Vegetation Conversion to Desirable Species Along Caltrans Rights-of-Ways

Final Report

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16. ABSTRACT

This study evaluates several establishment sequences to determine effective ways to convert existing annual non-native vegetation to native perennial species. Sustained weed control for several years is shown to be required for vegetation conversion. No single treatment was sufficient, but each provided different weed control characteristics. Burning provides control of non-native seeds and plants and stimulates native perennial plant growth. Tillage prepares the seed bed, stimulates germination of weed seed and provides soil volumes for root penetration. Ecotypic plant species are thought to be adapted to different topographic zones away from the road edge. Herbicide use was important to selectively reduce non-native annual plant species. Chemical treatments to control weeds included 1) postemergence, non-selective (glyphosate), 2) postemergence, broadleaf selective (clopyralid) and 3) preemergence, non-selective (chlorsulfuron). After vegetation conversion, herbicide use is shown to be reduced or eliminated except for occasional weed control. After three years of cultural and chemical management, we found native perennial grasses most abundant in sites that had been burned once and sprayed at least twice. In established roadside stands of native perennial grasses, a combination of spraying, mowing and/or burning for two consecutive years is required to reduce or eliminate non-native, invasive species, such as yellow starthistle. Once established, native perennial grass stands can persist for more than a decade and remain relatively weed resistant.

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FINAL REPORT

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EXECUTIVE SUMMARY:

Annual vegetation cover on roadside rights-of-way is associated with several undesirable characteristics, including fire hazard, and mowing and herbicide requirements and exclusion of native plants. Conversion to native perennial species can produce a stable plant community with potential to reduce annual grass and broadleaf cover and improve habitat, but establishment is difficult due to extensive pressure from invasive non-native annuals. This study evaluated several establishment sequences to determine effective ways to convert existing annual non-native vegetation to native perennial species.

Persistent weed control is shown to be required for vegetation conversion from annual to perennial grasses, and during the early years of establishment. No single treatment was sufficient, but each provided different weed control characteristics. Burning provides control of non-native seeds and plants and stimulates native perennial plant growth. Tillage prepares the seed bed, stimulates germination of weed seed and provides soil volumes for root penetration. Ecotypic plant species are thought to be adapted to different topographic zones away from the road edge. Herbicide use was important to selectively reduce non-native annual plant species. Chemical treatments to control weeds included 1) postemergence, non-selective (glyphosate), 2) postemergence, broadleaf selective (clopyralid) and 3) preemergence, non-selective (chlorsulfuron). After vegetation conversion from annual weeds to native perennial grass dominated systems, herbicide use is shown to be reduced or eliminated except for occasional weed control.

The frequency and intensity of additional herbicide use is anticipated to depend on several factors. If the native grass stand is dense, then starthistle, as an example weed,

is effectively excluded and will require no continuing treatment. Disturbance that opens up the canopy (low mowing, car tracks through wet soil, fires that remove thatch) can allow starthistle to establish, therefore requiring targeted herbicide application. Perennial weeds such as johnsongrass or perennial pepperweed, if they invaded, would require treatment even in an established stand. Thinner stands (with more open area between native grass plants) may require weed control during wet years but not during normal or dry years. Herbicide treatments would not need to be regularly scheduled, but would be triggered was weather patterns and new weeds trigger a response. Timing of existing "maintenance" activities like mowing can also be optimized to favor desirable plants, and thus reduce the need for secondary responses such as herbicide application. Reducing mowing from every year to every 2 or three years in some strips away from the road edge could be used to favor desirable perennial grass vegetation and reduce weed management effort by maintaining a denser canopy.

After three years of cultural and chemical management on annual grass sites, we found native perennial grasses most abundant in sites that had been burned once and sprayed at least twice. During the period of this study, the initial seed mix had little impact on the density and diversity of native perennial grass establishment. We also found that deep cultivation was not needed to establish native perennial grasses at two sites where soils prior to road construction were possibly used for farm production or pasture. In established roadside stands of native perennial grasses, a combination of spraying, mowing and/or burning for two consecutive years is required to reduce or eliminate non-native, invasive species, such as yellow starthistle. Once established, native perennial grass stands can persist for more than a decade and remain relatively weed resistant.

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Problem Statement

Rapid and dense growth of invasive annual plants in roadside rights-of-way and their associated problems of fire and invasive spread have led to a cycle of spraying, mowing and fire control. These invasive annual stands keep native perennial plants from colonizing and establishing in natural communities, which provide benefits to the roadway environment.

Introduction

The California Department of Transportation (Caltrans) manages approximately 15,000 miles of highway and more than 230,000 acres of right-of-way throughout the state. A major portion of Caltrans' management and maintenance effort is associated with vegetation control. This need is driven by safety concerns, such as ensuring visibility of traffic and highway structures and minimizing fire potential by reducing vegetative biomass. Additionally, vegetation control provides benefits by reducing the presence of noxious weeds and other pests. Vegetative cover is a major component of erosion and sedimentation control. Proper vegetative cover within Caltrans rights-of-way has the potential to improve motorist safety and erosion control, while reducing the need for mowing and/or herbicide use.

With the completion of an Environmental Impact Report (EIR) in late 1992, a shift in focus from relying solely on chemical vegetation control to establishing native grasses and low-growing non-native fescues has begun to take shape. As part of an integrated roadside vegetation management (IRVM) program, Caltrans has completed revegetation seeding projects on numerous construction sites. The results from these projects have not been monitored extensively to determine whether they were either successes or failures. In addition, the revegetation practices that can result in successful establishment have not been determined for the range of growing conditions within Lake, Colusa and Yolo counties.

The establishment of native species has many potential benefits that include: 1) prevention of new weed species from becoming established; 2) reduced weed corridors into native areas; 3) reduced long-term maintenance compared to current practices; 4) reduced use of herbicides; 5) reduced flash point for fires by the presence of green plant material, a less dense canopy and/or low-growing stature; 6) reduction in current weed populations; 7) increased plant species diversity; 8) increased control of sediment transport (erosion control); 9) increased duration of green plant tissue during summer and fall and 10) improved or changed aesthetic value that more closely matches pre-civilization landscapes in California.

The goal of this project is to select desirable plant materials and to improve the methodology for successfully establishing native or desirable, low-maintenance vegetation on sites/soils following road construction or where elimination of undesirable vegetation has occurred. The project was split into three phases facilitate the achievement of this goal:

The first phase (Phase I) of the project involves literature review and summary of information from personal contacts in Caltrans, University of California, Davis (UCD) and other knowledgeable sources (*i.e.* California Native Grasslands Association (CNGA), California Native Plant Society (CNPS), Society for Range Management (SRM)). Phase I will be ongoing throughout the first part of the project, and will summarize current revegetation procedures used by Caltrans. The information from Phase I provides both the evidence for needed changes in specifications for Caltrans revegetation projects and the justification for the chosen methods and materials in the second phase (Phase II). A common garden field experiment was conducted in Phase II, Part A to evaluate various plant materials at two locations (SR 29 in Lake County and I-505 in Yolo County), using the latest procedures and techniques from CNGA members or UCD researchers for establishing native perennial roadside grasses. A demonstration site using two large plots (greater than 1 mile) in the median of I-5 in Colusa County was established in Phase II, Part B to out-plant the most successful native perennial grasses identified in Part A while testing different cultural and chemical management operations for establishment. Phase III incorporated the successful procedures identified from Phases I and II into field sites where an existing stand of native perennial grasses has been overrun by non-native, annual species (*i.e.* yellow starthistle). Each successive phase utilizes information from other phases as available at the time.

Phase I: Literature and Site Review

Previous vegetation conversion projects as reported in Young, SL and Claassen, VP. 2004. Phase I: Roadside revegetation: Success and failure. Part 1: Literature review; Part 2: Site review. California Department of Transportation. Sacramento, CA.

Literature review: (bulleted summary)

Native species have been established along roadsides with appropriate management.

1) Several typical Sacramento Valley roadsides, consisting of several topographic zones (i.e. road edge, swale, back slope), have been converted to native species that persist for decades.

2) Native species can co-exist in a way that does not encroach or invade like many non-native, exotic species.

3) Initial cost to establish natives may be higher, but savings are expected to be realized over time as maintenance and replanting costs decline.

4) Site preparation, plant species selection and weed management are all important for improving the success of roadside revegetation projects with native perennial grasses.

Ecological factors must be considered for establishing native perennial grasses.

1) Non-native annual grasses gain a competitive advantage over native perennial grasses by establishing roots in the upper soil profile and depleting available water.

2) Intensive management is necessary during establishment of native grasses.

3) *Artemisia californica* germination, first season growth and survival were all reduced by neighboring annual grasses.

4) Inoculation with mycorrhizal fungi alone is insufficient for establishing *Nassella pulchra*; weed control practices still need to be employed.

5) Competition from exotic annual grasses has been shown to stress or kill oak seedlings.

Literature review: summary

Roadside revegetation research has a long history in departments of transportation (DOT) nationwide as well as in private restoration companies and academic institutions. Within this body of research, there have been a limited number of scientific studies on the subject of long-term establishment of native plants along roadsides. Therefore, it was determined that research literature on roadside revegetation be summarized. In addition, the most current and representative roadside revegetation projects within northern California would be surveyed to identify existing roadside locations that contain examples of native plant establishment and persistence. Phase I of this project was broken into two parts: 1) a comprehensive literature review of roadside revegetation studies and 2) a survey of vegetation cover and native plant establishment at roadside revegetation field sites that were related to Phase II and III of this project.

The literature cited examples at which short-term establishment of native plants along roadsides was accomplished with appropriate management techniques and with consideration for local ecological patterns. The main management components needed for success of native roadside vegetation conversion projects were site preparation, plant species selection and weed management. Initial costs to establish natives were high, but long-term savings were realized with declining maintenance and replanting costs. Several ecological factors must also be considered for establishing native plants. The topographic zones (*i.e.* road edge, swale, back slope) of a roadside range broadly in soil composition, vegetation diversity and available resources. Intense competition with non-native annual plants for root and shoot space, soil moisture and nutrients occurred during and following the establishment of native plants, so soil resources and competition were important factors to control.

A preliminary site review of roadside revegetation projects within Yolo County, California showed that establishment of native plant communities varied under three broad levels of management. Observations suggested that a low level of management, in which natives were planted and left to survive without any further assistance, lead to poor establishment and in some cases a reversion back to weeds. The effects of medium and high levels of management for establishing roadside native plants were difficult to determine with only observational ratings. Some level of management, whether mowing, spraying or burning, seemed to promote a good stand of native plants. At this point, native species establishment and cost for maintenance cannot be quantified without stand counts and management regimes. This data will be collected in the spring when plants are actively growing and landowners overseeing site maintenance can be identified.

The literature review and site surveys show quite clearly that a level of long-term management is needed following the initial, short-term establishment of native plants. Therefore, it has been concluded that the ecological considerations of the site, the proper native plant selection and at least a medium level of management are needed for the long-term establishment of native plants. The conclusions drawn from Phase I will be tested scientifically in Phase II, roadside native plant selection and Phase III, management of established roadside native plant stands.

Introduction

Roadside revegetation after construction disturbance is important for reducing erosion and weed invasion, and to improve aesthetic appearance. The greatest concern for roadsides projects is usually to reduce soil erosion by having some type of temporary erosion control vegetation. Fast growing plants are often selected without considering the growth habit, invasiveness, indigenous qualities or overall long-term sustainability. The initial flush of growth of fast growing plants in the first fall or spring after seeding eventually gives way to the persistent, weedy vegetation that is often similar to that which dominated the site prior to road construction.

Several state DOTs have incorporated native plants in roadside planting projects, including Iowa, Texas, and Minnesota. Research has been conducted on roadside revegetation, covering a wide range of topics, including plant competition and soil water relations. Several field studies have been conducted on roadside revegetation in California. Many of these studies were observational, without numerical analysis and publication. Evaluation of existing sites where native plants were used and treatment histories were recorded would be a valuable source of information for improving current methods of establishment. Therefore, the goal of this report is to summarize research on roadside revegetation and to identify existing roadside locations containing examples of native plant establishment and persistence.

This Vegetation Conversion project is divided into three phases. A literature review is presented as a Phase I report. Phase II involves regeneration or establishment of native vegetation on barren sites without existing native plant cover. Phase III involves evaluation of management effects used to increase desirable or native vegetation or to reduce weed invasion of sites without removing existing vegetation. Phase I objectives included in this report are twofold: Part 1 will be to summarize roadside revegetation research that is in print through a literature review and Part 2 will survey existing roadsides within northern California where varying success rates have occurred with native plants. Results from Phase I will be used to support treatments that are evaluated in Phase II, roadside native plant selection and establishment, and in Phase III, management of existing roadside native plant stands.

Literature review: revegetation studies

Roadsides evolve with roads

Roadside revegetation practices have changed with the modernization of roads, as roadway excavation has become more intensive and disruptive. In the earliest days when travel was by horse or wagon, roads were built cheaply and by following the easiest available route (Bowers 1950) with minimal grading. The permanent, hard-surfaced roads with their improved (more direct) alignment created larger erosion problems due to the greater number and depth of cuts and fills in mountainous, rolling or, in some cases, flat terrain (Bowers 1950).

From the Sierra-Nevada to the Pacific Ocean, the climatic variations in California have led to a wide range of erosion control problems along roadsides. Observations in 1950 by Bowers revealed that an undisturbed, natural slope was different from a disturbed slope. The prime factors for the difference related to vegetative cover, litter layer and topsoil presence and condition. The conclusion in 1950 (just like today) was, "… to endeavor to duplicate on the artificial slope the conditions which prevent damage on the natural slope." Even though it may have been difficult to do, the establishment of vegetation along roadsides was (and still is today) seen as the ultimate cure for erosion in order to stabilize the soil and/or slope to protect the road surface from collecting debris or being washed out. The long-term establishment of desirable vegetation along a roadside depends on plant species selection and equally, if not more importantly, the condition of the soil. A poor soil lacks the depth, nutrient and microbial content and water holding capacity that is needed for long-term support of native or desirable plant species.

Contrary to reports by Clements (1934), Beetle (1947), Burcham (1957) and Heady (1988), Bowers (1950) reported from notes taken by early-day explorers and missionaries that wildflowers, not grasses, were growing all across the state. If observations were made in passing, this could be a reflection of the time of year when wildflowers are abundant in many locations. He makes a comment that the common and widespread invasive annual and perennial plants that are now naturalized and today are erroneously referred to as "natives", were yet to be introduced to the state of California at the time of these early pioneers. Bowers does seem to be in agreement with the previously mentioned authors in terms of how non-native plants were first introduced to California: seeds from new plants were brought in by accident or on purpose, became naturalized and literally crowded out the true natives. It is interesting to note that today some of these same plants have become highly invasive and are costing state DOTs at least $1 million per year to control (Westbrooks 1998).

The search by California DOT for suitable vegetation for soil stabilization along roadsides began with trial plantings of grasses and forage plants over 50 years ago (Bowers 1950). Perennial plants were found to be too difficult to establish and provided no advantage that would prove them superior to annuals for their [Caltrans'] purpose. It was concluded that any annual plant with seed that was cheap, easy to obtain and germinated quickly with the first fall rains would be a good nurse crop to provide adequate and immediate protection for the natives. The annual natives were assumed to appear in the first or second year from topsoil or windblown seed that had been caught and held by stalks and stubble of the nurse crop.

Barley has been the most frequently used plant for soil stabilization along roadsides (Bowers 1950). Other plants commonly used in roadside plantings include rye grain, oats and vetch. Ice plant (*Mesembryanthemum crystallinum* L.) has been used in localized areas where extensive erosion has taken place and wildflower seeds have been tested with success limited to areas where sprinkling systems provide adequate irrigation. Some of the same plants and revegetation strategies discussed by Bowers (1950) are currently being used by Caltrans. Although some of the information is still applicable, there is a need for new research to find new, preferably native, plant species that will provide long-term cover and require less maintenance.

Roadside revegetation today

As of August 2002, there were only a handful of studies from Caltrans Office of State Landscape Architecture that were being conducted to address roadside vegetation issues. Statewide, Caltrans has eight projects under way (including this one) that focus on some aspect of the roadside environment. Only two of those are directly related to the establishment of native grasses. The other study areas include biological control of yellow starthistle, Russian thistle, German cape ivy, French broom and gorse, alternatives to synthetic chemicals for vegetation control, inoculation with mycorrhizal fungi for establishment of vegetation (native species) for erosion control and amendment of adverse soils to establish native plant species.

The first native grass study is entitled “Developing a native grass evaluation pilot program” (Contract No. 53A0032). This project is designed to install and monitor five 1-mile long native grass plantings using various planting methods. The roadside plantings are located in the first ten feet immediately adjacent to the road edge and include many plant material and seeding trials. Because replicated plots and unamended control plots were not constructed, and because the sites cover long sections of roadway, close comparison of plant growth on the different plots is difficult. The general trends that are observed on the sites can be evaluated with subsequent, more controlled experiments.

Difficulties of revegetation along roadsides

Roadsides can be difficult locations for establishing native plants. Site conditions that can limit the success of any revegetation effort include topography, soil, climate and existing vegetation. Brooks (1995) found that plant cover on fill slopes was significantly higher than on cut slopes along highways in the Tonto National Forest in central Arizona. The revegetation treatments used for visual impact mitigation, as judged by the public, were unsatisfactory on 72% of the cut slopes evaluated. Poor establishment of vegetation on disturbed sites following an operation like hydroseeding is often the result of improper species selection, seeding at an inappropriate time, and/or improper seed mixes, fiber and tackifier (Hallock et al. 2002). The end result can sometimes be a reversion to weeds in the years following a planting if a one-step hydroseeding process is used (Ivanovitch 1975). Harper-Lore (1998) conducted an informal search of natural communities for plants that tolerate the same problems in nature that are found on harsh roadside environments. Her most significant finding was a 50-year project at the University of Wisconsin, Madison to restore a native grassland on a highly disturbed agricultural site. It was shown that plant diversity is dependent on what is sown (not necessarily what exists naturally) and that the weeds that exist before the planting will continue to plague the project long after establishment. Similar studies have shown that relying solely on the seed bank for restoration of native vegetation is nearly impossible (Kalamees and Zobel 1998; Smith et al. 2002; Laughlin 2003), except in rare cases (Dreman and Shaw 2002). In order to overcome these problems, the solution was to prepare the site before planting and select a diverse range of plant species when seeding. Harper-Lore (1998) found that the specific cultural practices were site specific and included fertilization, maintenance, seeding rate (7 and 20 lbs./acre), site preparation and method of planting. These two reviews and others (Robbins 1999; CNGA 2001; Woodward 2002) emphasize the importance of site preparation, plant species selection and weed management for improving the initial success of roadside revegetation projects. Soil amendment was not considered by Robbins (1999) and CNGA (2001) because locations were predominantly in alluvial valley landforms. For long-term maintenance for establishment of native species, future work activities must be planned for and may include reseeding, refertilization, remulching and/or erosion protection for areas, which responded poorly to the initial attempt at seeding. (Ivanovitch 1975; Hansen et al. 1991).

Roadside revegetation by Caltrans

Only a few studies have been conducted exclusively by Caltrans that pertain specifically to revegetation of roadsides (Harris 1970; Edmundson 1976; Clary 1983). Many conclusions in these earlier studies are also observational in nature and were not numerically documented. One study, "Planting techniques and materials for revegetation of California roadsides (Clary, 1983) address both the problems and geographic areas along California highways. He discusses 1) the establishment of herbaceous and shrub species in several areas around California and the revegetation of problem soils; 2) the determination of the rate of invasion of woody plants onto disturbed sites; and 3) the reevaluation of plantings made during the Caltrans-SCS cooperative study between 1970 and 1975. Only observational information was collected from the studies with no attempts to perform statistical analyses on the data. He collects information on 1) herbaceous and woody plant material [non-native] in plots on both Mojave Desert and problem soils (serpentine, high boron, high/low pH soils) establishment (survival), erosion control and aesthetics; 2) plant invasion and rate of natural revegetation by woody plants on cut and fill slopes and slopes of different ages along roadsides and 3) changes in plant performance that could influence current seeding and planting recommendations, which were noted in the 1970-1975 cooperative plots. First, he concluded that no perennial grass [non-native or native species were not distinguished] performed well enough for use in a seeding mixture for the Mojave Desert. Annual grasses [non-native] and legume species were the best herbaceous plants to seed. He found that woody plants were the most successful seeded species, using direct drill seeding with straw mulch whenever possible. Second, he determined that woody plant invasion onto highway cut and fill slopes was a slow process influenced by herbaceous competition, availability of seed and slope conditions. Third, he found that “problem soils” (defined as substrates that are difficult to vegetate due to their structure or toxicity) could be attributed to four different types of plant growth limiting problems: droughtiness, low fertility, high magnesium-to-calcium ratios or toxic levels of trace elements. Finally, he noticed in seeded plots that annual species were non-existent and only four perennials and one legume were growing from original plantings in sites in the North-Central Coastal and Sierra Nevada Foothills. Eight woody species were doing well in the same region. In the Tahoe Basin, seven perennial grasses (pubescent wheat grass, intermediate wheat grass, fairway crested wheat grass, big bluegrass, smooth brome, orchardgrass) and one perennial legume (cicer milkvetch) appeared to do better over a nine year period. Several shrub species grown from containers also appeared to be outstanding. Because of the observational format of the study, there are no numbers to support the observations, and no comparisons to untreated controls. The perennial grasses and legume “appeared” to do better. The shrubs from containers “looked” to be outstanding. Woody species were “doing well”. This information is, however, useful for the time and the location in which it was observed.

Edmundson (1976) conducted a plant materials study in northern California with study sites from the North Central Coastal Foothills to the Lake Tahoe Basin. His objectives were to 1) evaluate and select or develop self-perpetuating, drought-tolerant annual and perennial grasses, legumes and other ground cover plants for erosion control; 2) evaluate and select native shrubs and trees suitable for revegetation; 3) evaluate shrubs for general landscape use; and 4) conduct special studies. He established several grasses, legumes and California poppy along highways in northeastern California and evaluated them for erosion control, fire control and aesthetic purposes. “Shrubby” species were also evaluated for revegetation and general landscaping. There were special and supplementary studies conducted that were relevant to plant propagation and establishment. The plants in each study were evaluated on representative highway sites using “common methods applied by contractors”. The establishment and evaluation methods used in this study were only generally described, leaving out details necessary for repeating his studies or making close evaluation of the results. From observational studies, he was able to make the following broad conclusions. 1) Once a grass-legume (non-native) cover was established and initial erosion control was provided, there seemed to have been little need for maintenance. 2) Successful establishment was observed where soils were not too droughty, competition from herbaceous species was low and some type of control was used on the mice, grasshoppers and other predators present. 3) Forty pounds of seed per acre “seemed” to be satisfactory for seeding of grasses and legumes where erosion was not critical. 4) No winter active herbaceous species “seemed” to be immune to herbicide sprays applied by Caltrans. 5) California poppy “seemed” to be persistent only in rocky, gravelly or sandy soils where herbaceous species offer little competition. From these studies, a general guide to herbaceous seeding and a list of native shrubs and trees classified by major land resource areas were produced for California. Edmundson had additional observational studies on cereal grains, erosion control materials, fertilizers, irrigation, and seed inoculant, but they are not relevant to this report.

Techniques for revegetation of problem soils are another area of Caltrans research. Parks and Nguyen (1984) observed that topsoil, lime and revegetation treatments were used to neutralize the acidic leachate at two out of three highway cut slopes sites. The third site contained serpentine soil and could not be evaluated. They describe the mitigation measures for these types of problem soils and evaluate their effectiveness. Again, many sites were evaluated but data were not collected.

Out of all the documented roadside revegetation studies conducted exclusively within Caltrans, only one was found to have used a scientific approach. Harris (1970) experimented with woody and herbaceous plant establishment in a range of environmental conditions without irrigation. He used three methods of seeding (spot and range drill seeding and hydromulch seeding) at five [geographic] locations (Point Reyes, Yosemite, Davis, Bakersfield, Los Banos). He found that direct seeding resulted in the establishment of 23 of 54 species seeded, although the definition of “establishment” changed with time at the field sites. The response of species grown at various sites indicated differences in environmental conditions between locations and within location, making a good argument for site-specific revegetation, as opposed to a region-wide approach. Seedlings in either dry compared to moist or wet areas (Bakersfield or Yosemite and Point Reyes, respectively) were established. In some areas direct seeding failed due to extreme environmental conditions and the lack of knowledge in the limitations of species adaptation and seeding technique. He found that spot and range drill seeding were more satisfactory than hydromulch seeding. He concluded that the varying environmental conditions required both the selection of species with a wide range of adaptability and the seeding of several potentially suitable species to assure greater establishment success. Other aspects that were found for successful seeding included time of seeding, seed quality, seeds per hole, seed dormancy, seeding depth, fertilization, weed and pest control, soil preparation, mulching and irrigation. Unfortunately, the data was not available for tabular listing at this time.

The results from numerically documented studies such as Harris (1970) are what Caltrans needs to support its decision-making regarding use of various techniques and materials for roadside revegetation. The conclusions are based on sound, scientific data that has been tested with replications and control plots. The results have been subjected to statistical analyses and the methods can be repeated for verification and/or demonstration of the results, if needed.

Other attempts at roadside revegetation

Other roadside studies have taken into consideration plant mixture for establishing natives along roadsides (Bugg et al. 1997; Anderson and Long 1999; Bugg and Brown 2000; M.C. Wolfe and Associates 1988). Both polycultures and monocultures were used by Bugg et al. (1997) to evaluate the establishment of non-native (desirable) and native perennial grasses. They were trying to determine if several native grass species of a local strain could be established and managed on disturbed sites. They seeded either a mix of native grasses (polyculture) or single species (monoculture) into a rural roadside near the town of Winters, California, consisting of several topographic zones (*i.e.* road edge, swale, back slope).

There was no significant difference in the amount of canopy cover for the polycultures on different topographic zones, but the biomass of the natives was less than for the non-natives. In the monocultures, California brome (*Bromus carinatus*), blue wildrye (*Elymus glaucus*), slender wheatgrass (*E. trachycaulus*), meadow barley (*Hordeum brachyantherum* ssp. *brachyantherum*, California barley (*H. brachyantherum* ssp. *californicum*), purple needlegrass (*Nassella pulchra*) and nodding needlegrass (*Nassella cernua*) had good canopy cover. Sheep fescue (*Festuca ovina*), squirreltail (*E. multisetus*), Idaho fescue (*Festuca idahoensis*), creeping red fescue (*F. rubra*) and pine bluegrass (*Poa secunda* ssp. *secunda*) had poor canopy cover. Polycultures performed well in all topographical zones. Monocultures with persistent stands were established for several species. Competition from resident vegetation (weeds) was found to influence establishment in both the polycultures and monocultures. They concluded from their study that, despite difficulties due to herbicides, persistent stands of local native species could be used along roadsides and other rights-of-way in the Sacramento Valley. They deem accessions retaining 25% or greater canopy cover in monocultures to be suitable for use in roadsides in the Sacramento Valley.

The Bugg et al. (1997) study would have been stronger had they evaluated the sites for longer than three years. The importance of weed control cannot be overlooked for establishing native grasses along roadsides and to state that a 25% minimum canopy cover for natives would have been greater had the herbicides been more effective is a large assumption. There was mention of a range in soil moisture conditions in all blocks for the polycultures, but no data were presented that supported this statement. Soil depth and water holding capacity could play a significant role in establishment of native plants along roadsides.

In another roadside study by Bugg and Brown (2000), existing stands of native grasses were used in combination with native forbs to control non-native (undesirable) species. The idea was to determine the establishment efficiency of local forbs and perhaps use the most robust and vigorous species as an alternative to conventional management (herbicides, mowing or blading) for controlling undesirable species. The methods employed included either seeding a mixture of forbs into both established native perennial bunchgrasses and tilled, bare ground or transplanting two perennial forbs into both established native perennial bunchgrass stands and tilled, bare ground. They found that Arroyo lupine (*Lupinus succulentus*), California poppy (*Eschscholzia californica*), chick lupin (*Lupinus microcarpus*) and Spanish clover (*Lotus tanacetifolia*) established well when seeded into tilled, bare ground, while annual tansy (*Phacelia tanacetifolia*) and the perennials, narrow-leaf milkweed (*Asclepias fascicularis*) and blue-eyed grass (*Sisyrinchium bellum*), were poorly established. None of the forbs tested established well by direct seeding into pre-existing stands of native perennial bunchgrasses. When transplants were inserted within plots of established native perennial bunchgrasses, their vigor was not significantly reduced compared to those placed in tilled plots.

Revegetation of roadside-like sites

Revegetation projects are not restricted to roadsides. Other locations with similar conditions to roadsides include irrigation canals, farm hedgerows and nature reserves (M.H. Wolfe 1999; Anderson and Long 1999; Harper-Lore; 2000). Similar to the Bugg and Brown (2000) search for alternatives to conventional weed control, Wolfe (1999) conducted a study to evaluate the use of revegetation as a tool to minimize chemical weed and pest control along irrigation canals in central California. They also investigated the possibilities for reduced erosion and maintenance costs with revegetation. They conducted a series of revegetation trials to test the establishment of numerous native perennial and two naturalized (desirable) annual species of grasses, forbs and shrubs. They made both qualitative and quantitative analyses on germination and establishment of individual species and on planted seed mixes for cover, shrub densities and ground squirrel burrows, respectively. From their qualitative data, needle-and-thread grass (*Hesperostipa comata* (Trin. & Rupr.) Barkworth) was the most successful individual species evaluated. They also found that creeping wild rye (*Leymus triticoides* (Buckley) Pilger), Indian ricegrass (*Achnatherum hymenoides* (Roemer & Schultes) Barkworth), Arizona brome (*Bromus arizonicus* (Shear) Stebb.) and meadow barley (*Hordeum brachyantherum* Nevski) had strong results, although the precise definition for "strong results" was unclear. Of the shrubs tested, they found that California buckwheat (*Eriogonum fasciculatum* Benth.), bladderpod (*Isomeris arborea* Nutt.) and desert saltbush (*Atriplex hymenelytra* (Torr.) S. Wats.) were all successful, while goldenbush and winterfat (*Krascheninnikovia lanata* (Pursh) A.D.J. Meeuse & Smit) failed to produce viable stands. Mainly through observations, it was found that successful establishment of plant populations and beneficial insects resulted in substantially lower pressure of invasive weeds and injurious insects on seeded plots and less need for herbicide and soil sterilizers. Costs associated with erosion and wild land pest controls were also lowered considerably with an increase in the aesthetic and ensuing real estate values, enhanced by the increase in plant and wildlife biodiversity.

In a more scientifically based study by Anderson and Long (1999), costs of establishing hedgerows were measured on field crop farms in Yolo county, California. In addition to determining costs of establishment, they wanted to develop management practices for “insectary” hedgerows on field crop farms. They selected sites based on diversity of soil type, site location and farmer practices. They also took into account the adjacent canals, fences and roads that would impact the hedge plants. Hedge plants in plots 15’ by 1,500’ were perennial California species (highly adaptable, require little to no irrigation after two years). Most were chosen with a range of flowering periods that would be available for beneficial insects. Native perennial grasses were planted after the hedge plants and a mix was selected based on environmental tolerances and soil type. They found that the costs for establishing a hedgerow fell into five categories: 1) site preparation $350, 2) hedge plants $685, 3) perennial grasses $385, 4) weed control $1,045, 5) irrigation $760, for an estimated total cost of $3,235 for a 1,500’ hedgerow. Hedgerows take time and money to establish, but a couple of the benefits from hedgerows, once they are self-sustaining, include acting as a filter strip, wind break and/or dust barrier and stabilizing the soil which provides natural weed control and habitat for beneficial insects and wildlife. In this case, it is apparent that native species (hedgerows or grasses) co-exist in an environmentally friendly way that does not encroach or invade like many of the non-native exotic species. The initial cost to establish natives is high, but savings can be realized over time with a decline in maintenance and replanting costs.

National parks and recreation areas are not exempt from roads and the need for establishment of native or desirable species (Legg et al. 1980; Moritsch and Muir 1993; Zabinski et al. 2002). Harper-Lore (2000) took a 1,553 mile long road trip with highway department and roadway engineers from Victoria, New South Wales and Queensland. The author found that roadways in Australia are critical for preservation of native flora. She found that roadside rights-of-way are termed "road reserves" because they contain 25% of all endangered species and 45% of remaining native grasslands. Named World Heritage Areas by the United Nations, these particular roadsides have raised awareness and validity to conservation practices. The Roadside Conservation Advisory Committee defines management objectives, strategies, actions plans, assessments and support for roadside conservation. A coalition of public and private agencies has been formed that works together with same goals: 1) to work with the community and 2) to achieve sustainable land and water resources through improving vegetation management practices. Although this probably is not carried out nationwide, it provides a good example and motivation for other areas where establishment of native or desirable roadside vegetation is a major concern.

Other revegetation studies

Native plant establishment along roadsides is an area of research that often receives little attention. Through this project, factors for the successful long-term establishment of a native plant community are being reviewed in the literature and in current field sites, researched in the field and documented for practical field application(s).

In addition to the broad field of roadside native plants, two other topics related to restoration are of particular interest to the author. These topics, important to restoration of both roadsides and landscapes in general, include native plant community competition (rivalry between siblings and relatives) and purity (keeping invaders out of the family). The questions being asked are: 1) what is the pattern of water use by both native and weedy species and can this resource be manipulated to favor the native plants? 2) Does interplanting with native forbs successfully keep exotic annuals from invading an established native grass community? 3) How is the competition for soil moisture in a native plant monoculture (single species) different from a polyculture (multiple species)?

The major emphasis for the following section of the report will be on studies dealing with inter- and intraspecific competition, plant water use and invasiveness. Studies from non-roadside landscapes are cited because they are much more numerous than roadway-related research.

Native plant community competition

Plant competition

Numerous experiments have been conducted on the inter- and intraspecific competition of native species (Hamilton et al. 1999; Dyer and Rice 1997; Carlsen et al. 2000; Brown and Rice 2000; Schultz 1996; Eliason and Allen 1997; Nelson and Allen 1993). Hamilton et al. (1999) wanted to determine 1) if interference among native perennial and non-native annual grasses was important across all life-stages of the perennial, *Nassella pulchra*, 2) if *N. pulchra* competes with non-native annual grasses and 3) if competition for water is an important component of these interspecific interactions in a water-limited system. They conducted a series of field and greenhouse experiments using removals of neighboring plants and additions of water. They found that the natural recruitment of *N. pulchra* seedlings from grassland soil was extremely low, but the addition of water to field plots increased density and total aboveground biomass of established *N. pulchra* plants. A simulated drought early in the growing season had a greater negative effect on the biomass of the annual seedlings than on the seedlings of *N. pulchra*. This may have been due to the deeper or more established rooting system of the native grass. The presence of annuals reduced growth and seed production of all sizes of *N. pulchra*, and these effects did not decrease as *N. pulchra* individuals increased in size. The addition of water caused the same increases in aboveground biomass and seed production of *N. pulchra* as removing all annual neighbors. Persistence of native bunchgrass species like *N. pulchra* maybe enhanced by greater mortality of annual than perennial seedlings during drought and possibly by reduced competition for water in wet years because of increased resource availability.

Several conclusions can be inferred from the work conducted by Hamilton et al. (1999). 1) In locations that have a low level of a naturally occurring seed bank of a particular native grass species (in this case *N. pulchra*), it may be important to add more seeds. 2) Additional water increases the size of the first year seedlings, which could provide an advantage in later years when competing with non-native annuals. 3) The removal of weeds results in higher production of native seeds and biomass while decreasing the stress on the plants. 4) Annual grass seedlings are not influenced by the removal of native perennial grasses. 5) Native grasses tolerate drought better than non-native annual grasses. 6) Native grass seedling establishment is primarily limited by water availability due to depletion by annual plant neighbors. 7) If water is limited, then non-native annual plants influence native grass growth but if water is unlimited, then non-native annuals have no effect on native grass growth. 8) The two ways to minimize negative effects from weed on native grass establishment are to kill them or to provide abundant water to cancel the effects of the non-native annuals, even though their size may become excessive.

The result of the presence of the annual fescue, *Vulpia myuros* (Zorro fescue), on native perennial grass aboveground biomass, density and seedling size was studied by Brown and Rice (2000). They evaluated the growth and performance of a mixture of California native perennial grasses and resident weeds when grown with varying densities of *V. myuros*. They found that the perennial grass seedling survival and aboveground biomass decreased with increasing seeding densities of *V. myuros*. They also found that *V. myuros* suppressed other weeds and had a more negative effect on weed densities than on native perennial grass densities. Nevertheless, the suppression of weeds by *V. myuros* is far from what could be considered a selective tool for weed control. To date, no studies have shown that *V. myuros* or any other grass, for that matter, can distinguish whether a neighboring plant is a weed or native perennial but may functionally do so by competing for a specific resource such as water.

Selection of plant material for roadside revegetation is critical when considering the long-term plant establishment. Brown and Rice (2000) state that the two most common purposes for reseeding (*i.e.* post-construction) are for establishment of native plants and for erosion control. Through their research, they found that neither of these goals were met when *V. myuros* was used in seeding mixtures. Furthermore, the idea of annual grasses acting as nurse plants to native perennial grasses was not supported by their results. Annual plants, such as *V. myuros*, are poor choices for weed suppression, prior to the planting of native perennial grasses. A more aggressive approach (*i.e.* mechanical, chemical) is better suited to controlling weeds in preparation for planting native grasses.

When considering fast germinating annuals for erosion control, the rainfall pattern is very important. A young stand of annuals is likely to be too small to provide erosion control from an early-season downpour. A more effective approach would be to apply mulch or to control drainage of early season water movements. Overall, Brown and Rice (2000) found that the inclusion of the exotic annual *V. myuros* in native seed mixtures is counterproductive to restoration efforts because of the suppressive effects on native grasses and the fact that erosion control with annuals is highly susceptible to fluctuating weather patterns.

In addition to native grasses, the establishment of native shrubs can also be heavily impacted by exotic annual species (Schultz 1996; Eliason and Allen 1997). Schultz (1996) and Eliason and Allen (1997) both studied the seedling establishment of native shrubs in a Mediterranean annual grassland. Schultz (1996) examined how exotic invasions could affect a coastal sage scrub and how they produce a type conversion from shrubland to grassland. Similarly, Eliason and Allen (1997) looked at the mechanisms by which grasses might exclude native shrubs and persist after release from disturbance. *Artemisia californica*, a dominant native shrub on the coast of California, was planted into different densities of grasses. *A. californica* germination, first season growth and survival were all negatively related to the density of neighboring annual grasses and most likely due to the depletion of soil water by the grasses. In the second season, the effects of the grasses were no longer significant on *A. californica*. They concluded that while succession alone may not return annual grasslands to their former shrubland composition, restoration might be possible with container plantings or removal of the grasses prior to seeding.

Out-competing the exotics

From these studies and many others like them, it is clear that native species, including grasses, are under intense pressure from non-native or exotic annual species during and following establishment. Therefore, it is important to find ways to reduce competition through cultural practices such as weed control and species selection.

In studies conduct-ed by Dyer and Rice (1997), the objective was to assess the general effectiveness of burning and grazing as grassland management strategies for increasing *N. pulchra* abundance and reducing competition from annual species. These two management techniques are probably not applicable to roadsides unless used in altered forms such as controlled burn or flaming and mowing. They measured the influence of competition on growth and survival of *N. pulchra*. They used summer fire and spring sheep grazing to reduce weed competition in non-weeded plots. They also established plots to determine the effect of rooting volume on the competitive interactions. Their results indicated that diffuse competition (a competitive neighborhood composed of high densities of many species) had the biggest negative influence on *N. pulchra* growth in all treatments. Burning had longer-lived effects in weeded plots and *N. pulchra* mortality was significantly increased by diffuse competition. Finally, survival was greatest in plots that were weeded, grazed and had soil deeper than 50 cm; all management techniques that could be implemented for roadsides following road construction. Intensive management is often necessary for the early establishment of native grasses. The conclusion by Dyer and Rice (1997) was that the recruitment of *N. pulchra* within inland California grasslands is reduced by the adverse environment created by high densities of alien annual species.

Carlsen et al. (2000) studied native grasses as a management tool for weed control for a rare California native forb, which was a different approach for the use of native species than just simply trying to establish them. Their objectives were to determine 1) if the forb, *Amsinckia grandiflora* would perform better in a matrix of native perennial bunchgrasses compared to a matrix of annual exotic grasses and 2) if competition for water played a significant role in the performance of the forb. They transplanted *A. grandiflora* seedlings into experimental plots of either exotic annual grassland or restored perennial grassland of *Poa secunda* in a field competition experiment. They found that *P. secunda* and exotic annual grasses reduced soil water potential from -1 to -3 MPa and also reduced production of *A. grandiflora* inflorescences. The exotic annual grasses at low or intermediate densities reduced *A. grandiflora* to a greater extent than did *P. secunda*. They concluded that restored perennial grasslands at intermediate densities have a high habitat value for the potential establishment of the native annual *A. grandiflora*. This could be extrapolated to heterogeneous native grass communities (both early (*Poa*) and later (*Nassella*) phenology) to allow a mix of native forbs.

Nelson and Allen (1993) studied the affect of vesicular-arbuscular mycorrhizae on the growth and competition between the native perennial *Stipa pulchra* and the introduced annual, *Avena barbata*. They found that mycorrhizae did not alleviate the negative effects of competition of *A. barbata* on *S. pulchra*, similar to demonstrations between other weedy and non-weedy species. They also found that once annual grassland has been revegetated with the native *S. pulchra*, the original fungal species composition may return relatively quickly. Their conclusions were that inoculation with mycorrhizal fungi alone will not suffice for establishing *S. pulchra* and the usual practices for control of weed competition need to be employed.

Water: a resource that can dictate plant community development

The use of water by native species is critical to their establishment and ultimate survival. Several studies have been conducted that address the use of water by native species and the role that undesirable species play in limiting the amount available (Hamilton et al. 1999; Gordon et al. 1989; Gordon and Rice 1992; Holmes and Rice 1996; Momen et al 1994; Gordon and Rice 1993). Many non-native annual grasses gain a competitive advantage over native perennial grasses by quickly establishing roots in the upper soil profile and depleting available water before the slower-developing natives can get to it. Persistence of native grasses could be enhanced either if non-native annual populations are decreased or if resource availability is increased (Hamilton et al. 1999).

Gordon and Rice (1992) compared soil water depletion for an annual forb and grass common in California. Holmes and Rice (1996) conducted studies on the alteration of soil water availability by exotic cool season annuals and the resulting effect on native perennial bunchgrasses. In both studies, the annuals produced extensive roots in the upper soil surface resulting in quick depletion of the available water. The native perennial bunchgrass, *Nassella pulchra*, produced more uniform distribution of roots to depths exceeding 0.5 m. It has been hypothesized that even though native grasses continue soil-water utilization well into the dry season, their growth habit is an energy-consuming behavior that can be detrimental in either drought years or under severe competition with a large population of exotic annuals.

Holmes and Rice (1996) measured rooting patterns of native perennial bunchgrasses and exotic cool season annuals and point out the lack of research on the impacts of exotic annuals and native perennial grasses on the soil-water regimes in California. They address the importance of understanding how invasive annuals have altered soil-water status and the resulting displacement of native species, hypothesizing that differing patterns of soil-water utilization could be based on the life histories of these two types of grasses. Annuals avoid drought by completing their life cycle while soils are moist, allocating a high proportion of their biomass to photosynthetic activity (rapid growth). On the other hand, native perennials develop an extensive, deep system of dense roots to get to water beyond the reach of annual plants and dry-season soil evaporation.

Despite this apparent partitioning of soil water utilization with depth when they are mature, annual plants compete directly with perennial seedlings during fall and winter establishment when both plant types are small and have shallow root systemsIn addition, data from the second and third year of the Holmes and Rice (1996) study show that the exotic annuals depleted the surface water that would have recharged the deeper root zone. Additionally, root biomass of native perennial plants will continue to grow year after year, while exotic annuals will produce just enough roots to complete their life cycle.

Astrategy for native plant establishment is to exploit the growth habit of the exotic annuals in a way that benefits the natives. The first germinating rain of the autumn season will result in a flush of weeds that can be killed with either cultivation or herbicide. This same technique can be used following planting by killing the emerging weeds with herbicide prior to native grass emergence, which is often slower by a week or more.

Reduced water uptake by native perennial bunchgrass roots may explain their poor survivability in dense stands of exotic grasses. Holmes and Rice (1996) suggest monitoring transpiration and soil evaporation throughout the growing season in conjunction with recording measurements of soil water potential to provide a picture of water balance at the stand level for a particular native grass. Additionally, they encourage further investigations into the effects on soil-water status by other exotic cool season annuals and native perennial bunchgrasses, especially given the diversity of the two grass types in California. There has yet to be any reported work on soil plant water relations in the areas mentioned by Holmes and Rice (1996).

In other soil-water relations studies, Momen et al. (1994) and Gordon et al. (1989) studied the effects of available seedling water on blue oak establishment within a California woodland. Results indicated that the exotic annual grasses were the cause of either stressed or dead oak seedlings. Similar to what Holmes and Rice (1996) found in native grass species, competition for soil water also effects blue oak seedling establishment. Oak seedling emergence and growth responses were significantly affected by annual plant density (Gordon et al. 1989). Only 20% of the acorns planted in high density *Bromus diandrus* neighborhoods showed aboveground shoot growth; 56% of those planted in low density *B. diandrus* or *Erodium botrys* emerged. Furthermore, relative growth rates of oak seedling root and shoots were directly dependent on soil water potentials.

Competition for water is the key factor for survival for all plants and its availability could be directly related to the water holding capacity of a soil. Dahlgren et al. (2003) found that blue oak trees [and possibly native herbaceous plants also] created islands of enhanced soil organic matter, water holding content and fertility across a variety of soil parent materials. The combination of soil water availability and soil quality appear to be related and may be the reason why In degraded soils with lower water availability, seedlings of blue oak and native perennial grasses are poor competitors with exotic annual grasses, which complete their lifecycles during the winter season when there are frequent rainfall events to recharge the soil.

Native plant community resistance to invasion

Native plant communities are susceptible to invasion from exotic alien species. Successful invasion of a natural community requires dispersal, establishment and survival, with the number of species in an area being determined by a balance between immigration and extinction (Lonsdale 1999). If most invading species fail to establish, as suggested by Williamson (1996), then the likelihood of successful invasion is usually low. The abundance of invasive problems in California may also be attributed to faulty management practices. The potential of open niches or ecosystems in California to be invaded by non-native or exotic species is also a problem that relates to proper management, not just to efficient invaders.

Riparian zones, coastal meadows and grasslands are a few of the ecosystems where exotic species have been introduced (accidentally or purposefully) and established to varying degrees (Robinson et al. 1995; Stohlgren et al. 1995; Planty-Tabacchi et al. 1996; Kotanen 1997; Rice et al. 1997; Tilman 1997; Thompson et al. 2001; Zalba and Villamil 2002). The inconsistency in experimental results and controversy in the invasibility theory (Lonsdale 1999) have led to differing views in the field of ecology pertaining to the influence that species richness has on determining invasibility. One theory suggests that areas that are more species rich are assumed to have a more complex or efficient use of limiting resources, and thus be less invasible (Robinson et al. 1995). Elton (1958) first hypothesized this scenario thinking that exotic species might more easily invade areas of low species diversity than areas of high species diversity. In contrast, May (1973) argues that a highly diverse community is intrinsically unstable, with some species dropping in and out routinely. In a global review, Rejmanek (1996) found little evidence to support the idea that native species richness between 50º N and 50º S latitude was directly responsible for greater resistance to invasion, although Elton's hypothesis was generally supported at continental scales.

Invasion rates depend on the plant community being invaded and the plant species that are invading. Many factors determine the invasibility of plant communities. Tilman (1997) studied experimental plots for a year before seed addition to quantify initial plant species composition and abundance, species richness, the amount of bare mineral soil, the extent of recent soil disturbance by gophers and extractable levels of soil nitrate and ammonium. His objective was to determine if local interactions were the overriding factor determining local diversity or if "open sites" allowing for greater recruitment in plant communities were the mechanism that allowed numerous species to coexist when competing for a single resource. He found that both local biotic interactions and recruitment dynamics determined diversity, species composition and species abundances in native grassland communities. Bergelson et al. (1993) also studied the significance of "open spaces" in terms of invasion by weeds outside an established plant community. Specifically, the objective was to determine how the spatial distribution of bare ground influences the rate at which offspring of an introduced invader spread through a perennial ryegrass community. They found that gap size and distribution within a plant community significantly affected the rate of spread of *Senecio vulgaris* and that plants moved a greater distance when the gaps were large and underdispersed.

Thompson et al. (2001) tested the roles of productivity and disturbance as major factors controlling invasibility of plant communities. They found that invasibility in an unproductive limestone grassland was correlated with the availability of unused resources. Furthermore, both disturbance and fertilizer addition increased the availability of resources and invasibility was clearly greater where both were combined. Kotanen (1997) also studied the effect of soil disturbance in field experiments conducted with natives and aliens in California grassland vegetation. He disturbed the soil using either excavation, burial or simulated gopher mounds and then measured revegetation and compared it between disturbed and undisturbed control plots for three years. He found that native bulbs and perennial graminoids were slow to recover, while exotic annual grasses became increasingly dominate.

In another grassland study, Rice et al. (1997) reported that the conversion of valley grasslands of California from a perennial bunchgrass prairie to an annual grassland was nearly complete. They found that Mediterranean exotic annual grasses produced dense canopies that reduced light to bunchgrass seedlings at the time as the plants needed photosynthate for root development into deeper soil layers. The conversion of California grasslands from a deep-rooted perennial bunchgrass system to a shallow-rooted annual grassland is thought to have significantly increased moisture at soil depths below 75 cm, allowing the invasion of other exotic species (*i.e. Centaurea solstitialis*).

In addition to plant community characteristics, such as spatial scale, biome and vegetation type, availability of resources and species-specific responses to disturbances (Stohlgren et al. 1999) that might lead to favorable conditions for invasion, the characteristics of the invader must also be considered. In a 5-year study by Thompson et al. (2001), seeds from 54 native species were sown into a grassland at the Buxton Climate Change Impacts Laboratory in the UK. They found that early stages of invasion (first two years) favored invaders with regenerative traits (seed mass and germination characteristics), but after 5 years, these traits were unrelated to success of the invaders. Additionally, they found that no single trait was a good predictor of invasiveness and the most successful invaders were perennial grasses. This is consistent with the hypothesis that the identity of successful invaders depends strongly on the invaded environment, excluding Tilman’s (1997) findings because of the strongly nitrogen-limited system he was working in at Cedar Creek.

Gerlach and Rice (2003) examined thistles from the *Centaurea* family in order to determine whether each one’s invasiveness was related to differences in life history traits. They compared each thistle congener (different thistles related by family) using qualities of 1) seed germination and seedling establishment, 2) vegetative growth under competition, 3) vegetative growth and flowering, 4) breeding systems. They found that *C. solstitialis* (yellow starthistle) was strongly positive in its response to combinations of clipping and canopy gaps (annual grass competitors) and its ability to extend its growing season into the dry summer months when competition from annuals is minimal. They found that the less invasive *Centaurea* species were more self-compatible than *C. solstitialis*. They concluded that *C. solstitialis* is such an effective invader due to its persistence in competition with annual grasses and its plastic growth and reproductive responses to open, disturbed habitat patches.

These and other studies on plant invasions are beginning to provide information for understanding of the role of plants both as established natural communities and as invaders. Even so, Stohlengren et al. (1999) notes that community ecologists do not yet understand the causes and patterns of native species richness. Therefore, it is the hope that fieldwork related to Phase I will provide additional, California-specific information on the interaction between exotic alien species and native plant communities. Mack (1996) states that the need for prediction [of plant invasions] is the same as in epidemiology: early detection of an invader combined with knowledge of its attributes and limitations allows maximization of a control effort. Here, the control effort will be through modification of water resources (improving soil depth and water holding capacity) and planting the appropriate species (late season native forbs that compete directly with exotic annuals).

Site review: (Yolo County, California)

(bulleted summary)

Establishment of native plant communities varied under three broad levels of management.

1) Observations suggested that a low level of management, in which natives were planted and left to survive without any further assistance, leads to poor establishment and in some cases a reversion back to weeds (Table 1).

2) The effects of medium and high levels of management for establishing roadside native plants were difficult to determine with only observational ratings. Some level of management, whether mowing, spraying or burning, seemed to promote a good stand of native plants.

Table 1. Preliminary visual observations of vegetation communities for roadside revegetation sites established by the Yolo County Resource Conservation District.

Site	Location	Est.	Grasses		Forbs		Rating*	Comments**
			Native	Exotic	Native	Exotic		
1	Rd 27, N side, ½ mile E of Rd 88	1993	√	√	√	√	3.5	Exotics: PL, WO, others Natives: GC, ES, milkweed, MR, NP, EG, shrubs Management: regular
2	Rd 27, S side, ½ mile E of Rd 88	1993	√	√	√	√	3.5	Exotics: PL, WO, others Natives: GC, NP, EG Management: burned/mowed
5	Rd 88, W side from Rd 26 to 27	1983	√		√	√	4.5	Exotics: PL, WO single plants Natives: Dense EG, MR, NP Management: regular
8	Rd 89, W side, from ½ mile S of Hwy 16 to Rd 23A	1995	√	√		√	3.5	Exotics: PL and others Natives: grasses and shrubs Management: some, but could be better
9	Rd 23, N side, from Rd 89 to Rd 31	2001	√	√		√	1.0	Exotics: mowed Natives: mowed Trees planted along back ditch Management: not for natives

10	Rd 102, E side, from Rd 16 to Rd 15	1998		√		√	0.0	Management: weed cover managed between road and field edges.
12	Rd 89, W side, from ¾ mile N of Rd 31 to ¼ mile N of 31	1999	√	√		√	4.0	Exotics: PL, YST, Alfalfa? Natives: NP, EG, HBB Management: road edge mowed and spot handweeding on 9/8/03.
15	Rd 95, E side, from Rd 19 to Rd 18A	1990	√	√		√	3.5	Exotics: PL, BW, YST some Natives: NP, EG, LT, MR Management: mow edge & between poles
17	Rd 20, S side, from ¼ mile W of Rd 97 to 97	1996	√	√		√	2.0	YST dominates; PL, BW, WO NP dominates; LT? Management: mowed once (not recently)
19	I-505, E side (adjacent to NB lane), from Rd 14 along Rd 12A	2001	√	√		√	4.0	Exotics: YST Natives: EG, NP Management: sprayed with transline; mowed once or twice?
21 A	Russell Blvd, N side, from Rd 97 to Glide Ranch E	2001	√	√		√	3.5	Exotics: BW, YST, PL Natives: EG, LT, MR, ES Management: little/none?
21 B	Russell Blvd, S side, from 1 mile W of Glide Ranch to Glide Ranch	2001	√	√		√	3.5	Exotics: Mustard spp, BW, PL, Ryegrass Natives: EG, NP, HBB?, ES Management: little/none?
26	Rd 95, W side, from Rd 96 to Rd 97	2000	√	√		√	1.0	Exotics: PL, YST dominate Natives: where? Management: none?
27	Rd 31, S side, from Rd 98 to Lake Blvd	1997	√	√	√	√	2.5	Exotics: johnsongrass, mustard spp, YST, others Natives: shrub row and MR Management: little

*0 = reject (no natives, all exotics); 1 = poor (a few natives, mainly exotics); 2 = fair (some natives, many exotics); 3 = average (natives and exotics equal); 4 = good (mostly natives, a few exotics); 5 = excellent (all natives, no exotics).

**Exotics: PL (prickly lettuce), YST (yellow starthistle), WO (wild oat), BW (field bindweed). Natives: NP (*Nassella pulchra*), EG (*Elymus glaucus*), ES (*Eremocarpus setigerus*), LT (*Leymus triticoides*), HBB (*Hordeum brachyantherum* ssp *brachyantherum*), HBC (*Hordeum brachyantherum* ssp *californicum*), MR (*Mulenbergia ripens*), GC (*Grindelia camporum*)

Phase II: Roadside native plant establishment

Native grasses are under intense pressure from non-native or exotic annual species during and following establishment. Therefore, it is important to find ways to reduce competition through cultural practices such as species selection, site development and weed control. In order to allow for the sustainable growth of native perennial grasses along roadsides, we designed our project to determine:

1) Desirable plant materials (Phase II, Part A)

2) Site preparations (Phase II, Part B)

3) Maintenance procedures (Phase III).

Phase II, Part A: Desirable plant materials

Introduction

Field studies were initiated along two interstate highways in north central California. Twelve native grass species that typify the valleys and foothills of northern California were selected from a local seed source for planting along State Route 29 (SR29) in Lake County and Interstate 505 (I505) in Yolo County (Table 2).

Table 2. Native perennial grass species out planted along highway rights-of-way in Northern California.

Common name	Species name	lbs/A
Blue wild rye	*Elymus glaucus*	4
California barley	*Hordeum brachyantherum californicum*	3
California brome	*Bromus carinatus*	3
California onion grass	*Melica californica*	4
Creeping wildrye	*Leymus triticoides*	6
Foothill needlegrass	*Nassella lepida*	2
June grass	*Koeleria macrantha*	1
Meadow barley	*Hordeum brachyantherum brachyantherum*	4
Nodding needlegrass	*Nassella cernua*	6
One sided bluegrass	*Poa secunda secunda*	2
Purple needlegrass	*Nassella pulchra*	10
Squirrel tail	*Elymus multisetus*	3

Single species were drill seeded from the edge of the highway in a perpendicular direction to the road. Site preparation and maintenance included typical cultural practices (*i.e.* soil analysis, soil seedbed preparation and weed control) that have been demonstrated to be most effect for establishing a native plant community (Anderson and Long 1999; Brown and Rice 2001; CNGA and CCIA 2001; Anderson 1999; Wolfe et. al. 1999). Observational studies were used to monitor plant growth. In spring and summer, establishment of native perennial grasses was determined by measuring the density of plants in drill rows that had been staked shortly after planting in the fall.

The goal was to determine which native perennial grasses (Table 1) would establish at what location (edge, swale, back slope) away from the highway edge.

Methods for installation of plant species

2002-2003 Season

In October, two experimental research sites were established along Caltrans rights-of-way in Lake County (State Route 29, mile 3.1, along southbound lane) and in Yolo County (Interstate 505, mile 14.9, between northbound on-ramp and highway). Each site had particular features that warrant experiments on establishing native or desirable species. The first site in Lake County (hereafter referred to as SR29A) was flat with a uniform stand of annual non-native plants growing abundantly. This site represented a typical condition for native perennial grass establishment in an oak savanna type landscape. The Yolo County site (hereafter referred to as I505), represented a valley soil on which native perennial grasses would be established, similar to SR29A.

Fall was selected for planting because best germination occurs when soil temperatures are about 70° F and rain is imminent to re-fill the soil profile (McGourty 1994). Because frequent irrigation applications are not practical for roadside maintenance, native species establishment must be initiated in the fall for adequate plant development before daytime temperatures begin to rise in late spring.

Following the general guidelines described by Wrysinski (1999) and Anderson (1999), I505 and SR29A were burned on November 22 and 19, respectively to remove existing vegetation. The controlled burn at both sites was incomplete due to green vegetation that had begun to emerge with the onset of fall rains. The I505 site had been mowed a month before the burn by Caltrans, which further reduced the amount of thatch needed to carry a hot fire.

Plant species to be included in the out-plant test included perennial grasses native to California that would be most suitable for roadside establishment from pavement edge out to 15 m (Table 1). Growth characteristics were similar to native plants used by Bugg (1997) with plant height as an important characteristic because of the affect on maintenance to sight clearance, fuel loads for fires and wildlife cover. The grasses most adjacent to the road (unimproved/recovery area) consisted of the shortest species and included *Bromus carinatus* (California brome) and *Poa secunda ssp secunda* (One-sided bluegrass). Grasses selected for the side slope area included medium height species such as *Festuca idahoensis* (Idaho fescue), *Hordeum brachyantherum ssp brachyantherum* (Meadow barley), *Melica imperfecta* (Coast range melic) and *Nassella cernua* (Nodding stipa). For the area beyond the side slope (could include open-cut ditch) the tallest grasses selected were *Elymus glaucus* (Blue wildrye) and *Muhlenbergia rigens* (Deergrass).

In addition to height, other important considerations (Anderson 1999; Bugg, et. al.

1997; CNGA and CCIA 2001; McGourty 1994; Wrysinski 2000) for species selection were season of growth (cool or warm), soil or habitat (soil moisture content, air temperatures, soil characteristics), life form (perennial or annual), level of tolerance to fire (remaining green during the summer season) and/or mowing and others (*i.e.* competitiveness, root structure and depth).

The I505 site was drill seeded on December 3 using a Truax™ no-till planter pulled by a farm tractor. The planter was calibrated to deliver 25-35 lbs of native grass seed per acre. Treatment plantings were laid out according to Figure 1.

-- Freeway --

---- 1 m from road edge ----																																
	a	a	b	c	d	a	**a**	b	c	d	a	**a**	a	a	**a**	a	b	c	d	**a**	b	c	d	a	a	b	c	d	b	c	d	a
---- 10 m from road edge ----																																
	a	a	b	c	d	a	**a**	b	c	d	a	**a**	a	a	**a**	a	b	c	d	**a**	b	c	d	a	a	b	c	d	b	c	d	a
---- 15 m from road edge ----																																
	a	a	b	c	d	a	**a**	b	c	d	a	**a**	a	a	**a**	a	b	c	d	**a**	b	c	d	a	a	b	c	d	b	c	d	a
Plot position (north end = 1, south end = 31)	00	01	02	03	04	05	**06**	07	08	09	10	**11**	12	13	**14**	15	16	17	18	**19**	20	21	22	23	24	25	26	27	28	29	30	31
Block		A	A	A	A		P	B	B	B	B	P			P	C	C	C	C	P	D	D	D	D	E	E	E	E	F	F	F	F

a = best guess mix: north 6 rows = mix 1; south 6 rows = mix 2 (12 rows = 1 drill pass or 10 feet)
b = single species 1: 3 rows each of NP, HBC, MC, NL (12 rows = 1 drill pass or 10 feet)
c = single species 2: 3 rows each of PSS, NC, KM, EM
d = single species 3: 3 rows each HBB, EG, BC, LT

*Figure 1. The experimental layout for drill seeding with native perennial grasses. Native grass species code: NP (*Nassella pulchra*), HBC (*Hordeum brachyantherum californicum*), MC (*Melica californica*), NL (*Nassella lepida*), PSS (*Poa secunda secunda*), NC (*Nassella cernua*), KM (*Koeleria macrantha*), EM (*Elymus multisetus*), HBB (*Hordeum brachyantherum brachyantherum*), EG (*Elymus glaucus*), BC (*Bromus carinatus*) and LT (*Leymus triticoides*).*

The same planting procedure and experimental layout was used at SR29A on December 12 (Figure 2). Glyphosate (Roundup Ultra® at 1 qt./A) was applied less than nine days after planting at I505 and SR29A for annual weed control prior to emergence of native perennial grasses (Anderson and Long 1999). Native grass seed germination usually occurs in about 2-4 weeks when planted in the fall (Anderson 1999). Once native grasses had emerged and begun to establish (early to mid-spring), selective herbicides were applied to control broadleaf weeds.

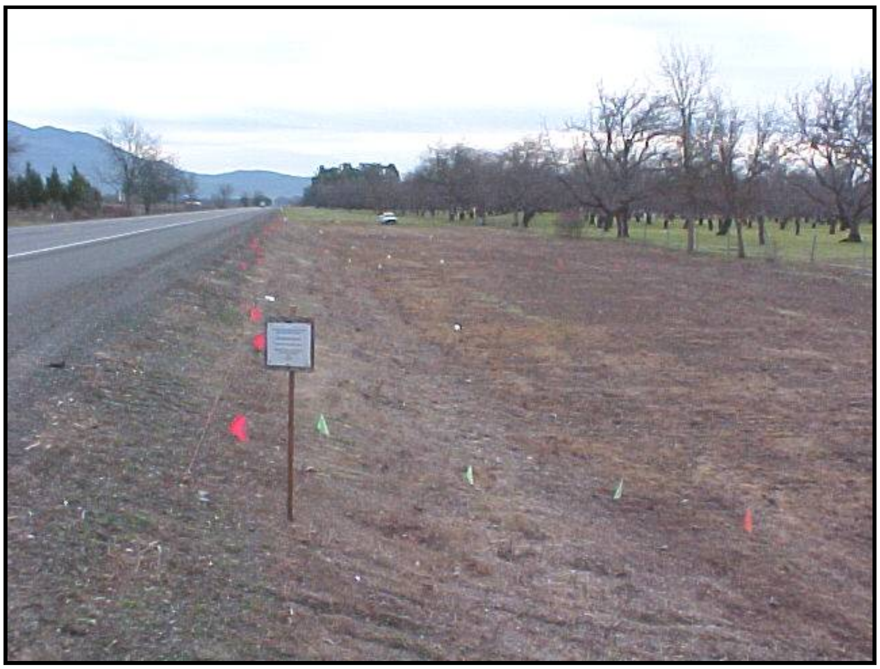


Figure 2. Experimental layout at SR29A following the drill seeding of native perennial grasses on December 12, 2003.

Native grasses emerged at I505 and SR29A by January 6 and 14, respectively. The stand at I505 was poor (Figure 3) and was thought to be due to the cold weather. By January 29, weed control was not adequate from the glyphosate so Buctril® was applied at 0.5 pt./A on February 14.

Figure 3. Native perennial grass emergence is sparse in the experimental plots at I-505 on February 11, 2003

Poor germination of native grasses continued at I505 because of possible ‘damping off’ disease, which attacks grass seed, damage from spraying glyphosate to close to native grass emergence or seed loss from predation by birds and varmints (Figure 4).

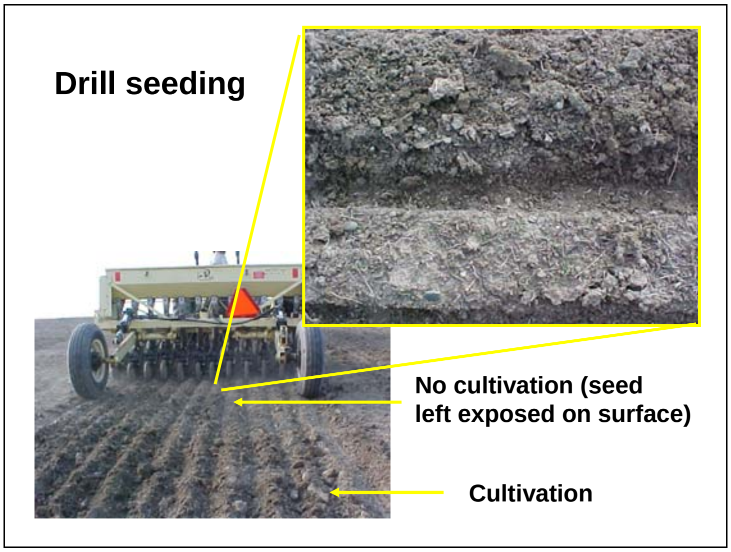


Figure 4. Potential problem for planting with no-till drill seeder.

A field visit to I505 with a local native grass grower on March 4 confirmed a poor native grass stand because of disease or predation. Even though greater numbers of native grasses had emerged in spots where the controlled burn was hottest, overall emergence was below normal. The Buctril® could have damaged the young plants, especially if no adjuvant was used or the spray tank had not been thoroughly rinsed from a previous use.

By March, a good stand of native grasses had emerged at SR29A (Figure 5). In the previous month, Caltrans sent notification that the highway was due for widening and installation of a lighted intersection, which would severely impact a major part of the site and fatally harm the native grasses. Construction was to begin in July, so the site was monitored and data collected up until ground breaking. An application of triclopyr (Garlon™ 4 at 1.2 pt/A with non-ionic surfactant) was made at SR29A on March 26. At I505, clopyralid (Transline™ at 6 oz./A) was sprayed on March 29 to control broadleaf weeds, especially yellow starthistle.

Figure 5. Native perennial grass stands at SR29A on May 2, 2003. Native grasses include Hordeum brachyantherum californicum, Bromus carinatus and Elymus glaucus.

Figure 6. Poor stand of native perennial grasses at I505 on May 13, 2003. (A year of weed control, but native perennial grasses were not persistent enough to establish. A new planting was designed for the same site to begin fall 2003.)

Figure 7. Young stands of native perennial grasses at SR29A on June 18, 2003. At the road edge is Nassella pulchra (A), Elymus multisetus (B) and Leymus triticoides (C). (Unforeseen road construction at Lake 29 that began in July 2003 caused SR29A to be lost. Once a new location was identified, (SR29) the organization process of preparing and planting the site in fall 2003 was started immediately.)

The SR29 site was cultivated on April 5, to preserve soil moisture and eliminate late emerging weeds in preparation for planting native grasses in the fall. *Nassella pulchra* emergence was lagging behind the other native grasses on May 2 at SR29A. *Koeleria macrantha* and *Poa secunda* were emerging slowly, while all remaining native grasses had emerged from drill seeded rows (Figure 5).

The final stand counts at 20 meters from the road edge were made at I505 on May 14. Sparse populations of native grasses would be problematic for trying to establish a competitive stand to resist annual weeds (Figure 6). I505 was sprayed with glyphosate (Roundup Ultramax® at 2.5 pt./A) on May 15 in preparation for another native grass planting in fall 2003. Before spraying I505, stand counts were taken along the back slope (Graph 1). Stand counts of native grasses at SR29A were taken on May 28 at 1 m, 4 m and 10 m from the road edge (Graph 2). Glyphosate (Roundup Ultramax® at 2.5 pt./A) was sprayed at SR29 on May 29 to control summer annual weeds in preparation for planting in fall 2003. Final observations of native perennial grass establishment were made at SR29A prior to road construction (Figure 7).

On July 24, I505 was burned to remove dead vegetation and reduce annual weed seed load (Figure 8).

Figure 8. Burning at I-505 (July 24, 2003)

2003-2004 Season

After poor establishment (I505) and road construction leading to loss of research plots (SR29A) in 2002-2003 season, planning and site preparations were started anew for the 2003-2004 season. A year's worth of weed control was obtained at I505 along with more knowledge on seedbed preparation (*i.e.* spray timing and avoidance of cold weather conditions) and the problems of native grass pests (*i.e.* disease and predators). The planting success at SR29A prior to construction would hopefully be transferred to the new site, SR29, at mile 10 between the northbound on-ramp and highway at Hill Road overcrossing in Lake County. The site was fallowed, beginning in early spring 2003.

Soil samples were taken at I505 and SR29 on September 19 and 23, respectively, and analyzed at the A&L Lab in Davis (Tables 2 and 3).

Table 2a. Soil characteristics near and back from road edge at I505, Yolo County, CA.

Location	OM	HCO_3_P	pH	K	Mg	Ca	Na	CEC	%K	%Mg	%Ca	%Na
20 m from road	1.7	21	8.0	282	1881	3505	22	34	2	46	52	0
1 m from road	1.9	14	7.8	269	1335	4001	61	32	2	35	63	1

Table 2b. Soil characteristics near and back from road edge at I505, Yolo County, CA.

Location	NO_3_N	S	Zn	Mn	Fe	Cu	B	S__SALTS	%SAND	%SILT	%CLAY
20 m from road	7.7	10.4	0.1	7.1	9.1	1.1	0.5	0.3	20	34	45
1 m from road	7.0	8.0	0.2	39.6	33.9	1.2	0.5	0.3	25	34	41

Table 3a. Soil characteristics near and back from road edge at SR29, Lake County, CA.

Location	OM	HCO_3_P	pH	K	Mg	Ca	Na	CEC	%K	%Mg	%Ca	%Na
10 m from road	1.6	11	6.9	138	2069	2245	63	30	1	57	38	1
1 m from road	1.5	11	6.8	173	1947	2143	57	30	2	54	35	1

Table 3b. Soil characteristics near and back from road edge at SR29, Lake County, CA.

Location	NO_3_N	S	Zn	Mn	Fe	Cu	B	S__SALTS	SAND	SILT	CLAY
10 m from road	10.0	1.6	0.2	70.2	45.4	1.3	0.1	0.3	49	20	31
1 m from road	9.2	2.2	0.1	49.0	35.5	0.9	0.1	0.3	27	34	39

In addition to lab analysis, soil pits were dug to determine soil morphological characteristics and identify factors (*i.e.* hard pan layers, poor soil structure) that could be contributing poor native grass establishment. On October 31, deep soil ripping (60 cm on ½ m centers) treatments were conducted at I505 (Figure 9). Ripping and discing operations were conducted after the burn to provide soil seedbed preparation and control weed seedlings. The seedbed was made firm and smooth so seed could be seeded with a Truax machine drill. Additionally, a light cultivation to approximately 3 cm was done on November 4.

Figure 9. Ripping and cultivation at I505, Yolo County, CA (October 2003).

Similar ripping and cultivation treatments as at I505 were conducted at SR29 on November 3 (Figure 10).

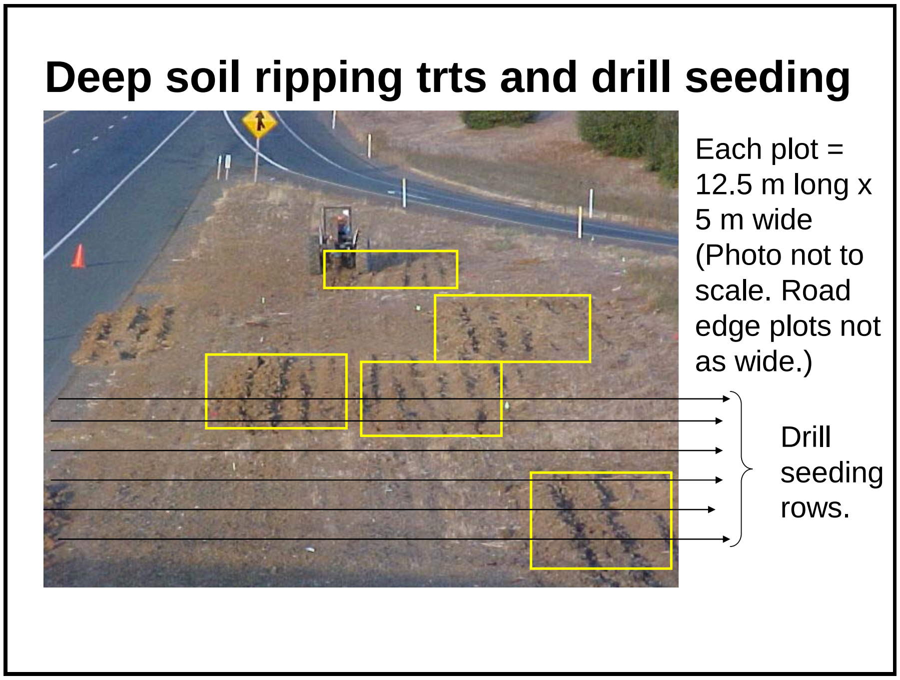


Figure 10. Soil ripping plots constructed prior to drill seeding at SR29 in Lake County, CA (November 3, 2003).

At both sites, non-ripped control plots were included for comparison following native grass planting and establishment. Soil structure at SR29 appear to be more developed than at I505. Near the road edge, soils were subangular blocky or platey from 0-20 cm deep, while away from the edge structure was subangular blocky down to 30 cm. At both sites, soil structure below 30 cm was massive with little structural development.

On November 13 and 18, native grasses were drill seeded at I505 and SR29, respectively. The planting format was similar to fall of 2002 (see Figure 1) with the addition of deep soil ripping and cultivation treatments at both sites (Figure 11).

---------- Freeway ----------																																
---------- 1 m from road edge ----------																																
		n	n	n	n			r	r	r	r					n	n	n	n		r	r	r	r	n	n	n	n	r	r	r	r
---------- 10 m from road edge ----------																																
		n	n	n	n			r	r	r	r					n	n	n	n		r	r	r	r	n	n	n	n	r	r	r	r
---------- 15 m from road edge ----------																																
		r	r	r	r			n	n	n	n					r	r	r	r		n	n	n	n	r	r	r	r	n	n	n	n
Plot position (north end = 1, south end = 31)																																
	0	0	0	0	0	0	**0**	0	0	0	1	**1**	1	1	**1**	1	1	1	1	**1**	2	2	2	2	2	2	2	2	2	2	3	3
	0	1	2	3	4	5	**6**	7	8	9	0	**1**	2	3	**4**	5	6	7	8	**9**	0	1	2	3	4	5	6	7	8	9	0	1
Block																																
		A	A	A	A			B	B	B	B					C	C	C	C		D	D	D	D	E	E	E	E	F	F	F	F

r = deep soil rip + cultivation; n = no deep soil rip + cultivation

Figure 11. Experimental layout with soil ripping (r) and no soil ripping (n) treatments applied prior to drill seeding of the native grasses. Treatments r and n tested at the road edge (1 m) and away from the road edge (10-20 m).

At both sites, seeding was done perpendicular to the highway and crossed the ripped and non-ripped treatments. The slope back from the road edge at I505 was steeper and wider (> 20 m) than at SR29 (Figure 12).

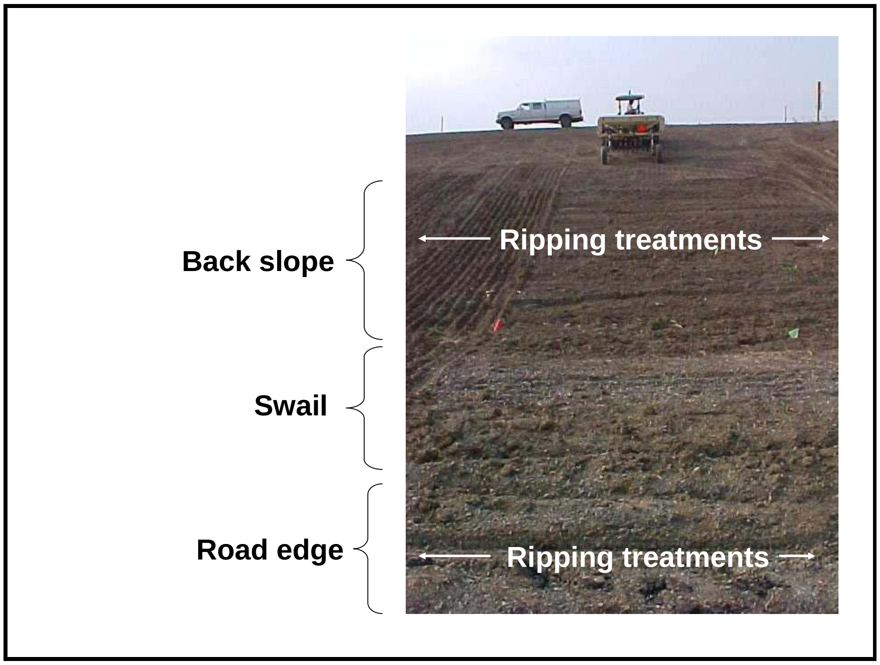


Figure 12. Drill seeding a second time at I505 after poor native grass emergence and persistence the previous year (November 13, 2003).

Following drill seeding, soil in each row was raked lightly over the seed trench to insure against native grass seed loss from predation by birds and varmints as in 2002-2003. The open seed trench condition seemed to be more common in 2003-2004 because of drill seeding into damp soil, which was less friable than earlier in the fall.

On November 24 and 25, glyphosate (Roundup Ultra® at 2 pts/A) was applied to kill annual weed seedlings prior to native grass emergence at I505 and SR29, respectively. Following herbicide application, native grass straw (*Melica californica*) was applied at 2 tons/A or approximately 3/4” deep (2002 Caltrans/CNGA workshop) to control soil loss and disturbance of native grass seed (Figures 13 and 14).

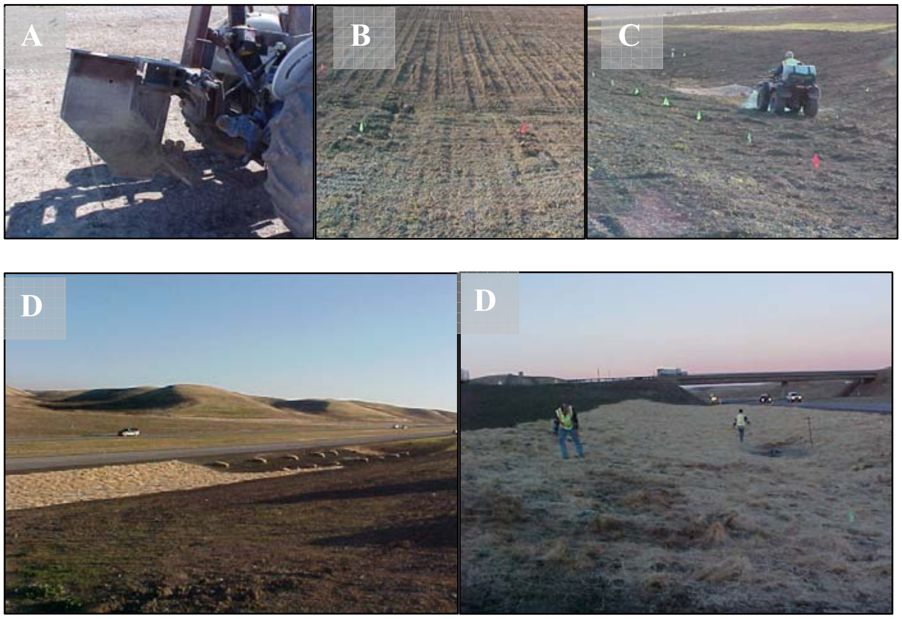


Figure 13. I505 (Fall 2003). A close-up view of the deep ripper used at I505 and SR29 prior to planting in fall 2003 (A). The planted seedbed was raked by hand to insure good soil to seed contact and prevent seed loss by wild life (B). A post-planting herbicide application was made to control weeds before emergence of native perennial grass seedlings (C). Straw was applied prior to the rainy season to control excessive soil loss (D).

Figure 14. SR29 was drill seeded with native perennial grasses (A), sprayed with glyphosate to control weeds before native grasses emerged (B) and covered with straw to control excessive soil loss across the site and along the road edge (C) (November 2003).

On December 16, native grasses had begun to emerge mainly along the road edge at I505 where the straw mulch was thinner. Early after planting, low emergence is not uncommon, especially during excessively cool and wet periods, but in spots with excessive straw mulch (>3/4”), native grasses were less likely to be found. The emergence of native grasses at SR29 had yet to occur and ponding water was observed in several locations.

Native grasses began to emerge in both heavily mulched (>3/4”) and lightly mulched (<3/4”) areas of I505 by January 23 (Figure 15).

Figure 15. Native grass emergence at I-505 on January 23, 2004.

The straw mulch was either non-selective in slowing the emergence of weeds and native grasses or the herbicide application was very effective or the straw mulch was having no effect as weather conditions were adversely inhibiting weed and native grass emergence. Whichever the case, weed control was near 100% at I505 and SR29 in late January.

On February 4, native grasses continued to come up through the mulch and weed growth was beginning at I505. The straw mulch, in addition to controlling soil loss, may have inhibited some growth of the native grasses by retaining water in an already excessively wet condition, maintaining low temperatures, blocking light and physically impairing vegetative growth. Native grass seedlings were in the 2-3 leaf stage at I505 on February 9 and still emerging from under the straw mulch.

Native grasses were slow to emerge at SR29. The site was still very wet on February 20 with ponding water visible in a few spots. The growth of weeds was minimal to nil with only a few small patches of grasses and some sedges here and there.

On March 3, clopyralid (Transline® at 6 oz/A) was sprayed at I505 to control vetch and other annual broadleaf weeds. The application may have injured the young native grasses seedlings (3-5 leaves and 6-10”), but the weeds were becoming a problem and could have inhibited native grass growth, especially with warm, dry weather conditions. The application was effective for control of the vetch and yellow starthistle, but ineffective on fiddleneck and certain species of mustard. On March 15, exotic annual and native perennial grasses were growing well in patches and appeared to have either not been injured or recovered from injury by the clopyralid application.

An attempt was made at uprooting weeds at I505 on March 22, but removal of broadleaves and vetch (tares) also caused damage to the desired plants, so they were left in the field to be controlled by burning (Matthew, 1952) other chemical, mechanical or cultural means, such as tillage or native perennial grass competition. At this time, annual grasses (*i.e.* ripgut brome, Italian ryegrass) were still vegetative and above the native perennial grasses.

On March 23, native grasses had clearly emerged in many of the drill rows from the fall planting at SR29. An application of clopyralid (Transline™ at 6 oz/A) was made to control broadleaf weed growth, which was beginning to impeded native grass establishment.

A selective mowing was conducted at I505 on March 30. The site was mowed at approximately 10-12”, which was just above the tallest native grasses, yet low enough to remove the inflorescences of many of the annual grasses. McGourty (1994) recommends mowing native grasses in early spring to a height of four inches to suppress winter weeds and promote tillering of the developing grasses, but we elected not to mow due to adequate control from glyphosate applied in the fall. When mowing was done, the mower height was kept at a height that would kill weeds (~10"), but that prevented permanent damage to the native grasses. Anderson and Long (1999) mowed hedgerow plots with native grasses once or twice in the spring to control annual grasses before they set seed. Timed mowings are also recommended by Wrysinski (1999) as a weed control tool that can reduce annual weed canopy and allow sunlight to reach shorter, less vigorous natives. Mowing of native grasses in this study was employed in a similar fashion for weed control, albeit later in the growing season than recommended.

Preliminary observations were made on number of native perennial grasses and weed growth in ripped and non-ripped treatments at I505 on March 30. Of the 12 native perennial grass species planted, *Bromus carinatus*, *Melica californica*, *Elymus glaucus*, *E. multisetus*, and *Hordeum brachyantherum* ssp *brachyantherum* were present in 4 to 6 out of 6 replications at row lengths of 1 m or greater. *Nassella lepida*, *Nassella pulchra* and *Koeleria macrantha* were present in 2 out of 6 replications and *Nassella cernua*, *Poa secunda* ssp *secunda*, *Hordeum brachyantherum californicum* and *Leymus triticoides* were not present during the spring stand count. Weed growth appeared to be reduced in non-ripped treatments compared to ripped treatments, irregardless of nearness to road edge. The observation of greater weed growth in ripped treatments is not uncommon as previous research has documented the stimulatory effect that soil disturbance has on weed seed germination.

On May 29, native grasses were establishing at SR29 in drill rows from the fall. The most prevalent native grasses were *B. carinatus*, *E. glaucus*, *E. multisetus*, *H. brachyantherum* ssp *brachyantherum*, *P. secunda* ssp *secunda*, *K. macrantha* and *H. brachyantherum californicum* (Figures 16 and 17). Although native grasses seldom filled out an entire drill row from road edge to back slope, plants that were present were robust, green and appeared to be growing with vigor. Native grass species that had been planted yet were not seen were *N. lepida*, *N. pulchra*, *N. cernua*, and *L. triticoides*.

Figure 16. Native perennial grass establishment at Lake 29 on June 18, 2004. Elymus glaucus (A) and Hordeum brachyantherum californicum (B) growing in drill rows planted in November 2003.

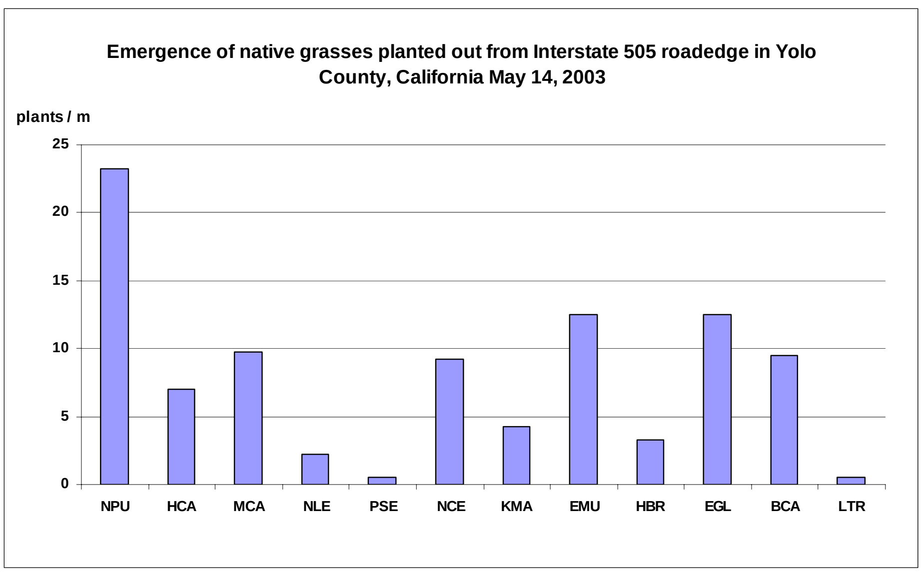
Figure 17. Native grass emergence at Lake 29 on June 18, 2004. A robust stand of Elymus multisetus (A) and Leymus triticoides (B).

Stand counts were recorded for native grasses at I505 and SR29 on June 19 (Graphs 4-7). The number of native grasses was greater at SR29 than I505. Native grass establishment had occurred at SR29, even though many weeds were still present (Figures 16 and 17). This is not an uncommon phenomenon, as most native grass restoration projects require 3 to 5 years of maintenance following the initial planting to become the dominant plant type that out compete weeds. At I505, native grasses were present, but weeds were overwhelming most of the native grass plants. A more vigilant approach to weed control appears to be necessary (*i.e.* preemergent herbicide in fall, selective wiping of taller annual grasses in spring, mowing techniques that avoid knocking annual weeds down without actually cutting them).

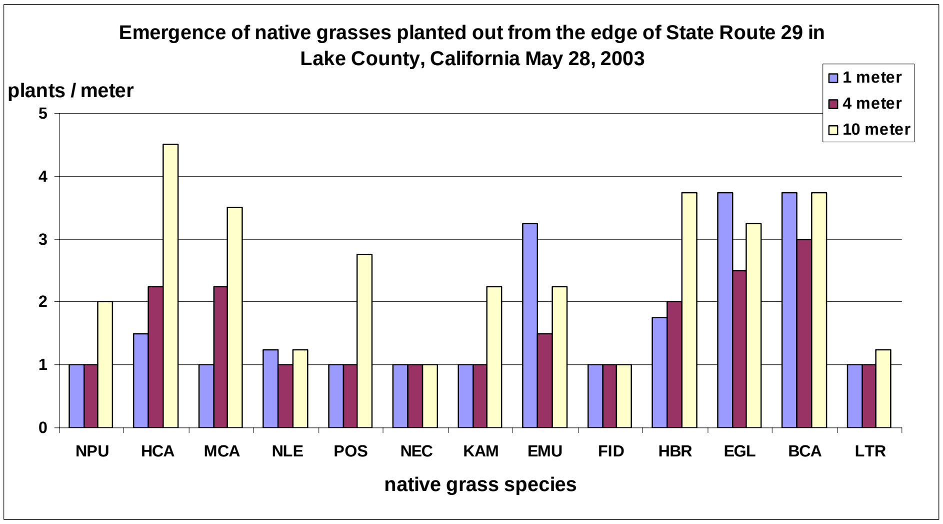
Results of native perennial grass species selection

2002-2003 Season

Single species of *N. pulchra* (NPU), *E. multisetus* (EMU) and *E. glaucus* (EGL) emerged at a rate of greater than 10 plants/m along the road edge at I505 in spring 2003 (Graph 1). Populations of *H. brachyantherum* ssp *californicum* (HCA), *M. californica* (MCA), *H. brachyantherum* ssp *brachyantherum* (HBR), *E. glaucus* (EGL) and *B. carinatus* (BCA) had at least 3 plants/m stand counts at 10 m from the road edge, while *E. multisetus* (EMU), *E. glaucus* (EGL) and *B. carinatus* (BCA) had greater than 3 plants/m stand counts at 1 m from the road edge at SR29A spring 2003 (Graph 2).



Graph 1. Native grass emergence at Interstate 505 in Yolo County, CA (May 14, 2003).



Graph 2. Native grass emergence at State Route 29A in Lake County, CA (May 28, 2003).

2003-2004 Season

Single species stands of *Elymus glaucus* (Blue Wildrye), *Bromus carinatus* (California Brome), *Elymus multisetus* (Squirrel Tail), *Melica californica* (California Onion Grass) and *Hordeum brachyantherum californicum* (California Barley) had an establishment rate of greater than 2 plants per m^2 at SR29 and I505 in year one after seeding. In the ripped plots at the road edge of I505, *Blue wildrye*, *B. carinatus* and *E. multisetus* establishment was 4, 3 and 4 plants per m^2, respectively. Except for *M. californica* and *Hordeum brachyantherum* (Meadow Barley), plant establishment in the back slope of I505 was not different for ripped and non-ripped areas. At SR29, establishment in the back slope was 4, 6, 3, 5 and 4 plants per m^2 in the ripped treatments for *H. brachyantherum californicum*, *E. multisetus*, *H. brachyantherum*, *Blue wildrye* and

Leymus triticoides (Creeping Wildrye), respectively. Except for *H. brachyantherum californicum*, *E. multisetus* and *H. brachyantherum*, plant establishment was similar in ripped and non-ripped plots at the road edge of SR29. At SR29 and I505, establishment for *Nassella pulchra* (Purple Needlegrass), *Nassella lepida* (Foothill Needlegrass), *Poa secunda secunda* (One-sided Bluegrass), *Nassella cernua* (Nodding Needlegrass) and *Koeleria macrantha* (June Grass) did not exceed 1 plant per m^2.

Establishment varied at each site with respect to location (road edge or back slope) and cultural amendment (soil ripping or non-ripping). Native grass establishment was greater along the back slope at SR29 (Fig. 4), but soil ripping was not beneficial in both locations (Figs. 5 and 6). Conversely, I505 had the best native perennial grass establishment at the road edge (Fig. 7) and ripping tended to improve establishment at both road edge and back slope locations (Figs. 8 and 9). We found that first year establishment of native perennial grasses were affected by micro-site differences (*e.g.* climate, soil), which resulted in variation in plant numbers, but only eliminated between 1 to 4 out of the 12 plant species that were tested. The effect from ripping was not determined in subsequent years.

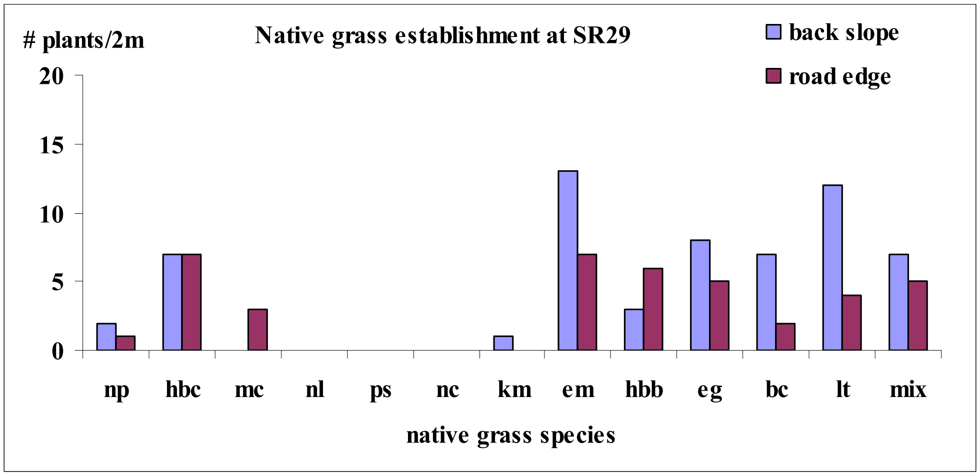


Figure 4. Establishment of native perennial grasses along the road edge and back slope of a Caltrans' highway right-of-way in Lake County, CA (June 19, 2004).

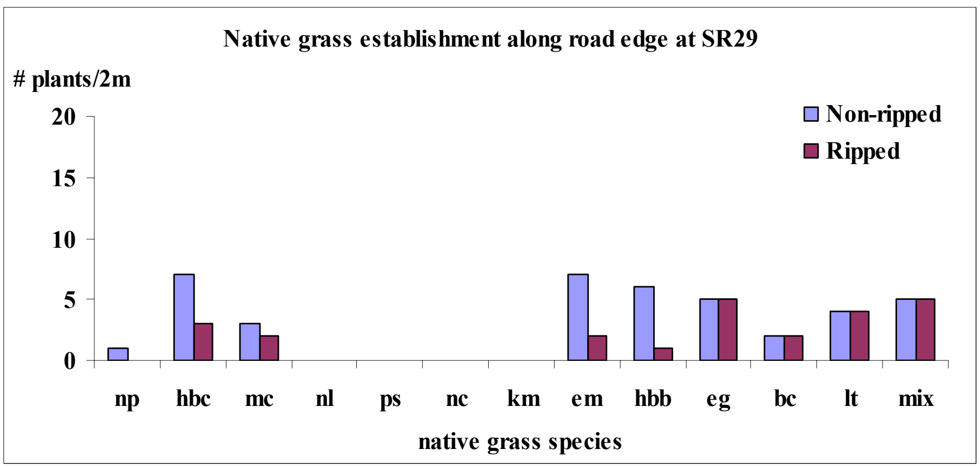


Figure 5. Establishment of native perennial grasses along the road edge of a Caltrans' highway right-of-way in Lake County, CA using cultural treatments (June 19, 2004).

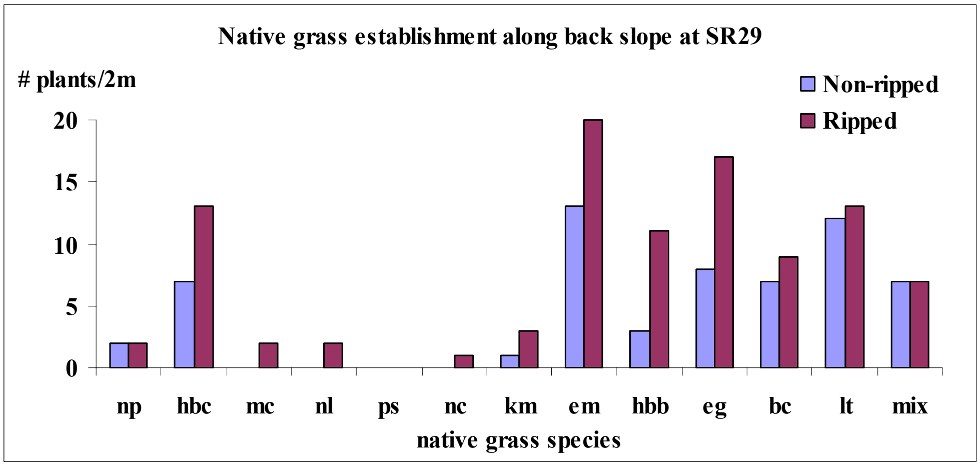


Figure 6. Establishment of native perennial grasses along the back slope of a Caltrans' highway right-of-way in Lake County, CA using cultural treatments (June 19, 2004).

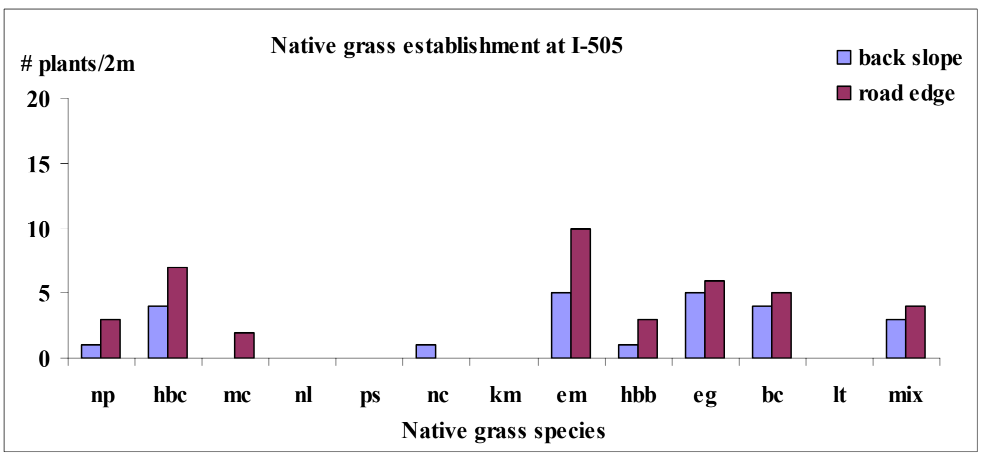


Figure 7. Establishment of native perennial grasses along the road edge and back slope of a Caltrans' highway right-of-way in Yolo County, CA (June 19, 2004).

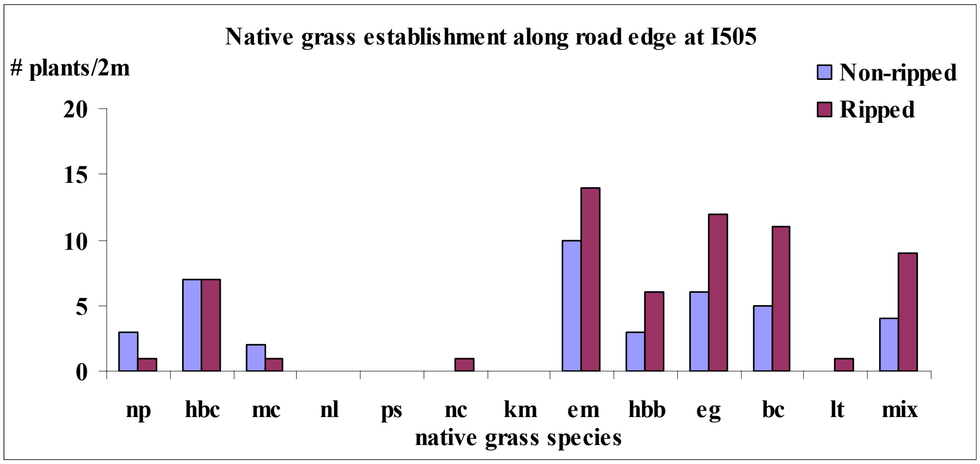


Figure 8. Establishment of native perennial grasses along the road edge of a Caltrans' highway right-of-way in Yolo County, CA using cultural treatments (June 19, 2004).

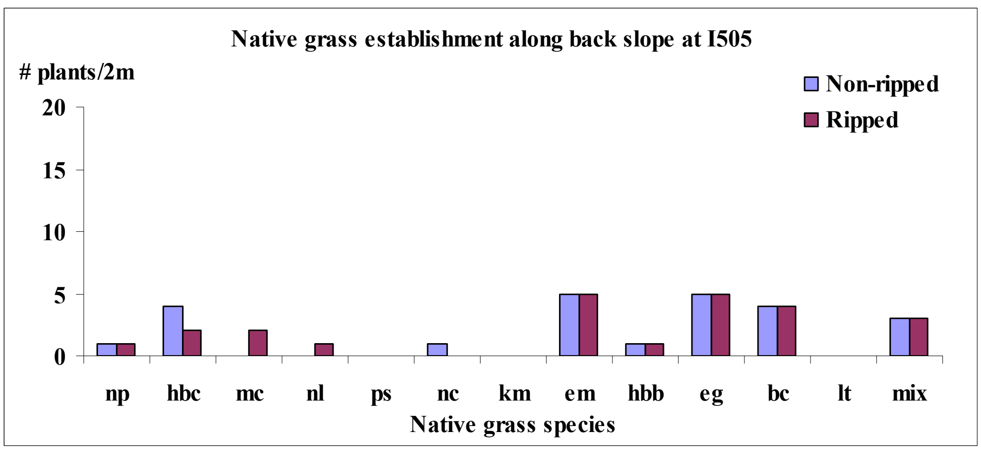


Figure 9. Establishment of native perennial grasses along the back slope of a Caltrans' highway right-of-way in Yolo County, CA using cultural treatments (June 19, 2004)

Conclusions

The study in 2002-2003 and 2003-2004 seasons gave a comparison of plant growth in bands of different species from the road edge, through the shoulder, swale and backslope areas. Due to road construction disturbance and seeding failure (fungal damping off during an early wet period) in 2002-2003, experiments were repeated at or near the original locations in 2003-2004. In 2003-2004, additional seedbed preparation operations were employed in the form of cultivation and deep soil ripping. Native grass combinations and individual species were planted similar in both years.

Establishment of native perennial grasses along the road edge and back slope was dominated by: *Hordeum brachyantherum californicum* (hbc), *Elymus multisetus* (em), *Elymus glaucus* (eg), *Bromus carinatus* (bc) and *Hordeum brachyantherum californicum* (hbc), *Elymus multisetus* (em), *Elymus glaucus* (eg), *Bromus carinatus* (bc), *Leymus triticoides* (lt), respectively. Other native perennial grass species with potential included *Nassella pulchra*, *Melica californica*, *H. brachyantherum* and *Disticulus spicata*, but these were not planted because seed was not available at time of planting.

Phases II, Part B: Site preparations (I-5 median trials)

Summary

The establishment of native perennial grasses within sections of California highway rights-of-way has the potential to maintain motorist safety and improve erosion control, while reducing the need for mowing and/or herbicide use. Prior to native perennial grass planting and establishment, specific cultural and chemical management treatments are needed to control non-native vegetation. Field studies were initiated at two sites (I-5 North and I-5 South) along Interstate 5 near Williams, California to determine the effect of burning, spraying, cultivating and species selection on the establishment of native perennial grasses and persistence of non-native annual vegetation. Two perennial grass mixes of species native to northern California were selected using local seed accessions. These include *Hordeum brachyantherum*, *Nassella pulchra*, *Elymus multisetus*, *Elymus glaucus* and *Poa secunda* in a "dry site" mix. A "wet site" mix included *H. brachyantherum*, *Leymus triticoides*, *E. multisetus* and *E. trachycalus* . Burning and spraying had the most significant effect on native grass establishment and non-native vegetation persistence at both sites. Burning increased *H. brachyantherum* and decreased *L. triticoides* establishment at both sites, but significantly lowered the persistence of non-native annual grasses and increased the persistence of non-native forbs at I-5 North. Non-native annual forb cover was significantly less in the clopyralid or chlorsulfuron herbicide regimes at I-5 South, while non-native annual grasses were reduced in the chlorsulfuron herbicide regime at I-5 North. Cultivation and species selection had no significant effect on native perennial grass establishment or non-native

annual vegetation persistence. A major limiting factor in the establishment of native perennial grasses is non-native vegetation, which can be easy to eradicate but often hard to manage, once highway rights-of-way have been planted with native perennial grasses. Cultural and chemical management techniques are necessary to improve the establishment success of native perennial grasses in the first two to five years after planting along highway rights-of-way in California.

A properly timed prescribed burn and two or more herbicide applications can provide good control of non-native annual vegetation in the year prior to and the first two years after drill seeding native perennial grasses. Following establishment, a less costly non-native control plan can be used to manage a highway right-of-way stand of native perennial grasses in northern California

Introduction

Native species are known to have slow germination, low seedling vigor and slow growth rates (Wrysinski 1999). Intensive management is required in the first few years to reduce competition from more vigorous, non-native annual species. Roadside projects that are funded for only a year of vegetation control often result in a return to the typical weedy vegetation. Anderson and Long (1999) found that weed control was 34% of the total cost for establishing four hedgerows that included native grasses in Yolo County. The other remaining costs were for site preparation, plants, grasses, pest control and water that were 8%, 20%, 18%, 4% and 16%, respectively, of the total revegetation cost. While management is important for establishing native grasses along roadsides, persistence of native plants after establishment occurs at some sites with even minimal management (O'Dell et al. 2007). In most instances, it is desirable to control weeds for an entire year or more prior to planting native species in order to reduce the weed seed bank (Kimball and Lamb 1999). Although time and resources may restrict this practice, it could mean the difference between success and failure for establishing a native plant community.

Roadsides can be difficult locations for establishing native plants. Site conditions that can limit the success of any revegetation effort include topography (steepness), soil (shallow, rocky, compacted, chemically imbalanced), climate (region, slope, aspect, seasonal variation) and existing vegetation (competition, invasion).

Figure 1. Restoration of severe slopes along highways in Northern California. Photos courtesy of S. L. Young.

Brooks (1995) found that plant cover on fill slopes was significantly higher than on cut slopes along highways in the Tonto National Forest in central Arizona. The revegetation treatments used for visual impact mitigation, as judged by the public, were unsatisfactory on 72% of the cut slopes evaluated. Poor establishment of vegetation on disturbed sites following surface applications like hydroseeding are often the result of improper species selection, seeding at an inappropriate time, and/or improper seed mixes, fiber and tackifier (Hallock et al. 2002) or soil preparation. The end result can sometimes be a reversion to weeds in the years following a planting if a one-step hydroseeding process is used (Ivanovitch 1975).

Studies have shown that relying solely on the seed bank for restoration of native vegetation is nearly impossible (Kalamees and Zobel 1998; Smith et al. 2002; Laughlin 2003), except in rare cases (Dreman and Shaw 2002). In order to overcome these problems, the solution was to prepare the site before planting and select a diverse range of plant species when seeding. Harper-Lore (1998) found that the specific cultural practices were site specific and included fertilization, maintenance, seeding rate (7 and 20 lbs./acre), site preparation and method of planting.

Other roadside studies have taken into consideration the effects of plant mixtures for establishing natives along roadsides (Anderson and Long 1999; Bugg and Brown 2000; M.C. Wolfe and Associates 1988). Both polycultures and monocultures were used by Bugg et al. (1997) to evaluate the establishment of non-native (desirable) and native perennial grasses. A mix of native grasses (polyculture) or single species (monoculture) was seeded into a rural roadside consisting of several topographic zones (*i.e.* road edge, swale, back slope) near the town of Winters, California. There was no significant difference in the amount of canopy cover for the polycultures on different topographic zones, but the biomass of the natives was less than for the non-natives. In the monocultures, California brome (*Bromus carinatus*), blue wildrye (*Elymus glaucus*), slender wheatgrass (*E. trachycaulus*), meadow barley (*Hordeum brachyantherum* ssp. *brachyantherum*), California barley (*H. brachyantherum* ssp. *californicum*), purple needlegrass (*Nassella pulchra*) and nodding needlegrass (*Nassella cernua*) had good canopy cover. Sheep fescue (*Festuca ovina*), squirreltail (*E. multisetus*), Idaho fescue (*Festuca idahoensis*), creeping red fescue (*F. rubra*) and pine bluegrass (*Poa secunda* ssp. *secunda*) had poor canopy cover. Polycultures performed well in all topographical zones, developing different community compositions. Monocultures with persistent stands were established for several species of the abovementioned species. Competition from resident vegetation (weeds) was found to influence establishment in both the polycultures and monocultures. They concluded from their study that, despite difficulties due to herbicides, persistent stands of local native species could be used along roadsides and other rights-of-way in the Sacramento Valley. They deem accessions retaining 25% or greater canopy cover in monocultures to be suitable for use in roadsides in the Sacramento Valley.

In another roadside study by Bugg and Brown (2000), existing stands of native grasses were used in combination with native forbs to control non-native (undesirable) species. The idea was to determine the establishment efficiency of local forbs and perhaps use the most robust and vigorous species as an alternative to conventional management (herbicides, mowing or blading) for controlling undesirable species. The methods employed included either seeding a mixture of forbs into both established native perennial bunchgrasses and tilled, bare ground or transplanting two perennial forbs into both established native perennial bunchgrass stands and tilled, bare ground. They found that Arroyo lupine (*Lupinus succulentus*), California poppy (*Eschscholzia californica*), chick lupin (*Lupinus microcarpus*) and Spanish clover (*Lotus tanacetifolia*) established well when seeded into tilled, bare ground, while annual tansy (*Phacelia tanacetifolia*) and the perennials, narrow-leaf milkweed (*Asclepias fascicularis*) and blue-eyed grass (*Sisyrinchium bellum*), were poorly established. None of the forbs that were tested established well by direct seeding into pre-existing stands of native perennial bunchgrasses. But, when transplants were inserted within plots of established native perennial bunchgrasses, their vigor was similar to those placed in tilled plots.

Figure 2. Roadsides in Northern California restored with native perennial grasses. Photos courtesy of S. L. Young.

Native perennial grasses have characteristics that allow for usefulness in highway rights-of-way locations. Aesthetic, ecologic and economic values make native perennial grasses a good decision for use in roadside situations. We have found little documented research that has provided guidelines for establishing native perennial grasses along roadsides in xeric regions similar to the Sacramento Valley in northern California. Therefore, the objectives of the current study are to determine the effectiveness of establishment methods for native perennial grass seed mixes along highway rights-of-way using various herbicide, cultivation and fire treatments to control weeds.

Methods for planting and establishing native perennial grasses

Dry site and wet site perennial grass mixes native to northern California were selected from a local seed and included *Hordeum brachyantherum*, *Nassella pulchra*, *Elymus multisetus*, *Elymus glaucus* and *Poa secunda* (included in a "dry site" mix) and *H. brachyantherum*, *Leymus triticoides*, *E. multisetus* and *E. trachycalus* (a "wet site" mix).

In the first year (summer 2003), half of each site was burned by wildfire. Both sites divided into different treatment plots and were then sprayed with glyphosate in the second year (March 2004), followed by cultivation (May 2004) and mowing (August 2004) to prevent weed seed production. Late season weeds (*i.e.* Russian thistle) were mowed and a final cultivation was conducted just before drill seeding the native grass mixes in November 2004. Following the drill seeding, glyphosate was applied to all plots at both sites to selectively control newly emerging weeds prior to the emergence of native grasses. In 2005, clopyralid and chlorsulfuron was applied over two-thirds and one-third of the plots, respectively, for selective weed control. The sites were mowed once or twice, depending on vegetative biomass, to reduce competition and maintain traffic safety. Except for the glyphosate, a similar herbicide regime was followed in 2006. Stand counts for native and non-native vegetation were conducted in May 2005 and 2006.

<u>Site and treatment description</u>

Two sites (I-5 South and I-5 North) were identified in the median of Interstate 5 on California Department of Transportation right-of-way in Colusa County, California (Figure 3). The I-5 South site was located from COL 5 mile 15.3 to 16.5, spanning the Husted Road overcrossing and the I-5 North site was located from COL 5 mile 31.1 to 32.9, spanning the Delevan overcrossing.

Figure 3. Field plots located in the median of I-5 in Colusa County, CA. Northern Site near Deleven Overcrossing from MP 31.1-32.9 (A). Southern Site near Husted Overcrossing from MP15.3 to 16.5 (B).

Recent wildfire that had began in both sites from vehicle spark, motorist's cigarette or something similar had been allowed to continue in order to uniformly reduce vegetative biomass that had been especially prone to fire danger. Cultural treatments included 1) burning to remove excess thatch and destroy weeds/seeds, 2) disc cultivation to control weeds and prepare the seedbed for drill seeding and 3) a combination of burning and cultivating to increase weed control and native grass establishment (Table 1). Mowing was conducted once in the spring and summer to maintain traffic safety for motorists, law enforcement officials and Caltrans maintenance personnel and to reduce fire risks. Chemical treatments to control weeds included 1) postemergence, non-selective (glyphosate), 2) postemergence, broadleaf selective (clopyralid) and 3) preemergence, non-selective (chlorsulfuron) (Table 1).

Native perennial grasses were drill seeded with a Truax Drill Seeder™ (Figure 4).

Figure 4. Drill seeding operation at I-5 North on November 23, 2004.

The native species selected were based on those most commonly found in the bioregions of northern and central California and most suitable for roadsides. Primary considerations included estimated height, tolerance to extreme weather and soil conditions, ability to establish and commercial availability. These species have been shown to be the most successful or have the most potential in revegetation/restoration projects, including roadsides. Native perennial grass species in the dry site mix consisted of *Hordeum brachyantherum*, *Nassella pulchra*, *Elymus multisetus*, *Elymus glaucus* and *Poa secunda*, while the wet site mix included *H. brachyantherum*, *Leymus triticoides*, *E. multisetus* and *E. trachycalus*.

Field layout

The median was 18 m from pavement edge to pavement edge. There were 12 m of vegetation in the center with 3 m sprayed or bladed on each side. The drill for seeding is 3 m wide. The wet site and dry site mixes will be drill seeded in alternating rows across the median leaving the 3 m sprayed edge on each side. The 3 m of non-planted area on each side was controlled for weeds and used for work space (data collection, herbicide application) to stay clear of on coming traffic. Schematically, from road edge to road edge within the median the distances will be: pavement, 3 m bladed area, 3 m dry site mix, 3 m wet site mix, 3 m dry site mix, 3 m wet site mix, 3 m bladed area, pavement. For the approximately 300 m at I-5 North, 4 replications of the 3 cultural treatments (burn, cultivate or burn+cultivate) that each contain 6 chemical treatments yield a total of 96 treatments or plots. The 96 plots spread evenly over the site (300/96) equal 30 m long (width equals 3 m). The 30 m long plots were seeded alternately with the dry site and wet site mixes (Figure 5). All plot treatments were replicated 4 times.

Table 1. Treatment applications prior to and following drill seeding of native perennial grasses in the median of I-5 in northern California.

Treatment	Cultural treatments*	Chemical treatments#
1	Burn, Cultivate, Dry site mix	glyphosate
2	Burn, Cultivate, Dry site mix	glyphosate+clopyralid
3	Burn, Cultivate, Dry site mix	glyphosate+clopyralid+chlorsulfuron
4	Cultivate, Dry site mix	glyphosate
5	Cultivate, Dry site mix	glyphosate+clopyralid
6	Cultivate, Dry site mix	glyphosate+clopyralid+chlorsulfuron
7	Burn, Dry site mix	glyphosate
8	Burn, Dry site mix	glyphosate+clopyralid
9	Burn, Dry site mix	glyphosate+clopyralid+chlorsulfuron
10	Burn, Cultivate, Wet site mix	glyphosate
11	Burn, Cultivate, Wet site mix	glyphosate+clopyralid
12	Burn, Cultivate, Wet site mix	glyphosate+clopyralid+chlorsulfuron
13	Cultivate, Wet site mix	glyphosate
14	Cultivate, Wet site mix	glyphosate+clopyralid
15	Cultivate, Wet site mix	glyphosate+clopyralid+chlorsulfuron
16	Burn, Wet site mix	glyphosate
17	Burn, Wet site mix	glyphosate+clopyralid
18	Burn, Wet site mix	glyphosate+clopyralid+chlorsulfuron

*Applications prior to seeding
#Application following seeding

\- - - - - I-5 northbound - - - - -

Bridge||----burned (1.5 km)---- | ---no burn (0.5 km)-----||Overpass||---no burn (1.0 km) ---

\- - - - - I-5 southbound - - - -

Figure 5. Burn treatments applied in year 1 (2002-2003) to the native grass experiment at I-5 North in Colusa county, California.

At I-5 South, the site is (160 m) and was broken up into 96 evenly spaced plots, similar to I-5 North. Each plot was 16 m long and 3 m wide. The same planting layout that was used for I-5 North was used for I-5 South (burn, cultivate, burn+cultivate) (Figure 6).

\- - - - - I-5 northbound - - - - -

Bridge||---no burn (0.8 km)--- ||Overpass|| ---burn (0.8 km)--- ||weed carcasses from burn

\- - - - - I-5 southbound- - - - -

Figure 6. Burn treatments applied in year 1 (2002-2003) to the native grass experiment in the median of I-5 Colusa county near Husted Road (southern site).

Field operations

Site preparations began in spring 2003 with prescribed burns and have continued with spraying, mowing, cultivation, drill seeding, spraying, plant density counts and mowing (Table 2). In the first year (summer 2003), a prescribed burn was conducted on half of each site. Both sites were sprayed with glyphosate in the second year (March 2004), followed by cultivation (May 2004) and mowing (August 2004) to prevent weed seed production. Late season weeds (i.e. Russian thistle) were mowed and a final cultivation was conducted just before drill seeding the native grass mixes in November 2004. Following the drill seeding, glyphosate was applied to all plots at both sites to selectively control newly emerging weeds prior to the emergence of native grasses.

Figure 7. Native perennial grasses. Emergence in the median of I-5 South on February 11, 2005 (A) and I-5 North on February 25, 2005 (B).

Following emergence of native perennial grasses (Figure 7), clopyralid and chlorsulfuron was applied over two-thirds and one-third of the plots, respectively, for selective weed control in early spring 2005. The sites were mowed once or twice, depending on vegetative biomass, to reduce competition and maintain traffic safety. Except for the glyphosate, a similar herbicide regime was followed in 2006. Stand counts for native and non-native vegetation were conducted in May 2005 and 2006. Transects for stand counts were located 10 feet apart within the plots.

Table 2. Operations conducted and observations at the sites throughout the native grass restoration project in the I-5 median of northern California.

Date	**Operation**	
	I-5 South	**I-5 North**
Spring 2003	prescribed burn	prescribed burn
Summer 2004	spray and mow	spray and mow
Fall 2004	weed cover data	weed cover data
Nov. 8, 2004	cultivation to 8 cm	cultivation to 8 cm
Nov. 23, 2004	drill seeding	drill seeding
Nov. 30, 2004	glyphosate applied	glyphosate applied
Dec. 3, 2004	straw applied (2240 kg/ha)	straw applied (2240 kg/ha)
Dec. 13, 2004	site monitoring begins	site monitoring begins
Dec. 22, 2004	first native grasses emerge; stand counts	--
Jan. 6, 2005	stand counts taken in 1 meter row	first native grasses emerge; stand counts
Jan. 19, 2005	stand counts in 1 m row samples	stand counts in 1 m row samples
Feb. 8, 2005	stand counts in 1 m row samples	stand counts in 1 m row samples
Mar. 9, 2005	clopyralid+triclopyr 2/3 of plots	clopyralid+triclopyr 2/3 of plots
May 16, 2005	transects to measure vegetation density	--
May 27, 2005	--	transects to measure vegetation density
Jun. 15, 2005	mowed in reverse at 10” height	mowed in reverse at 10” height
Oct. 4, 2005	mowed non-burned section at 6-10”	mowed non-burned section at 6-10”
Nov. 1, 2005	chlorsulfuron 1/3 of plots	chlorsulfuron 1/3 of plots
Dec. 9, 2005	weed cover data	weed cover data
Mar. 9, 2006	clopyralid 1/3 of plots	clopyralid 1/3 of plots
Apr 25, 2006	*N. pulchra* inflorescence	--
May 17, 2006	transects to measure vegetation density	--
May 24, 2006	--	transects to measure vegetation density
Jun. 16, 2006	mowed entire site at 8-10”	mowed entire site at 8-10”

Statistical analysis

The effect of year, burn, herbicide, cultivation and plant mix on native and non-native plant density was analyzed by comparing mean number of plants/cm and by evaluating the significance of means. The Ryan-Einot-Gabriel-Welsch (REGWQ) Multiple Range Test ($p = 0.05$) (SAS™ Version 8.2) was used for all statistical evaluation.

Results

Native grass establishment after two years

Native perennial grass seed that was drill seeded in November 2004 resulted in an average rate of 6 and 4 plants/cm at I-5 North and I-5 South, respectively, in 2006 (Table 3). From 2005 to 2006, mean plants/cm for individual native grass species, except *H. brachyantherum* and *E. multisetus*, increased significantly at I-5 North. At I-5 South, *N. pulchra* and *P. secunda* increased to 1.57 and 0.75 plants/cm, respectively, in 2006, which was a significantly greater density than in 2005. The density of non-native annual grasses increased significantly at both sites from 2005 to 2006. During the same period, non-native annual forb density declined to less than 1 plant/cm at I-5 South and increased to almost 2 plants/cm at I-5 North. Total non-native vegetation at I-5 North and I-5 South was 6 and 8 plants/cm, respectively, in 2006.

Table 3. Native grass establishment and non-native annual plant persistence two years after planting at I-5.

Site	Year	*H. brach.*	*E. mult.*	*N. pulc.*	*P. secu*	*L. trit.*	*E. glau./ trach.*	Native grasses	Annual grasses	Annual forbs
		mean plants/cm								
I-5 South	2005	2.34a	0.27a	0.61b	0.32b	0.30a	1.18a	5.01a	1.09b	4.18b
I-5 South	2006	0.52b	0.09b	1.57a	0.75a	0.44a	0.42b	3.81b	7.62a	0.54a
		mean plants/cm								
I-5 North	2005	1.48a	0.18a	0.59b	0.00a	0.00b	0.47b	6.32a	1.33b	0.59b
I-5 North	2006	1.13b	0.03b	1.27a	0.02a	2.41a	1.17a	6.02a	4.50a	1.65a

Values followed by the same letter within each column for each site (I-5 South or I-5 North) do not significantly differ.

Native grass establishment after burning

At I-5 North and South, total native plant density in the burned section was similar at less than 5 plants/cm, while the non-burned sections were also similar between sites at just over 4 plants/cm (Table 4). Individual native grass species that were most responsive to the burn treatment were *P. secunda*, which increased at I-5 South, and *L. triticoides,* which decreased at I-5 North and South.

Total non-native vegetation was 6.58 and 6.85 plants/cm in the burned and non-burned sections at I-5 South, respectively, while plant density was 4.32/cm in the burned and 3.75/cm in the non-burned sections at I-5 North. Non-native annual grass density was significantly less in the burn section of I-5 South, but significantly greater in the burn section of I-5 North. Non-native annual forb density was significantly greater only in the non-burned section of I-5 North.

Table 4. The effect of burning on native plant establishment and non-native annual plant persistence at I-5.

Site	Burn	*H. brach.*	*E. mult.*	*N. pulc.*	*P. secu*	*L. trit.*	*E. glau./ trach.*	Native grasses	Annual grasses	Annual forbs
		mean plants/cm								
I-5 South	Burn	1.56a	0.15a	0.96a	0.99a	0.19b	0.81a	4.67a	4.06b	2.52a
I-5 South	No Burn	1.30a	0.21a	1.21a	0.08b	0.55a	0.79a	4.14a	4.65a	2.20a
		mean plants/cm								
I-5 North	Burn	1.86a	0.11a	1.07a	0.02a	0.55b	0.89a	6.64a	3.62a	0.70b
I-5 North	No Burn	0.75b	0.10a	0.79a	0.00a	1.86a	0.75a	5.70b	2.21b	1.54a

Values followed by the same letter within each column for each site (I-5 South or I-5 North) do not significantly differ.

Native grass establishment after spraying with herbicides

Total native grass density was similar (4.4 plants/cm) for the three herbicide regimes at I-5 South, even though non-native annual vegetation was significantly higher in the glyphosate regime (Table 5). For individual native grass species, only *E. glaucus/trachycalus* was significantly less in the glyphosate regime compared to the higher intensity herbicide regimes (clopyralid and chlorsulfuron). Similarly, at I-5 North, in addition to *E. glaucus/trachycalus*, the plant densities for *H. brachyantherum* and *E.*

multisetus were significantly less in the glyphosate regime compared to clopyralid and chlorsulfuron. At I-5 North, total native grass density was 5.02, 4.54 and 3.55 for chlorsulfuron, clopyralid and glyphosate herbicide regimes, respectively. Only the non-native annual grass density was significantly lower in the chlorsulfuron herbicide regime. Total non-native plant density was 3.67, 4.4 and 4.06 for chlorsulfuron, clopyralid and glyphosate herbicide regimes, respectively, at I-5 North.

Table 5. The effect of herbicide regime on native plant establishment and non-native annual plant persistence at I-5.

Site	Spray regime	*H. brach*	*E. mult.*	*N. pulc.*	*P. secu*	*L. trit.*	*E. glau./ trach.*	Native grasses	Annual grasses	Annual forbs
		mean plants/cm								
I-5 South	Ru+ Tr+Te	1.49a	0.18a	1.02a	0.50a	0.30a	0.93a	4.34a	4.32b	2.01b
I-5 South	Ru+Tr	1.54a	0.22a	0.93a	0.56a	0.34a	0.81a	4.38a	4.84a	1.79b
I-5 South	Ru	1.26a	0.15a	1.31a	0.56a	0.48a	0.65b	4.51a	3.91b	3.28a
		mean plants/cm								
I-5 North	Ru+ Tr+Te	1.3ba	0.12a	1.26a	0.00a	1.31a	1.01a	7.02a	2.62b	1.05a
I-5 North	Ru+Tr	1.54a	0.16a	0.78a	0.01a	1.13a	0.92a	6.60a	3.31a	1.09a
I-5 North	Ru	1.05b	0.04b	0.75a	0.03a	1.14a	0.54b	4.89b	2.83ba	1.23a

Values followed by the same letter within each column for each site (I-5 South or I-5 North) do not significantly differ.

Native grass establishment with dry site and wet site seed mixes

Native grass density in dry site and wet site mixes were not significantly different for individual species, except for *H. brachyantherum* at I-5 South (Table 6). Only non-native annual forbs were significantly lower in the dry site mix at I-5 South.

Table 6. The effect of planting mix on native plant establishment and non-native annual plant persistence at I-5.

Site	Seed mix	*H. brach.*	*E. mult.*	*N. pulc.*	*P. secu*	*L. trit.*	*E. glau./ trach.*	Native grasses	Annual grasses	Annual forbs
		mean plants/cm								
I-5 South	Dry	1.62a	0.19a	1.03a	0.42a	0.33a	0.87a	4.31a	4.41a	1.92b
I-5 South	Wet	1.24b	0.17a	1.14a	0.65a	0.41a	0.73a	4.50a	4.31a	2.81a
		mean plants/cm								
I-5 North	Dry	1.38a	0.12a	0.85a	0.02a	1.36a	0.84a	6.64a	6.40a	1.06a
I-5 North	Wet	1.23a	0.09a	1.01a	0.00a	1.05a	0.80a	5.70b	5.94a	1.19a

Values followed by the same letter within each column for each site (I-5 South or I-5 North) do not significantly differ.

Discussion

After three years of cultural and chemical management, we found native perennial grasses most abundant in sites that had been burned once and sprayed at least twice. Within the time of this study, seed mix had little impact on the density and diversity of native perennial grass establishment. We also found that deep disc cultivation was not needed to establish native perennial grasses on these two sites, at which soils prior to road construction had been used for farm production.

Figure 8. Native perennial grasses establishing at I-5 North on June 3, 2005. Elymus multisetus (A). E. multisetus, N. pulchra, E. glaucus, E. trachyc., H. brach.(B).

From 2005 to 2006, a significant change occurred in the composition of non-native vegetation from annual forb dominated at I-5 South or low annual grass density at I-5 North to predominately annual grasses at both sites. A number of factors could have led to the large increase in non-native annual grasses including broadleaf selective herbicide, lack of residual affect from burning, shift in competition from forb-types to grass-types and herbicide resistant annual ryegrass (*Lolium multiflorum*). Since native perennial grasses have been established, a properly timed prescribed burn would probably help to kill new and any recently deposited non-native annual grass seed.

Individual native grass species have established at different densities (see Figure 8). *Nassella pulchra* increased to greater than 1 plant/cm after two years, demonstrating its colonizing characteristics especially in non-crop areas with substandard growing conditions. *Leymus triticoides*, a common wet site species, increased in density at I-5 North, which had soil with a higher clay content (data not shown), and also showed establishment potential in the wetter areas of I-5 South over the two year period. The closely related species of *E. glaucus* and *E. trachycalus* increased in density at I-5 North, but declined at I-5 South, most likely because of competition from ryegrass and the coarse soils with lower water holding capacity.

Burning and herbicide were the most effective cultural and chemical treatments for establishing native perennial grasses. The treatments reduced both vegetative biomass and more importantly, seed deposited to the soil seed bank (data not shown). With the exception of *L. triticoides*, the burn either improved or did not significantly change native grass establishment. High densities of non-native annual vegetation are known to compete with native perennial grasses by consuming resources at a greater rate or a total overall quantity. Most of the non-native annual vegetation was reduced by burning, except for non-native grasses at I-5 South. The effects of burning (lower vegetative biomass and reduced soil weed seed banks) are short-lived in areas with high potential for disturbance and re-seeding from nearby non-native annual vegetation. The medians of many highways in northern California run through agriculture or other managed ecosystems that are potential seed sources. Additionally, highway medians are notorious for disturbance from automobiles, maintenance personnel and wildlife. The combination of disturbance and a nearby non-native annual vegetation seed source is an effective combination for revegetating with exotic, invasive species. We would not expect the effects from the burn conducted in summer 2003 to remain effective in 2006 and this influenced non-native density at the two sites, with I-5 South at a lower level than I-5 North. Nevertheless, the burn was still important in the establishment of native perennial grasses at these two sites (see Figures 9 and 10).

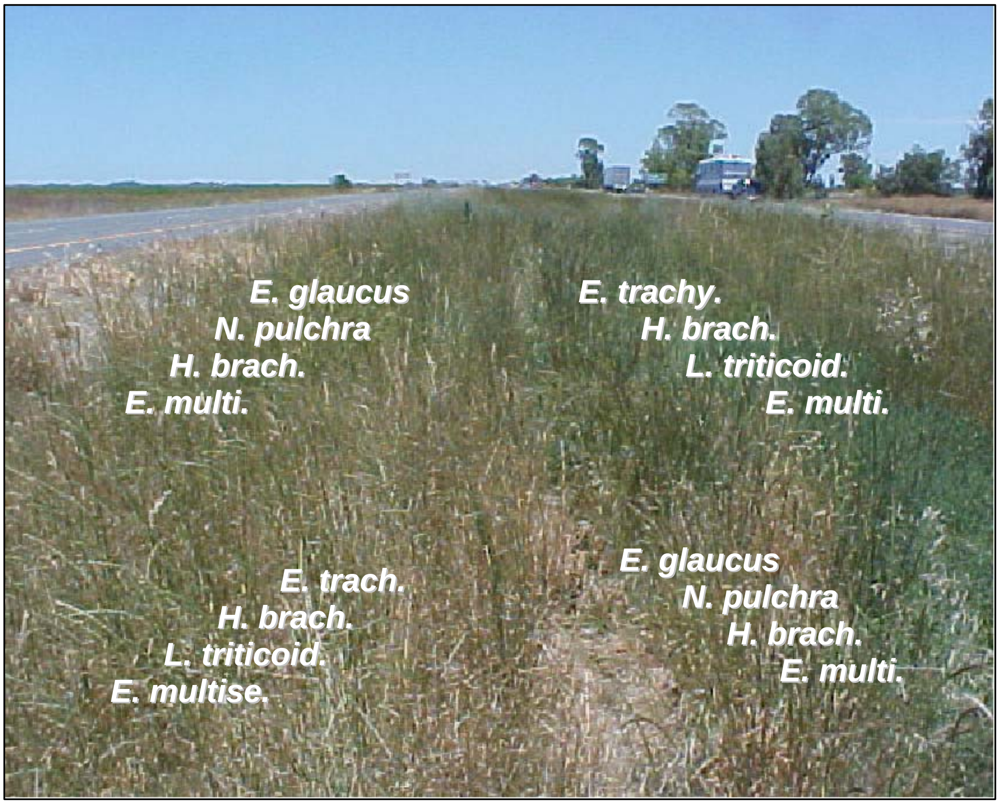


Figure 9. An established stand of native perennial grasses in a previously burned section of the median of I-5 North, Colusa County, CA on June 3, 2005.

Figure 10. An established stand of native perennial grasses in a previously burned section of the median of I-5 South, Colusa County, CA on May 9, 2006.

Herbicide regimes with two or more applications (glyphosate + clopyralid or glyphosate + clopyralid + chlorsulfuron) increased the plant density of most individual native perennial grass species with the exception of *Leymus triticoides* at I-5 South and *Poa secunda* at I-5 North. Non-native annual grasses increased at I-South with clopyralid and chlorsulfuron herbicide regimes because 1) the initial glyphosate application in fall 2004 was effective only on post emergence plant material; 2) clopyralid is selective for broadleaf control and 3) the efficacy of chlorsulfuron applied preemergence in fall 2005 may have been less than 100%, especially for a heavy infestation of annual ryegrass. At I-5 North, non-native annual grasses were reduced with the chlorsulfuron herbicide regime because of greater competition from native grasses (5.02 plants/cm at I-5 North versus 4.42 plants/cm at I-5 South) and no significant change in non-native annual forb density from glyphosate to chlorsulfuron herbicide regimes. The growth form of the dominant native grasses at each site could change the level of competition with non-native annual vegetation. For instance, *Leymus triticoides*, *E. glaucus*, *E. trachycalus* and *N. pulchra*, which can have tall shoots and dense leaves, were the more prevalent native grasses at I-5 North, while the lower growing and sparsely vegetated *H. brachyantherum*, *E. multisetus* and *Poa secunda* were greater in abundance at I-5 South. The impact of growth form on competition between plant species has been studied on an individual basis, but interactions at large scales are less known.

The two planting mixes (dry site and wet site) had no significant impact on native perennial grass establishment or non-native annual vegetation persistence. Similarly, cultivation lacked significance in improving native grass establishment (data not shown). The classification of a native perennial grass species as preferring 'wet site' or 'dry site' locations is based on observations of field response at different sites, and the plant's range of tolerance was evidently large enough to span those conditions that occurred in this present study. We found native grasses with both classifications growing in all areas of our sites, whether wet site or dry site locations.

Conclusions

Burning and spraying had the most significant effect on native grass establishment and reducing non-native vegetation persistence at both sites. Burning increased *H. brachyantherum* and decreased *L. triticoides* establishment at both sites, but significantly lowered the persistence of non-native annual grasses and raised numbers of forbs at I-5 North. Non-native annual forbs were significantly less in the clopyralid or chlorsulfuron herbicide regimes at I-5 South, while non-native annual grasses were reduced in the chlorsulfuron herbicide regime at I-5 North. Cultivation and species selection had no significant effect on native perennial grass establishment or non-native annual vegetation persistence. A major limiting factor in the establishment of native perennial grasses is non-native vegetation, which can be easy to eradicate initially, but is often hard to manage once highway rights-of-way have been planted with native perennial grasses. Cultural and chemical management techniques are both necessary to improve the establishment success of native perennial grasses in the first two to five years after planting along highway rights-of-way in California.

The main factor that inhibits the establishment of native perennial grasses along highway rights-of-way in California is the persistence of non-native vegetation. Similar to croplands, rights-of-way are infested with weeds that reduce production; in this case production of native perennial grasses. An assertive approach to weed control is required to prepare the soil, plant, grow and harvest an agricultural crop. A similar approach to the management of weeds is required in order to successfully establish a roadside stand of native perennial grasses. A properly timed prescribed burn and two or more herbicide applications can provide good control of non-native annual vegetation in the year prior to and the first two years after drill seeding native perennial grasses. Following establishment, a less costly non-native control plan can be used to manage a highway right-of-way stand of native perennial grasses in northern California, as discussed in the next section below.

Phase III: Maintenance procedures for improving native grass performance

Summary

A well-maintained stand of native perennial grasses along highway rights-of-way

in northern California can have desirable environmental, economic and aesthetic qualities. The health and density of a stand of native perennial grasses can decline rapidly when invasive, non-native annual species are allowed to establish. Restoring roadside native perennial grass stands regenerates these benefits. A field study was conducted along State Route 20 near Williams, California to determine the effect of mowing, burning or spraying alone and in combination on an existing stand of native perennial grasses with dense populations of non-native annual species, especially *Centaurea solstitialis*. *Elymus glaucus* and *Nassella pulchra* had been established at the site in fall 2000. Following establishment, the entire site was sprayed once with clopyralid in spring 2001 and the road edge maintained by periodically spraying glyphosate. The entire site was mowed in late winter of 2004 to clear excess vegetation and debris. Vegetation control treatments were applied in spring 2004. After one year, *C. solstitialis* was no longer present in spray+mow, spray+burn and spray+mow+burn treatments and in two years, *C. solstitialis* was eliminated in all treatments except burning and native perennial grasses were dominant where management included at least two vegetation control techniques. As a negative control, untreated plots continued to be dominated by *C. solstitialis*. At the end of two years, the native perennial grass density and percentage with green foliage was greatest in the burn+spray, mow+spray+burn and mow+spray. A combination of well-timed vegetation control techniques was necessary to eliminate *C. solstitialis* and other non-native annual species from this stand of native perennial grasses in this highway right-of-way location in northern California.

Introduction

An established stand of native grasses along roadsides has been shown effective in controlling non-native weeds, increasing native habitat and reducing erosion (Bugg et al. 1997). In general, the value of native species increases due to their many benefits (see Table 1). Along roadside rights-of-way, vegetation has direct and indirect impacts on the environment, economic resources and aesthetic quality. After native perennial grasses are established, weed populations are often decreased. Additionally, soil sediment transport declines with increasing numbers of native perennial grasses, either because of their thatch or mulch formation or because of their deeper soil development, compared to annual grasses. For roadside locations with some soil moisture through summer, native grasses remain partially green and the flash point for fires is reduced. Alternatively, for sandy soils, native plants with low stature and summer dormancy will produce less fuel loads for fire situations. Indirectly, native perennial grass establishment reduces maintenance costs as the need for herbicide, mowing and other weed control measures is reduced. The reduction in non-native plant populations will disrupt weed corridors along roadsides and provide an alternative and more desirable view for motorists.

Losses associated with the spread of non-native species

Many non-native species have invasive habits; they have a propensity to move in, become established and propagate profusely, developing into a low diversity stand that crowds out many other species, natives in particular. In addition to reduced diversity, infestations of non-native plants along roadsides can threaten rare and endangered species, reduce wildlife habitat and forage, alter fire frequency, increase erosion and deplete soil moisture and nutrient levels (DiTomaso 2000). Yellow starthistle is one of many non-native plants that have had a large impact on a single ecosystem, such as the once productive grasslands of California (Pimentel et al. 2005). In addition to the loss of native species, the spread of non-native species has an impact on outdoor recreation activities such as fishing, hunting, hiking, wildlife viewing and water-based recreation (Eiswerth et al. 2005).

The spread of invasive species is thought to be expedited by roadways and railways. Hansen and Clevenger (2005) found that transportation corridors can have a significant affect on plant species composition, especially the spread and establishment of invasive non-native species. They suggest that corridor edges and grassland habitats act as microhabitats for non-native species, especially if they are disturbed. Sixteen year old revegetation sites along roads and pipelines near the Homestake-McLaughlin gold mine in northern California had proliferations of *Bromus madritensis* ssp. *madritensis*, *Bromus hordeaceus* and *Lolium multiflorum* (Williamson and Harrison 2002). Williamson and Harrison (2002) found propagule addition and disturbance to be most important in promoting the establishment of relatively nonaggressive non-native species, which they cautioned could eventually invade and have a wider range of establishment.

Cost for control of non-native species

Once non-native species have become established, the cost for control increases dramatically. Weed control costs for noxious weeds in the United States is estimated at about $5 billion/year (Babbitt, B. 1998). Westbrooks (1998) estimates the cost to control invasive plants by state DOTs to be at least $1 million per year. Regardless of the dollar figure, the cost to control non-native, invasive species is a significant financial drain on most land management agencies, both public and private. Duncan et al. (2004) summarized the environmental and economic impacts of 16 non-native, invasive plants in the United States. The current rate of spread for downy brome, musk thistle, yellow starthistle, Canada thistle, perennial pepperweed and medusahead, weeds commonly found along Department of Transportation (Caltrans) rights-of-way in California, is an average between 10-24% per year in the United States.

A concerted effort to control the spread of non-native, invasive species along roadsides using current practices would increase maintenance costs significantly. Motorists across the United States are concerned about roadside vegetation, but their feelings about the contribution of additional resources is less clear (Wolf 2003). In northern England, Akbar et al. (2003) found in a survey of road users that a majority of the respondents did not support higher expenditures to create visually attractive roadside vegetation. The present high cost of roadside non-native species management compared to the future savings of reduced management with native species was not included in the survey.

The support by the public of DOTs to use additional dollars to control non-native, invasive species on roadsides with current techniques is not likely to occur in the near future. Farmers, which are some of the biggest neighbors to roadsides in California, often rank weeds as the number one pest problem with Caltrans as the number one pest (personal communication).

Public perception of roadsides

Many roadside revegetation projects are conducted in response to public interest (FHWA 2005). Motorists and neighboring land owners are not well informed as to the objectives of roadside revegetation, other than to maintain safe traveling conditions. Little research exists on the impacts of the aesthetics of roadside vegetation on the road user. Wolf KL (2003) conducted a survey of motorists opinions about roadside features in the United States and found that vegetation views rated highest out of five categories, indicating that quality landscape is valued by the public. Under suitable uses for roadside lands, respondents ranked "managed to protect native plants" the highest out of four choices in the category of ecological functions. A questionnaire survey by Akbar et al. (2003) revealed that a majority of the respondents described the roadside vegetation as unpleasant and drab. The respondents preferred native grass species with flowering herbs near the road and trees further away.

Figure 1. Public signage pertaining to roadside native vegetation. Photo courtesy of S.L. Young

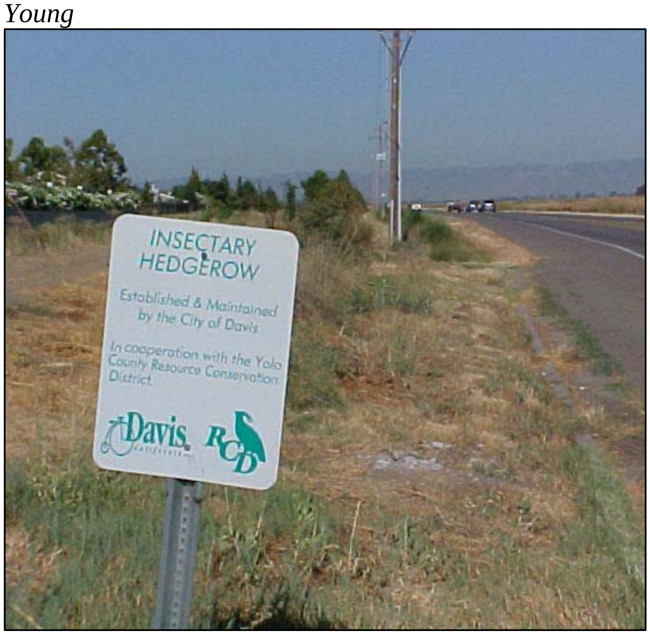


Figure 2. Public signage pertaining to roadside native vegetation. Photo courtesy of S.L. Young

It is clear from environmental, economic and aesthetic factors that there is a need to change the composition of the vegetation that currently dominates many roadsides. In northern California, the lack of native species and the cost to control non-native species are points of contention between public and private stakeholders, creating a demand for more efficient and cost effective management strategies.

Reevaluating roadside management

Strategic management along roadsides involves several phases, beginning with identification, followed by control and ending with management (Sheley 2004). An integrated roadside vegetation management (IRVM) plan requires sustained effort, constant evaluation and adoption of improved strategies. An established stand of native perennial grasses has numerous benefits (Table 1), but conversion from annual to perennial grasses has several management costs, such as intensive up-front weed control, and reduced but periodic and time-critical weed control later. The long term management costs are expected to be reduced relative to the need for complete and repeated mowing of the state's right of way. Limited research has been conducted on the long-term maintenance of native plant communities along roadsides (Brown and Rice 2001). Weed control is the primary activity required in maintaining native plant stands (Anderson 1999; Anderson and Long 1999; Brown and Rice 2001; Bugg et. al. 1997; CNGA and CCIA 2001; Kimball and Lamb 1999; Wrysinski 1999). Wrysinski (1999) suggests weed control maybe required for up to six years after planting depending on native grass species, site conditions and prior weed levels. Integrating different vegetation management options into a strategic plan that includes native perennial grasses can be low-cost and, with proper timing of control treatments, very effective in maintaining native plants at a desired height and biomass level (Wrysinski 1999).

Table 1. The benefits of establishing native perennial grasses in roadside rights-of-way.

1) Prevention of new weed species from becoming established.
2) Reduced weed corridors into native areas.
3) Reduced long-term maintenance compared to current practices.
4) Reduced use of herbicides.
5) Reduced flash point for fires by the presence of green plant material, less canopy density and/or low-growing stature.
6) Reduction in current weed populations.
7) Increased plant species diversity.
8) Increased control of sediment transport (erosion).
9) Increased duration of green plant tissue during summer and fall.
10) Improved or changed aesthetic value that more closely matches pre-invasion landscapes in California.

The goal of this phase of the study was to document how the impacts of management intensity affect native and non-native plants in an existing stand of native perennial grasses. The objectives were to 1) determine the effect of high and low intensity management on the cover of non-native and native plants and 2) measure the density and dormancy/activity of native perennial grasses late in the season when suppression of certain weeds is needed.

Methods of integrated vegetation management

The study site was located in Colusa County about 20 miles west of Williams, CA along State Route 20 mile 9.1 (Figure 3). The site was revegetated in 2000 with native perennial grasses by Caltrans following a highway widening project that began in 1998. The stand of native perennial grass, dominated by *N. pulchra* and *E. glaucus*, was sparse by 2004 and under pressure from *C. solstitialis* and other non-native invasive weeds which border the site on three sides.

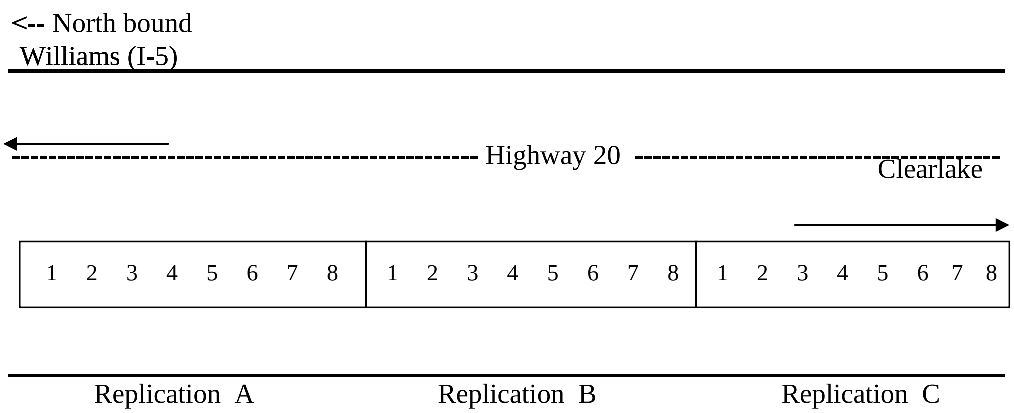


Figure 3. Study site located on the west side of the highway. The entire site is 30 feet wide x 576 feet long (for 3 reps, plots size = 30 feet x 24 feet). The beginning of the site is located at PM 9.0 (just past dirt pullout/oak trees), extending south for approximately 0.1 miles.

Timeline of treatment applications and plant response: 2004

Plots were established on February 27 along an approximately 600 foot stretch of roadside adjacent to the highway (Figure 4).

Figure 4. Location of native grass restoration project along Highway 20, Colusa County, CA (MP 9.1).

The plots are 24 feet long and extend 30 feet away from the road edge. The experimental design is randomized complete block with 8 treatments and 3 replications. Treatments consisting of low (burn, mow, spray or nothing) and high (burn+mow, mow+spray, spray+burn or burn+mow+spray) intensity management were applied as needed to control yellow starthistle and stimulate native perennial grass growth (Table 2).

Table 2. Management regimes for restoring an established stand of native perennial grasses infested with *C. solstitialis*.

Low intensity treatments:	High intensity treatments:
1 – Burn	5 – Burn + mow
2 – Mow	6 – Mow + spray
3 – Spray	7 – Burn + spray
4 – Nothing	8 – Burn + mow + spray

The entire site was mowed to a height of approximately 8 inches on March 8, 2004 to reduce standing dead plant material from previous years and improve spray efficacy the first year. Yellow starthistle was in the rosette stage and less than 8 inches in height while clumps of *N. pulchra* had new growth approximately 10-12 inches on March 22. On April 7 cover of native perennial grasses and yellow starthistle was measured using a 0.5 m^2 quadrat. Sampling was conducted at three locations within each plot that were equidistant from both plot edge and between locations. *Centaurea solstitialis* and native perennial grass density was determined by estimating cover of each species with the quadrat (0 = not present, 100 = complete cover).

The spray treatment was made on April 23. Transline® (clopyralid) was applied at 8 ounces per acre using a backpack mounted sprayer that was calibrated to deliver 1.5 gallons spray solution per plot. By May 14, *N. pulchra* had gone to seed and the inflorescence of *E. glaucus* was in the pollination stage or later. *Centaurea solstitialis* was beginning to bolt in the non-spray treated plots.

The first mow treatment was applied on May 19. Low and high intensively managed plots were mowed to a height of 6 to 8 inches when most of the *C. solstitialis* had reached the early flowering stage (less than 5% of the population flowering). *Centaurea solstitialis* is best controlled by mowing when plants just begin to flower (Benefield et al. 1999). The mow and mow+burn plots were mowed a second time on June 16. Because a range of plant growth stages can exist in one population, a complete kill was not obtained with the May 19 mowing. Control of *C. solstitialis* in the mow+spray plots was being achieved more by the spray and less by the mow.

On July 27 the mow and mow+burn plots were mowed a third time to control *C. solstitialis* before full flowering. The spray+mow and spray+mow+burn treatments were mowed selectively to control individual *C. solstitialis* plants. The burn treatment was applied on August 25. The timing of the burn was later in the season due to higher priority commitments by California Department of Fire Protection (CDF).

The native perennial grasses were producing green shoots in the burn, mow+burn, spray+burn and spray+mow+burn on September 29 (Figure 5).

Figure 5. Elymus glaucus regrowth prior to fall rain in a burn treatment at Highway 20, Colusa County, CA on October 3, 2005.

A few *C. solstitialis* plants were flowering in the mow treatments and were mowed off before full flowering. By December 19, *N. pulchra* was growing in both treated and untreated plots.

Timeline of treatment applications and plant response: 2005

A visual observation of each plot was made on March 9 (data not shown). In addition to yellow starthistle, other non-native annual forbs were present in both treated and untreated plots including lupine, fiddleneck, clover and filaree. Plant density was measured on April 11 by estimating percent cover using a 0.5 m^2 quadrat. This same technique was used on April 7 of the previous year.

The spray treatment was made to spray, spray+mow, spray+burn and spray+mow+burn plots on April 22, similar to 2004 except that Transline was applied at 6 ounces per acre. *Centaurea solstitialis* was either in the rosette or early bolting stage of development. On May 13 *E. glaucus* and *N. pulchra* were green and robust, but not flowering yet. The growth of *C. solstitialis* in the treated plots was not as robust as in 2004. On June 3 *C. solstitialis* was in the rosette to pre-bloom growth stage. The first mow treatment was applied on June 15 in a similar manner as the previous year. *Centaurea solstitialis* was 10 to 24 inches tall and less than 5% of the population was in the flowering stage. Native perennial grass foliage was green and 2.5 feet tall and inflorescence was near or past the seed dispersal stage.

On June 17 *C. solstitialis* plants were mainly green due to the late and excessively wet spring. The prescribed burn was conducted in the burn, spray+burn, mow+burn and spray+mow+burn plots on June 27. An early season burn was applied due to the availability of CDF and the increased chance for control of non-native annual vegetation. The second mow treatment was made on July 29. In plots that had high intensity management, few *C. solstitialis* plants remained due to the spray or burn and a selective mowing was applied. In the less intensively managed plots, the mow treatment was applied similar to the previous year.

Native perennial grasses and non-native vegetation were counted on October 13. In each plot, plant density was determined using quadrats and whole plots were used for counting native perennial grasses.

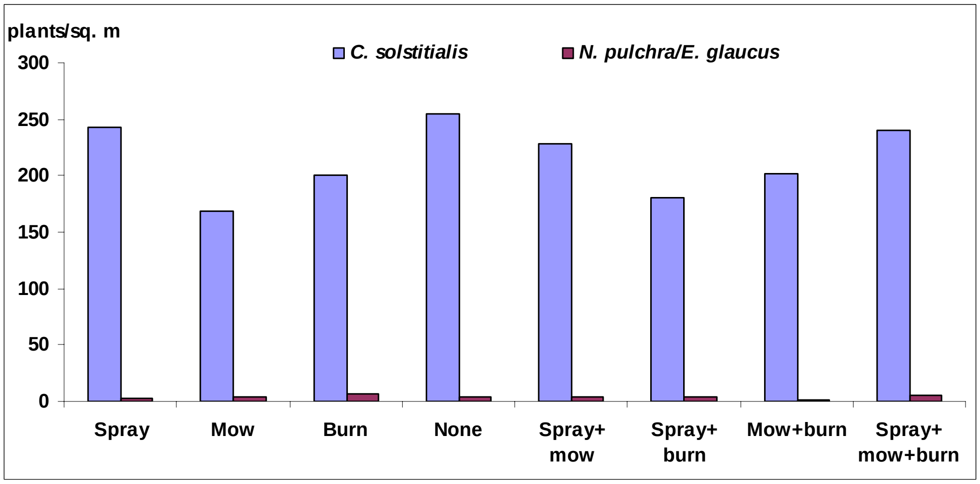
Timeline of treatment applications and plant response: 2006

On March 9 visual observations of vegetation growth was made for each plot (data not shown). Similar to the previous year, lupine, clover, fiddleneck, filaree and many non-native annual grasses were present. Plant density was measured, similar to the previous two years, on April 18 by estimating percent cover using a 0.5 m^2 quadrat. Except for the untreated plots, *C. solstitialis* populations had declined to low levels, especially in the spray, spray+mow, spray+burn and spray+mow+burn plots. Therefore, with almost no *C. solstitialis* plants present in the spray plots, the application of Transline was omitted in 2006. In studies by DiTomaso et al. (2000), they have shown that two consecutive years of Transline® can almost eliminate *C. solstitialis*. The first mow treatment was applied to mow, spray+mow, mow+burn and spray+mow+burn plots on June 27. The growth stage of *C. solstitialis* was in the early flowering stage.

Plant density was measured on October 2. A single mow treatment and no burn or spray treatment was done to simulate the effects of a year when there is a lapse in management. Long-term maintenance of an established stand of native perennial grasses may include a year of neglect, loss of interest or change of management personnel. This additional component in managing an established stand of native perennial grasses could be invaluable in determining the overall sustainability of native perennial grasses along roadsides.

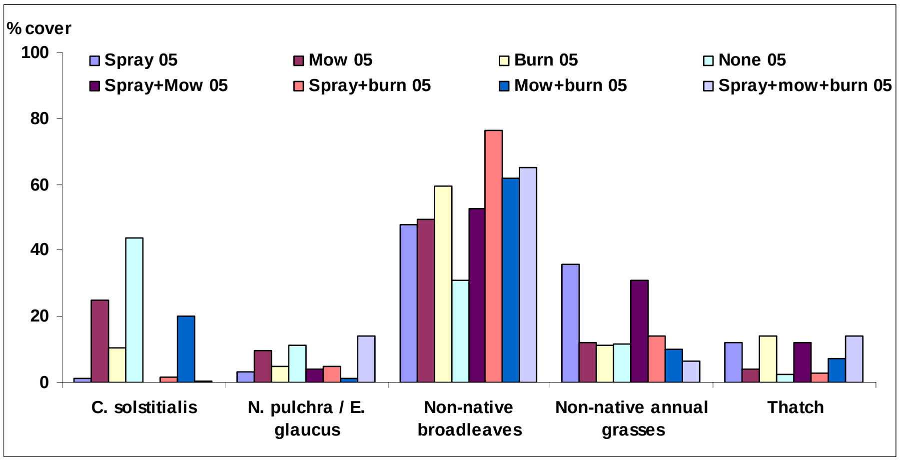
Results

The site was dominated by *C. solstitialis* in spring 2004, after a poor initial establishment of native grasses and prior to treatment applications (Graph 1). A few native perennial plants were present in all treatments, except the mow+burn.



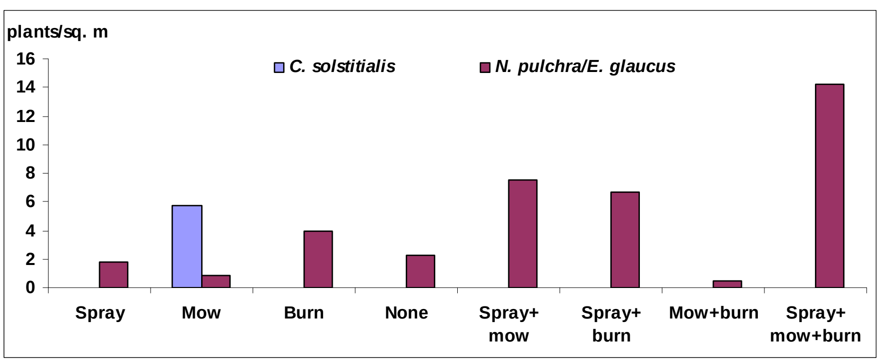
Graph 1. Density of C. solstitialis and native perennial grasses along State Route 20 near Williams, CA prior to treatment applications were initiated on April 12, 2004.

In spring 2005, cover of *C. solstitialis* was greatest in the mow, mow+burn and none treatments, while plots receiving spray and a late season burn had less than 11% cover (Graph 2). With the exception of the None treatments, non-native broadleaves were dominant for all treatments after a year of management. Spraying a selective herbicide was least affective at controlling non-native annual grasses. After one year, the spray+mow+burn treatment was most effective for increasing cover of *N. pulchra* and *E. glaucus*.



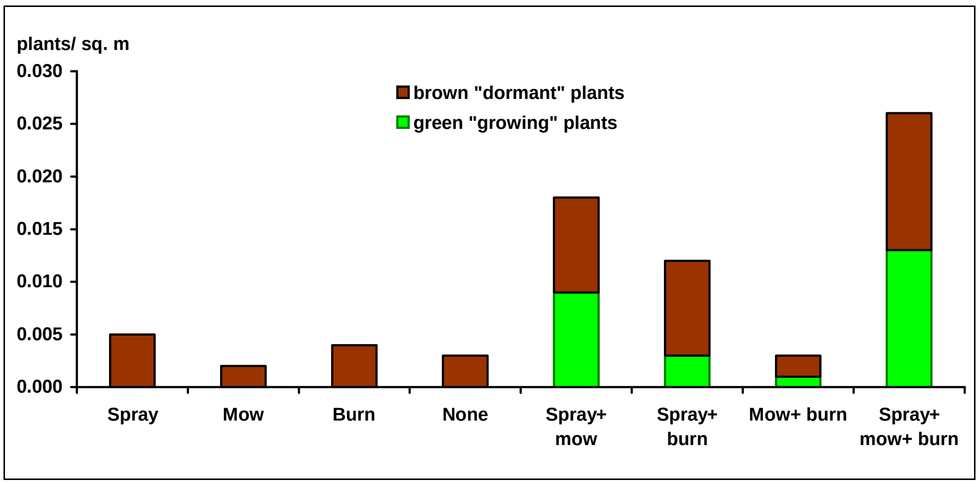
Graph 2. Vegetation cover of plants along State Route 20, near Williams, CA on April 7, 2005, following a year of treatments and growth.

At the end of the second year (2005), *C. solstitialis* populations were zero for all treatments, except mowing (Graph 3). The mow and mow+burn had the lowest number of native perennial grass plants per square meter (less than 1). The spray+mow+burn had almost 15 *N. pulchra* and *E. glaucus* per square meter and the high intensity management regimes, except for mow+burn, had higher numbers of native perennial grasses than the low intensity regimes.



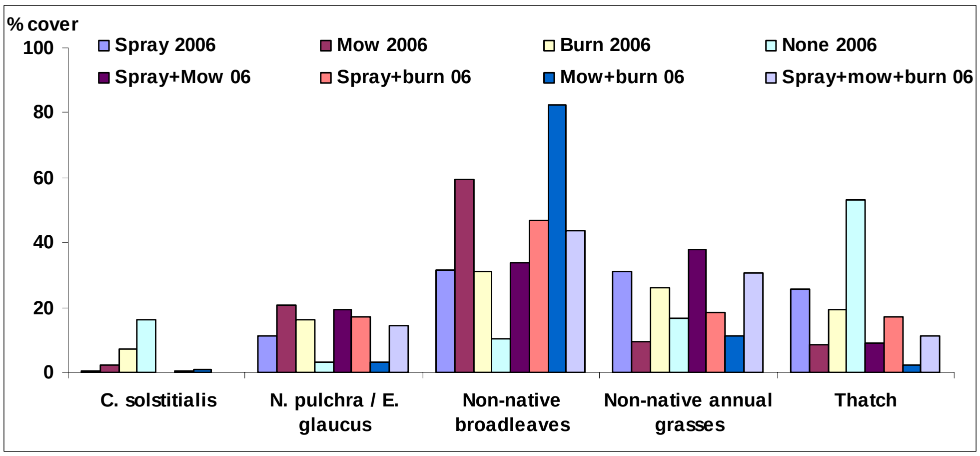
Graph 3. Density of C. solstitialis and native perennial grasses along State Route 20 near Williams, CA on October 13, 2005 after two years of treatments.

Dormancy of native perennial grasses occurred mid to late season and was characterized by browning of leaves and shoots. Native perennial grasses can break dormancy before and after the fall rainy season. A complete understanding of the mechanism which triggers the “greening up” of dormant native perennial grasses is yet to be found, but may be related to available soil water and changes in daylength and diurnal temperature patterns. *Nassella pulchra* and *E. glaucus* began to green up in the high intensity management treatments prior to October 13, 2005 (Graph 4), which was more than two months before the first rain of the fall season.



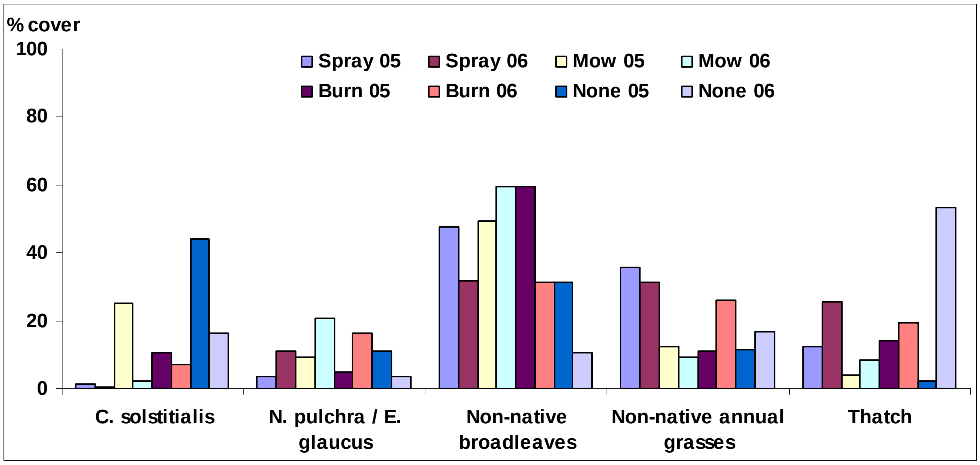
Graph 4. Native perennial grass density and vigor along State Route 20 near Williams, CA on October 13, 2005.

In spring 2006, two years of management reduced *C. solstitalis* cover to less than 7% for all treatments (Graph 5). Cover of *C. solstitialis* in the None treatment was 16%, which was lower than in 2005 (44%), and thatch cover in 2006 was 53%. Non-native annual broadleaf cover was greater than 50% in the mow and mow+burn treatments, while non-native annual grass cover was greater than 25% in treatments that included spray, except for the spray+burn. The none and mow+burn treatment had the lowest cover of *N. pulchra* and *E. glaucus*, while the remaining treatments had between 11 and 21% native perennial grass cover.



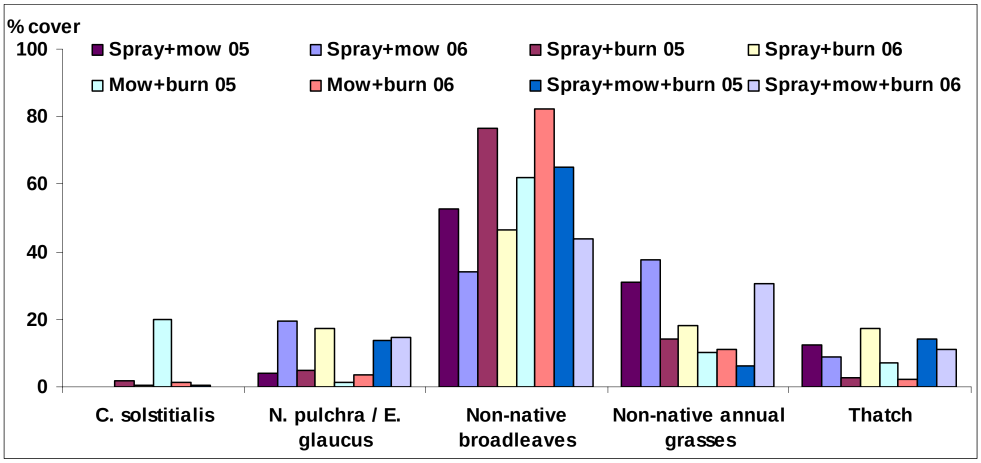
Graph 5. Vegetation cover of plants along State Route 20, near Williams, CA on April 14, 2006, following two years of treatments and growth.

For low intensity management, cover of *C. solstitialis* was consistently low in the spray treatment (Graph 6). In the mow and burn treatments, *C. solstitialis* cover decreased to less than 10% following two years of management. The difference in the increase in native perennial grass cover between 2005 and 2006 was similar for all low intensity management regimes (7-11%). *Nassella pulchra* and *E. glaucus* cover decreased to 3% in plots that were not maintained (None treatment). Cover of non-native annual broadleaves was reduced in the treatments that were either sprayed or burned, while cover of non-native annual grasses declined and was lowest in the mow treatments. The amount of thatch increased in managed and None treatments, but was greatest in plots that were left unmanaged (53%).



Graph 6. The effect of low intensity management on vegetation cover along State Route 20 near Williams, CA in spring 2005 and 2006.

All high intensity management treatments reduced *C. solstitialis* cover to less than 2% by the spring of 2006 (Graph 7). Spray+mow and spray+burn treatments lowered non-native broadleaf cover by 19 to 29%, while non-native annual grass cover increased 4 to 7% in 2006. Cover of non-native annual species in the spray+mow+burn declined to less than 50% for the broadleaves and increased to greater than 30% for the grasses. Treatments that included spray increased native perennial grass cover to 14 to 21% in 2006. Cover by non-native annual species was dominant (> 90%) in the mow+burn treatments after two years of management.



Graph 7. The effect of high intensity management on vegetation cover along State Route 20 near Williams, CA in spring 2005 and 2006.

Discussion

We found that after 2 years of low intensity treatments, yellow starthistle was reduced but not completely eliminated and native perennial grasses were increasing in cover compared to levels before treatment. Although the use of a single vegetation control method (*i.e.* burn, spray or mow) is more economical, there are drawbacks for repeated use of any one method within the season or over several seasons.

While burning reduces plant biomass and stimulates perennial plant growth, niches can be created for the establishment of non-native, annual plants. In addition, a single season of plant biomass is often inadequate to carry a fire when using burning over successive seasons for vegetation control. Spraying with herbicide eliminates some or all plants, depending on selectiveness of the chemical(s), but successive seasonal use increases the potential for development of resistant species. Repeated mowing reduces standing plant material, but creates large amounts of residue and selects for low-growing plant species. The tendency to mow at extremely low heights to reduce the number of trips in a season can fatally harm any native perennial grasses that may exist within the treated area.

High intensity treatments applied over 2 years were effective at eliminating yellow starthistle in treatments that included spraying and increasing native perennial grasses. Additionally, the late season vigor (greening and regrowth before the rains) occurred on 30 to 50% of total native perennial grass biomass in the high intensity treatments. A potential beneficial feature of native perennial grasses that could help to lessen the impacts of fires sparked along roadsides is that they break dormancy and green up late in the season when conditions are ripe for grass fires. Using native perennial grasses to fight wild fires could bring favor to an agency known for lack of progressive leadership in many areas of roadside management.

Conclusion

The use of multiple treatments in restoring a non-native infested stand of roadside native perennial grasses allows for the maximization of the different treatment combinations, thereby preventing niches, resistant or low-growing species and a build up of plant residue. By taking an adaptive management approach to roadside vegetation management and maintenance, native perennial grass dominance can persist while returning ecosystem function and aesthetic value.

Single plants of Elymus glaucus on August 5, 2005 growing without irrigation in a herbicide+mow treatment along Highway 20, Colusa County, CA.

Overall Project Summary

Factors for the establishment of native perennial grasses along Caltrans' rights-of-way in Northern California:

- Ω Native perennial grass species that establish best along the road edge include *Hordeum brachyantherum californicum*, *Elymus multisetus*, *Elymus glaucus* and *Bromus carinatus*. Similarly, for establishment along back slopes *Hordeum brachyantherum californicum*, *Elymus multisetus*, *Elymus glaucus*, *Bromus carinatus* and *Leymus triticoides* are the best selections. Other native perennial grass species with potential include *Nassella pulchra* and *Melica californica*.
- Ω A properly timed prescribed burn and two or more herbicide applications will provide good control of most non-native annual vegetation in the year prior to and the first two years after drill seeding native perennial grasses.
- Ω After three to five years, a less costly non-native vegetation control plan can be used to maintain a newly established stand of native perennial grasses.
- Ω In well-established stands of native perennial grasses, a combination of well-timed vegetation control techniques (i.e burning, spraying and mowing) applied for at least two consecutive years is necessary to eliminate *C. solstitialis* and other non-native annual species.
- Ω Once established and treated occasionally as needed for non-native invasions, native perennial grass stands can persist for more than a decade and remain relatively weed resistant.

Management Scenarios

Mowing
Leave the grass canopy intact (by either not mowing or mowing at 10 inches height) through the late summer and winter. The canopy that is left shades weeds and reduces growth and allows the perennials to retain leaf area and maintain growth. Mowing at 4 inches weakens perennials by making them regrow their leaves, and it opens the canopy for the more rapid growth of weeds, which shade the slower growing perennials.

Mowing perennial grass stands in alternate years can remove thatch if fire is a concern. Swathing (10 inch height) and bailing removes thatch and removes weed seed from infested areas if it is done before seeds are produced. If done after the weeds have dropped seeds, it is not effective for weed control. If the cutting height is too low, it may encourage dominance of faster growing weeds.

Mowing after the annual grasses have dropped their seeds is non-effective for weed control.

Herbicides
If broadleaf weeds are in small patches, spot spraying with a broadleaf herbicide before seed set is effective and fast.

Established communities of perennial grasses can withstand low rates of glyphosate (about 50 % ?? of label) without lasting damage.

Heavily infested areas respond well to treatment if it is done consistently for two or three consecutive seasons. In this study, two years of post emergent broadleaf herbicide along with either burning or mowing reduced YST to near zero. If broad scale herbicide use is undertaken, make sure that perennial grasses are generally present on the site, even if they are small and widely scattered. Then, when the weeds are knocked back, the perennials can reemerge. If perennials are not present, another weed will colonize the open site. During the conversion from annual to perennial grasses, several years of intensive weed management will be required, after which the perennial grass populations can be expected to be established and stable.

Native grasses
Native perennial grasses are adaptable and robust if 1) they are well established and 2) if growth conditions are modest or better. Heavy traffic compacts the soil and reduces root growth. Continued erosion from steep hillsides strips off the fine soils. Different native grasses tend to do better in different types of locations. In general (in northern California), x and x tend to be more competitive on drier sites. Moister sites tend to have populations of xx and xx. Shallower soils tend to have populations of xx as widely scattered clumps. In southern california, xx and xx grasses are found, but communities often tend to have more shrub components. In the desert regions xx.

Literature cited

Akbar KF Hale WG and Headley AD. 2003. Assessment of scenic beauty of the roadside vegetation in northern England. Landscale and Urban Planning 63:139-144.

Anderson J. 1999. Direct seeding of California native grasses in the Sacramento Valley and foothills. Pages 5-12. in P. Robbins ed. Bring farm edges back to life! 4th Edition. Yolo County Resource Conservation District. Woodland, California.

Anderson J, Long R. 1999. Hedgerows: turning farm waste areas into active IPM life cycles. Yolo County Resource Conservation District, California Department of Pesticide Regulation - Pest Management Grants Final Report #97-0247. 20 pp.

Babbitt B. 1998. Statement by Secretary of the Interior on invasive alien species. *In* Proceedings of the National Weed Symposium; 8-10 April 1998. Bureau of Land Management: Web page: http//www.blm.gov/weeds/ sympos98/agenda.html. Accessed: May 2003.

Beetle AA. 1947. Distribution of the native grasses of California. Hilgardia. 17:309-357.

Benefield CB, DiTomaso JM, Kyser GB, Orloff SB, Churches KR, Marcum DB, Nader GA. 1999. Success of mowing to control yellow starthistle depends on timing and plant's branching form. California Agriculture. Vol. 53. No. 2. pgs. 17-21

Bowers HD. 1950. Erosion control on California state highways : reprint of a series of articles published in "California highways and public works." State of California, Department of Public Works, Division of Highways, Sacramento. 70 pp.

Brooks MA. 1995. Evaluating roadside revegetation in Central Arizona. Proceedings: Wildland Shrub and Arid Land Restoration Symposium, USDA, USFS and Intermountain Research Station. pp. 68-73.

Brown CS, Rice KJ. 2000. The mark of zorro: effects of the exotic annual grass *Vulpia myuros* on California native perennial grasses. Resoration Ecology. 8(1): 10-17.

Brown CS, Rice KJ. 2001. Inputs and maintenance for revegetation with native herbaceous species. Department of Agronomy and Range Science, University of California, Davis, CA. Sponsoring agency: Division of New Technology, Materials and Research, Environmental and Engineering Services. California Department of Transportation, Sacramento, CA. FHWA/CA/TL-2001/06. 164 pages.

Brown CS, Rice KJ, Claassen VP. 2000. The effects of soil amendments and mulches on establishment of California native perennial grasses: a summary of selected results. Grasslands 10(1), Winter. pp 8.

Bugg RL, Brown CS, Anderson JH. 1997. Restoring native perennial grasses to rural roadsides in the Sacramento Valley of California: establishment and evaluation. Restoration Ecology. 5(3): 214-228.

Bugg RL, Brown CS. 2000. Effects of perennial grasses on introduction of native forbs in California. Restoration Ecology. 9(1): 38-48.

Burcham LT. 1957. California range land. California Department of Forestry, Sacramento.

Carlsen TM, Menke JW, Pavlik BM. 2000. Reducing competitive suppression of a rare annual forb by restoring native California perennial grasslands. Restoration Ecology. 8(1): 18-29.

Clary RF. 1983. Planting techniques and materials for revegetation of California roadsides. USDA Soil Conservation Service. Department of Transportation. Sacramento, CA. USA.

Clements FE. 1934. The relict method in dynamic ecology. Journal of Ecology. 22:39-68.

CNGA (California Native Grasslands Association) and California Crop Improvement Association (CCIA). 2001. The use of native grassland plant species for roadside revegetation. Training workshop for Caltrans (California Department of Transportation) and roadside managers. Sacramento, CA. October 2-3, 2001.

Dahlgren RA, Horwath WR, Tate KW, Camping TJ. 2003. Blue oak enhances soil quality in California oak woodlands. California Agriculture. 57 (2): 42-47.

DiTomaso JM. 2000. Invasive weeds in rangelands: Species, impacts, and management. Weed Science 48:255-265.

DiTomaso JM, Kyser GB, Orloff SB, Enloe SF. 2000. Integrated approaches and control option considerations when developing a management strategy for yellow starthistle. California Agriculture 54 (6):30-36.

Dyer AR, Rice KJ. 1997. Intraspecific and diffuse competition: the response of *Nassella pulchra* in a California grassland. Ecological Applications 7(2), pp. 484-492.

Dremann CC, Shaw M. 2002. Releasing the native seed bank. Ecological Restoration 20: 103-107.

Duncan CA, Jachetta JJ, Brown ML, Carrithers VF, Clark JK, DiTomaso JM, Lym RG, McDaniel KC, Renz MJ and Rice PM. 2004. Assessing the economic, environmental and societal losses from invasive plants on rangeland and wildlands. Weed Technology

Formatted: Dutch (Netherlands)

18:1411-1416.

Edmunson GC. 1976. Plant materials study: a search for drought-tolerant plant materials for erosion control, revegetation and landscaping along California highways. Soil Conservation Service, Lockeford, Calif. Lockeford Plant Materials Center. California State Dept. of Transportation, Sacramento. Office of Landscape and Architectural Design.; Federal Highway Administration, Washington, D.C. Jun. 276p. Report: USDA/SCS/LPMC-1; FHWA/CA76-01

Eiswerth ME, Darden TD, Johnson WS, Agapoff J, Harris TR. 2005. Input-output modeling, outdoor recreation, and the economic impact of weeds. Weed Science 53:130-137.).

Eliason SA, Allen EB. 1997. Exotic grass competition in suppressing native shrubland re-establishment. Restoration Ecology, 5(3): 245-255.

Elton CS 1958. The ecology of invasions by animals and plants. Methuen, London, UK.

Elzinga CL, Salzer DW, Willoughby JW. 1998. Measuring and monitoring plant populations. U.S. Department of the Interior, Bureau of Land Management, National Applied Resource Sciences Center, Denver, CO. BLM/RS/ST-98/005+1730. 492 pages.

FHWA (Federal Highway Administration), U.S. Department of Transportation. 2000. Starthistle reduced by prescribed burn. In Greener Roadsides. Federal Highway Administration, Office of Environment and Planning. Washington, D.C. Publishing No. FHWA-EP-01-006. 8 pages.

FHWA (Federal Highway Administration), U.S. Department of Transportation. 2005. Traveler opinion and perception survey. Federal Highway Administration, Washington, DC

Gordon DR, Welker JM, Menke JW, Rice KJ. 1989. Competition for soil water between annual plants and blue oak (*Quercus douglasii*) seedlings. Oecologia 79: 533-541.

Gordon DR, Rice KJ. 1992. Partitioning of space and water between two California annual grassland species. American Journal of Botany 79(9): 967-976.

Guertal, E. 2000. Nitrogen: finding the form that fits. Grounds Maintenance. September. pp. 15-18.

Hallock B, Scharff M, Rein S, Curto M. 2002. Plant establishment with rainfall simulators for erosion control. Proceedings of the 33rd International Erosion Control Association Conference. Orlando, FL. February.

Hamilton JG, Holzapfel C, Marshall BE. 1999. Coexistence and interference between a native perennial grass and non-native annual grasses in California. Oecologia 121:518-526.

Hansen MJ and Clevenger AP. 2005. Influence of disturbance and habitat on the presence of non-native plant species along transport corridors. Biological Conservation 125:249-259

Hansen DJ, McKell CM. 1991. Native plant establishment techniques for successful roadside revegetation. Weber State University. Ogden, UT. pp. 266.

Harris RW. 1970. Establish drought tolerant perennial plants by seeding. UC Davis, Dept. of Environmental Horticulture, US Department of Transportation, FHWA (Highway Research Report) in cooperation with the U. S. Bureau of Public Roads.

Harper-Lore BL. 1998. Do native grasslands have a place on roadsides? Land and Water. July/August, pp. 29-31.

Harper-Lore BL. 2000. A vegetation manager’s tour of Australian roadsides. Land and Water. January/February, pp. 26-29.

Heady HF 1988. Valley grassland. *In* M. G. Barbour and J. Major (eds.) Terrestrial Vegetation of California. Special publication number 9. California Native Plant Scociety, Sacramento. pp. 491-514.

Holmes TH, Rice KJ. 1996. Patterns of growth and soil-water utilization in some exotic annuals and native perennial bunchgrasses of California. Annals of Botany 78: 233-243.

Ivanovitch LJ. 1975. Roaside revegetation in Montana. Environmental and Landscape Unit, Preconstruction Bureau. Montana Department of Highways. pp. 40.

Kalamees R, Zobel M. 1998. Soil seed bank composition in different successional stages of a species rich wooded meadow in Laelatu, western Estonia. Acta Oecologica 19: 175-180.

Kimbal M. and C. Lamb. 1999. Establishing hedgerows for pest control and wildlife. Pages 13-22. in P. Robbins ed. Bring farm edges back to life! 4th Edition. Yolo County Resource Conservation District. Woodland, California.

Matthew, 1952. The Gospel According to Matthew. *In:* The New Testament. Matthew 13:26-30.

Kotanen PM. 1997. Effects of experimental soil disturbance on revegetation by natives and exotics in coastal Californian meadows. Journal of Applied Ecology 34: 631-644.

Laughlin DC. 2003. Lack of native propagules in a Pennsylvania, USA, limestone prairie seed bank: futile hopes for a role in ecological restoration. Natural Areas Journal 23: 158-164.

Legg M, Farnham K, Miller E. 1980. Soil restoration on deteriorated campsites in Texas. Southern Journal of Applied Forestry. 4: 189-193.

Lonsdale, W.M. 1999. Global patterns of plant invasions and the concept of invasibility. Ecology 80 (5): 1522-1536.

May, R.M. 1973. Stability and complexity in model ecosystems. Princeton University Press, Princeton, New Jersey, USA.

McGourty, G. 1994. Cover crops for North Coast vineyards. Practical Winery & Vineyard. July/August. 6 pp.

Momen, B., J.W. Menke, J.M. Welker, K.J.Rice, F.S. Chapin. 1994. Blue-oak regeneration and seelding water relations in four sites within a California oak savanna. International Journal of Plant Science 155(6): 744-749.

Moritsch, B.J. and P.S. Muir. 1993. Subalpine revegetation in Yosemite National Park, California: changes in vegetation after three years. Natural Areas Journal 13: 155-163.

Nelson, L.L., E.B. Allen. 1993. Restoration of *Stipa pulchra* grasslands: effects of mycorrhizae and competition from *Avena barbata*. Restoration Ecology, March 1993. pp. 40-50.

O'Dell R, Young SL, Claassen VP. 2007. Native roadside perennial grasses persist a decade after planting in the Sacramento Valley. California Agriculture. 61(2):79-84.

Parks, D.M., M.X. Nguyen. 1984. Revegetation of problem soils on road slopes. California State Dept. of Transportation, Sacramento. Office of Transportation Lab. Sponsor: Federal Highway Administration, Sacramento, CA. June. 99p. Report: TL-604165; FHWA/CA84/17

Pimentel D, Zuniga R, Morrison D. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics 52:273-288

Planty-Tabacchi, A.M., E. Tabacchi, R.J. Naiman, C. Deferrari and H. Decamps. Invasibility of species-rich communities in riparian zones. Conservation Biology 10 (2): 598-607.

Rejmanek, M. 1996. Species richness and resistance to invasions. *In* H. Orians, R. Dirzo and J.H. Cushman (eds.). Biodiversity and ecosystem processes in tropical forests.

Formatted: Dutch (Netherlands)

Ecological Studies. Volume 122. Springer-Verlag, Berlin, Germany.

Rice, K.J., J.D. Gerlach and A.R. Dyer. 1997. Closed canopies and open niches: patterns and mechanisms of sequential invasions in California grasslands. Supplement to Bulletin of the Ecological Society of America Annual Meeting. August 10-14. Albuquerque, New Mexico. Volume 78 (4): 30.

Robbins, P. 1999. Bring farm edges back to life! 4th Edition. Yolo County Resource Conservation District. Woodland, CA. 105 pages.

Robinson, G.R., J.F. Quinn and M.L. Stanton. 1995. Invasibility of experimental habitat islands in a California winter annual grassland. Ecology 76 (3): 786-794.

Schultz, G.P. 1996. Seedling establishment and competition in coastal sage scrub and annual grassland. University of California, Riverside. Masters of Science in Botany. pp 53.

Sheley RL 2004. Rangeland Weed Management. Montana State University Extension Service. MT199504 AG

Smith, R.S., R.S. Shiel, D. Millward, P. Corkhill and R.A. Sanderson. 2002. Soil seed banks and the effects of meadow management on vegetation change in a 10-year meadow field trial. Journal of Applied Ecology 39: 279-293.

Stohlgren, T.J., D. Binkley, G.W. Chong, M.A. Kalkhan, L.D. Schell, K.A. Bull, Y. Otsuki, G. Newman, M. Bashkin and Y. Son. 1999. Exotic plant species invade hot spots of native plant diversity. Ecological Monographs 69 (1): 25-46.

Thompson, K., J.G. Hodgson, P.J. Grime, and M.J.W. Burke. 2001. Plant traits and temporal scale: evidence from a 5-year invasion experiment using native species. Journal of Ecology 89: 1054-1060.

Tilman, D. 1997. Community invasibility, recruitment limitation and grassland biodiversity. Ecology 78 (1): 81-92.

Westbrooks, R.G. 1998. Invasive plants: changing the landscape of America: fact book. Washington, D.C.: Federal Interagency Committee for the Management of Noxious and Exotic Weeds. 107 pp.

Williamson J, Harrison S. 2002. Biotic and abiotic limits to the spread of exotic revegetation species. Ecological Applications. 12(1):40-51

Williamson, M.H. 1996. Biological invasions. Chapman & Hall, London.

Wolf KL. 2003. Freeway roadside management: the urban forest beyond the white line. Journal of Arboriculture 29(3):127-136

Wolfe, M.H. 1999. Innovations in pest management: revegetation for weed and pest control. California Department of Pesticide Regulation - Pest Management Grants Final Report #97-0236. 13 pp.

Woodward, R.A. 2002. Revegetation of perennial grasslands in the Peruvian Andes. Erosion Control. Sept/Oct. pp. 42-47.

Wrysinski, J. 1999. Roadside establishment of native perennial grasses. Pages 23-28. in P. Robbins ed. Bring farm edges back to life! 4th Edition. Yolo County Resource Conservation District. Woodland, California.

Wrysinski, J. 2000. Know your natives: a pictorial guide to California native grasses. Yolo County Resource Conservation District. Woodland, CA. 26 pages.

Zabinski, C.A., T.H. Deluca, D.N. Cole and O.S. Moynahan. 2002. Restoration of highly impacted subalpine campsites in the Eagle Cap Wilderness, Oregon. Restoration Ecology 10 (2): 275-281.

Zalba, S.M. and C.B. Villamil. 2002. Woody plant invasion in relictual grasslands. Biological Invasions 4: 55-72.