
Hycrest crested wheatgrass	Introduced	—	—	1
Western wheatgrass	Native	1	1	2
Four-wing saltbush	Native	3	0	11
Indian ricegrass	Native	0	0	0
Altai wildrye	Introduced	1	0	0
Western yarrow	Native	0	0	1
Bluebunch x thickspike wheatgrass	Native	0	0	0
Indian ricegrass	Native	1	1	2
Needle & threadgrass	Native	1	3	2
Bottlebrush squirreltail	Native	0	0	6
Bitterbrush	Native	1	0	0
Intermediate wheatgrass	Introduced	0	0	1
Kazakhstan Siberian crested wheatgrass	Introduced	—	—	0
Snake B Entries				
E24 thickspike x Snake River wheatgrass hybrid	Native	0	0	no data
Sodar thickspike wheatgrass	Native	0	0	no data
Secar Snake River wheatgrass	Native	0	0	no data
Goldar bluebunch wheatgrass	Native	0	0	no data
E20 thickspike x Snake River wheatgrass hybrid	Native	0	0	no data
Bannock thickspike wheatgrass	Native	0	0	no data
5702 Snake River wheatgrass	Native	0	0	no data
Whitmar bluebunch wheatgrass	Native	0	0	no data
P2 bluebunch wheatgrass	Native	0	0	no data
Yakima bluebunch wheatgrass	Native	0	0	no data
701 Snake River wheatgrass	Native	0	0	no data

we counted 56 native bluebunch wheatgrass plants that had invaded the sown plots. At the Snake B site we did not find any crested wheatgrass plants moving into the plots.

Older Seeded Areas

Because crested and Siberian wheatgrass are among the most promising species for our resilient cultivar development, we also prepared for the panel meeting by evaluating several training areas at Yakima that had been seeded with crested or Siberian wheatgrass 13–19 years ago. At these sites we measured along transects both inside the seeded areas and outside in the surrounding native range, counting "hits" of the sown species (crested or Siberian wheatgrass), any other species present, and bare ground. We took data at 0.3-m (1-ft) intervals along 30-m (100-ft) transects that were parallel to the plot boundary. The transects were 6, 12, 18, 24, and 30 m (20, 40, 60, 80, and 100 ft) from the plot boundaries.

Selah-Cold Creek Summit Site

This site was sown with crested wheatgrass in 1980 and includes deeper soils that receive 300 mm of precipitation annually. As shown in Table B2 the sown species was dominating this site within the sown area. Outside the sown areas we made two sets of transects. Only three plants of crested wheatgrass were found in one set of transects, while no crested wheatgrass plants were observed in the other (Table B3). Two of the plants were 6 m from the seeded area and the other was at 12 m. The native plant, bluebunch wheatgrass, was the dominant vegetative species outside the sown areas.

Table B2. Number of plants found on transects at the Selah-Cold Creek Summit Site inside the area sown with crested wheatgrass in 1980.

	6 m in	12 m in	18 m in	24 m in	30 m in
Crested wheatgrass	40	34	34	39	28
Bluebunch wheatgrass	0	0	2	0	0
Knapweed	1	3	2	2	3
Intermediate wheatgrass	0	0	0	0	4
Lichen	2	1	1	2	2
Lupine	4	1	0	0	0
Sandberg bluegrass	6	4	11	3	7
Yarrow	1	1	0	0	1
Yellow brush	1	1	1	0	0
Bare ground	13	22	24	21	17
Litter	33	33	25	33	38

Table B3. Number of plants found on transects at the Selah-Cold Creek Summit Site outside the area sown with crested wheatgrass in 1980.

	6 m out	12 m out	18 m out	24 m out	30 m out
Measurement # 1					
Crested wheatgrass	0	0	0	0	0
Bluebunch wheatgrass	2	45	48	45	34
Cheatgrass	14	2	0	0	0
Cusick bluegrass	3	2	0	0	0
Knapweed	3	0	1	0	0
Lichen	0	0	0	1	1
Lupine	4	2	2	3	3
Miscellaneous species	1	0	0	0	0
Rabbitbrush	3	4	1	1	4
Sandberg bluegrass	14	9	11	10	6
Three-tip sagebrush	0	0	3	9	5
Yarrow	13	3	0	3	2
Bare ground	2	4	7	6	6
Litter	41	29	27	22	39
Measurement # 2					
Crested wheatgrass	2	1	0	0	0
Bluebunch wheatgrass	11	12	36	32	20
Cheatgrass	1	0	0	0	0
Cusick bluegrass	0	0	0	14	0
Knapweed	6	4	0	0	0
Lichen	4	1	2	1	7
Lupine	2	2	0	3	2
Miscellaneous spp.	1	2	0	0	0
Rabbit brush	6	1	0	1	2
Sandberg bluegrass	15	12	15	3	7
Three-tip sagebrush	4	1	4	5	13
Yarrow	2	6	8	9	1
Bare ground	18	11	8	4	16
Litter	28	47	27	28	32

Moxee Site

This site was sown with crested wheatgrass and alfalfa in 1980. This was an area with less-well-developed soils and 180 mm of annual precipitation, and it was a likely site for invasion of noxious species. Within the sown area, both crested wheatgrass and the native Sandberg bluegrass were the dominant vegetative types (Table B4). There were small amounts of alfalfa still present after 19 years. Outside the sown area we made two sets of transects and again found Sandberg bluegrass to be a dominant plant, but we found no crested wheatgrass in either area (Table B5). The noxious weed cheatgrass predominated in one set of measurements outside the sown area, but there were few instances of it within the area sown with crested wheatgrass.

Table B4. Number of plants found on transects at the Moxee Site inside the area sown with crested wheatgrass and alfalfa in 1980.

	6 m in	12 m in	18 m in	24 m in	30 m in
Crested wheatgrass	22	17	13	20	15
Alfalfa	4	4	17	2	6
Bluebunch wheatgrass	0	0	0	0	0
Cheatgrass	1	1	3	6	11
Lichen	14	7	14	18	11
Sandberg bluegrass	25	18	14	6	10
Bare ground	12	24	7	4	9
Litter	21	29	32	43	37
Rock	1	0	0	1	1

Table B5. Number of plants found on transects at the Moxee Site outside the area sown with crested wheatgrass and alfalfa in 1980.

	6 m out	12 m out	18 m out	24 m out	30 m out
Measurement # 1					
Crested wheatgrass	0	0	0	0	0
Bluebunch wheatgrass	0	0	0	0	0
Cheatgrass	6	25	35	21	20
Daisy	1	0	0	1	0
Goats beard	0	0	2	5	3
Knapweed	4	1	3	2	1
Lichen	21	9	2	9	9
Sandberg bluegrass	10	12	17	15	24
Bare ground	13	13	5	9	3
Litter	45	40	36	38	39
Measurement # 2					
Crested wheatgrass	0	0	0	0	0
Bluebunch wheatgrass	0	0	0	0	0
Bottlebrush squirreltail	1	0	0	0	0
Cheatgrass	0	0	19	8	28
Daisy	0	0	2	1	0
Goats beard	0	0	1	2	4
Knapweed	0	0	3	2	1
Lichen	0	0	21	35	26
Mustard	0	0	1	0	0
Sandberg bluegrass	0	0	18	17	11
Bare ground	0	0	3	7	8
Litter	0	0	31	28	22

Badger Pocket Road near Selah Creek Crossing Site

This site was sown with Siberian wheatgrass in 1985 and 1986 and has shallow soils and 200 mm of annual precipitation. Siberian wheatgrass dominated this site within the sown area (Table B6). We found three Siberian wheatgrass plants 6 m from the sown area on only one of the two sets of transects measured outside the sown area. Both outside areas were dominated by big sagebrush (Table B7).

Table B6. Number of plants found on transects at the Badger Pocket Road Site near Selah Creek Crossing inside the area sown with Siberian wheatgrass in 1985 and 1986.

	6 m in	12 m in	18 m in	24 m in	30 m in
Siberian wheatgrass	18	16	23	21	30
Bluebunch wheatgrass	0	0	0	0	0
Lichen	0	6	4	9	8
Miscellaneous species	0	0	0	0	1
Russian thistle	0	0	0	0	2
Sandberg bluegrass	11	4	2	4	3
Wyoming big sagebrush	1	5	2	5	8
Bare ground	29	16	26	14	5
Litter	41	45	43	49	43

Table B7. Number of plants found on transects at the Badger Pocket Road Site near Selah Creek Crossing outside the area sown with Siberian wheatgrass in 1985 and 1986.

	6 m out	12 m out	18 m out	24 m out	30 m out
Measurement # 1					
Siberian wheatgrass	0	0	0	0	0
Astragalus spp.	0	1	0	0	1
Bluebunch wheatgrass	0	2	2	4	1
Bottlebrush squirreltail	2	2	0	0	0
Cheatgrass	4	2	0	1	6
Indian ricegrass	1	0	0	0	0
Knapweed	0	1	0	0	0
Lichen	1	3	3	11	6
Miscellaneous species	0	0	0	0	2
Thurber needlegrass	2	2	1	3	0
Sandberg bluegrass	3	9	6	10	4
Wyoming big sagebrush	15	20	23	23	22
Bare ground	29	26	25	25	17
Litter	43	32	40	23	39
Measurement # 2					
Siberian wheatgrass	3	0	0	0	0
Bluebunch wheatgrass	0	0	0	2	0
Bottlebrush squirreltail	5	3	1	1	1
Cheatgrass	1	0	1	4	3
Indian ricegrass	3	1	0	1	1
Knapweed	0	0	0	0	1
Lichen	2	2	3	3	0
Thurber needlegrass	0	1	1	1	15
Russian thistle	0	0	0	3	0
Sandberg bluegrass	10	4	1	5	4
Wyoming big sagebrush	13	27	13	15	5
Bare ground	29	30	44	21	15
Litter	34	32	36	45	55

Badger Pocket Road Telephone Cable Planting Site

This site was sown with crested wheatgrass in 1980 and has moderately deep soils and 230 mm of annual precipitation. Crested wheatgrass dominated the sown area (Table B8). Of the two sets of transects outside the sown area, we observed only a single crested wheatgrass plant 12 m into the native area. Native species dominated the area outside the seeding (Table B9).

Table B8. Number of plants found on transects at the Badger Pocket Road Telephone Cable Planting Site inside the area sown with crested wheatgrass in 1980.

	6 m in	12 m in	18 m in	24 m in	30 m in
Crested wheatgrass	22	28	24	36	33
Astragalus spp.	0	1	1	0	0
Bluebunch wheatgrass	0	0	0	0	0
Bottlebrush squirreltail	0	1	2	0	2
Cheatgrass	1	1	0	0	1
Cusick bluegrass	0	0	0	1	1
Fescue	0	0	1	0	0
Lichen	0	0	0	0	5
Needle and thread	1	0	1	0	3
Phlox spp.	1	0	0	1	0
Rabbitbrush	0	1	0	0	0
Sandberg bluegrass	0	1	13	4	13
Sedge	0	0	0	1	0
Wyoming big sagebrush	13	3	4	2	4
Bare ground	31	14	17	15	14
Litter	31	50	37	40	24

Table B9. Number of plants found on transects at the Badger Pocket Road Telephone Cable Planting Site outside the area sown with crested wheatgrass in 1980.

	6 m out	12 m out	18 m out	24 m out	30 m out
Measurement # 1					
Crested wheatgrass	0	1	0	0	0
Astragalus spp.	0	0	1	2	2
Bluebunch wheatgrass	0	5	11	4	1
Bottlebrush squirreltail	11	5	11	6	7
Cusick bluegrass	1	1	2	0	1
Daisy	1	0	0	1	0
Indian ricegrass	3	0	0	0	1
Lichen	3	7	3	4	10
Thurber needlegrass	8	21	21	18	15
Phlox spp.	0	0	0	1	0
Rabbitbrush	0	2	0	4	0
Sandberg bluegrass	21	16	14	20	19
Wyoming big sagebrush	7	12	1	8	7
Bare ground	17	14	9	9	19
Litter	28	16	27	23	18
Measurement # 2					
Crested wheatgrass	0	0	0	0	0
Astragalus spp.	0	0	0	2	0
Bluebunch wheatgrass	1	1	3	0	5
Bottlebrush squirreltail	4	6	8	7	7
Cusick bluegrass	2	1	3	2	0
Indian ricegrass	0	2	0	0	0
Knapweed	0	0	1	0	0
Lichen	15	6	7	15	8
Miscellaneous spp.	0	2	1	0	0
Thurber needlegrass	23	19	11	6	9
Rabbit brush	0	0	0	1	2
Sandberg bluegrass	12	20	12	18	26
Wyoming big sagebrush	5	6	18	10	9
Bare ground	8	7	5	13	11
Litter	30	30	31	26	22

Borden Bench Site

This site was sown with Siberian wheatgrass in 1985 and 1986 and has shallow soils and very low precipitation (130 mm annually). Siberian wheatgrass, Sandberg bluegrass, and bare ground dominated within the sown area (Table B10). We found no Siberian wheatgrass plants outside the sown area. Sandberg bluegrass and cheatgrass dominated the outside native area (Table B11).

Table B10. Number of plants found on transects at the Borden Bench Site inside the area sown with Siberian wheatgrass in 1984.

	6 m in	12 m in	18 m in	24 m in	30 m in
Siberian wheatgrass	9	22	15	34	22
Bluebunch wheatgrass	0	0	0	0	0
Cheatgrass	3	4	4	4	0
Knapweed	0	1	0	0	0
Miscellaneous species	0	1	0	1	0
Needle and thread grass	0	0	0	0	6
Sandberg bluegrass	20	9	21	23	16
Russian thistle	14	2	0	0	0
Wyoming big sagebrush	0	0	1	0	1
Bare ground	30	48	49	19	45
Litter	14	11	9	19	10
Rock	10	2	1	0	0

Table B11. Number of plants found on transects at the Borden Bench Site outside the area sown with Siberian wheatgrass in 1984.

	6 m out	12 m out	18 m out	24 m out	30 m out
Measurement # 1					
Siberian wheatgrass	0	0	0	0	0
Bluebunch wheatgrass	0	0	0	0	0
Bottlebrush squirreltail	0	1	0	0	0
Cheatgrass	10	5	22	24	36
Daisy	3	0	0	0	0
Sandberg bluegrass	20	26	17	15	11
Mustard	0	0	1	0	0
Russian thistle	1	2	5	3	2
Stiff sage	0	1	0	0	0
Bare ground	45	42	40	34	10
Litter	16	19	15	24	41
Rock	5	4	0	0	0
Measurement # 2					
Siberian wheatgrass	0	0	0	0	0
Cheatgrass	12	14	8	8	10
Bluebunch wheatgrass	0	0	0	0	0
Bottlebrush squirreltail	1	0	3	0	0
Knapweed	0	0	0	1	0
Needle and thread grass	0	0	1	7	0
Russian thistle	3	4	0	1	3
Sandberg bluegrass	20	20	20	22	25
Yarrow	0	0	0	1	0
Bare ground	34	38	42	38	40
Litter	28	22	21	20	19
Rock	2	2	5	2	3

Exit 11 Site

We made no evaluations of spread at the Exit 11 breeding site, but we visited this area during the tour with the invasive review panel. During that visit, panel members commented that they were seeing more natives coming into the seeded areas than introduced seeded plants moving out into the areas of native species.

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14. ABSTRACT
The objective of this project was to develop more wear-resistant plants and evaluate the relationships between military training and plant injury, regrowth, and wear resistance. Through plant breeding, we were able to improve traits related to resiliency and establishment in introduced and native species of range-land grasses. We selected for early spring growth, increased seedling vigor, improved tiller and rhizome development after disturbance, and resistance to abiotic and biotic stresses. Our improved plant materials will be ecologically compatible at the military sites because they were developed from collections of species native to or previously seeded at these sites. We made advances in relating molecular markers to plant characteristics and in using DNA fingerprinting techniques to characterize genetic diversity. We used markers to identify species and plants that can grow better at low temperatures. We now have the tools to assess the genetic differences and similarities in commercial and natural seed sources, enabling land managers to select seed sources that will ensure genetic compatibility with existing populations. Our tank traffic studies showed that naturalized, introduced species are more tolerant and recover more rapidly under repeated tracking than native plants. However, two improved native species, western wheatgrass and Snake River wheatgrass, showed promise as stabilization species because of their ability to colonize damaged areas. Our studies on what we call "ecological bridges" confirm that we can select seed mixtures that will establish more rapidly than all-native mixes and will ultimately lead to healthy and persistent stands of native plants. The species in the seed mixtures and the equipment needed are readily available, and the seeding can be done in one application, thus saving money. Our improved germplasm will make these seeding mixes even more desirable.

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Ecological bridge, Invasive weeds, Land rehabilitation, Military lands, Native grasses, Native plants, Plant germplasms, Rapid plant establishment, Revegetation, Seeding techniques

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