CENTRAL VALLEY PROJECT IMPROVEMENT ACT
LAND RETIREMENT DEMONSTRATION PROJECT

A SYNTHESIS OF RESTORATION RESEARCH CONDUCTED NEAR TRANQUILLITY, CALIFORNIA

U.S. Department of the Interior
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A SYNTHESIS OF RESTORATION RESEARCH CONDUCTED NEAR TRANQUILLITY, CALIFORNIA

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EXECUTIVE SUMMARY

Beginning in 2000, research efforts were initiated to identify strategies for restoring native plant communities on retired agricultural lands in the San Joaquin Valley. Significant challenges to successful restoration include: the depauperation of the native flora (i.e., potential seed sources), problematic site conditions (e.g., high soil salinity; heavy, highly motile clay soils; low topographic variability), limitations associated with rainfall (e.g., low mean annual precipitation; extremely variable precipitation patterns), weed pressure from non-native species, and enhanced nitrogen deposition from airborne pollution. Numerous experimental trials were initiated in which a variety of restoration strategies were evaluated. This research included evaluations of irrigation, different seeding techniques, modified planting conditions (e.g., furrow depth, row and plant spacing, topographic modification), non-chemical and chemical weed control, and seed-related factors (e.g., seed mixtures, soil rhizosphere augmentation, nurse and cover crops).

Based on this research, some general patterns and constraints are evident:

1. Results vary significantly among locations (due to local conditions) and years (due, in part, to timing and amount of precipitation), precluding the development of a single, "silver bullet" restoration strategy. Rather, restoration approaches will need to be carefully designed to take into account conditions at the particular site and, as much as is possible, weather conditions during the period of vegetation establishment.
2. Competition from weeds will generally be the most significant impediment to successful restoration. Fully-integrated weed control strategies will include an array of techniques. Weed control strategies incorporating pre-emergent herbicides and activated charcoal "safening" are particularly promising.
3. Moisture conservation will also be of primary importance. As with approaches to weed control, restoration strategies will need to consider a variety of moisture-conservation methods.
4. On some sites, suppression of insect damage will also be a key component of restoration strategies; however, it appears that some areas of the SJV will be relatively free from this concern.
5. Due to the extensive development of the SJV, little native upland habitat remains, and only a small fraction of the historical flora appears to remain. Generally, the existing native seed bank on the retired agricultural lands will contribute little to restoration efforts.

It is very evident from the literature that restoration of lands in the arid and semi-arid areas of the southwestern USA is a difficult undertaking. It is equally clear that the conditions that characterize the lands that have been targeted for land retirement will present a significant challenge to those attempting to restore them.

Based on our results and observations, we offer the following recommendations:

1. Species selection will need to be site-specific (i.e., formulated to address the particular conditions at the restoration site), with species' considerations based

primarily on soil texture and salinity, moisture regime, compatibility with weed control measures (particularly herbicidal), and availability and cost of seed. General suites of species have been formulated as generic mixtures that can be further tailored to address site-specific requirements and constraints.

2. Standard soil preparation practices (i.e., tillage and other measures common in local agronomic applications) appear adequate for proper seed bed preparation on soils characteristic of retired lands.
3. Commercial grass drills offered the greatest success of the seeding methods that were evaluated. Additionally, drilling is particularly well-suited to some of the recommended weed-control methods.
4. Due to the relative paucity of local native seed sources, efforts should focus on the amplification (i.e., seed increase through active field propagation) of local native seed stocks. Seed amplification efforts should be focused on the highest priority species that are not commercially available as local or regional ecotypes. Agency, industry and landowner collaboration and infrastructure development is needed to assure efficient technology transfer and timely seeding materials supply and delivery.
5. The objectives of large-scale restoration efforts should be refined. Considerations should include the identification of target species, habitat goals, and target plant community composition
6. “Core areas” and “linkage corridors” should be defined and delineated, and their relationships, priorities, and juxtaposition to LRDP habitat restoration efforts should be identified.
7. Research on chemical weed-control methods should continue, with a focus on refining herbicide selection, and herbicide and charcoal rates. This research would be laboratory-, greenhouse-, and field-based.
8. Additional chemical weed-control research should be initiated in which the effects of follow-up (secondary) applications are evaluated on existing native vegetation.
9. Research should be initiated in which the effects of grazing on native plants is evaluated. This research should also incorporate other weed-control approaches (e.g., chemical control, mechanical measures, etc.) in an integrated strategy.

ACKNOWLEDGMENTS

The research summarized in this document has been implemented with considerable collaborative effort. The Land Retirement Team [Stephen Lee and Bob May (Bureau of Reclamation), Bea Olsen (U.S. Fish and Wildlife Service), Tracy Rowland and Dr. Stephen Laymon (Bureau of Land Management)] has had the formidable role of overseeing a large and multifaceted project. Dr. Patrick Kelly, Coordinator of the Endangered Species Recovery Program (ESRP) has overseen the Program's participation in the Land Retirement Demonstration Project since its inception. Additionally, Bea Olsen, Stephen Lee, Pat Kelly, Dr. Brian Cypher (ESRP), and Harry McQuillen (FWS) all reviewed this document and provided critical feedback.

A number of individuals contributed greatly to the research presented in this document. Foremost among these was Adrian Howard (formerly of ESRP), who took the lead on the design and implementation of many of the trials. The work with pre-emergent herbicides and activated charcoal, in particular, resulted from Adrian's investigations of the literature, and he took the lead on developing the initial trial in which these methods were evaluated. The contributions of many additional current and former ESRP staff members need also be noted. Justine Kokx took the lead with Adrian Howard on the development of the Native Plant Seed Production Facility, and contributed greatly to the research in many additional capacities. Michelle Selmon, and Curtis E. Uptain, the senior author's predecessors as Biological Coordinator, both contributed to the research throughout their time with the project. Daniela Giovannetti provided essential administrative support and good humor. Jenn Britton managed the Seed Processing facility, participated in vegetation monitoring, and was meticulous in data entry and proofing. Other ESRP staff (presented here in alphabetical order) who contributed to the implementation and monitoring of the research are: Georgia Basso, Graham Biddy, Ellen Cypher, Scott Deal, Karen Dulik, Richard Gebhardt, Adam Harpster, Emily Magill, Steve Messer, Kimberly Kreitinger, Steve Messer, Gene 'Woody' Moise, Patrick Morrison, Darren Newman, Richard Rivas, Krista Tomlinson, Foung Vang, and Laurie Williams. Additional collaborators from the Denver Technical Service Center (Bureau of Reclamation) who participated in the installation and monitoring of the trials are: Vicki Johanson, Scott O'Meara, Steve Ryan, and Rick Wydowski.

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INTRODUCTION

In this document, we will: 1) summarize the challenges associated with the restoration of native plant communities in the San Joaquin Valley; 2) describe the various experimental and applied restoration activities that we have undertaken; 3) present the results from this work; 4) offer preliminary recommendations regarding the application of this work in a broader-scale setting; and, 5) offer suggestions regarding the direction of future research.

BACKGROUND ISSUES

The San Joaquin Valley Drainage Program, established in 1984, combined federal and state efforts to investigate drainage issues in the Valley, and to identify possible strategies for addressing these issues [38]. The program estimated that by 2040 approximately 160,000 to 225,000 ha (400,000 to 554,000 ac) would become unsuitable for irrigated agriculture if no actions were taken to remedy drainage problems.

Land retirement (i.e., the removal of lands from irrigated agriculture) was proposed as one strategy to reduce drainage-related problems. In this approach, lands that were characterized by low productivity, poor drainage, shallow water tables, and high groundwater selenium concentrations would be retired from irrigated agriculture through a willing seller program. The Central Valley Project Improvement Act (CVPIA), enacted in 1992 as Public Law 102-575 Title 34, Section 3408(h), authorized the purchase of land, water rights, and other property interests from willing sellers who received CVP water. The cessation of irrigated agriculture on these lands would facilitate the program goals of reducing drainage, enhancing fish and wildlife resources and making water available for other CVPIA purposes.

The Land Retirement Program (LRP) was developed cooperatively by an interagency Department of the Interior team with representatives from the Bureau of Reclamation (Reclamation), the U.S. Fish and Wildlife Service (FWS), and the Bureau of Land Management (BLM). The Land Retirement Team (LRT) was charged with the task of implementing the Land Retirement Program.

In order to study the environmental impacts of land retirement, the Land Retirement Demonstration Project (LRDP) was implemented at two sites: one in the western San Joaquin Valley (Tranquillity Site; Figure 1), and one in the Tulare Lake Basin (Atwell Island Site; Figure 1). The California State University – Stanislaus Foundation, Endangered Species Recovery Program (ESRP) has served as a major research partner with the Land Retirement Team in developing effecting means for restoring retired farmlands. The Reclamation Technical Service Center (TSC; Denver) has been a major research partner since 2003. Additional collaborators include the University of California - Davis Weed Science Center (UCD), and the Lockeford Plant Materials Center (USDA-NRCS; Lockeford). Data from the LRDP will be used to inform decisions regarding the broader-scale implementation of land retirement as a means to address agricultural drainage problems in the San Joaquin Valley (SJV).

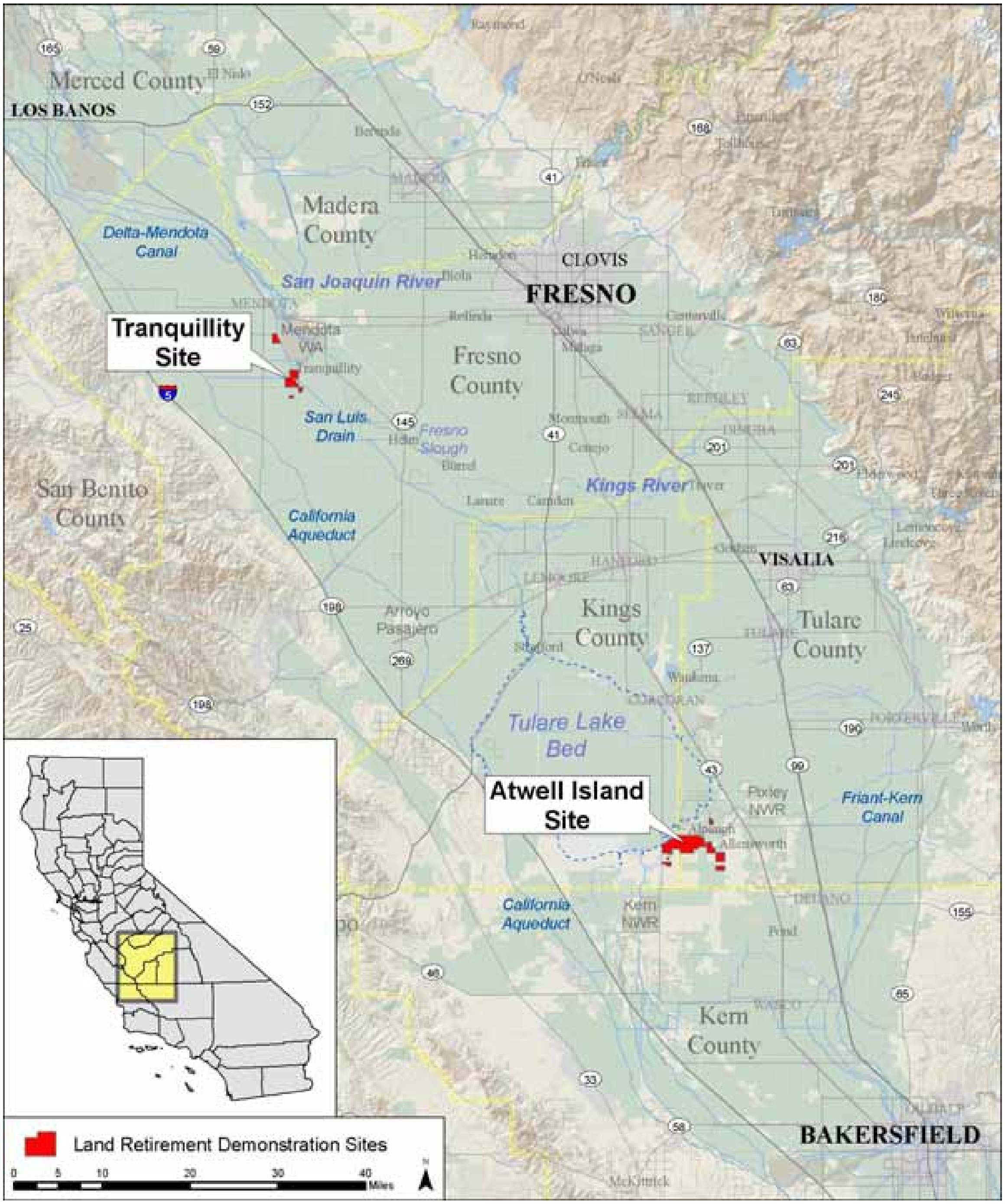

Figure 1. Location of the two Land Retirement Demonstration Project sites.

Research at the Tranquillity project site was initiated in 1999. Our research addresses native plant community establishment on dewatered cropland, and includes investigations of species selection and mixture formulation, species propagation and seed increase, seed conditioning, seed harvest and planting methods, soil amendments, and weed management. Other integrated strategies for weed suppression and native species establishment (e.g., mowing, fire and/or mechanical tillage measures) are also being evaluated. Study objectives also emphasize the development of revegetation prescriptions for land owners throughout the impacted area, with emphasis on restoration of native, salt-tolerant shrub/forb plant communities. It is intended that these restored communities will: 1) promote site stabilization and weed suppression; 2) enhance habitat values for wildlife, including endangered species [e.g., San Joaquin kit fox (*Vulpes macrotis mutica*) and kangaroo rat (*Dipodomys* spp.)]; 3) facilitate the recovery of the area's native flora; and, 4) provide grazing resources compatible with habitat goals.

ENVIRONMENTAL/ANTHROPOGENIC ISSUES

The San Joaquin Valley has already undergone extensive land conversion, and all indications suggest that land conversion will continue apace. Additional pressures are being brought to bear on the remaining habitat 'fragments' from a variety of forces, including population growth, air pollution, etc.

As of 2000, it was estimated that 3,320,096 persons were living in the Central Valley [(20)] (i.e., the Sacramento and San Joaquin Valleys); it is anticipated that by the year 2040 the population will more than double [(19)]. The San Joaquin Valley possesses the state's highest population growth rate [(5)], with the SJV population expected to grow by 39% from 2003 to 2020, and with growth in some counties predicted to approach 55% [(11)]. Over a slightly longer term, the population is estimated to be at approximately 240 percent of the 2000 level by the year 2050 [(20)]. A significant portion of the historical flora has apparently been extirpated from the western SJV [(35,36)]. As the Valley's population continues to grow and additional habitat is converted, the status of local populations of native species—the potential source of seed for proposed restoration efforts—will undoubtedly worsen.

Air quality in the SJV, along with the Los Angeles region, is now considered to be the worst in the United States [(5)]. Although there have been reductions in some emissions in the SJV and Sacramento Valley Air Basins, the number of days in which the air quality did not meet federal standards has risen since 2000 [(21)]. The effects of poor air quality on human health are well known. It is becoming increasingly evident that air pollution can also negatively impact native ecosystems and, by extension, restoration. For example, air pollution is said to promote weed growth in southern California shrublands [(1)] and grasslands [(52)]. Similarly, nitrogen oxide (NO_x) emissions frequently results in high concentrations of ozone (0_3), which is linked to severe injury in various plant species [(16)].

Of particular interest are the effects of nitrogen deposition on the environment. The buildup of nitrogen is occurring to such a degree that the biosphere has been likened to "a saturated gourmand … glutted with nitrogen compounds." [(31, p. 988)] The Los Angeles air basin is said to possess the highest known rates of nitrogen deposition, with rates estimated at 25 to 45 kg ha^{-1} yr^{-1} (22.5 to 40 lb ac^{-1} yr^{-1}), and 53.4 kg ha^{-1} yr^{-1} (44.5 lb ac^{-1} yr^{-1}) [(9)]. The rate of nitrogen deposition is said to potentially double during years with high fog deposition [(16)].

From a restoration standpoint, nitrogen deposition is of interest because elevated soil nitrogen levels can have fairly far-reaching affects on the biota. Nitrogen enrichment has been linked to community changes in vascular and non-vascular plants and mycorrhizae, even at relatively low levels (e.g. 3 to 8 kg ha^{-1} yr^{-1}; 2.7 to 7.1 lb ac^{-1} yr^{-1}) [(16)]. Nitrogen deposition is known to facilitate the spread of invasive species [(6,9,15,52)]. Additionally, increases in available nitrogen (which can translate to improved plant nutrition) can lead to increased insect fitness [29] and to increased herbivore consumption rates (*45*). Many invasive plant species are adapted to soils with higher nitrogen levels. As a result, some restoration strategies utilize "nitrate immobilization"; i.e., the removal of soluble nitrogen from the soil by microbial organisms [9,12,34,42]. It seems likely that the utility of this approach would be compromised by the nitrogen inputs associated with air pollution.

REVEGETATION SITE CHARACTERISTICS AND CONSTRAINTS

SOILS

The general locale inclusive of the specific study sites is characterized by surface and subsurface textures of sandy clay loam to clay. Other pertinent soil characteristics [mean topsoil (0-6 in; 0-15 cm) values] include slopes generally less than 0.5%; 1.3% organic matter; pH 7.7; EC_e 8.4 mmhos cm^{-1}; and SAR 8.5 meq L^{-1}. The predominance of extremely fine soil textures (primarily clays), characteristic throughout the upper portion of the soil profile corresponding to the root zone of seeded species, produces a matric soil moisture potential that severely constrains moisture availability (i.e., release for root uptake by seeded species).

The extreme motility of these clay soils has negatively impacted restoration at the site, as substantial cracking develops in the soil during the dry season. We have observed that if a large crack develops in the rooting area of a shrub, it frequently introduces sufficient stress such that the shrub is severely damaged or killed (Figure 2). This limited moisture availability is further compounded by the predominance of dicotyledonous (i.e., non-grass) shrub and forb species among the species with which we have had the most success, or which we consider to be priority species for the restoration of native plant communities (Table 2; Table 3). Many of these dicotyledonous species exhibit root systems that, in terms of root architecture and soil volume occupation, are predominantly vertically-oriented taproots with proportionally reduced fibrous (net-like, fine root filament) content. As such, ability of germinating seeds and young seedlings to capture limited soil moisture during early phases of establishment, particularly in the upper soil horizons where evaporative losses are greater, becomes even more limiting. Levels of soil salinity are moderate to moderately high, further constraining seeded species adaptation and selection to salt-tolerant species. All these factors combine to yield a harsh soil (i.e., growth medium) environment that inherently limits revegetation success, reduces native species adaptation and availability, and requires alterations to traditional revegetation strategies, management inputs, and techniques. This is particularly true in the absence of irrigation.

Figure 2. Severe cracking in the shrink-swell clay soils at the Tranquillity HRS site. White plastic tubes were used in watering the plants with DriWater™ (water bound in a gel matrix). The dead shrub at the end of the crack is a 3-year old *Atriplex polycarpa*.

CLIMATE

The LRDP study location is characterized by a semi-arid, winter-monsoonal (Mediterranean) climatic regime. Long-term mean annual precipitation (MAP) for the general site is 9.5 in (24.1 cm), of which approximately 80% (19.3 cm) is received during the winter monsoonal period of November through March. Precipitation is highly variable spatially and temporally, with pronounced differences in both year-to-year (Figure 3) and within-year (Figure 4) precipitation. In these figures, the bars represent monthly totals; the solid line represents the 30-year mean annual precipitation (1976-2006). Values above the bars in Figure 3 indicate the percentage of MAP represented by that particular year's precipitation.

The "feast or famine" nature of precipitation in the Tranquillity area is well- evidenced in the graph of precipitation for the 2005-06 hydrologic year (Figure 4). In this instance, not a single monthly total was within 25% of MAP, with precipitation in nine of the months well below MAP, and precipitation in the remaining three months well above MAP.

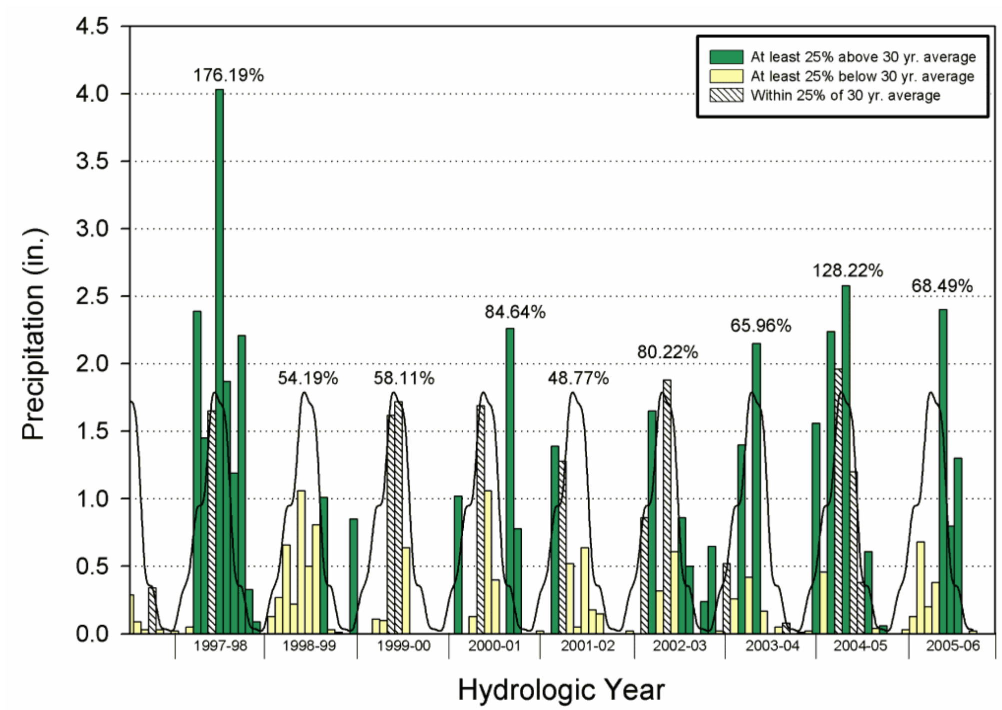

Figure 3. Precipitation during the course of the Land Retirement Demonstration Project (1997-present) at Tranquillity, CA. Data are from CIMIS Station #105; summarized by Howard & Ritter 2006.

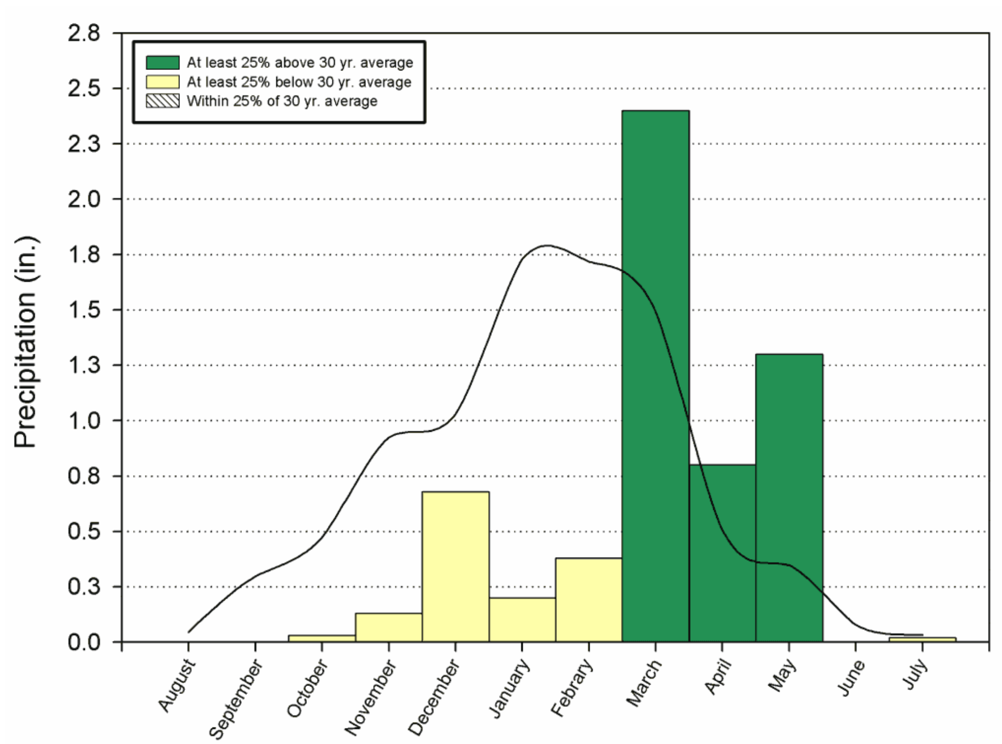

Figure 4. Precipitation at Tranquillity, CA during the 2005-06 hydrologic year (August, 2005 through July, 2006).

The relatively small amount of rainfall, combined with the variability in precipitation patterns, timing and duration, severely constrain revegetation efforts [A], requiring selection of native species that are extremely tolerant of variable, low-moisture conditions.

As will be discussed more fully below, one effect of this climatic variability is that restoration in the SJV, as in other semi-arid regions, is a very "uncertain" undertaking. A quote from Major [(28)] points to the obstructions that the climate might contribute to restoration efforts: "California's Mediterranean climate combines the worst features of several other climates. Excess precipitation in winter leaches and impoverishes the soils, and summer drought of desert intensity prohibits growth of most plants at that time." It has been recommended as a general guideline that restoration only be undertaken during years of favorable weather conditions. However, given the extreme stochasticity of precipitation in the SJV, it seems unlikely that restoration practitioners will be able to confidently predict rainfall during most years.

WEED PRESSURE

Retired agricultural lands in the western SJV are typified by (former cropland) fields that have been continuously disturbed by tillage for crop production and weed suppression. Upon discontinuation of these tillage practices, encroachment of annual and perennial weeds on these highly-disturbed, often bare surfaces is immediate. These conditions are particularly evident at the Tranquillity project site, although the wetter portions of the Atwell Island project site are particularly prone to invasion by five-hook Bassia (*Bassia hyssopifolia*).

Some general observations can be made about the vegetational colonization and development of the retired and fallowed lands in the Tranquillity area. However, it needs to be stressed that these observations have been made over a relatively limited period (five years).

At the onset of the first rains following the cessation of agricultural activities, various early winter weeds germinate and quickly become predominant. Most of the recently fallowed lands are colonized by dicot (broad-leaf) forbs. London rocket (*Sisymbrium irio*) is most commonly the dominant species, with the wetter portions frequently dominated by black mustard (*Brassica nigra*; Figure 5). Other common representatives of the early-season, non-native forbs are filaree (*Erodium cicutarium*) and old man in the spring (*Senecio vulgaris*). However, these species are generally found in much lower abundance than are the two mustards.

A variety of non-native grasses can also be present during the early stages of vegetational development, and over time these grasses become predominant. Red brome (*Bromus madritensis*) is a common dominant of these "later successional" lands. Foxtail barley (*Hordeum murinum*) is also a dominant on many retired areas; however, our impression is that it is somewhat less common than red brome. Other typical non-native annual grasses are ripgut brome (*Bromus diandrus*), various species of oats (*Avena* sp.), and to a lesser degree, small fescue (*Vulpia microstachys*) and soft chess (*Bromus hordeaceus*). On one quarter-section on the Tranquillity project site, littleseed canary grass (*Phalaris*

[A] For example, Bowers et al. (2004) reported that in their study in the Sonoran desert, only 2 of the 2008 seedlings that were tagged between 1987 and 1989 survived for as long as four years."

minor) is present as a co-dominant with black mustard. In this instance, it appears that this situation is due to the grass having previously been grown commercially on this portion of the site.

Figure 5. ESRP biologist, Adrian Howard in a stand of black mustard during the extremely wet 2004-05 hydrologic year.

After the onset of the dry season—during which time the early-season species senesce—a second "wave" of weeds can become established. This portion of the flora is also characterized by annual species, but most of the predominant species possess a shrub-like form. Typical species in this category are the "tumbling saltweeds" (*Atriplex rosea* and *A. argentea*), Russian thistle (*Salsola tragus*), lambsquarters (*Chenopodium album*), and five-hook Bassia (*Bassia hyssopifolia*). The tumbling saltweeds have been particularly problematic, and can form a dense cover over large areas (see discussion of irrigation, below).

Many of the shrub-like annuals are "tumbleweeds": breaking off from their base as they begin to senesce, and distributing their seeds as they're blown across the landscape. Additionally, although the tumbling saltweeds generally have declined in abundance in the years following their period in which they are extremely abundant, the repercussions from their dominance can be severe. Principally, as their biomass resists degradation, the saltweeds' "skeletons" (i.e., the stems of the previous year's plants) remain on site and limit the germination of other species. Establishment of the tumbling saltweeds, themselves, appears to be similarly limited by their skeletons; however, two species which are able to successfully become established under these conditions are London rocket and black mustard. London rocket also appears to be well suited to become reestablished under its own standing dead biomass (Figure 6).

It is important to recognize that this prevalence of weeds is not a situation that has developed merely with the cessation of agricultural activities. Rather, much of lowland California has long been plagued with invasive plants. California's grasslands have been used for grazing domestic animals since the arrival of the initial Spanish colonists in 1769 [(7)], and the seeds of introduced plants have been found in adobe bricks dating back more than 200 years [(40)].

Figure 6. ESRP biologist Justine Kokx in a dense stand of London rocket (*Sisymbrium irio*). The gray stems are standing dead stems from the previous year's growing season. The flush of green vegetation at the base of the stem is from the new year's growth.

A striking example of the abundance of invasive plants in the 1850's can be found in Cleland [(10)] who described the measures by which ranchers in southern California attempted to control black mustard [B]. As is clearly illustrated in Figure 5, similar conditions can be readily found in California 150 years later.

Issues pertaining to the flora of the San Joaquin valley

The recreation of historically complete plant communities may be beyond the scope of a large-scale restoration project. Nevertheless, restoration should be directed towards introducing more than just a few, "generalist" native species. One reason for maximizing the number of available species is that one species of a particular genus may not be a reasonable "substitute" for another species of the same genus. At times such a substitution may even have negative effects on the local fauna. For example, in one restoration project the endangered El Segundo blue butterfly (which is dependent on coastal buckwheat, *Eriogonum parvifolium*) was negatively impacted by the planting of *Eriogonum fasciculatum* [(26)].

Additional consideration needs to be given to the "source" of the seed (i.e., the area from which the seed was collected). It is widely recognized that local populations of plants are generally better adapted to local conditions that are non-local populations of the same species [(8,23,24,50)], within the context of limited (not severe) site disturbance that still facilitates secondary successional trajectories. Additionally, the use of seed from distant

Cleland (1941, p. 57) in his discussion of 'wild mustard' in southern California (subsequently identified by Burcham {1957} as black mustard, *Brassica nigra*) noted that: "In addition to the customary rodeos and the usual routine of ranch activities, some landowners found it necessary, at certain seasons of the year, to hold a special drive or roundup, probably unknown in any other part of the world. In southern California the growth of wild mustard was even more remarkable than that mentioned in Christ's striking parable. During the late spring, a sea of yellow bloom flowed over valleys, plains, and foothills; and the thickset stalks, higher than a man's head, made an ideal hiding place for cattle. Even when the bloom and the leaves died, a forest of dry, rustling stalks furnished ample covert (*sic*.) for livestock. In badly infested districts, neighboring ranchers and their vaqueros consequently united for a few days to carry on what was colloquially known as a 'run through the mustard'."

or dissimilar locations may have undesirable effects on local population genetics. The problems associated with "non-local" introductions are of considerable concern [30].

Although it is desirable that species utilized in restoration are grown from seed taken from local populations, it has become increasingly apparent that the species abundance status of the San Joaquin Valley's native vegetation is such that it is insufficient to cost-effectively or logistically provide the necessary quantities of seed for all but the most common species.

It has been noted that, in general, commercial seed producers provide local material, "for only a handful of common plant species that are easy to propagate" [30]. This situation is magnified for the SJV, as the region's flora is strikingly under-represented in the stocks of the four major commercial suppliers of California native seed. Further limitations arise as the seed of a particular species often has been grown-out from a single collection, which can potentially result in poor genetic diversity for that particular seed lot. Additionally, the seed of some desirable species can be prohibitively expensive. Hence, the availability of suitable supplies of native seed represents one more limitation that needs to be addressed in any large-scale restoration strategy for the Valley's retired agricultural lands.

In this Introduction, we have attempted to present an overview of the issues associated with ecological restoration in the SJV. It should be apparent that the conditions that characterize the lands that have been targeted for land retirement will present a significant challenge to those attempting to restore them. It is worth noting that this assessment is well in keeping with what has been noted for restoration in other arid and semi-arid regions [4,18,32,37].

THE RESEARCH

Numerous restoration trials were conducted throughout the course of the Land Retirement Demonstration Project (Table 2; Figure 7). Likewise, a variety of species have been utilized in these trials and/or cultivated in the Native Plant Seed Production Facility. A list of the species utilized in the trials and of the species that have been identified "core species", as described in Table 2 and Table 3.

Generally, trials were designed such that multiple factors were examined. For the purpose of discussion here, these factors can be grouped into six broad categories: irrigation; seeding technique; modified planting conditions; non-chemical weed control; chemical weed control; and, seed related factors (Table 2). The trials are presented in chronological order in Table 2; in this way, some general trends can be readily seen. The initial trials incorporated fairly "low tech" strategies, i.e., minimal weed control, with a primary focus on seeding technologies and species mixtures. Over time, as it became increasingly evident that restoration results were being "driven" by weed competition, the focus of the research shifted to weed control methods. As it became obvious that simple weed control methods were generally inadequate, the trials became more complex and incorporated more "intensive" approaches.

We present the findings of this research beginning with a discussion of our investigations of the remaining flora of the SJV. Following this, various strategies, concepts and techniques are summarized and presented, with a focus on the most important results (positive and negative). This discussion is structured following the six categories of Table 2. Finally, some broad issues regarding restoration in the western San Joaquin Valley will be addressed.

When presenting research, it is often compelling to avoid discussing the shortcomings of one's endeavors. However, in restoration there is much to be gained in discussing the elements of the research that were unsuccessful. Hence, we undertake this account of our research in the spirit of "full disclosure." To quote Wilson and Ingersoll [52], "Progress in restoration requires not only reports of successes, but also analyses of failures. Such analysis requires both a statement of the outcomes and consideration of the ecological processes responsible for success or failure".

STATUS OF THE VEGETATION OF THE SAN JOAQUIN VALLEY

As noted, it is highly preferable that seed from local populations be utilized in restoration. However, development in the SJV has been of such a scale that scant native habitat—and, hence, few sources of local seed—remains. Beginning in 1999, we have been surveying the western SJV for remnants of native upland vegetation, with intent to identify local seed sources for restoration efforts. Although this work was originally envisioned as being a relatively small component of the LRDP, it became increasingly evident that resources should be apportioned to locating local seed sources and amplifying stocks of local seed. Concurrently, as it became evident how little "native" upland habitat remained, we modified our concept of what constituted a "local" source: expanding the collecting radius from 15 miles (~24 km) to 50 miles (~ 80 km).

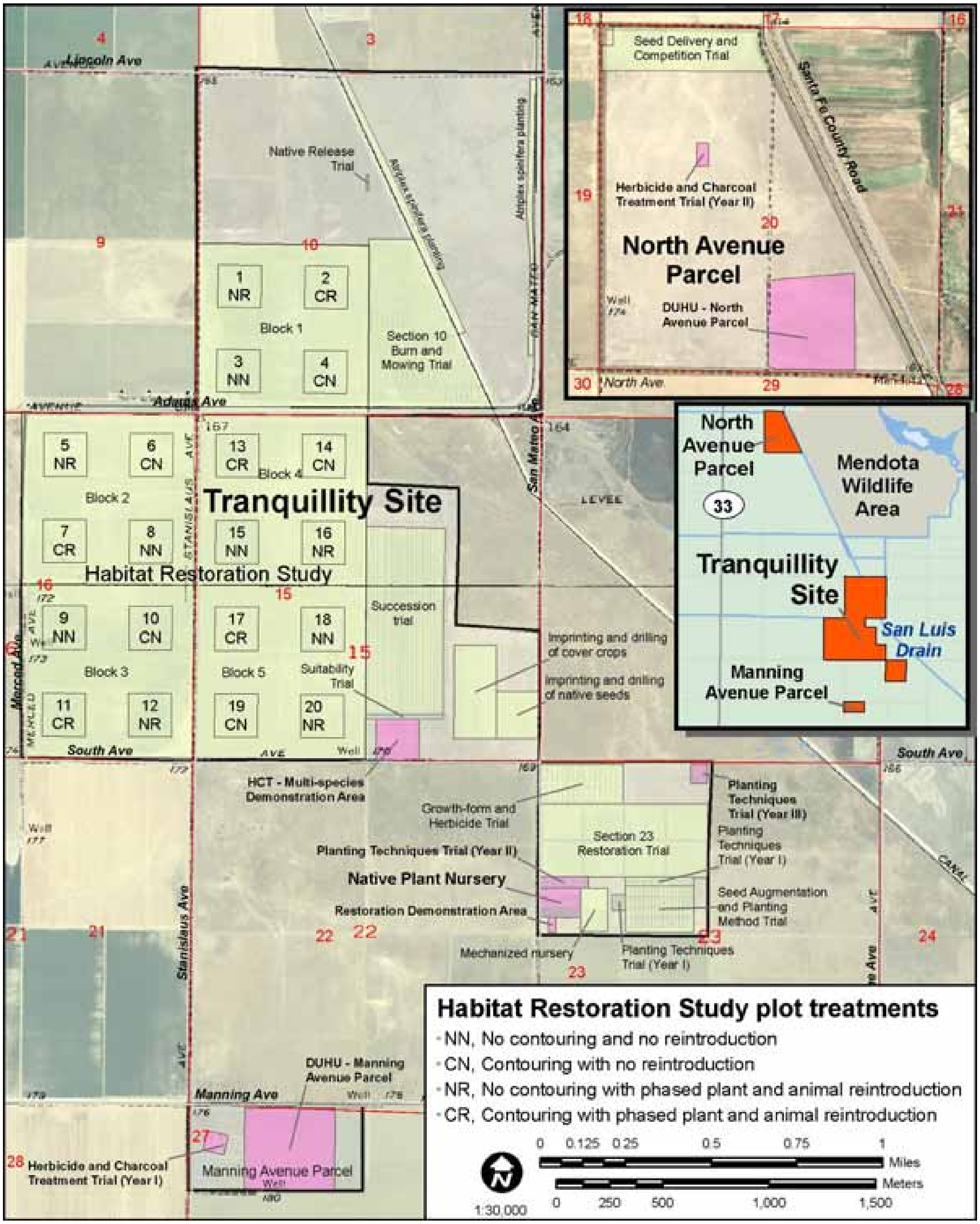

Figure 7. Restoration activities on the Tranquillity LRDP project site.

In this manner, we have located 41 collecting sites. These range in size from a few hundred square feet to ca. 1000 acres. In all, 159 native species have been encountered: a small fraction of those known historically for the area. More importantly, although few of these species would be considered rare on the state level, a significant number are clearly rare on the local level. Nearly two-thirds (64.7%) of the species were encountered in only 1-3 collecting areas, and some species were represented by just a single individual. Spiny saltbush (*Atriplex spinifera*), a species that once dominated a large portion of valley floor [30], was found in just a single valley-floor site within the collecting radius (Figure 8).

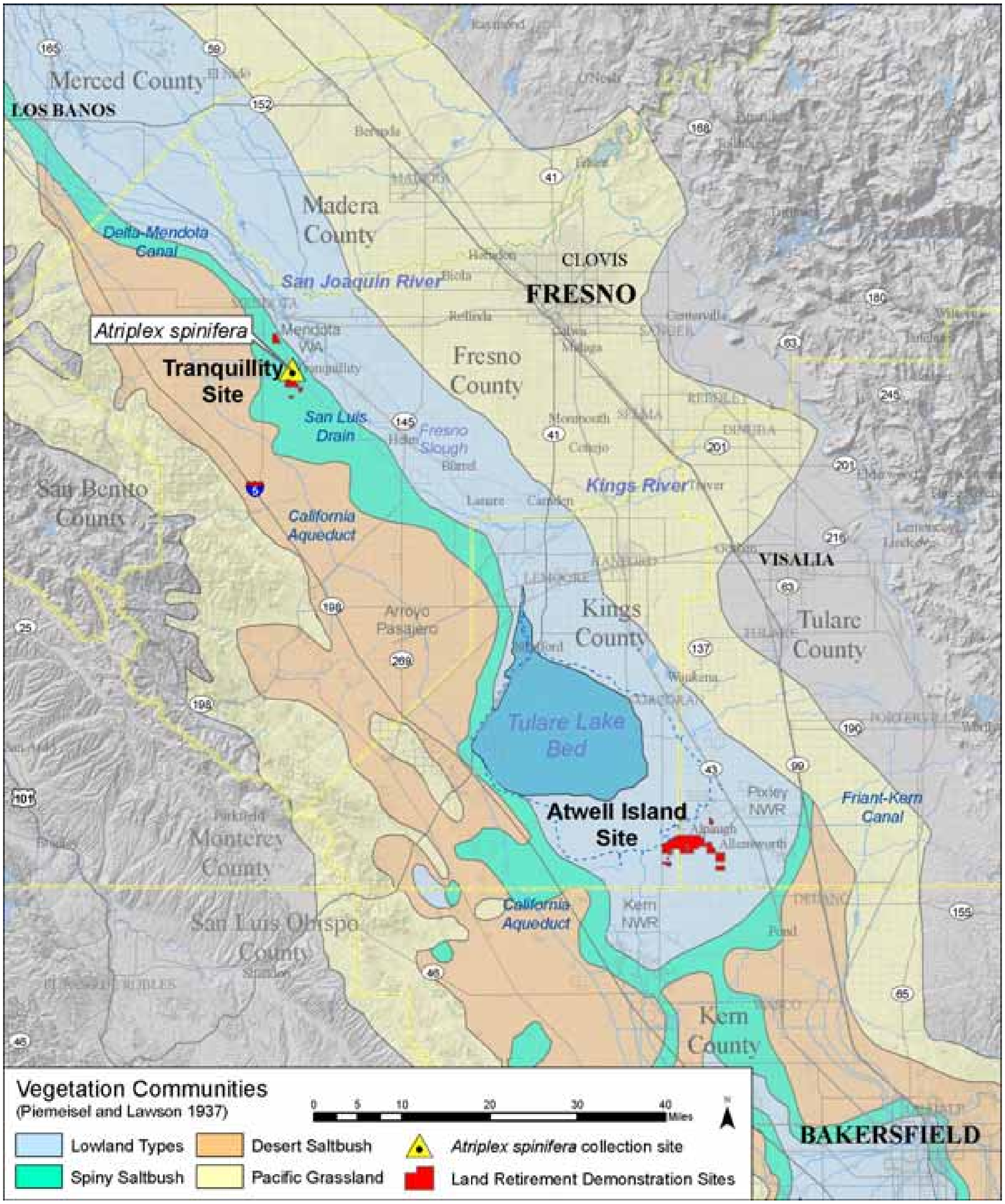

Figure 8. Vegetation of the San Joaquin Valley in the early 20th century (1937). The yellow area indicates the area dominated by *Atriplex spinifera* (spiny saltbush). The red dot indicates our sole valley-floor site for this species. The vegetation map is based on data from Piemeisel and Lawson [30].

Undoubtedly, many additional species and populations exist within the study area. Nevertheless, the activities outlined here represent a significant effort, and it is clear that any large-scale restoration efforts will be undertaken with a greatly reduced pallet of species.

As noted, many of the collecting areas are quite limited in area. Furthermore, a large portion of the collecting areas represent habitats that are vulnerable to human disturbance (e.g., roadsides, road cut-banks, the borders of evaporation ponds, etc.). The collecting area shown in Figure 9 clearly is subject to frequent perturbation, and would not likely be identified as an area that was contributing to the continuance of the Valley's flora.

Figure 9. ESRP Biologist Foung Vang collecting seed from the bank of a former evaporation pond.

Nevertheless, we have noted seven native species at this site, including one State Listed species (Lost Hills crownscale; *Atriplex vallicola*), as well as cupped monolopia (*Monolopia major*), a species that we have encountered in just one other valley-floor site.

A Native Species Seed Production Facility (NPSPF; Figure 10) was established at the Tranquillity project site in the fall of 2000. Initially, the NPSPF occupied 2 ac (0.8 ha); current size is 8.9 ac (3.6 ha).

Figure 10. The northern end of the NPSPF, showing beds of established perennial species.

The NPSPF was established with the following objectives: 1) to aid in the conservation of the remaining native flora; 2) to amplify stocks of locally-collected seed, i.e., to become a source of "foundation seed" for future restoration efforts; 3) to increase the number of species available for use in restoration; 4) to provide an accessible setting for tours, educational activities, and other forms of outreach; and, 5) to provide an on-site laboratory, where investigations of species' requirements can be conducted.

The NPSPF has developed into a unique repository of local genotypes of native species, one which should serve as a foundation for the seed requirements for proposed restoration activities. Since its inception, over 100 species of native plants have been cultivated in the NPSPF. In order to accommodate (i.e., dry, clean, and store) the seed produced in the NPSPF, and from 'wild' collections, an approximately 1500 ft² (139 m²) seed processing facility and warehouse was established in 2003. Since that time, a variety of seed processing equipment has been purchased and/or constructed, and the building has been "outfitted" (e.g. dust-collecting equipment has been installed, shelving has been built, etc., Figure 11).

Figure 11. The Seed Processing Facility, showing a portion of the seed-cleaning equipment. The large machine to the left is a Clipper

IRRIGATION

Rainfall is the most limiting factor in SJV ecosystems. This observation is concurrent with what has generally been observed for California lowland ecosystems [20,23,26]. Therefore, it is not surprising that precipitation has been identified as a major limiting factor in restoration efforts in lowland California and in other arid and semi-arid areas [3,15,16,47].

Although competition from weeds may generally be more limiting than irrigation in restoration of SJV ecosystems, there is no doubt that the amount and timing of precipitation plays a major role in restoration efforts. Irrigation can potentially be used to overcome the limitations associated with precipitation in the SJV. Nevertheless, irrigation has clearly proven itself to be a “dual-edged sword” in restoration efforts at the Tranquillity project site.

Some efforts have benefited greatly from irrigation. For example, the abundance of seeded species in some of the irrigated hedgerows that were installed at the Tranquillity project site clearly surpassed that of any non-irrigated efforts. Likewise, a number of species that have proved very difficult to establish through direct seeding in non-irrigated applications (e.g., iodine bush — *Allenrolfea occidentalis*; alkali heather — *Frankenia salina*) have done extremely well when grown in the irrigated Native Plant Seed Production Facility (NPSPF). It should be noted that because extensive weeding is conducted at the NPSPF, it is not possible to completely attribute the performance of species solely to water availability, as the seeded species are also relatively free from interspecific competition.

On the other hand, irrigation clearly benefits the non-seeded species. A striking example can be seen in the Berm & Mycorrhiza Trial (Figure 12). In this trial, it was only feasible to supply irrigation to four of the five replicates. The non-irrigated plots had virtually no vegetation establishment Figure 12-A). In contrast, many of the seeded species were observed to have germinated in the sprinkler-irrigated plot. However, these plots were characterized by a near continuous cover of non-native species (Figure 12-B). Consequently, only a small number of individuals of the seeded species were able to grow to maturity. A similar situation was observed in the Suitability Trial, which was conducted during the same year and was also sprinkler irrigated. In this trial, the percent cover of three of the six seeded species was above 10% at the time of monitoring (late spring), with the cover of one of these approaching nearly 20%. However, as with the Berm & Mycorrhiza trial, the irrigation facilitated the growth of weeds, and these subsequently overtopped and displaced the seeded species.

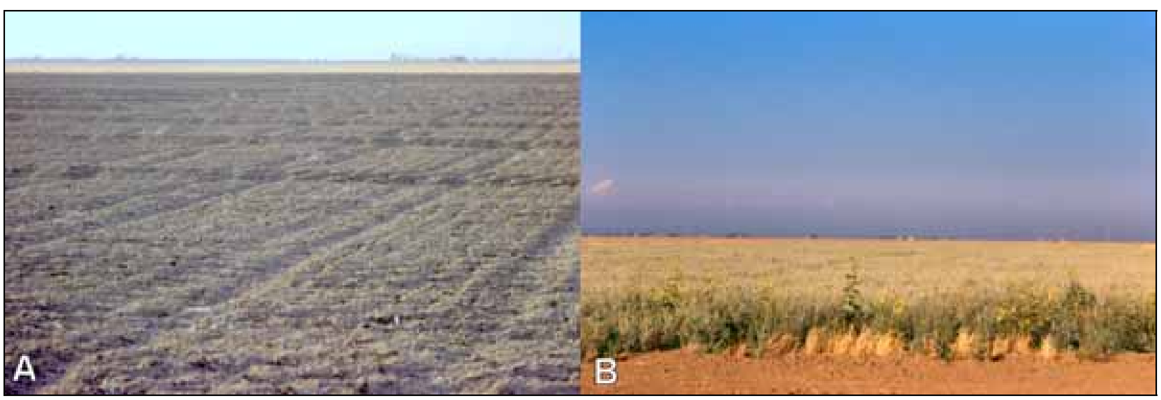

Figure 12. Comparison between non-irrigated (A) and irrigated (B) portions of the Berm & Mycorrhiza Trial.

SEEDING TECHNIQUE

Three mechanical seeding approaches have been utilized in restoration efforts at the Tranquillity LRDP site: drilling, imprinting, and “cultipacking” (Table 2). Each of the machines utilized for the three methods was equipped with multiple, specialized seed boxes designed to hold, agitate, and deliver seed in individual boxes according to seed size; shape; weight; and amount of hairs, awns or chaff (i.e., inert material). The experimental plot drill that was utilized in a number of the trials was also equipped to accurately meter and uniformly place small to minute quantities of seed in a small-plot setting.

In two of the trials, as well as in the attempted restoration of a 160 acre (64.8 ha) portion of the site, transplanting was also utilized as a restoration approach. However, no attempt was made to compare the success of transplanting with direct seeding. Additionally, in a few instances seeding was accomplished using mechanized rotary and manual broadcast seeders followed by harrowing or raking (in order to assure adequate soil:seed contact and cover). As with transplanting activities, no experimental comparisons were made between broadcasting and other seeding methods.

The largest portion of the restoration work (both experimental and applied) at the Tranquillity HRS has utilized imprinting as the seeding method. Imprinting is widely promoted as a seeding method for restoration in arid and semi-arid areas of the western US [see: *11,12,33,38,39,41,42,51*]. In imprinting, funnel-shaped teeth (Figure 13, A) create a series of imprints in the soil (Figure 13, B). These imprints concentrate rainwater, seed, litter, and topsoil, and provide a microhabitat ("micro-catchment") that serves to protect seedlings from sun- and wind-induced desiccation [*11*]. Additionally, soil-to-seed contact is improved via firming of the seedbed surface immediately surrounding the seed.

Figure 13. A. Close-up of the teeth on the LRDP imprinter. B. a series of imprints in the clay soil at the Tranquillity project site.

The results of a number of the restoration studies and related activities at the Tranquillity site do not support the routine use of this seeding technique on predominantly clay soils. A number of issues and observations support this finding. First, there were problems associated with imprinting the soil when it was wet. In one instance—the attempted restoration of the 80 ac (32.4 ha) 'Manning Avenue Parcel'—imprinting was undertaken when the soils {Ciervo clay [*44*]} were somewhat wet (from heavy fog). The sole warning regarding wet clay that we have encountered in the literature came from St. John and Dixon, who advised that imprinting on clay soils should be avoided while the soils were "so wet that substantial quantities of it stick to the roller" [*41, p. 18*]. With the exception of the initial hour, or so, in the morning, conditions during the imprinting of the Manning Avenue Parcel weren't sufficiently wet such that there was much build up of clay on the roller. Nevertheless, the soil was compacted to the degree that it was not possible for us to push a shovel into the soil. Not unexpectedly, germination of both seeded and 'seedbank' species was extremely limited.

A second, and perhaps more critical issue, is that the depressions that are formed by imprinting are unstable in the clay soils of the Tranquillity project site. This instability takes two forms: 1) a fairly brief "persistence"; and, 2) "wash-out". The short persistence of the depressions results from soil slumping, and from sediment deposition accompanying surface water flows during precipitation events.

Wash-out—our term for the formation of deep holes at the base of each depression—has been observed on many of the imprinted areas at Tranquillity. This process may have particularly negative consequences for restoration efforts, as seed which failed to germinate during the initial year of imprinting may be no longer be available for germination beyond the first seeding year.

Our observations at the Tranquillity site suggest that the depressions maintain their form longer, and are more resistant to washout in areas of Ciervo clay, versus those areas with Tranquillity and/or Lillis clay. Additionally, imprinting depressions in the Posochanet silt loam soils [44] of Study Area I at the Atwell Island project site (Figure 14) maintained their form far beyond what was observed at Tranquillity.

Figure 14. An imprint in the soil at the Atwell Island LRDP site (Study Area I). The yellow material in the bottom of the divot is accumulated *Lasthenia californica* "seed" (i.e., seed and floral parts).

During the initial years of the project, ESRP conducted two trials in which imprinting and drilling were compared [45,46]. Results from these trials suggested that the two methods were roughly equivalent, at least under conditions at the Tranquillity site. Nevertheless, as establishment of seeded species was extremely limited in many of the subsequent restoration efforts, the decision was made to undertake additional comparisons of seeding methods.

These investigations were undertaken as a thesis project by CSU Fresno Master's student, Emily Magill (advisor Dr. John Constable) in collaboration with ESRP. In this instance, comparisons were made among three seeding techniques: "broadprinting"; drilling; and, cultipacker-type seeding. Broadprinting is a coined term for a modified form of imprinting in which broadcast seed is worked into the soil using an empty (i.e., without seed) land imprinter. It was necessary to use this approach, rather than feeding the seed through the imprinter hopper, because of limitations associated with imprinting small areas (i.e. small experimental plots). For cultipacker-type seeding, a Truax Pull Type Broadcast Seeder (Model WF-64) was used. We use the term cultipacker-type seeding [(51)] here to clearly distinguish this method from rotary broadcasting. In cultipacker-type seeding, seed is fed from the seed boxes onto a segmented trough which distributes the seed across the width of the seeder (5 ft; 1.5 m). The seed drops from the trough onto the ground and is worked into the soil, first by drag chains and then by a cultipacker drawn behind the seeder. The three seeding techniques were compared using four native species in the first year's trial (2003-04), and among six species in 2004-05. Each species was planted in single-species plots (i.e., no comparisons of seed mixtures were made).

Given our previously noted reservations regarding imprinting on clay soils, we anticipated that both drilling and cultipacker-type seeding might be far superior to imprinting. Although some statistically significant differences were found in some of the comparisons (i.e., for a particular species using a particular technique), the differences in percent cover were generally small, and were not consistent across all species for a particular technique [(25)].

Our restoration research in recent years has primarily been conducted using a commercial grass drill. Drill technology optimizes seed depth placement and soil cover, and potentially minimizes intra-specific and inter-row competition for seeded species. Perhaps most importantly, drilling is well suited for approaches utilizing specialized herbicide application for weed suppression between seeded rows (see section on *Chemical Weed Control*, below).

MODIFIED PLANTING CONDITIONS

Four methods of modified planting conditions were evaluated: furrow depth; row spacing; plant spacing; and, topographic modification. The first two factors were evaluated in a single experiment (the Seed Augmentation and Planting Method Trial; Table 2). Similarly, plant spacing was evaluated in a single trial (the *Atriplex spinifera* Planting Trial; Table 2). Topographic modifications—which entailed the creation of low lying berms —were incorporated into a number of trials (Table 2) and in various restoration efforts.

The Seed Augmentation and Planting Method Trial was conducted during a year (the 2003-04 hydrologic year) in which rainfall was just two-thirds (65.96%) of the 30-year MAP (Figure 15); hence, all our observations of the utility of furrow depth and row spacing are limited to a single soil type, during a particularly dry year.

"Deep furrow" seeding (seed placement in the bottom of furrows created by leading furrow openers on the drill or previous tillage implement) was found to be an unsatisfactory approach under the conditions at the Tranquillity project site. The poor results are thought to be primarily attributable to the high amount of clods and deeper soil cover over seeds within the linear "micro-seedbed" in the bottom of the furrows created in these tight clay soils. Smoothing or breaking of the clods in the furrow bottoms by common "picker wheel" or "clod breaker" implements prior to seeding may provide more positive results for these mechanical treatments, as evidenced by pockets of high germination and emergence of seeded species where deposition of soil fines induced by precipitation runoff occurred within the furrows. The poor results from the furrowed treatments was in contrast to prior research indicating that furrowing is most consistently successful on fine and medium soils [(49)]. It is our opinion that the concept and theory of deep-furrow seeding still holds promise for enhanced moisture capture, amelioration of environmental extremes at the soil surface, and thus species establishment, if clods can indeed be minimized in the furrow bottoms.

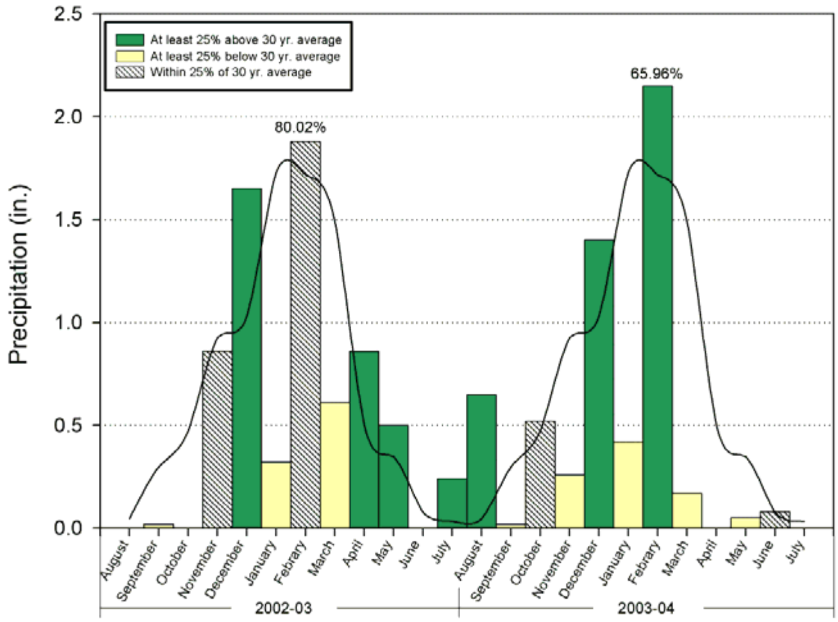

Figure 15. Precipitation at Tranquillity, CA during the 2002-03 and 2003-04 hydrologic years (August, 2002 through July, 2004).

The ability to discern the effect of row spacing on plant establishment was similarly compromised by the poor growing conditions during the Seed Augmentation and Planting Methods Trial. In all subsequent restoration activities in which a plot drill was used, we have relied on a 12 in (30.5 cm) row spacing (i.e., the closest possible spacing for that particular drill).

Investigations of the effects of plant spacing (i.e., the distance between transplanted seedlings) on establishment were similarly unrevealing. In the trial in which this factor was evaluated (the *Atriplex spinifera* Planting Trial), any effects of plant spacing were overridden by other factors (e.g., herbivory, fire, site heterogeneity, and vehicle damage from maintenance activities on the adjacent irrigation canal). In particular, the fire that burned this area was particularly important, in that it killed the majority of the shrubs before they had reached a size in which the effects of plant spacing would be expected to be evident (i.e., before the onset of competition between individuals).

Topographic modification, or “berming”, was easily the most confounding of factors examined during our work at the Tranquillity site. In some instances native species establishment was clearly positively correlated with berms and their adjacent trenches; while in other instances there was a clear negative correlation between berms and establishment. Both patterns were most strongly evidenced in shrubs. A clear example of a negative correlation can be seen in the Section 23 Restoration Trial (Figure 16). In this instance, shrub establishment was extremely successful in the "flats" (i.e., the areas between the berms), while shrub establishment on the berms and trenches was rare (Figure 16).

Figure 16. Shrub establishment in the Section 23 Restoration Trial. The arrow points to the center most berm in the photograph. The lighter green shrubs are allscale saltbush (*Atriplex polycarpa*); the dark green shrubs, which are more abundant towards the far end of the area, are bush seepweed (*Suaeda moquinii*).

At times (e.g., the Tranquillity HRS plots and restoration efforts on the North Avenue Parcel) the positive correlation appears to have been attributable to increased water availability (in the trenches) and perhaps to a reduced seed bank in the bermed soil. The factors contributing to a negative correlation are less certain, but it seems likely to be associated with particular weeds having a competitive advantage on the berms.

NON-CHEMICAL WEED CONTROL

In all cases, the non-chemical weed control methods that were evaluated (pre-irrigation, mowing, and burning; Table 2) were not sufficient to overcome the weed load at the Tranquillity project site. Furthermore, in one trial (the Section 10 Burning and Mowing Trial) two of these techniques were combined, again to relatively little effect.

However, it should be noted that in all trials in which the primary focus was mechanical weed control, treatments were only applied once, and no trials were continued beyond their initial year. In two of the three trials in which mowing was evaluated (the aforementioned trial and the Mowing Trial; Table 2), it was intended that each trial would be mowed multiple times throughout the growing season. However, conditions during that particular hydrologic year (2002-03) were extremely dry. Plant growth was such during that year that the weeds did not grow much after the initial mowing; hence, additional mowing was unwarranted.

Mowing may also serve as a surrogate for grazing, and thus enable the estimation of the potential for grazing as a weed control method in restoration efforts. Given the previously discussed findings, our investigations of mowing were insufficient to allow such a comparison. Nevertheless, although we have not conducted any formal experimental investigations of grazing, ESRP has been incorporating sheep grazing as a management tool for the Tranquillity project site for the last two years (i.e., the 2004-05 and 2005-06 hydrologic years). However, no formal tests were conducted to evaluate the relationship between grazing and the establishment of native plants.

Two approaches were taken to examine the utility of burning in restoration: 1) seeding areas of the site that had undergone “unplanned” burns (i.e., either through arson or by accident); and, 2) burning with an agricultural flamer (Figure 17). The experiment in which a recently burned area was seeded with native species (the Section 10 Burn and Mowing Trial; Table 2), showed little promise as a restoration approach. However, as the fire had occurred during the dry season of the preceding hydrologic year, the timing was such that the red brome—which dominated the burned area—had already produced seed during that growing season.

Figure 17. Flaming with an agricultural flamer on the Native Release Trial (2004-05 growing season).

An agricultural flamer was used in one formal experiment (the Native Release Trial; Table 2; Figure 17), and was also frequently used for weed control in the Native Plant Nursery. The Native Release trial was developed in order to examine the possibility of promoting germination of native seed in the seed bank by reducing competition from weeds (using burning, mowing, and two post-emergent herbicides). Plots were situated in an area that formerly supported a large population of snakes head (*Malacothrix coulteri*). The treatments were applied early in the season, after the dominant red brome had germinated, but before the snakes head had germinated. In this instance, flaming appeared to do little to facilitate the establishment of native species from the seedbank. We attribute this poor response to difficulties in controlling the intensity of burning when using a handheld flamer. A tractor-drawn flamer would likely afford more uniform, temperature-controlled suppression.

Pre-irrigation, the final “non-chemical” weed control method, is a technique in which an area is irrigated prior to the onset of the winter rains, with intent to stimulate weed germination. The weeds are then suppressed by various mechanical methods (e.g., disking), and the area is then seeded. Pre-irrigation appeared to be particularly unsuited for conditions at the Tranquillity HRS site. In essence, a single year's application of this approach did little but stimulate weed growth. Given the costs associated with this approach, as well as the infrastructural difficulties associated with providing large-scale irrigation, this approach is not recommended as a component of any "herbicide-free" restoration strategy for the SJV. Nevertheless, pre-irrigation could conceivably be used in conjunction with various herbicide treatments, if time constraints necessitated that an area be seeded before the onset of the winter rains.

CHEMICAL WEED CONTROL

Chemical weed control trials at the Tranquillity project site have utilized both pre- and post-emergent herbicides (Table 2). One trial—the Herbicide and Growth-form Trial—was focused exclusively on post-emergent herbicides, with chemical treatments targeted to suppress either grasses, broad-leaved species (forbs), or both, and with treatment-specific seed mixtures (i.e., mixtures composed of species that would be minimally affected by the herbicide applied to that particular treatment). Although this type of approach is common in restoration, conditions at the experimental area (specifically, the agricultural history of Section 23) were such that both grasses and broad-leaved weeds were well represented in the weed seed bank. Hence, when a grass-specific herbicide was applied, the plots were subsequently dominated by broad-leaved weeds (primarily *Brassica nigra*; Figure 18). Likewise, when a herbicide selective for broad-leaf species was applied, the plots were soon dominated by the non-native grass *Phalaris minor*.

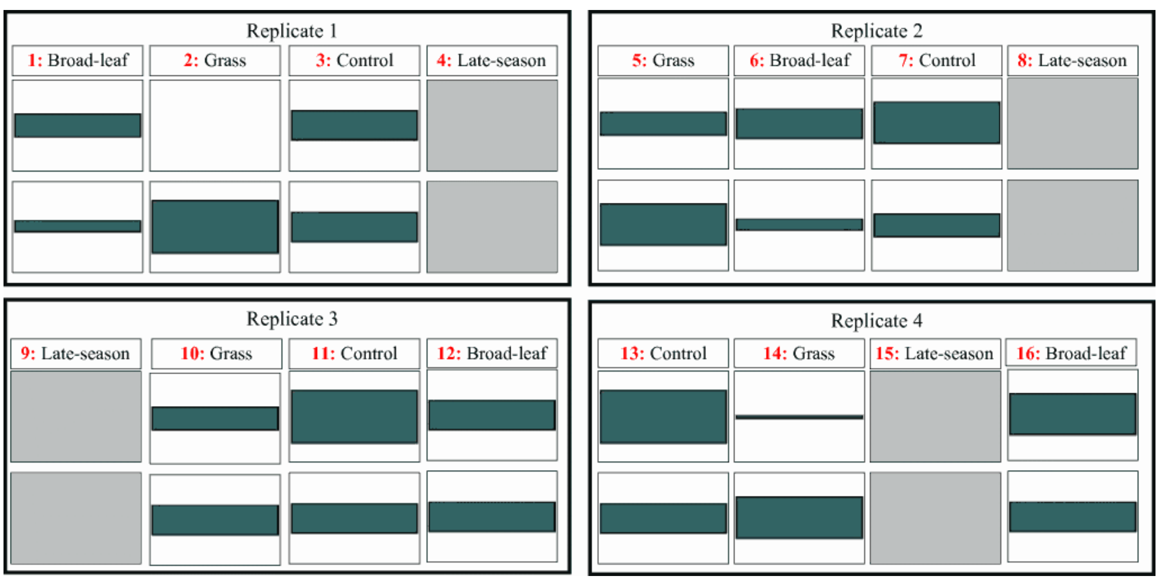

Figure 18. Graphical representation of the abundances (percent cover) of *Brassica nigra* (the upper half of each plot), and *Phalaris minor* (the lower half of each plot). The thickness of the bar is proportional to the abundance of the species on that plot. Plots shown in gray are those that were sprayed with Roundup (i.e., plots from which these two species had been controlled).

The treatment that showed the most promise was an application of a broad-spectrum herbicide (e.g., glyphosate) after the early-season weeds were well-developed. In this treatment, the plots had been seeded with a mixture of late-germinating native species. Although this approach was hopeful, the restoration response was not consistent across replicates. More importantly, precipitation during that year (the 2002-03 hydrologic year) was such that an unusually large amount of rain fell late in the growing season (Figure 15); hence, there was undoubtedly more moisture available for the late-germinating species than would be found in most years.

In the past two years of the project, our research focus has been centered on the use of pre-emergent herbicides (i.e., those exhibiting residual activity in the soil and absorbed via weed roots, often with concurrent foliar contact activity by the same chemical). Herbicide selection was problematic as various herbicides considered for these trials either exhibited activity on the seeded species, or insufficient information was available regarding the effects of the herbicides on these species. Therefore, the pre-emergent herbicides have been applied in conjunction with activated charcoal. The banded charcoal protects the seeded species within the drill row from the subsequently broadcast pre-emergent herbicides ("safening"). This approach is common in the ryegrass and turfgrass seed industries, and is being evaluated for adaptation to seeding of native species.

In the first-year's investigation of this technique (the Manning Avenue trial; Table 2), we compared two methods of applying the charcoal: "banding", in which a charcoal slurry band [approximately 3 inch (7.5 cm) width] is sprayed over the seed row (Figure 19), and "incorporating", in which the charcoal in dry powdered form was incorporated into the seed row in a similar band. Results from this trial indicated that both methods were approximately equal in ability to protect the native seed from herbicide injury within the applied band. Since that initial trial, we have relied exclusively on wet slurry banding for applying the charcoal because of its relatively simpler and more efficient field application.

Results from the first year's Herbicide and Charcoal Treatment Trial were quite promising, with three of the five herbicides [Landmark MP™ (chlorsulfuron + sulfometuron methyl), Telar DF™, and Goal 2XL™ (chlorsulfuron)] demonstrating good to excellent weed suppression. Chlorsulfuron + sulfometuron methyl was particularly effective at suppressing all species, although seeded native species also incurred injury, reducing their emergence and vigor. However, there were also indications that a reduced application rate would still control weeds while allowing seeded species to avoid injury and become established.

In the second year's research with pre-emergent herbicides, we attempted to "fine tune" herbicide application rates, addressing refinement of these techniques for restoration applications. The largest impediment involved the incursion of weed seeds into the drill row. Specifically, the seed of various exotic species (primarily foxtail barley and red brome) was abundant on the soil surface and in the existing grass thatch. A portion of this seed fell into the furrows during drilling and was sprayed with the charcoal slurry (and, hence protected from the effects of the herbicide). As a result, the initial growth on the study plots resembled a series of "mohawks", with the non-native grasses forming dense strips. An approach involving the pre-emergent herbicide and charcoal, preceded by a broad-spectrum pre-treatment (e.g., glyphosate) appears to be very promising. Perennial species on the first year's trial have continued to flourish. Bush seepweed (*Suaeda moquinii*) has done particularly well, with numerous propagules having become established in a number of plots.

Figure 19. Applying the treatments (seed, herbicide, and charcoal banding) on the North Avenue Herbicide and Charcoal Treatment Trial – 2005.

SEED-RELATED FACTORS

This heading is used to group a broad variety of factors (Table 2): comparisons of seed mixtures, various amendments to the soil rhizosphere, and the use of nurse crops and cover crops. Under the heading of "seed mixture comparisons" we include both those activities where multi-species mixtures were compared, as well as those trials where comparisons were made among a suite of individual species. A few broad observations can be made. Generally, the most successfully established species were either early successional species and/or "weedy" natives (e.g., *Atriplex polycarpa, Isocoma acradenia,* and *Hemizonia pungens*). Some species were extremely variable in their establishment success. For example, *Atriplex polycarpa* was very successfully established in the Section 23 Restoration Trial, and did well in the HRS plots at both Tranquillity and Atwell Island. In contrast, this species had little success in both Herbicide and Charcoal Treatment Trials, as well as in the two Planting Technique trials in which it was used. Most often, only a few species in the multi-species mixtures were able to become successfully established. Frequently, it was clear that the poor performance of the unsuccessful species could not be attributed to competition with the other seeded species (e.g., in single species applications). Rather, the unsuccessful native species were likely suppressed by non-native species.

Under the heading of "rhizosphere augmentation" we include salt-remediation products, seed coatings, and mycorrhizae. Soil rhizosphere augmentation using salt-remediation products (HydraHume™), or polyacrylamide polymer (incorporated in seed coatings) did not appear to provide immediate or long-term benefits for native species establishment. However, it should be noted that these factors were investigated in a single trial (the aforementioned Seed Augmentation and Planting Methods Trial).

The sole trial in which mycorrhizal additions were examined was the Berm and Mycorrhiza Trial (Table 2). Although there was a fair amount of heterogeneity in the establishment of the seeded species, the over-riding dominance of weeds, in particular the "tumbling saltbushes" (Figure 12-B) precluded discernment of any treatment effect. Some research has indicated that restoration of abandoned agricultural fields can be enhanced by mycorrhizal additions (*32*). Nevertheless, it is uncertain that mycorrhiza are limiting at the Tranquillity project site. During the initial stages of the project, the site was visited by restoration and mycorhhizae specialist, Dr. Ted St. John. His evaluation was that the soils were not deficient in mycorrhiza. Additionally, a significant portion of the species that we have targeted as priority species in restoration efforts are members of the Chenopodiaceae—a plant family that in almost all known cases does not have strong associations with mycorrhiza.

An additional potential rhizosphere augmentation, the application of fertilizers, was examined in the Seed Augmentation and Planting Method Trial. In this trial, phosphate fertilizer was applied because of the predominance of forbs and shrubs in the suite of seeded species evaluated. No differences in response to any of the seed (rhizosphere) augmentation treatments were detected for *Lasthenia chrysantha*. However, *Phacelia ciliata* displayed a highly significant ($P<0.01$), positive response to addition of phosphate (PO_4) fertilizer alone, while other treatments [coated seed with PO_4; HydraHume + PO_4; and no augmentation (control standard)] were similarly poorer in effect. Nevertheless, as noted in the discussion of nitrogen deposition, it seems most likely that restoration efforts will be hampered by elevated nutrient levels, rather than nutrient deficiencies.

Interim planting of dryland barley (*Hordeum vulgare*) cover crops appears to provide suitable temporary cover during the growing season for site protection and weed suppression during field non-use periods while awaiting restoration. Barley seeded at standard agronomic seeding rates has been shown to be effective in temporary (seasonal or annual) suppression of the majority of annual and perennial weeds during years with precipitation amounts and timing at, or near, long-term annual and seasonal means. However, as we witnessed during the very wet 2004-05 hydrologic year (Figure 3), weeds (particularly the annual mustards) may still dominate in excessively wet years, even amid uniform agronomic stands of seeded barley. Grazing (preferably) or tillage, may be required for interim weed suppression between barley harvest and seeding of the following year's crop, in order to address the problem of late-season weed species. Use of a barley nurse crop in alternate rows with seeded natives appeared to aid establishment in the Seed Augmentation and Planting Methods Trial (Figure 20). In theory, the barley should ameliorate environmental extremes (heat, wind, low moisture) at the soil surface for the new seeding, and provide at least limited suppression of weeds. The alternate barley rows serve, in essence, as a nurse crop for seeded natives, with row spacing sufficiently wide (minimum 12 inches; 30.5 cm) to minimize inter-specific competition between adjacent rows.

Results from 2004 data indicate that goldfields (*Lasthenia chrysantha*) and Great Valley phacelia (*Phacelia ciliata*) exhibit a highly significant ($P<0.0001$) and similar planting method effect. Standard drilling (non-deep furrow) with alternate barley nurse crop rows on 12-inch (30 cm) centers showed highest establishment of these two species. Standard drilling on 12-inch centers without barley nurse crop ranked second in establishment, while both deep-furrow drilling treatments (4-inch [10 cm] and 8-inch [20 cm]) exhibited similarly poor establishment.

Figure 20. Goldfields (*Lasthenia chrysantha*, the orange-flowered species) interplanted with barley in the Seed Augmentation and Planting Methods trial.

CONCLUSIONS

Some general patterns can be easily discerned from our restoration research at Tranquillity and Atwell Island. The most obvious pattern is the variability in response among the same treatment when tried in different locations, or in different years. A striking example can be seen in ESRP's work at the Atwell Island HRS (Figure 21). The HRS is composed of three study areas, each of which contains sixteen, 2-acre (0.8 ha) test plots. The study areas all received the same experimental treatments, and are separated by just 3.5 miles (5.6 km). On two of the study areas, native species establishment was extremely poor (Figure 21-A, B), while restoration on the third study area was very successful (Figure 21-C). This is just one of many such examples, but it should serve to emphasize a critical consideration: namely, that it is important to consider this type of intrinsic variability (i.e., unpredictability) when evaluating restoration efforts.

Figure 21. Differences in restoration response among the three study areas of the Atwell Island HRS. A. Study Area 3; B. Study Area 2; C. Study Area 1.

The pronounced year-to-year variability in both the timing and amount of precipitation is also extremely problematic. It is common to find references in the literature to restoration in arid and semi-arid regions being best undertaken during "suitable years" [*2,8,16,47*]. However, given the unpredictability of precipitation in the SJV, there can be little certainty in attempting to anticipate whether or not a particular year might be suitable. For example, one trial (the Section 23 Restoration Trial) was developed to compare a particular seed mixture that had been imprinted during a relatively dry year (1999-2000; 58.1% MAP) with what was predicted to be a wet year (2002-03). Mild El Niño conditions had been predicted for 2002-03; however, precipitation was just 80.0% of MAP.

A second prevalent pattern is that competition from weeds will most likely be the primary impediment to successful restoration, at least during all but the driest years and/or in the driest areas. Although some restoration approaches utilizing fairly minimal weed control methods have been reasonably successful (e.g., Study Area 1 at the Atwell Island HRS;

Figure 21-C), it seems inescapable that successful restoration strategies will frequently need to incorporate some form of chemical weed control.

In addition to issues attendant upon non-native plants, restoration at the Tranquillity site has been severely impacted by insect pests. The most severe problems have been from false chinch bugs *Nysius* sp.). These insects occur in large swarms, and can quickly cover vegetation (Figure 22). As these outbreaks generally occur during the dry season, the greatest portion of the vegetation on the lands surrounding the Tranquillity sites has already senesced, and the native perennial species on the LRDP appears to be a favored "target".

Figure 22. False chinch bugs (*Nysius* sp.) feeding on *Atriplex* spp.

Although severe infestations have not occurred during all years of the project, during most years there has been at least one area of the Tranquillity site that has been severely impacted. In extreme cases, false chinch bug damage has resulted in the death of most of the native species in some of these areas.

We have successfully combated these outbreaks on a small scale using Malathion™; however, fairly constant monitoring (i.e., weekly site visits) has been required in order to be able to begin control measures before extensive damage occurs. Fortunately, these species have not yet been a problem at the Atwell Island HRS. Nevertheless, if conditions at Tranquillity are representative for the majority of the drainage-impacted lands, then pest control will undoubtedly be an essential component of any restoration activities.

Another broad observation is that, at least insomuch as conditions at the Tranquillity HRS represent typical conditions on the remainder of the drainage-impaired lands, the existing seed bank will generally contribute little to the restoration of retired lands. In the six years following the installation of the HRS study at Tranquillity, few non-seeded native species have been observed on the HRS plots, and these have generally been in low abundance. A partial exception is Great Valley Phacelia (*Phacelia ciliata*), which in wetter years has been fairly abundant on the most saline and longest-fallowed area of the Tranquillity HRS.

RECOMMENDATIONS

GENERAL NEEDS

Significant progress has been made through the course of research funded via LRP-CVPIA in terms of developing and refining techniques for use in land restoration prescriptions for LRDP lands, particularly in terms of native species selection and site adaptation, planting methods, and weed suppression.

Weed management (suppression, control, or eradication, as applicable on a site-by-site basis) is, and will continue to be the overriding limitation to successful restoration of native plant communities on LRDP retired (dewatered) lands. Probability is high that site restoration can be accomplished within 3-5 years of seeding on most sites, **if** weed suppression can be adequately planned, implemented and sustained through the establishment period, and if any necessary insect control measures are applied. Site restoration in this context is herein defined as establishment of a self-sustaining, native plant community having desirable values for wildlife habitat, site stabilization and erosion control, and weed suppression. Restoration of these lands is extremely problematic because of immediate encroachment upon cessation of cropping of:

1. annual grasses (e.g., *Bromus madritensis, Hordeum* spp., *Avena* spp.);
2. perennial grasses (e.g., *Lolium perenne*)
3. annual broadleaf herbs (e.g., *Brassica, Sisymbrium, Bassia,* and *Atriplex* spp.);
4. perennial broadleaf herbs (e.g., *Acroptilon repens*).

Fully integrated weed management strategies incorporating an array of techniques (chemical, mechanical, cultural, pyric, and biological) will be needed that address weed suppression needs over the duration of native species establishment periods (3-5 years). Single-year or single-technique approaches will typically be insufficient to suppress weeds to the point that establishing native vegetation can sustain itself and provide intrinsic weed suppression as a result.

Second only to weed management as a primary concern in native plant community establishment is moisture conservation. As noted, the semi-arid environment of the western San Joaquin Valley is characterized by long-term mean annual precipitation less than 10 inches (25 cm) and fine-textured soils (clays, clay loams) exhibiting high matric potential (retention) and slow release rates for plant root uptake. As a result, moisture capture and conservation assumes equally paramount importance for successful revegetation. Traditional as well as innovative measures for moisture conservation must be employed integrally with seedbed preparation and/or seeding applications, including amelioration of both environmental and anthropogenic moisture depletion impacts. These practices may include (as examples): mulches, stubble residue cover crops, live cover crops, and/or nurse crops. Examples include salt-tolerant varieties of common barley (*Hordeum vulgare*); salt-tolerant varieties of grain, forage or sudan sorghums (*Sorghum* spp.) or millets (*Panicum miliaceum*); "wind barrier" rows or strips of dryland-adapted, salt-tolerant perennial grasses alternating with blocks of seeded native mixtures, initially established under limited irrigation (e.g., tall wheatgrass, *Elytrigia elongata*; creeping wildrye, *Leymus triticoides*).

1. soil surface roughening to reduce effects of wind, including coarse disking, ripping, chiseling or plowing;
2. artificial, designed micro-relief (depressions) for moisture capture, including contour berms and associated borrow areas, contour furrowing, land imprinting (on suitable soils), deep-furrow seed drilling, pitter-seeding, etc; and,
3. similar biotic and/or abiotic measures that combine moisture capture and conservation (retention) with weed suppression capabilities.

These practices, however, must be applied within the practical context of routinely available or easily modifiable tillage, seedbed preparation, and seeding equipment and seed materials in order to remain cost-effective. These practices are primarily intended for application during non-use periods (i.e., no seeding or crop production) as measures to be temporally and spatially integrated (i.e., alternatively rotated) with routine tillage, herbicide application, and/or grazing in order to reduce weed load prior to subsequent restoration seeding.

SPECIES SELECTION

Seeded plant communities on LRDP lands restored to native plant communities will be characterized by dominance of shrub / forb associations, with native grass establishment as a minor component. These associations, growth forms and life histories ecologically and botanically: a) correspond to realistic capabilities on formerly irrigated agronomic fields and soils; and b) approach reference plant communities and habitats within the western San Joaquin Valley (e.g., Alkali Sink Ecological Reserve) that have been recognized as exhibiting desirable habitat values for targeted species (T&E species, as well as other, more common components of the fauna), site stability, and weed suppression.

Species selection and mixture formulation has been refined over the duration of LRDP research and demonstration studies. Numerous species (see Table 2 and Table 3) have been collected and evaluated for utility in the LRDP in terms of desirable traits, meeting adaptation criteria such as:

1. seed source
   - first preference / priority – endemic to west-central San Joaquin Valley
   - second preference / priority – endemic to southern San Joaquin Valley
   - third preference / priority – endemic to southern California sites of similar soils, elevation and climate
2. ease of establishment in field situations characteristic of lands enrolled in the LRDP
   - high germination, seedling vigor and sustainability
   - practical seedbed preparation and seeding methods for field establishment
3. suppression of / resistance to / tolerance of weed competition
4. reproductive success (sexually - seed production; asexually – vegetative spread by tillering, sprouting, root extension)
5. favorable pollination requirements

6. insect and disease resistance
7. ease of seed harvest, cleaning, conditioning, processing, viability testing and storage – utilizing mechanized and/or seed industry standard methods wherever possible
8. availability and quantity (commercial stocks and non-commercial harvest)
9. forage quality (palatability, lack of phytotoxins, etc.)

Many species exhibit successful characteristics of germination, seedling growth, establishment and productivity under irrigated or otherwise intensively managed conditions. Only a subset of these species, however, satisfy the adaptation criteria above within the context of adaptation to non-irrigated, highly disturbed, saline/sodic, weed-infested field sites characteristic of the vast majority of agronomic fields likely to be retired from irrigated agriculture. In addition to adaptation to these field growth conditions, an equally important factor is cost-effectiveness in light of programmatic budget constraints. This places emphasis on commercial availability of a significant proportion of the recommended species, particularly for local ecotypes of perennial shrubs and grasses known to be commercially available in most years (i.e., California southern Central Valley generally; western San Joaquin Valley specifically). Recommended seed mixtures that rely more heavily on shrub, forb or grass species that: a) are not commercially available; b) are characterized by reduced (often infrequent and dispersed) field populations; and/or, c) require manual (i.e., non-mechanized), often specialized techniques for seed collection, cleaning, conditioning, storage or viability testing will inflate vegetation costs significantly.

The following recommendations reflect LRDP field research study and nursery results; extensive literature review; consultation with academia, professional organizations, commercial firms, and individuals expert in revegetation science within the San Joaquin Valley; and the authors' professional judgment. These species (as well as additional species listed in Table 2 and Table 3) meet the majority of adaptation criteria for desirable native plants, and are recommended to form the core or key set of species from which to formulate individual seed mixtures that are adapted and tailored to specific site (field) and environmental conditions across the western San Joaquin Valley.

Individual seed mixtures, reflecting variable proportions of shrubs, forbs and grasses, will be specifically formulated to address varying field conditions and environmental constraints imposed on a site-by-site basis. These environmental constraints, however, are anticipated to occur predominantly within four generalized physiognomic regimes, based primarily on soil moisture and salinity limitations. Within these four regimes, species selection would be further guided and constrained by overriding objectives of: a) rapid establishment, enabling site stabilization and weed suppression in the establishment year(s); b) achievement of species diversity, structure, function and abundance that approaches or meets ecological and botanical habitat requirements and goals; and, c) cost-effectiveness, with priority on species having current commercial availability of desired local ecotypes. Generally described, these physiognomic regimes include:

1. Predominantly mesic, less saline/sodic sites receiving sub-irrigation from ditch, canal or reservoir seepage.
   - Conceptual example: higher proportion of grasses and annual / perennial forbs; decreased proportion of Chenopod shrubs and forbs

Species	**Common Name**	**Family**	**Life-form**
Astragalus asymmetricus	San Joaquin milkvetch	Fabaceae	perennial herb
Distichlis spicata	inland saltgrass	Poaceae	perennial grass
Frankenia salina	alkali heath	Frankeniaceae	perennial herb
Heliotropium curassavicum	seaside heliotrope	Boraginaceae	perennial herb
Isomeris arborea	bladderpod	Capparidaceae	shrub
Lasthenia chrysantha	alkali goldfields	Asteraceae	annual herb
Layia glandulosa	white layia	Asteraceae	annual herb
Leymus triticoides	creeping wildrye	Poaceae	perennial grass
Phacelia ciliata	Great Valley phacelia	Hydrophyllaceae	annual herb
Sporobolus airoides	alkali sacaton	Poaceae	perennial grass
Trichostema ovatum	San Joaquin bluecurls	Lamiaceae	annual herb

2. Ephemeral mesic, highly saline/sodic sites receiving designed surface flows or point-source inundation of saline tailwater (e.g., evaporation ponds).
   - Conceptual example: higher proportion of halophytic Chenopod species (e.g., *Allenrolfea*, *Suaeda*); no grasses

Species	**Common Name**	**Family**	**Life-form**
Allenrolfea occidentalis	iodinebush	Chenopodiaceae	shrub
Amsinckia vernicosa	green fiddleneck	Boraginaceae	annual herb
Atriplex lentiformis	quailbush	Chenopodiaceae	shrub
Heliotropium curassavicum	seaside heliotrope	Boraginaceae	perennial herb
Hemizonia pungens	common spikeweed	Asteraceae	annual herb
Hutchinsia procumbens	prostrate Hutchinsia	Brassicaceae	annual herb
Kochia californica	rusty molly	Chenopodiaceae	shrub
Suaeda moquinii	bush seepweed	Chenopodiaceae	perennial herb

3. Arid, moderately to highly saline/sodic sites.
   - Conceptual example: mixture of shrubs, forbs and grasses; emphasis on more halophytic species

Species	**Common Name**	**Family**	**Life-form**
Allenrolfea occidentalis	iodinebush	Chenopodiaceae	shrub
Amsinckia vernicosa	green fiddleneck	Boraginaceae	annual herb
Atriplex polycarpa	allscale saltbush	Chenopodiaceae	shrub
Grindelia camporum	gumplant	Asteraceae	perennial herb
Gutierrezia californica	California matchweed	Asteraceae	subshrub
Hemizonia pungens	common spikeweed	Asteraceae	annual herb
Hordeum depressum	alkali barley	Poaceae	annual herb
Isocoma acradenia	goldenbush	Asteraceae	shrub
Lasthenia chrysantha	alkali goldfields	Asteraceae	annual herb
Layia glandulosa	white layia	Asteraceae	annual herb
Phacelia ciliata	Great Valley phacelia	Hydrophyllaceae	annual herb
Sesuvium verrucosum	western sea-purslane	Aizoaceae	perennial herb
Sporobolus airoides	alkali sacaton	Poaceae	perennial herb
Suaeda moquinii	bush seepweed	Chenopodiaceae	perennial herb

4. Arid, less saline / sodic sites.
   - Conceptual example: mixture of shrubs, forbs and grasses; broader spectrum of adapted species; higher proportion of forbs and grasses

Species	**Common Name**	**Family**	**Life-form**
Atriplex polycarpa	allscale saltbush	Chenopodiaceae	perennial shrub
Atriplex spinifera	spinescale saltbush	Chenopodiaceae	perennial shrub
Eriogonum fasciculatum	California buckwheat	Polygonaceae	perennial herb
Grindelia camporum	gumplant	Asteraceae	perennial herb
Hordeum depressum	alkali barley	Poaceae	annual herb
Isocoma acradenia	goldenbush	Asteraceae	perennial shrub
Isomeris arborea	bladderpod	Capparidaceae	perennial shrub
Lasthenia chrysantha	alkali goldfields	Asteraceae	annual herb
Layia glandulosa	white layia	Asteraceae	annual herb
Malacothrix coulteri	snake's head	Asteraceae	annual herb
Mentzelia laevicaulis	blazing star	Loasaceae	annual herb
Phacelia ciliata	Great Valley phacelia	Hydrophyllaceae	annual herb
Phacelia tanacetifolia	tansy-leaved phacelia	Hydrophyllaceae	annual herb
Poa secunda	one-sided blue grass	Poaceae	perennial herb
Sesuvium verrucosum	western sea-purslane	Aizoaceae	perennial herb

SEEDBED PREPARATION

Standard, preparatory, tandem disk tillage followed by cultipacking (“ring roller” or similar mechanical measure for clod reduction, seedbed firming and smoothing), as routinely performed in agronomic applications in the project locale, appears adequate for proper seedbed preparation of the soils characteristic of the study area. On sites with a dense "plow-pan" (long-duration tillage layer) of compressed clays below the soil surface, deep chiseling or ripping may be necessary to improve tilth and plant root penetration capability. If these latter measures are required, follow-up disk tillage and/or cultipacking may be necessary to reduce clods brought to the soil surface by the chisel or ripping operation.

The poor results from "deep furrow" drilled seeding (seed placement in the bottom of furrows created by leading furrow openers on the drill, or by previous furrow tillage implement) was considered to be primarily attributable to the high amount of clods and deeper soil cover over seeds within the linear "micro-seedbed" in the bottom of the furrows created in these tight clay soils. Smoothing or breaking of the clods in the furrow bottoms by common "picker wheel" or "clod breaker" implements prior to seeding may provide more positive results for these mechanical treatments, as evidenced by pockets of high germination and emergence of species where deposition of soil fines induced by precipitation runoff occurred within the furrows. The concept of deep-furrow seeding still holds promise for enhanced moisture capture, amelioration of environmental extremes at the soil surface, and native species establishment IF clods can be minimized in the furrow bottoms.

The use of barley as a nurse crop in alternate rows with seeded natives appears to aid germination in some native species by ameliorating environmental extremes (heat, wind, low moisture) at the soil surface for the new seeding, and by providing limited suppression of weeds. The alternate barley rows serve, in essence, as a nurse crop for seeded natives, with row spacing sufficiently wide (minimum 12 inches [25 cm]) to minimize inter-specific competition between adjacent rows. On sites where efficacy of prior weed suppression measures is limited or is otherwise constrained, this approach may provide a degree of added weed suppression during the first seeding (establishment) year that can be augmented with subsequent herbicide applications, as appropriate.

LRDP studies conducted to determine utility of selected soil amendments indicate that soil rhizosphere augmentation using salt-remediation products (e.g., HydraHume™), fertilizers, mycorrhizal inoculation, or polyacrylamide polymer (incorporated in seed coatings) does not appear to provide immediate or long-term benefits for native species establishment. Super-treble phosphate (PO_4) fertilizer did provide establishment benefit for Great Valley phacelia, but no other tested species demonstrated any response to phosphate fertilization. Evaluation of nitrogen fertilization was not conducted because the predominance of native species planned for use in LRDP restoration efforts are docotyledonous plants, exhibiting limited response to nitrogen augmentation. Likewise, as described previously, nitrogen addition may severely exacerbate ruderal (annual) weed pressure.

SEEDING METHODS

As with species selection and adaptation evaluations, numerous seeding methods have been evaluated in LRDP research trials and demonstrations. These methods have included use of commercial standard rangeland (grass) drills; "broadcast"-type grass drills (e.g., Trillion™); rangeland imprinters with/ and without attached seeding mechanisms; standard agronomic grain drills; and mechanized or manual rotary broadcast seeders followed by harrowing or similar mechanical measure for assuring adequate soil-to-seed contact and cover. All commercial drills are equipped with multiple, specialized seed boxes designed to hold, agitate, meter and deliver seed (including mixtures of species) in individual boxes according to seed size; shape; weight; and amount of hairs, awns or chaff (i.e., inert material). Rangeland imprinters are designed to create a pattern of micro-catchments on the soil surface to enhance capture and retention of precipitation, and also to improve soil-to-seed contact via firming of the seedbed surface immediately surrounding the seed.

Commercial grass drills exhibited higher degrees of consistent success in establishing native vegetation than did methods involving grain drills or broadcast technology. Use of drill technology optimizes seed depth placement and soil cover; minimizes intra-specific, inter-row competition for seeded species; and facilitates specialized herbicide application for weed suppression between seeded rows (see section on *Weed Management*, below). The technique of "broadprinting" (use of a land imprinter following broadcast seeding) also yielded moderately successful results in first-year germination and emergence of seeded species. However, patterns of micro-catchments (depressions) created by the imprinter are generally unstable on typical study site soils (primarily fine-textured clays) such that rapid filling resulting from sediment deposition accompanying surface water flows occurred during precipitation events. Upon such filling, enhanced moisture capture properties and subsequent soil moisture availability for root uptake are reduced or negated, thereby reducing seeding establishment success beyond the first seeding year. Additional limitations with imprinting were encountered on some of soils at the Tranquillity site as the imprinting depressions tended to develop deep fissures, which also reduced the potential for seedling establishment.

WEED MANAGEMENT

Interim planting of dryland barley cover crops appears to provide suitable temporary cover during the growing season for site protection and weed suppression during field non-use periods while awaiting restoration. This non-use typically corresponds to time periods between cessation of cropping and seedbed preparation for habitat restoration seeding, and may also include buffer zones planted between experimental or demonstration revegetation studies. Barley seeded at standard agronomic seeding rates has been shown to be effective in temporary (seasonal or annual) suppression of the majority of annual and perennial weeds during years with precipitation amounts and timing at or near long-term annual and seasonal means. The barley crop may also simultaneously yield marketable products for grain, grazing, straw, etc. Based on field scouting, occasional tillage may be required for interim weed suppression between barley harvest and seeding of the following year's crop.

In the absence of barley (or other, suitable dryland agronomic grain crop or cover crop) during interim periods before restoration, repeated tillage, herbicide applications, and/or grazing will be necessary for weed suppression. An array of herbicides with foliar contact and/or soil residual capabilities are labeled for use in California for this purpose (e.g., glyphosate, 2,4-D, dicamba, oxyfluorfen, simazine, sethodim, etc.). Use of herbicides exhibiting soil residual capabilities should be chosen and applied in accordance with local ordinances and labeling restrictions pertaining to sensitive groundwater restriction zones in Fresno County and neighboring counties.

When restoration activities are delayed, a recommended strategy in the year immediately preceding planned restoration is to treat the fields with: a) initial tillage (to reduce existing weed standing crop and seed production, and to stimulate germination of the soil seed bank); and b) subsequent residual herbicide(s) to suppress weed regrowth through the growing season. This approach will minimize the weed load (seed bank plus growing weeds) leading into the planned restoration year. In the absence of seeded natives during this preceding year, designed formulation and application of herbicide tank mixes (as needed) that widen the spectrum of target weed species across multiple weed growth forms and life histories is also facilitated.

Upon initiation of site restoration using native species, several tested herbicides show good to excellent weed suppression, with seeded native species exhibiting good emergence and survival using charcoal banding concepts. Charcoal banding (wet slurry) over the seed row appears to be a practical and cost-effective measure for multi-species weed suppression and protection ("safening") of drilled native seedlings from the effects of herbicides applied. Conversely, broadcast seeding methods are highly reduced in efficacy because of weed pressure that is not amenable to herbicide application, particularly in native seed mixtures comprised of both dicotyledonous and monocotyledonous plants (which severely limit herbicide options). This type of charcoal banding requires minimal modification of existing drill and tractor equipment, utilizing herbicide spraying equipment, pumps, and tractor straddle tanks common to agronomic applications. This approach would also be amenable to alternate-row barley nurse crop seeding, as described above.

Further study is warranted to refine experimental approaches, involving testing across additional seeded species and different application rates for charcoal and herbicides, within the herbicide types shown to be effective in these studies. If one (or more) of the herbicides that prove superior in weed suppression and safety to seeded natives (as tested under the Experimental Use Permit [EUP] employed for the LRDP research studies) have restricted labeling for use in California and/or Fresno County, a special local need permit may be pursued through the California Department of Agriculture, Fresno County Department of Agriculture, and/or the Environmental Protection Agency (EPA) for broader-scale use within the CVPIA-Land Retirement project.

INSECT CONTROL

Control or suppression of insect damage to seeded native species, particularly from false chinch bugs (*Nysius* spp.), is also a key consideration. A large portion of the retired agricultural lands and fallowed fields in the western SJV typically support dense populations of exotic species (e.g., *Sisymbrium irio* and *Brassica* spp.) that are associated with the chinch bug life-cycle. Because these outbreaks generally occur during the dry season, the greatest portion of the vegetation on the lands surrounding the Tranquillity sites has already senesced. As a result, the native perennial species on the LRDP appear to be favored "targets." During most years there has been at least one area of the Tranquillity site that has been severely impacted. In extreme cases, false chinch bug damage has resulted in the death of most of the native species in these impacted areas.

Constant monitoring (i.e., weekly site visits) during the dry season is necessary to adequately scout for determination of false chinch bug presence and levels of infestation.

This frequent scouting enables initiation of control measures before extensive damage occurs, and should be incorporated into LRDP restoration plans as a required measure, having equal importance with all other revegetation activities. When significant infestations occur, immediate localized treatment using products such as Malathion™ have proven successful in reducing or eradicating the infestation for that season. Reduced levels of infestation may also be addressed via use of attractant traps and/or insecticide-treated baits. To the extent that conditions at Tranquillity are representative of the majority of the drainage-impacted lands, pest scouting and applied pesticidal or trap control measures will undoubtedly be essential components of any restoration activities.

NPSPF Continuation and Management

The LRDP Native Plant Seed Production Facility holds importance to the LRDP botanically and functionally within the context of:

1. research, demonstration and public educational value, being a unique collection of numerous native species endemic to the western San Joaquin Valley that is not known to exist elsewhere;
2. supply of “foundation” (archival) seed from numerous core species of importance to the LRDP (see Table 2 and Table 3), facilitating subsequent provision of seed to commercial growers for seed increase to supply a larger-scale LRDP land enrollment program.

FUTURE RESEARCH AND PROGRAMMATIC DIRECTION

GRAZING

Grazing trials incorporating sheep are needed to evaluate: a) efficacy of sheep as a weed management tool, integrated with herbicidal and mechanical measures, for cultural suppression (herbivory via prescribed, controlled grazing management) of grass and broadleaf weeds within seeded plant communities; and b) resistance to / tolerance of sheep grazing by established, seeded native species. These trials would evaluate effects of varied timing, intensity (stocking rates), and duration of grazing on efficacy of weed suppression simultaneous with evaluation of survival and vigor of seeded natives under these grazing regimes. The herbicide / activated charcoal trials (Manning and North Avenue studies) and portions of the Habitat Restoration Study (HRS) Plot are most suited for this application because of adequate establishment of seeded natives since 2005 and 2006, respectively. Grazing trials are planned for initiation on one or more of these study sites in early 2007.

HERBICIDE / CHARCOAL PRODUCT AND RATE REFINEMENT

Greenhouse and spray chamber experiments are needed to further characterize, refine and quantify the most efficacious commercial products and rates of herbicide(s) and activated charcoal, utilizing characteristic soils and seeded native species previously evaluated within the LRDP as indicators. Additional plant species (minimum of 75% of the core species; see Table 2 and Table 3) would be evaluated to test herbicide sensitivity under varying charcoal application regimes. This testing would result in a concise, focused recommendation for weed suppression in LRDP native seedings, facilitating a reduced, but validated, number of herbicide and charcoal products and rates.

FOLLOW-UP (SECONDARY) HERBICIDE TREATMENT (PRODUCTS, RATES, TIMING)

Further testing is needed to determine efficacious products and rates for follow-up (secondary) herbicide treatment on established stands of seeded native species. Activated charcoal treatment for seed safening is only valid for the first establishment year (i.e., growing season) using drilled seedings. Upon emergence and establishment of seeded natives, charcoal cannot be re-applied in ways that would permit understory weed suppression. Various herbicides are available as selections for weed suppression, but little is known about their impacts on existing native species. Subject to seeded stand composition and dominant weed species, herbicides would be tested in both field and greenhouse applications to determine optimum combinations of weed suppression and native species tolerance.

INFRASTRUCTURE FOR SEED COLLECTION, CONDITIONING, CLEANING, STORAGE, AND COMMERCIAL INCREASE (NRCS)

Ongoing collaboration with the USDA Natural Resources Conservation Service (Lockeford Plant Materials Center), interested native seed suppliers, and the California nursery industry is still a critical need. Considerable research is still needed, particularly on seed harvest, pre-conditioning (scarification, stratification), and storage techniques; supplemental water needs during initial plant establishment phases (as applicable); and economically sound infrastructure logistics connecting seed production to demand. This latter activity entails development and dissemination of strategies and techniques that integrate BOR research results with end user land retirement needs, CVPIA and Westlands Water District (WWD) stakeholders, NRCS Plant Materials Centers, and the commercial seed industry. Of particular importance is development of revegetation protocols, agency / commercial / private infrastructure, and product (native seed, planting guidelines) delivery avenues sufficient to fully address land retirement needs on a landscape scale.

SELECTED MANAGEMENT IMPLICATIONS

Costs

Revegetation costs will be highly variable subject to costs of materials, equipment and labor at the time of initiation of restoration activities, and restoration objectives. Greatest variability will be introduced by materials cost for seed and herbicides. To the extent that: a) greater proportions of species in seed mixture formulations are commercially available; and b) greater proportions of selected herbicides are in common, commercial use in the project locale – revegetation costs will be significantly and proportionately reduced.

Actual costs can be formulated for existing revegetation trials in the LRDP, but further analysis is needed to refine, normalize, extrapolate and project these costs to future, landscape-scale applications. These costs, however, are based on experimental trials incorporating varied, often innovative techniques and materials. Further analysis and refinement is required to assure that cost estimates represent actual field- or landscape-scale applications using established protocols and standard, commonly available equipment.

REVEGETATION STRATEGIES IN RELATION TO T&E HABITAT RESTORATION OBJECTIVES AND DESIRED REVEGETATION TRAJECTORIES

NEEDS

There are specific issues of concern that need to be addressed by the lead administrative and technical agencies and staff involved in the LRDP. Clarification of these issues, coupled with better definition of stated habitat objectives, will permit improved planning and more concise recommendations for habitat restoration via native plant community revegetation efforts. Examples include:

1. What are the true target wildlife species (and associated habitat goals) for the LRP — T&E species, non-T&E species, or some combination of both? Formulation of seed mixtures, seedbed preparation techniques, and weed management prescriptions will vary greatly between these targeted species / populations.

2. Concise documentation of habitat profiles for each targeted wildlife species (needs and characteristics; e.g., Habitat Suitability Indices, or similar evaluations), to be used as guides and planned trajectories for revegetation recommendations.
3. Definition and ecogeographic delineation of “core” areas, “linkage corridors”, and their relationships, priorities, and juxtaposition to LRDP habitat restoration efforts as projected for landscape-scale LRDP enrollments in the future.

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APPENDIX A. TABLES

Table 1. Species that have been identified as "core species" (i.e., species considered as key components of restoration strategies) and/or species that have been seeded in the various restoration trials at the Tranquillity LRDP site, including common name, botanical family, and growth-form/life history. Core species are delineated in boldface.

Species	Common Name	Family	Growth Form/Life History
Allenrolfea occidentalis	iodinebush	Chenopodiaceae	shrub
Amsinckia menziesii	Menzie's fiddleneck	Boraginaceae	annual herb
Amsinckia vernicosa	green fiddleneck	Boraginaceae	annual herb
Aristida ternipes var. hamulosa	Spreading threeawn	Poaceae	perennial herb
Artemisia californica	California sagebrush	Asteraceae	shrub
Astragalus asymmetricus	San Joaquin milkvetch	Fabaceae	perennial herb
Astragalus lentiginosus	freckled milk-vetch	Fabaceae	annual or perennial herb
Atriplex coronata	crownscale	Chenopodiaceae	annual herb
Atriplex covillei	leafcover saltweed	Chenopodiaceae	annual herb
Atriplex fruticulosa	valley saltbush	Chenopodiaceae	perennial herb
Atriplex minuscula	lesser saltscale	Chenopodiaceae	annual herb
Atriplex polycarpa	allscale saltbush	Chenopodiaceae	shrub
Atriplex spinifera	spinescale saltbush	Chenopodiaceae	shrub
Bromus carinatus	California brome	Poaceae	perennial herb
Camissonia californica	California suncup	Onagraceae	annual herb
Elymus glaucus	blue wildrye	Poaceae	perennial herb
Elymus multisetus	big squirreltail	Poaceae	perennial herb
Eremalche parryi	Parry's mallow	Malvaceae	annual herb
Eriogonum fasciculatum	California buckwheat	Polygonaceae	shrub
Eschscholzia californica	California poppy	Papaveraceae	annual herb
Frankenia salina	alkali heath	Frankeniaceae	perennial herb
Gilia tricolor	bird's-eye gilia	Polemoniaceae	annual herb
Grindelia camporum	gumplant	Asteraceae	perennial herb
Gutierrezia californica	California matchweed	Asteraceae	perennial herb
Heliotropium curassavicum	seaside heliotrope	Boraginaceae	perennial herb
Hemizonia pungens	common spikeweed	Asteraceae	annual herb
Holocarpha obconica	San Joaquin tarweed	Asteraceae	annual herb
Hordeum depressum	alkali barley	Poaceae	annual herb
Hordeum vulgare	barley	Poaceae	annual herb
Hutchinsia procumbens	prostrate hutchinsia	Brassicaceae	annual herb
Isocoma acradenia	goldenbush	Asteraceae	shrub
Isomeris arborea	bladderpod	Capparaceae	shrub
Kochia californica	rusty molly	Chenopodiaceae	perennial herb
Lasthenia californica	California goldfields	Asteraceae	annual herb
Lasthenia chrysantha	alkali goldfields	Asteraceae	annual herb
Layia glandulosa	white layia	Asteraceae	annual herb
Lessingia glandulifera	valley lessingia	Asteraceae	annual herb
Leymus triticoides	creeping wild-rye	Poaceae	perennial herb
Lotus scoparius	deerweed	Fabaceae	perennial herb

Species	Common Name	Family	Growth Form/Life History
Lupinus bicolor	bicolored lupine	Fabaceae	annual or perennial herb
Lupinus succulentus	arroyo lupine	Fabaceae	annual herb
Machaeranthera carnosa	shrubby alkali aster	Asteraceae	shrub
Madia elegans	common madia	Asteraceae	annual herb
Malacothrix coulteri	snake's head	Asteraceae	annual herb
Mentzelia laevicaulis	smooth-stem blazing star	Loasaceae	perennial herb
Monolopia major	cupped monolopia	Asteraceae	annual herb
Monolopia stricta	Crum's monolopia	Asteraceae	annual herb
Nassella cernua	nodding needlegrass	Poaceae	perennial herb
Nassella pulchra	purple needlegrass	Poaceae	perennial herb
Phacelia ciliata	Great Valley phacelia	Hydrophyllaceae	annual herb
Phacelia tanacetifolia	tansy-leafed phacelia	Hydrophyllaceae	annual herb
Sesuvium verrucosum	Western sea-purslane	Aizoaceae	perennial herb
Sporobolus airoides	alkali sacaton	Poaceae	perennial herb
Suaeda moquinii	bush seepweed	Chenopodiaceae	sub-woody perennial
Trichostema ovatum	San Joaquin bluecurls	Lamiaceae	annual herb
Vulpia microstachys	small fescue	Poaceae	annual herb
Wislizenia refracta	jackass clover	Capparaceae	annual or perennial herb

Table 2. Restoration techniques and experimental factors examined in research conducted at the Tranquillity Land Restoration Demonstration Project Site. Items marked with an asterisk are those which were utilized in a trial but which were not experimental factors in that particular trial.

		Seeding Technique				Modified Planting Conditions				Non-Chemical Weed Control			Chemical Weed Control			Seed-related Factors		
Trial	Irrigation	Drilling	Imprinting	Cultipacker	Transplanting	Furrow Depth	Row Spacing	Plant Spacing	Topography	Pre-irrigation	Mowing	Burning	Post-emergents	Pre-emergents	Activated Charcoal	Seed Mix Comparison	Rhizosphere Augmentation	Nurse Crop/Cover Crop
Habitat Restoration Study			√*		√*				√									√*
Imprinting vs. Drilling of Native Species Trial		√	√															√*
Imprinting vs. Drilling of Cover Crops Trial		√	√													√		√
Atriplex spinifera Planting					√*			√										
Berm and Mycorrhiza Trial	√*		√*						√								√	
Succession Trial			√*													√		√
Suitability Trial	√*		√*													√		
Growth Form and Herbicide Trial			√*										√			√		
Pre-irrigation Trial	√		√*							√								
Section 10 Burn and Mowing Trial			√*								√	√						
Mowing Trial			√*								√							
Section 23 Restoration Trial			√*						√*							√		
Seed Augmentation and Planting Method Trial		√*				√	√									√	√	√
Planting Techniques Trial (Year I)		√	√	√												√		
Herbicide and Charcoal Treatment Trial - Manning		√*											√*	√	√	√		
Planting Techniques Trial (Year II)		√	√	√												√		
Seed Delivery and Competition Trial			√	√					√*							√		
Native Release Trial											√	√	√					
Herbicide and Charcoal Treatment Trial - North Avenue		√*											√*	√	√	√		
Herbicide and Charcoal Treatment Demonstration		√*												√	√	√		
Planting Techniques Trial (Year III)			√															

Table 3. List of species, the trials in which they were used, and their use in the Native Plant Seed Production Facility (NPSPF). Note: not all species that have been cultivated in the NPSPF are listed in this table. Rather, only those species which have been used in an experimental setting and those species which have been identified as "core species" (in boldface) are included here. Species which are recorded as "—" for all years are those for which local populations are known, but which have not been cultivated in the NPSPF. Species with no data recorded for the NPSPF are those for which no local populations are known. Key: "EP" — "Established perennials", i.e. perennial species which had been planted during a previous year. "V" — Species that were not planted during that particular year, but which became established as"volunteers."

Species	Habitat Restoration Study (HRS)	Imprinting & Drilling: Natives	Imprinting & Drilling: Cover Crops	Atriplex spinifera Planting	Berm & Mycorrhizae Trial	Succession Trial	Suitability Trial	Growth-form & Herbicide Trial	Pre-irrigation Trial	Section 10 Burn & Mowing Trial	Mowing Trial	Section 23 Restoration Trial	Seed Augmentation & Planting	Planting Techniques Trial: Year I	Herbicide and Charcoal Trial – Manning	Planting Techniques Trial: Year II	Seed Delivery & Competition Trial	Herbicide and Charcoal Trial - N.A.P.	Herbicide and Charcoal Demonstration	Planting Techniques Trial: Year III	Native Seed Production Facility 2001-02	2002-03	2003-04	2004-05	2005-06
Allenrolfea occidentalis	√				√	√		√	√	√		√					√		√		—	√	EP	EP	EP
Amsinckia menziesii			√																		√	√	V	V	V
Amsinckia vernicosa																					—	—	—	√	√
Aristida ternipes var. hamulosa								√				√													
Artemisia californica																					—	—	√	√	EP
Astragalus asymmetricus																					—	—	√	√	EP
Astragalus lentiginosus																					—	√	√	√	√
Atriplex coronata																	√				—	—	√	√	V
Atriplex covillei																					—	—	—	√	V
Atriplex fruticulosa																					—	—	√	√	EP*
Atriplex minuscula																					—	—	√	√	√
Atriplex polycarpa	√		√		√	√		√	√			√	√	√	√	√	√		√		√	√	EP	EP	EP
Atriplex spinifera	√			√	√	√				√											—	√	√	EP	EP
Bromus carinatus	√	√			√	√	√	√				√									—	—	—	—	—
Camissonia californica																					—	—	—	—	√
Elymus glaucus							√																		
Elymus multisetus							√																		

Species	Habitat Restoration Study (HRS)	Imprinting & Drilling: Natives	Imprinting & Drilling: Cover Crops	Atriplex spinifera Planting	Berm & Mycorrhizae Trial	Succession Trial	Suitability Trial	Growth-form & Herbicide Trial	Pre-irrigation Trial	Section 10 Burn & Mowing Trial	Mowing Trial	Section 23 Restoration Trial	Seed Augmentation & Planting	Planting Techniques Trial: Year I	Herbicide and Charcoal Trial – Manning	Planting Techniques Trial: Year II	Seed Delivery & Competition Trial	Herbicide and Charcoal Trial - N.A.P.	Herbicide and Charcoal Demonstration	Planting Techniques Trial: Year III	Native Seed Production Facility				
																					2001-02	2002-03	2003-04	2004-05	2005-06
Eremalche parryi																					—	—	—	√	√
Eriogonum fasciculatum							√														—	—	√	EP	EP*
Eschscholzia californica								√													—	—	—	—	
Frankenia salina	√				√	√		√	√	√		√									√	√	EP	EP	EP*
Gilia tricolor								√				√									—	√	—	V	—
Grindelia camporum								√			√	√			√	√	√	√	√		—	√	EP	EP	EP
Gutierrezia californica																					—	—	√	√	EP*
Heliotropium curassavicum	√				√	√		√			√						√				—	√	√	EP	EP
Hemizonia pungens	√				√	√		√	√	√	√	√	√	√		√	√				√	√	√	√	√
Holocarpha obconica																	√				—	√	√	√	√
Hordeum depressum			√															√	√		—	—	—	√	√
Hordeum vulgare		√																							
Hutchinsia procumbens																					—	—	—	√	√
Isocoma acradenia	√		√		√	√							√								√	√	√	EP	EP
Isomeris arborea																					—	√	√	√	EP*
Kochia californica																					—	√	√	EP	EP*
Lasthenia californica	√		√		√	√		√	√	√		√									—	√	√	√	—
Lasthenia chrysantha													√						√		√	√	√	√	√
Layia glandulosa																√	√		√		—	—	—	—	V
Lessingia glandulifera																					—	—	√	√	√
Leymus triticoides	√	√	√		√	√																			
Lotus scoparius																					—	—	√	√	√
Lupinus bicolor								√				√									—	—	√	√	√

Species	Habitat Restoration Study (HRS)	Imprinting & Drilling: Natives	Imprinting & Drilling: Cover Crops	Atriplex spinifera Planting	Berm & Mycorrhizae Trial	Succession Trial	Suitability Trial	Growth-form & Herbicide Trial	Pre-irrigation Trial	Section 10 Burn & Mowing Trial	Mowing Trial	Section 23 Restoration Trial	Seed Augmentation & Planting	Planting Techniques Trial: Year I	Herbicide and Charcoal Trial – Manning	Planting Techniques Trial: Year II	Seed Delivery & Competition Trial	Herbicide and Charcoal Trial - N.A.P.	Herbicide and Charcoal Demonstration	Planting Techniques Trial: Year III	Native Seed Production Facility 2001-02	2002-03	2003-04	2004-05	2005-06
Lupinus succulentus																					—	—	—	—	√
Machaeranthera carnosa																					—	—	—	√	—
Madia elegans																					—	—	—	—	√
Malacothrix coulteri																					—	√	√	√	√
Mentzelia laevicaulis																					—	—	√	√	—
Monolopia major																					—	—	—	—	√
Monolopia stricta																	√				—	√	√	√	√
Nassella cernua							√	√													—	—	—	—	—
Nassella pulchra							√	√				√													
Phacelia ciliata								√			√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Phacelia tanacetifolia																					—	—	√	√	√
Sesuvium verrucosum									√	√	√						√		√		—	√	√	EP	EP
Sporobolus airoides	√		√		√	√		√		√		√	√								√	√	√	√	EP*
Suaeda moquinii	√		√		√	√		√	√			√	√	√	√	√		√	√		√	√	√	√	EP
Trichostema ovatum													√								—	√	√	√	V
Vulpia microstachys	√	√	√		√	√		√	√			√							√		—	—	—	√	—
Wislizenia refracta																					√	√	√	√	√