TWENTY TWO

Exotic Plant Management in California Annual Grasslands

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California grasslands have experienced tremendous changes in vegetative composition over the last few centuries, with significant declines in native perennial vegetation and concomitant increases in aggressive, non-native, weedy species. The changing grassland composition is the result of numerous processes that are reviewed elsewhere in this volume, including many plant introductions, primarily from Europe and Asia (Heady 1977). Burcham (1956) characterized four waves of invasion that were dominated by European annual grasses and shallow-rooted winter annual forbs. In the last half century, a fifth wave of annual invaders, characterized by a later season phenology and deeper rooting pattern, has moved across the grasslands with unrelenting progress. However, individual species from all of these waves of invasion still dominate large grassland areas, with wide population fluxes from year to year, depending upon environmental conditions and local- and landscape-scale processes (Pitt and Heady 1978). As observed in every wave of invasion, probably the most striking shared characteristic of invaders in California's valley and coast range grasslands has been the success of the annual life history. This chapter will focus primarily on annual grassland systems occupying the coastal ranges, central valley, and Sierra Nevada foothills. To be consistent with terminology elsewhere in the book, annual grassland systems will be referred to as "valley grassland" systems. In contrast, some of the more dominant invasive species in coastal prairies are perennial grasses and shrubs (see D'Antonio et al., Chapter 6). Similarly, perennial species represent the vast majority of invasive non-native species in wetland or riparian areas within grassland settings.

Over 73% of the major invasive non-native species in valley grassland are winter annuals, about 11% are biennials, and 16% typically act as perennials, although members in both of these lesser groups can sometimes act as biennials or annuals. Although some woody species, such as Himalaya blackberry *(Rubus armeniacus)* and the native junipers (*Juniperus* spp.), can encroach into grasslands, they are not considered as significant a threat as herbaceous species in valley grasslands. In some coastal range grasslands, including some that are annual-dominated, it is not uncommon for invasive shrubs, such as the brooms *(Genista monspessulana, Cytisus scoparius, Spartium junceum)* or gorse *(Ulex europaeus),* to invade these systems (see Chapter 6). Of the 44 most commonly encountered invasive valley grassland species in the state, about 80% belong to either the sunflower (Asteraceae) or grass (Poaceae) family, with an equal distribution between the two families (Table 22.1). Other important families of non-native plants in these grasslands include the Brassicaceae, Geraniaceae, and Fabaceae.

Of the interior valley grassland invasive plants recently listed in the "California Invasive Plant Inventory" published by the California Invasive Plant Council (Cal-IPC 2006), eight species are classified in the "High" concern category (Table 22.1). These are considered the species having the greatest impact on valley grassland habitats and include yellow starthistle *(Centaurea solstitialis),* artichoke thistle *(Cynara cardunculus),* Scotch thistle *(Onopordum acanthium),* barb goatgrass *(Aegilops triuncialis),* red brome (*Bromus madritensis* ssp. *rubens*), downy brome *(Bromus tectorum),* and medusahead *(Taeniatherum caput-medusae).* For close-ups showing distinctive features of yellow starthistle, barb goatgrass, and medusahead see Figures 22.1 and 22.2. All of these species belong to either the sunflower or the grass family. Among the remaining species occurring in valley grassland on the Cal-IPC list, 48% are listed as "Moderate" in their impacts, and 34% are categorized as "Limited."

Among the species listed as "High" in their impacts, downy brome and yellow starthistle are considered the two most invasive species in the 17 western states, with 56 and 15 million acres infested, respectively (Duncan and Clark 2005). Medusahead is considered the ninth most invasive species in the western United States, with an estimated infestation of 2.4 million acres. Among the most problematic

TABLE 22.1
Most Common Non-native Invasive Species in California Valley and Foothill Grasslands, Including their Growth Form and Cal-IPC Classification

Common name	*Scientific name*	*Family*	*Growth habit*	*Cal-IPC category*
Fennel	*Foeniculum vulgare*	Apiaceae	Perennial	High
Italian thistle	*Carduus pycnocephalus*	Asteraceae	Winter annual	Moderate
Slenderflower thistle	*Carduus tenuiflorus*	Asteraceae	Winter annual	Limited
Woolly distaff thistle	*Carthamus lanatus*	Asteraceae	Winter annual	Moderate alert
Purple starthistle	*Centaurea calcitrapa*	Asteraceae	Annual to perennial	Moderate
Malta starthistle (tocalote)	*Centaurea melitensis*	Asteraceae	Winter annual	Moderate
Yellow starthistle	*Centaurea solstitialis*	Asteraceae	Winter annual	High
Squarrose knapweed	*Centaurea virgata* var. *squarrosa*	Asteraceae	Perennial	Moderate
Rush skeletonweed	*Chondrilla juncea*	Asteraceae	Biennial	Moderate
Bull thistle	*Cirsium vulgare*	Asteraceae	Biennial	Moderate
Artichoke thistle	*Cynara cardunculus*	Asteraceae	Perennial	Moderate
Smooth catsear	*Hypochaeris glabra*	Asteraceae	Winter annual	Limited
Common catsear	*Hypochaeris radicata*	Asteraceae	Winter annual	Moderate
Scotch thistle	*Onopordum acanthium*	Asteraceae	Biennial	High
Bristly oxtongue	*Picris echioides*	Asteraceae	Annual or biennial	Limited
Tansy ragwort	*Senecio jacobaea*	Asteraceae	Biennial	Limited
Blessed milk thistle	*Silybum marianum*	Asteraceae	Winter annual	Limited
Dyer's woad	*Isatis tinctoria*	Brassicaceae	Biennial	Moderate
California burclover	*Medicago polymorpha*	Fabaceae	Winter annual	Limited
Rose clover	*Trifolium hirtum*	Fabaceae	Winter annual	Moderate
Broadleaf filaree	*Erodium botrys*	Geraniaceae	Winter annual	Not listed
Shortfruited filaree	*Erodium brachycarpum*	Geraniaceae	Winter annual	Not listed
Redstem filaree	*Erodium cicutarium*	Geraniaceae	Winter annual	Limited
Common St. Johnswort	*Hypericum perforatum*	Hypericaceae	Perennial	Moderate
Barb goatgrass	*Aegilops triuncialis*	Poaceae	Winter annual	High
Silver hairgrass	*Aira caryophyllea*	Poaceae	Winter annual	Not listed
Slender oat	*Avena barbata*	Poaceae	Winter annual	Moderate
Wild oat	*Avena fatua*	Poaceae	Winter annual	Moderate
Big quakinggrass	*Briza maxima*	Poaceae	Winter annual	Limited
Little quakinggrass	*Briza minor*	Poaceae	Winter annual	Not listed
Ripgut brome	*Bromus diandrus*	Poaceae	Winter annual	Moderate
Soft brome	*Bromus hordeaceus*	Poaceae	Winter annual	Limited
Red brome	*Bromus madritensis* ssp. *rubens*	Poaceae	Winter annual	High
Downy brome (cheatgrass)	*Bromus tectorum*	Poaceae	Winter annual	High
Hedgehog dogtailgrass	*Cynosurus echinatus*	Poaceae	Winter annual	Moderate
Orchardgrass	*Dactylis glomerata*	Poaceae	Perennial	Low
Tall fescue	*Festuca arundinacea*	Poaceae	Perennial	Moderate
Mediterranean barley	*Hordeum marinum*	Poaceae	Winter annual	Moderate
Hare, smooth and wall barley	*Hordeum murinum*	Poaceae	Winter annual	Moderate
Italian ryegrass	*Lolium multiflorum*	Poaceae	Winter annual	Moderate
Medusahead	*Taeniatherum caput-medusae*	Poaceae	Winter annual	High
Squirreltail fescue	*Vulpia bromoides*	Poaceae	Winter annual	Not listed
Rattail fescue	*Vulpia myuros*	Poaceae	Winter annual	Moderate
Bellardia	*Bellaria trixago*	Scrophulariaceae	Winter annual or biennial	Limited

FIGURE 22.1 Close-ups of flowerheads of two common invasive *Centaurea* species in California. Left: *C. melitensis* (tocalote or Malta starthistle). Right: *C. solstitialis* (yellow starthistle). Note that the spines on *C. solstitialis* are approximately twice the length of those found on *C. melitensis*.

invasive plants in California's valley grasslands, the two most common species are yellow starthistle and medusahead (see Figures 22.1, 22.2). Downy brome, despite its widespread western impact, has caused significant problems only in the northeastern (Modoc Plateau) part of the state, so it will not be discussed further here.

Impacts

Invasive non-native plants in California grasslands can have significant ecological and economic impacts. Although a more thorough treatment of ecological impacts can be found in Chapter 6, a number of key impacts will be discussed here. Since the California grasslands have historically played a major role in livestock production, weed impacts have often been strongly associated with that industry. Impacts include interference with grazing practices; reductions in forage productivity or quality; increased costs of managing and producing livestock; reduced animal weight gains; reduced quality of meat, milk, wool, and hides; and livestock poisoning. Medusahead, for example, is of low value because of its high silica content (George 1992). This reduces the forage quality and makes it less palatable to livestock and wildlife compared to other forage grasses. In areas heavily infested with medusahead, livestock carrying capacity can be reduced by as much as 75 to 80% (Major et al. 1960; Hironaka 1961; George 1992). One of the more recent animal issues to come to light is the impact of many invasive plants on the horse industry, especially where small acreage development is occurring. Invasive forbs such as yellow starthistle, Russian knapweed, houndstongue, and tansy ragwort can result in poisoning and death to horses when consumed at high levels (Cordy 1954).

Direct impacts of grassland weeds on humans and quality of life include increased allergens in the air, sickness or death from inadvertent consumption of poisonous plants, damage to recreational equipment, and injury or discomfort from physical contact with spiny thistles such as milk thistle and yellow starthistle or abrasive parts such as the awns of ripgut brome *(Bromus diandrus)*. With increased use of grasslands for recreational activity, including hiking and biking, direct impacts on humans are now much more prevalent (DiTomaso 2000).

In addition to impacts on humans and animals, many invasive plants may alter ecosystem structure and functional processes, including hydrologic, fire, and nutrient cycles. Structural changes in invaded plant communities typically cause reduced native species richness and diversity and changes in canopy structure (Belcher and Wilson 1989; Parmenter and MacMahon 1983; Rikard and Cline 1980; Wallace et al. 1992). In one study reported on by DeLoach (1991), the number of plant species present in California grasslands increased by 35% following biological control of common St. Johnswort *(Hypericum perforatum)*. When large scale conversions of vegetational life history strategies and phenology occur, the potential for functional changes to hydrology, nutrient, and fire cycles probably increases. This has been observed with the late-maturing, deeply rooted forb yellow starthistle when it invades the early-maturing, shallow-rooted annual grass communities. Yellow starthistle has been shown to deplete soil moisture reserves and alter water cycles in annual grasslands (Enloe et al. 2005). This could cause large annual economic losses in water conservation costs in California. In Siskiyou County, for example, it was estimated that the potential water loss due to yellow starthistle would be more than 100,000 m^3, or 26,400,000 gallons, per year (Enloe 2002). The depletion of soil moisture

FIGURE 22.2 Close-ups of inflorescences of two "high-impact" invasive annual grasses in California. Left: *Taeniatherum caput-medusae* (medusahead). Right: *Aegilops triuncialis* (barb goatgrass).

by yellow starthistle on invaded sites compared to annual grasslands is equivalent to a loss of 15–25% of mean annual precipitation (Jetter et al. 2003). Thus, yellow starthistle infestations can actually create drier than normal conditions even in subsequent years with average rainfall (Gerlach et al. 1998).

Another lesser studied but demonstrable negative effect of this type of structural change is the impact on soil erosion. Spotted knapweed *(Centaurea maculosa),* a deeply rooted forb that has invaded millions of acres in Montana, has been shown to cause reduced water infiltration rates and subsequent increased surface water runoff and increased stream sediment yields compared to bunchgrass communities in Montana (Lacey et al. 1989). Although not yet quantified for yellow starthistle in the context of California's annual grasslands, it is possible that similar effects may be occurring.

Management Techniques

There are several tools for invasive plant management in the California grasslands. It is important to recognize the following key issues for weed management in the grasslands. First, weed management is a long-term process, and there are no "silver bullets" for immediate success. The biological attributes of most invaders provide mechanisms that allow for some survival in subsequent years after periods where reproduction is completely inhibited (which is also equated to a successful weed control event). These mechanisms include some survival via soil seed banks, temporal windows of resistance to fire, and herbivory and asexual reproduction via adventitious bud formation on the roots of many perennial species. If managers initiate control methods with little follow-up, failure is inevitable, as has been repeatedly demonstrated.

Second, in many cases there may be limitations to the tools available for weed management. Not every tool can be used in every grassland area. For example, steep, rocky landscapes may limit reseeding with rangeland drills; proximity to urban areas may prevent the use of prescribed fire; and local ordinances have banned herbicide use in certain areas. Additionally, special regulations may apply if threatened or endangered species are present in the management area. These limitations are realities in many areas of California and serve to increase the challenges of successful weed management.

Third, the principles of adaptive weed management should be applied whenever possible. These include establishing land management goals, identifying and prioritizing those species that threaten the goals, assessing available weed management techniques, developing and implementing a weed management plan, post treatment monitoring and assessment of impacts, and review and modification to get better results (Klinger and Randall 1997). To be successful, adaptive weed management requires flexibility and persistence.

The fourth key concept, which has only recently been embraced by many land managers, is early detection and rapid response (EDRR) to new invaders. This concept entails immediate and aggressive action to eradicate incipient populations of exotic plants in a given area. Successful eradication has been clearly shown to be possible when invasions cover very small areas (Rejmánek and Pitcairn 2002). EDRR does not always allow for a thorough risk assessment to occur before investing resources toward eradication, especially for unfamiliar or novel taxa. Although there is a good chance that many incipient populations may fail to become serious problems (Williamson and Fitter 1996), there is still an increasing consensus among land managers that it is better to be safe now than sorry later. Thus land managers are beginning to use EDRR efforts to essentially "draw a line in the sand" to prevent new harmful invaders from becoming widespread problems. While many weeds, such as yellow starthistle, are well beyond the scope of EDRR in California, there are still many species to which this approach can be applied locally and regionally. In grasslands these include Scotch thistle, woolly distaff thistle, artichoke thistle, and spotted knapweed. EDRR may also be integrated into adaptive management strategies with little conflict.

Mechanical Control

A number of mechanical methods are used to control herbaceous grassland weeds, including hand labor, mowing, and cultivation techniques. In many cases these techniques are not practical or cost-effective, but there are situations in which they can be used very effectively. They also can be used effectively and with little training for volunteer-based stewardship programs or "weed pulling days."

Hand Labor

Hand labor methods for weed control in grasslands include hand pulling and tools such as weed whips, sling blades, clippers, shovels, hoes, mattocks, and Weed Wrenches™. There has been little published research comparing hand labor to other weed control methods in the California grasslands, so most available information has been translated from agricultural systems or is anecdotal in nature. Hand labor is widely used for controlling small weed patches but is difficult and expensive to use on large infestations. Hand labor is also more commonly used where volunteer help is available and in follow-up control programs where few plants remain after several years of intensive management (Sheley et al.1998). The relative success of hand labor in grasslands is dependent upon removal of a plant's growing points. For annuals and biennials, severing the plants below the crown (i.e., cutting or breaking plants off a few inches below the soil surface) is all that is necessary. For creeping perennials, removing the vertical and lateral roots or rhizomes is essential for success. The difficulty of doing this in most soil types is immense, with the exception of moist, sandy soils. Therefore, hand weeding techniques are typically more effective on annual and biennial species and less effective on perennials, which often regenerate from adventitious buds on deep lateral and vertical roots. Plant height is also important, as low-growing rosettes are generally more difficult to remove by hand pulling than plants with bolted or elongated stems as long as the soil remains moist. These factors result in optimal control timing, which is when plants reach the late bolting to early bud stage before soils become too dry. This timing also often coincides with the end of the germination period for many winter annual weeds that dominate California grasslands. This reduces the potential for new cohorts to emerge following the disturbance caused by hand labor.

A benefit of hand removal is that desirable species, if present, can be left in place. In Marin County, repeated hand pulling with a Weed Wrench not only proved to be an effective method for French and Scotch broom control in small infestations, but also encouraged native plant recovery (Alexander and D'Antonio 2003a). It was also more effective than mowing.

Mowing and Clipping

Mowing is a common vegetation management technique primarily used along roadsides and right-of-ways throughout California. Its main purposes include maintaining the safety recovery zone or "clear zone," keeping visibility high, and reducing fuel loads to prevent wildfires. Mowing has also been used for weed management in both the interior and coastal California grasslands. Although not generally effective for weed eradication, mowing has primarily been used to reduce seed production of both exotic grasses and forbs, and proper timing is critical for its effectiveness. Mowing too early in the spring increases light penetration without removing a significant proportion of weed biomass. This generally benefits weedy species by stimulating rapid recovery of growth while soil moisture is still abundant. Mowing too late in the summer does not prevent seed production and may serve to work the seeds down into the seed bank better and disseminate weed seeds to new areas.

The optimum time for mowing most annual species is in the flowering stage before seed development. This generally results in the greatest reduction of seed production. However, when soil moisture is plentiful following mowing, the effectiveness of control may be greatly reduced. For example, mowing diffuse knapweed *(Centaurea diffusa)* under adequate soil moisture resulted in compensatory growth and ultimately greater seed production compared to plants in an unmowed area (Sheley et al. 1999). Although mowing is more often used as a tool for control of noxious annual weeds, it can successfully control some biennial and perennial weeds (Benefield et al. 1999; Tyser and Key 1988). Repeated mowing on perennial broadleaf species can prevent seed production, reduce root carbohydrate reserves, and give advantages to desirable perennial grasses.

Properly timed mowing has been demonstrated to be a successful tool for the control of yellow starthistle (Benefield et al. 1999). However, the growth form of the plants is critical for success. If plant architecture is characterized by profuse basal branching, then mowing tends to make the growth form prostrate, and the result is limited control. However, if the growth form is primarily elongated stems with little basal branching, such as those found within dense cover, mowing can be very effective (Benefield et al. 1999). Consequently, mowing for yellow starthistle control is best employed where competition for light results in elongated yellow starthistle stems.

Mowing or clipping for vegetation management has also been shown to shift species composition in California coastal prairie from exotic annual grasses to exotic forbs (Hayes and Holl 2003b) or mixes of native and exotic forbs (Maron and Jefferies 2001). In pastures, mowing may reduce grass canopy cover and release more desirable short-statured legumes (DiTomaso 2002). In addition, it can remove the flowering stems of late-season undesirable invasive species, thus preventing or reducing new seed recruitment into the soil seed bank. When desirable perennial grasses are present, mowing can maintain their vigor and remove the unpalatable lower-quality growth or accumulated thatch.

In many California grassland settings, mowing is of limited use because of safety concerns associated with steep terrain and physical damage that may occur to equipment. Also, mowing can create a fire hazard because of sparks generated by contact of the equipment with rocks. Even when mowing is employed as a control technique, it is not always successful and can decrease the reproductive efforts of insect biocontrol agents, injure late-growing native forb species, and reduce fall and winter forage for wildlife and livestock.

Tillage

One of the most common mechanical weed control techniques used in agricultural systems is cultivation or tillage. Tillage equipment can include plows or discs, which control annual weeds by burying plant parts, including seeds. In contrast, the use of harrows, knives, and sweeps will damage root systems or separate shoots from roots (DiTomaso 2002). Tillage must be conducted when the surface soil is dry; otherwise, fragmented plant segments will regrow and thereby exacerbate the problem. For example, in new seedings of alfalfa in northeastern California, the spread of perennial pepperweed *(Lepidium latifolium)* from small populations was greatly exacerbated by preplant tillage operations (R. Wilson, personal communication). Despite its effectiveness in the control of annual weeds, tillage can also have the negative effect of increasing atmospheric dust levels and soil erosion. Tillage can, on occasion, effectively control some invasive species in grasslands. For example, early summer tillage can damage yellow starthistle and give adequate control. In most California grasslands, however, cultivation is not practical and does not achieve the intended objective, since it tends to select against desired species as well as undesirable ones. In addition, tillage can enhance a perennial weed problem, such as Canada thistle *(Cirsium arvense)*, by spreading root fragments or stimulating emergence of new shoots from roots just below the tillage line in soil (Young et al. 1998). Tillage in California grasslands is most commonly used to create firebreaks just beyond highway right-of-ways, where wildfires are frequently started, or to create hayfields that are grazed after harvest. Tillage may also serve as an important tool in the early stages of restoring historically farmed lands to native grasslands (see Jantz et al., Chapter 23). In these areas, tillage can effectively be used to eliminate the early fall or spring cohorts of weeds before reseeding with natives (Stromberg et al., Chapter 21).

Thatch Removal

The competitive ability of medusahead in annual grasslands is primarily due to the slow breakdown of its silica-rich thatch. It has been shown that the thatch layer is the main component responsible for suppressing other competing species (Kyser et al. 2007). Removing the thatch by either tillage or mowing in the fall can reduce the competitiveness of medusahead and provide better than 50% reduction in medusahead the following year. In addition, thatch removal can dramatically improve the efficacy of the herbicide imazapic, regardless of whether the removal technique is through burning, tillage, or mowing followed by thatch removal (Kyser et al. 2007).

Thatch buildup is also associated with dominance of other sometimes undesirable non-native annual grasses in California. For example, ripgut brome, a species that is palatable to livestock when young but not when in fruit (DiTomaso 2000), if not grazed or mowed, can accumulate a great deal of thatch (Biswell 1956). This, in turn, may inhibit the germination of other species in subsequent years—a trait that contributes to the listing of this species by the California Invasive Plant Council as a threat to native grassland species (Table 22.1).

Biological Control Methods

Biological control agents (generally insects or pathogens) are mobile and are expected to move from the release area and spread throughout the region. As a result, this control method is not specific to an invaded site or weed infestation. The goal of biological control is to establish self-sustaining populations of beneficial organisms that build up high numbers on the target weed. It is hoped that attack by the biological control agents will reduce the invasiveness of the host weed and result in a substantial reduction in its abundance. A key requirement of the control agents is their high level of specificity to the target weed. Many years of research are necessary to find the appropriate natural enemies and to perform the necessary host specificity tests. Once completed, the results are submitted for review by the U.S. Department of Agriculture (USDA)-Animal and Plant Health Inspection Service (APHIS), the agency that approves permits for the introduction of living organisms into the United States.

In California, over 50 noxious and invasive weeds have been the target of biological control efforts. Of these, 16 species are considered grassland weeds (Table 22.2); 11 species are annual or biennial forbs, and five are perennial forbs. No exotic grass has been the recipient of a biological control agent release; however, efforts to explore for biological control agents against medusahead are currently under way by USDA. The results of successful biological control have been mixed: Five weeds are considered to be under successful biological control, four weeds are thought to be under moderate control, and eight weeds have shown little or no control or their level of control is unknown. Control of some weeds in grassland settings, such as common St. Johnswort and tansy ragwort *(Senecio jacobaeae)*, has been spectacular (Huffaker and Kennett 1959; McEvoy et al. 1991). Although preliminary, another success appears to be developing against

TABLE 22.2
List of Grassland Weeds Targeted for Biological Control, in Chronological Order

Weed	*Scientific name*	*Growth habit*	*Level of control*	*Year of first agent*
Common St. Johnswort	*Hypericum perforatum*	Perennial forb	High	1945
Tansy ragwort	*Senecio jacobaea*	Biennial	High	1959
Puncturevine	*Tribulus terrestris*	Annual	High	1961
Canada thistle	*Cirsium arvense*	Perennial forb	Low	1966
Yellow starthistle	*Centaurea solstitialis*	Annual	Moderate to low	1969
Blessed milk thistle	*Silybum marianum*	Annual	Low	1971
Slenderflower thistle	*Carduus tenuiflorus*	Annual	Unknown	1973
Rush skeletonweed	*Chondrilla juncea*	Biennial	High	1975
Spotted knapweed	*Centaurea maculosa (C. biebersteinii)*	Perennial forb	Moderate	1976
Mediterranean sage	*Salvia aethiopis*	Perennial forb	Unknown	1976
Bull thistle	*Cirsium vulgare*	Biennial	Unknown	1976
Italian thistle	*Carduus pycnocephalus*	Annual	Moderate	1976
Scotch thistle	*Onopordum acanthium*	Biennial	None	1976
Diffuse knapweed	*Centaurea diffusa*	Biennial	Moderate	1980
Squarrose knapweed	*Centaurea virgata* var. *squarrosa*	Perennial forb	High	1995
Purple starthistle	*Centaurea calcitrapa*	Biennial	Low	1998
	Growth habit category	*Proportion*	*Control category*	*Proportion*
	Perennial forb	0.31	High	0.31
	Biennial	0.38	Medium	0.25
	Annual	0.31	Low	0.19
			None	0.06
			Unknown	0.19

NOTE: Further information on the biological control efforts against these weeds is available in Coombs et al. (2004).

squarrose knapweed *(Centaurea virgata* var. *squarrosa)* (Woods and Villegas 2004). Releases of two seed head weevils have resulted in the destruction of nearly all annual seed production at several locations in eastern Shasta County. Even though the plant is a perennial, annual monitoring of field populations shows a steady decline in seedling recruitment and adult plant abundance.

The biological control agents approved for use in California are listed in Table 22.3. Most of the weeds have had more than one biological control agent released against them. Usually, only one or two of the agents have been observed to show some effectiveness against their target weed. These have been rated as "good" or "excellent," and it is recommended that land managers use only these agents if they are not already present in their area. All of the biological control agents in Table 22.3 are available through county agricultural commissioners' offices in California.

The most significant grassland weed in California is yellow starthistle. Biological control research efforts against this weed have been on-going since the 1960s. A total of six biological control insects have been approved for use in the United States: the gall flies *Urophora jaculata* and *U. sirunaseva;* the weevils *Bangasternus orientalis, Eustenopus villosus*, and *Larinus curtus;* and the fruit fly *Chaetorellia australis* (Pitcairn et al. 2004). Of these, five have established in California and three are widespread, occurring almost wherever yellow starthistle grows (Pitcairn et al. 2002). A seventh insect, the false peacock fly, *Chaetorellia succinea,* was accidentally introduced in the early 1990s (Balciunas and Villegas 1999); hence its absence from Table 22.3. This insect has a strong affinity for yellow starthistle and has also spread throughout California. The weevil *E. villosus* and the fly *C. succinea* are the two most common insects found on yellow starthistle in California (Pitcairn et al. 2003). Annual monitoring data at two long-term study sites show a steady increase in the seed head attack rate and a concomitant decrease in seed production, seedling recruitment, and adult plant abundance. Both study sites are located in undisturbed grasslands, so these results may be limited to this kind of habitat. However, these data do suggest that some level of control by the combined attack of *E. villosus* and *C. succinea* may occur in the appropriate habitats.

Most recently, the autoecious, brachycyclic rust fungus *(Puccinia jaceae* var. *solstitialis)* received an experimental use

TABLE 22.3

List of Biological Control Agents Against Grassland Weeds, Approved for Release in California

Weed	*Scientific name*	*Biological control agent*	*Distribution*	*Year of intro*	*Infestation*	*Control*
Common St. Johnswort	*Hypericum perforatum*	*Agrilus hyperici*	Established widely	1950	Moderate	Unknown
		Chrysolina hyperici	Unknown	1945	Unknown	Unknown
		Chrysolina quadrigemina	Established widely	1946	Heavy	Excellent
		Chrysolina varians	No establishment	1952	Absent	Unknown
		Zeuxidiplosis giardi	Established limited	1950	Light	Poor
Diffuse knapweed	*Centaurea diffusa*	*Bangasternus fausti*	Established widely	1994	Moderate	Good
		Larinus minutus	Established widely	1995	Moderate	Good
		Sphenoptera jugoslavica	Established widely	1980	Heavy	Unknown
		Urophora affinis	Established widely	1976	Light	Poor
		Urophora quadrifasciata	Established limited	1990	Slight	Poor
Spotted knapweed	*Centaurea maculosa (C. biebersteinii)*	*Agapeta zoegana*	Established limited	1993	Light	Poor
		Cyphocleonus achates	Established limited	1993	Light	Poor
		Larinus minutus	Established limited	1995	Light	Good
		Terellia virens	Established limited	1995	Light	Poor
		Urophora affinis	Established widely	1976	Light	Poor
		Urophora quadrifasciata	Established limited	1990	Light	Poor
Squarrose knapweed	*Centaurea virgata* var. *squarrosa*	*Bangasternus fausti*	Established widely	1996	Moderate	Excellent
		Cyphocleonus achates	No establishment	1995	Absent	None
		Larinus minutus	Established widely	1997	Heavy	Excellent
		Sphenoptera jugoslavica	Established limited	1998	Moderate	Fair
		Terellia virens	No establishment	1998	Absent	None
		Urophora affinis	No establishment	1998	Absent	None
		Urophora quadrifasciata	Established widely	1998	Light	Poor
Puncturevine	*Tribulus terrestris*	*Microlarinus lareynii*	Established widely	1961	Heavy	Excellent
		Microlarinus lypriformis	Established widely	1961	Heavy	Excellent
Tansy ragwort	*Senecio jacobaea*	*Longitarsus jacobaea*	Established widely	1969	Heavy	Excellent
		Pegohylemyia seneciella	Established widely	1966	Light	Poor
		Tyria jacobaeae	Established widely	1959	Light	Good
Mediterranean sage	*Salvia aethiopis*	*Phrydiuchus tau*	Established limited	1976	Light	Unknown

Rush skeletonweed	*Chondrilla juncea*	*Cystiphora schmidti*	Established widely	1975	Moderate	Poor
		Eriophyes chondrillae	Established widely	1977	Moderate	Fair
		Puccinia chondrillina	Established widely	1976	Moderate	Good
Purple starthistle	*Centaurea calcitrapa*	*Bangasternus fausti*	No establishment	1999	Absent	None
		Larinus minutus	No establishment	1998	Absent	None
		Terellia virens	No establishment	1998	Absent	None
Yellow starthistle	*Centaurea solstitialis*	*Bangasternus orientalis*	Established widely	1985	Light	Poor
		Chaetorellia australis	Established widely	1988	Light	Poor
		Eustenopus villosus	Established widely	1990	Heavy	Good
		Larinus curtus	Established limited	1992	Light	Poor
		Puccinia jaceae var. *solstitialis*	Initial release	2003	Unknown	Unknown
		Urophora jaculata	No establishment	1969	Absent	None
		Urophora sirunaseva	Established widely	1984	Moderate	Poor
Slenderflower thistle	*Carduus tenuiflorus*	*Rhinocyllus conicus*	Established widely	1973	Moderate	Fair
Bull thistle	*Cirsium vulgare*	*Rhinocyllus conicus*	No establishment	1976	Absent	None
		Urophora stylata	Established limited	1993	Moderate	Unknown
Canada thistle	*Cirsium arvense*	*Altica carduorum*	No establishment	1966	Absent	None
		Ceutorhynchus litura	No establishment	1971	Absent	None
		Urophora cardui	Established limited	1977	Light	Poor
Italian thistle	*Carduus pycnocephalus*	*Rhinocyllus conicus*	Established widely	1976	Moderate	Fair
Blessed milk thistle	*Silybum marianum*	*Rhinocyllus conicus*	Established widely	1971	Light	Poor
Scotch thistle	*Onopordum acanthium*	*Rhinocyllus conicus*	No establishment	1976	Absent	None

NOTE: Further information on each of these agents is available in Coombs et al. (2004).

permit for release on yellow starthistle in California. The rust was originally collected from yellow starthistle in its native range of Turkey in 1978 (Woods and Villegas 2004). *Puccinia jaceae* var. *solstitialis* is an obligate parasite of yellow starthistle and is associated with the thistle over a wide area, at least from Spain to Turkey (Savile 1970). It completes its life cycle on a single host plant and has all five spore forms. It causes nonsystemic foliar infections that can reduce fresh and dry weights of inoculated yellow starthistle in controlled studies (Bruckart 1989; Shishkoff and Bruckart 1993). Spores, however, may not persist over the winter.

Despite considerable research on host specificity of *Puccinia jaceae* var. *solstitialis* and nontarget plant safety at the USDA-Agricultural Research Service (ARS) facility in Ft. Detrick, Maryland, little is known about the plant-pathogen interaction under field conditions, including information on the most effective inoculation timing window to maximize infection rates and foliar damage. Furthermore, while the rust has been shown to reduce root biomass, it is unknown whether this is due to a decrease in lateral root production or to the ability of yellow starthistle to produce deep roots. Such information may significantly impact our capability to predict the effect of the pathogen on yellow starthistle's ability to develop tolerance to water stress. Moisture levels have been shown to correlate directly with seed production. If root depth is limited by pathogen stress, this may subsequently impact plant growth, seedhead production, and ultimately reproductive output. In addition, nothing is known on how the *Puccinia* rust will interact with the established biological control insects or how it will change the competitive ability of yellow starthistle compared to other grassland vegetation under different environmental conditions. Results of these studies can greatly improve the capacity to predict the potential effectiveness of the *Puccinia* rust under a number of abiotic and biotic conditions.

Chemical Control

Herbicides are an important method of weed control in grassland systems. Herbicides can be applied to grasslands by a number of methods, including fixed-wing aircraft, helicopters, ground applicators, backpack sprayers, and rope wick applicators. Herbicides registered for use in grasslands of the western United States are listed in Table 22.4, along with pertinent information on each compound. Some of these products, including picloram and metsulfuron, are not registered in California. Of these compounds used in grasslands, the auxinic, or growth regulator, herbicides have played the most important role in broadleaf weed control.

For large-scale use, herbicides are typically considered to be the most economical option. The most widely used grassland herbicides in California are those that have postemergence activity (DiTomaso 2000). These include 2,4-D, triclopyr, dicamba, clopyralid, chlorsulfuron, and glyphosate. Of these, clopyralid, 2,4-D, triclopyr, and dicamba are growth regulator herbicides that are selective on broadleaf species and have little activity on grasses. Clopyralid also has excellent preemergence activity and is highly effective for control of yellow starthistle and other members of the Asteraceae. However, it may have some negative impacts on some native plants within the Asteraceae, Fabaceae, Polygonaceae, and Apiaceae and short-term impacts on Violaceae (Reever Morghan et al. 2003). Chlorsulfuron is an amino acid inhibitor and is also very effective on most broadleaf species, particularly members of the mustard (Brassicaceae) and figwort (Scrophulariaceae) families. It has both preemergence and postemergence activity on most species, but only preemergence activity on yellow starthistle. Like the growth regulator compounds, chlorsulfuron is fairly safe on most grasses. Glyphosate is a nonselective aromatic amino acid inhibitor and provides excellent control of annual and perennial grasses and broadleaf weeds, but it will also damage desirable plants.

Aminopyralid is a new growth regulator herbicide registered in California in 2006. It has about three times the activity of clopyralid on yellow starthistle. In addition to its activity against yellow starthistle, aminopyralid has a broader spectrum of selectivity and has also been shown to be very effective on knapweeds, many other thistles, and fiddlenecks (*Amsinckia* spp.) (Kyser et al. 2007). Both products will injure native legumes during the growing season, but some can be used safely when treatments are made after senescence or during the dormant phase of perennial legumes. Another newly registered herbicide (not yet in California), imazapic, has proven to be very effective on medusahead, downy brome, ripgut brome, barb goatgrass, and other annual grasses, without significantly injuring seedlings of many native perennial grass or broadleaf species (Kyser et al. 2007).

Timing of herbicide applications can determine the effectiveness of the treatment. For yellow starthistle control, the best timing for application of clopyralid and aminopyralid seems to be between December and the end of March, depending on the location (DiTomaso et al. 1999b). Fall or spring applications of imazapic can be effective for the control of annual grasses, depending on the location. In areas with snowpack, spring applications may be more desirable, but in typical Central Valley or foothill conditions, fall applications have proven successful. For perennials, timing of application can depend on the herbicide. Chlorsulfuron can control perennial species with spring, summer, or fall treatments (Drake and Whitson 1989; Whitson et al. 1989; Young et al. 1998), whereas glyphosate is best applied in spring, when invasive plants are at the late bud to early flowering stages (Waterhouse and Mahoney 1983; Young et al. 1998).

Herbicides are generally applied as broadcast treatments over the entire field or directed (spot) applications to control early weed invasions or to prevent the spread of small infestations. However, it is also possible to achieve selective control of a particular weed with otherwise nonselective or relatively nonselective postemergence herbicides by employing a rope wick or wick applicator. These can be either hand-held or vehicle-mounted boom wipers. As a benefit, this application method reduces the potential for herbicide drift and

TABLE 22.4

Commonly Used Herbicides for Grassland Invasive Weed Control

Common name	*Trade name*	*Mode of action*	*Weed spectrum*	*Soil residual*	*Registered in California*	*Effective timing*
2,4-D	Weedar®, Weedone® and many others	Growth regulator	Broadleaf species	Less than 2 weeks	Yes	Postemergence only, from seedling to bolting
Aminopyralid	Milestone®	Growth regulator	Certain broadleaf families (between clopyralid and picloram)	Full season	Yes	Effective both pre- and postemergence; applied fall, winter, or spring
Chlorsulfuron	Telar®	Amino acid synthesis inhibitor	Mainly broadleaf species	At least 2 months	Yes	Preemergence only
Clopyralid	Transline™	Growth regulator	Certain broadleaf families (e.g., Asteraceae, Fabaceae, Apiaceae, Solanaceae, Polygonaceae)	Most of the season	Yes	Effective both pre- and postemergence; applied fall, winter or spring
Dicamba	Banvel®, Vanquish®	Growth regulator	Broadleaf species	Less than 1 month	Yes	Postemergence only, from seedling to bolting
Glyphosate	Roundup®, and others	Amino acid synthesis inhibitor	Nonselective	None	Yes	Postemergence only, from seedling to early flowering
Imazapic	Plateau®	Amino acid synthesis inhibitor	Nonselective, but best on annual grasses	Full season	Registration expected in 2007 or 2008	Mainly as a preemergence treatment, postemergence control with seedlings or rosettes
Metsulfuron	Escort®	Amino acid synthesis inhibitor	Broadleaf species	At least 2 months	No	Fairly effective; preemergence only
Picloram	Tordon™	Growth regulator	Broadleaf species, weak on mustards	Up to 3 years	No	Effective both pre- and postemergence; applied fall, winter or spring
Triclopyr	Garlon®, Remedy®	Growth regulator	Broadleaf species	Less than 1 month	Yes	Postemergence only, good on seedlings, fair on mature plants

injury to adjacent sensitive agricultural crops and can be used to selectively control invasive species around vernal pools, streams, and other bodies of water, or in areas with rare and endangered species or other desirable plants.

Residual thatch can influence the effectiveness of herbicides with preemergence activity. Some herbicides, such as imazapic, can adsorb to standing thatch or other dried debris on the soil surface, thus reducing the effectiveness of the application. However, this does not appear to be a characteristic of aminopyralid or clopyralid (DiTomaso et al. 1999b).

Although herbicides are effective for the control of invasive grassland weeds, they generally do not provide long-term control of weeds when used alone (Bussan and Dyer 1999). In the absence of a healthy plant community composed of desirable species, one noxious weed may be replaced by another equally undesirable species insensitive to the herbicide treatment (DiTomaso 2000). Thus, herbicides in grasslands are best used as part of an integrated weed management system.

Cultural Control

Grazing

Grazing can be an effective way of managing undesirable species in some grasslands both in California and elsewhere (see also Huntsinger et al., Chapter 20). The effectiveness depends on the plant species present, the type of grazer used, and the timing and intensity of the grazing program. Under some conditions grazing can increase undesirable nonnative species, or other less palatable or poisonous species. Intensive grazing can also disturb soil and enhance weed seed germination, reduce competition from more desirable species, and increase soil compaction (Elmore 1992). So, if grazing is to be used, it must be used judiciously with prescriptions designed for individual sites.

Successful invasive weed management can also depend on the type of grazer and timing of grazing. For example, the foraging behaviors of both cattle and goats are conducive to the management of yellow starthistle when plants are grazed at the bolting stage, whereas only goats are effective when plants are in the spiny stages of growth (Thomsen et al. 1993). The ideal time to graze is when the noxious species are most susceptible to defoliation or when the impact on the desirable vegetation is minimal (Kennett et al. 1992).

Stocking rates of livestock can also be adjusted to maximize invasive plant management. Lower stocking rates will generally allow livestock to graze preferred plants and avoid less palatable species. If the invasive species is preferred, then lower stocking rates can be effective. In most cases, however, grasslands with low cattle stocking rates have higher weed infestations compared to areas that are more intensively grazed. Higher stocking densities can minimize the grazers' ability to avoid less palatable invasive weed species. This can lead to a more uniform composition of plant species and more balanced competitive relationships among native and invasive species (Olson 1999).

High-intensity, short-duration grazing, practiced on a rotational basis, is a management system widely adopted in other countries (DiTomaso 2002) that is becoming increasingly recommended in California grasslands (see Jackson and Bartolome, Chapter 17). This can be logistically difficult and generally requires electric fencing to keep animals confined to a specific area. Once grassland has been intensively grazed, it is allowed to recover for about a month before being grazed again. This system usually leads to more uniform forage use (including many weeds) by the grazer. In many cases, this method has been shown to provide much better control of specific weeds than season-long livestock grazing (see review by DiTomaso 2000).

High-intensity grazing of both cattle and sheep has been tested experimentally for the control of medusahead. George et al. (1989a) found that two years of intensive grazing with cattle significantly reduced medusahead from 45% of the total species composition to only 10%. In another study using sheep, intensive mid-spring grazing (April/May) reduced medusahead by greater than 80% the following year (DiTomaso, Kyser and Doran, unpublished data).

Prescribed Burning

There has been increasing interest in the use of prescribed fire for vegetation management in recent years, including in California grasslands (see Reiner, Chapter 18). Purposes for prescribed burning have included invasive weed control, thatch removal, nutrient release from dead, dried plant matter, and stimulation of early growth of desirable species in the spring. However, while most of these purposes are best accomplished with late fall burns, burning designed to control invasive species in California grasslands generally needs to be conducted in late spring or summer. Unfortunately, this timing coincides with the period when there is high risk of fire escapes. Moreover, air quality problems and liability issues can also present a problem when burns are conducted near populated areas. In areas where biological control agents are present, burning may cause damage to these insect populations. In some areas, burning can lead to rapid invasion by other undesirable postfire colonizers with wind-dispersed seeds, particularly members of the sunflower family.

The main objective of using controlled burns for invasive plant control is to deplete the soil seed bank, destroy seeds that are on the plant, and prevent sexual reproduction, which would in turn replenish soil seed reserves. To successfully control annual species with fire, it is critical to either kill plants before their seeds become viable (DiTomaso et al. 1999a) or destroy the seeds before they disperse (Allen 1995; Menke 1992). For annual species, burns should be conducted when the target plant's seeds are still undispersed and are exposed to direct flames in the canopy, but desirable species have dispersed their seeds to the ground. Seeds on the soil surface are not generally exposed to lethal temperatures in grassland fires (Sweet 2005). For perennial or herbaceous plants with protected meristems (e.g., rosettes or rhizomes), the burn must be hot enough to damage the vegetative reproductive tissues and prevent resprouting. For this reason, prescribed burning is rarely effective for the management of perennials and in most cases can stimulate their growth (DiTomaso et al. 1999a). It has, however, been used to reduce the seed bank of French broom within California grassland settings (Alexander and D'Antonio 2003b). Fire stimulates broom seed germination, and the flush of seedlings is then cut, treated with an herbicide, or reburned prior to plants becoming reproductively mature.

Annual species that are most susceptible to control with prescribed burning are those that produce seeds after the fire season begins, have flowering structures either embedded within the fuel bed or exposed to direct flames, and have short-lived seed banks. For control of these late-season annual grasses and forbs, the timing of the burns is critical. Burns conducted before the target species have fully cured their seeds are most effective (Brooks 2001). To be successful, however, fine fuels to carry the fire should not be limiting. However, fine fuels are often patchy across landscapes, and the result is a mosaic burn pattern that results in variable weed control.

Invasive grasses with long-awned seeds (e.g., medusahead, downy brome, ripgut brome, red brome, and barb goatgrass) rely on animal dispersal. In many of these species, the seeds remain in the inflorescence longer than most desirable grasses, and, as a result, they are more susceptible to destruction by the direct heat of burning (Dahl and Tisdale 1975, Young et al. 1970). Effective control of medusahead with prescribed burning (more than 90%) was demonstrated as far back as 1953 (Furbush 1953) and has been demonstrated on a number of other occasions (George 1992; McKell et al. 1962; Pollak and Kan 1998; Sharp et al. 1957; Betts 2003; DiTomaso et al., unpublished). However, in some cases burning has not proven successful on medusahead. Young et al. (1972) found that repeated annual burning in mid-summer increased medusahead infestations while decreasing the population of more desirable annual grasses. This inconsistency is probably due to differences in the length of flame exposure and to the heat of the burn. Other invasive long-awned annual grasses, including barb goatgrass (DiTomaso et al. 2001; Hopkinson et al. 1999) and ripgut brome (DiTomaso et al. 1999a; Kyser and DiTomaso 2002) have also been controlled with one or multiple years of burning, although exception can also be found (A. Levine and C. D'Antonio, unpublished data). In contrast, downy brome and red brome are difficult to control with burning because their seedheads begin to shatter and the seeds fall to the soil surface before enough fuel is available (Brooks 2002; Young and Evans 1978).

Late season forbs, particularly yellow starthistle, can also be controlled by repeated early summer burns (DiTomaso et al. 1999a; Kyser and DiTomaso 2002). Because the seed of starthistle survives for more than two years in the soil and germination is enhanced by a preceding burn (DiTomaso and Kyser, unpublished data), a single year of burning will not control an infestation. In one case, three consecutive years of burning were required to reduce the yellow starthistle seed bank by 99% (DiTomaso et al. 1999a). In other studies (DiTomaso and Kyser, unpublished data; Miller 2003), integrating a first year burn with a second year herbicide treatment was the most effective strategy.

Like other control strategies, prescribed burning requires a follow-up program to prevent escaped or isolated plants from completing their life cycle. Where the seed bank is short-lived, a follow-up program may take only a couple of years; in other cases, it may take longer.

Since multiple burns are not usually practical or permitted, and fuel loads may not be sufficient to allow multiple year burns, integrated approaches are often more appropriate than using burning as a sole control option.

Revegetation

The goal of grassland management should be to improve degraded communities and make them less susceptible to noxious weed invasion. Revegetation with desirable and competitive plant species is one approach to achieving long-term, sustainable suppression of weed population growth, while providing high forage production or desirable plant diversity (Borman et al. 1991; Lym and Tober 1997).

The choice of species used in a revegetation effort is critical to its success. Seeded species need to be adapted to the soil conditions, elevation, climate, and precipitation level of the site (Jacobs et al. 1999). Only a limited number of species have proven to be aggressive enough to resist establishment of problematic invasive species, and the proper species choice varies depending on the location and objective. Perennial bunchgrasses are among the most commonly used species for revegetating western rangelands and grasslands, and they have been shown to reduce the growth and reproduction of weeds such as yellow starthistle (Lym and Tober 1997; Roché et al. 1994; Dukes 2001a; Reever Morghan and Rice 2005). Some native broadleaves, including *Hemizonia congesta,* have a similar life cycle to and can suppress the growth of yellow starthistle (Duke 2001a). Introduced broadleaf species such as legumes can also be used in revegetation programs to suppress rangeland or grassland weeds. For example, Thomsen et al. (1997) and Thomas (1996, 1997) tested several legume species for their competitive effect on yellow starthistle. Thomsen et al. (1997) found subterranean clover *(Trifolium subterraneum)* varieties to be the most competitive when combined with grazing and mowing, but they did not provide adequate seasonal control of yellow starthistle in the absence of other control options. Thomas (1996, 1997), however, used a combination of subterranean clover and/or crimson clover *(Trifolium incarnatum)* as a cover crop in yellow starthistle–infested pasture. In a completely infested field, he reported an 80–90% reduction in yellow starthistle one year after planting with crimson clover. However, use of legumes may increase soil nitrogen, which can cause other potentially undesirable effects (see Dukes and Shaw, Chapter 19).

Combination of Herbicides and Revegetation

An integrated approach combining herbicide treatments and perennial grass revegetation was tested in a heavily infested yellow starthistle grassland site near Yreka, California (Siskiyou County). The goal was to provide ranchers and land managers with economical and sustainable management programs that maximized forage production or restored and preserved desired ecosystem functions, including reducing the susceptibility of their lands to reinvasion or invasion by other noxious weeds.

In this severely degraded site, a mid-February treatment with glyphosate (one treatment) and clopyralid (one, two, or three annual spring treatments) was used to provide a window of reduced competition for the subsequent establishment of pubescent wheatgrass drill-seeded in early March (Enloe 2002; Enloe et al. 2005). This seeding timing, while not appropriate for much of California, has been shown to work well for far Northern California (Kay and Street 1961), where sufficient rain falls after early March to support wheatgrass establishment.

The study area was monitored for six years (Enloe et al. 2005). Clopyralid treatment significantly reduced yellow starthistle, and glyphosate gave control of the annual grasses. This combination allowed pubescent wheatgrass seedlings to establish with a single year of treatment. Once pubescent wheatgrass seedlings survived the first year, additional applications of clopyralid to control the starthistle did not improve their establishment. In the absence of clopyralid and glyphosate, pubescent wheatgrass establishment was very limited.

The integrated approach gave long-term suppression of yellow starthistle and other exotic annual grasses and forbs over the six year period. Treatments with clopyralid alone (e.g., without seeding of wheatgrass), gave good control of yellow starthistle, but the plant community initially became dominated by undesirable annual grasses, particularly downy brome. Downy brome, in turn, offered little competitive resistance to starthistle reinvasion, and within a couple of years after the final clopyralid application this site reverted to yellow starthistle (Enloe et al. 2005).

Long-term Management Using Prescribed Burning and Clopyralid

As was previously discussed, repeated burning is generally impractical and can negatively impact air quality as well as compromise establishment of biocontrol agents. The continuous use of clopyralid can also have undesired outcomes. As a result, an integrated strategy was developed combining clopyralid and prescribed burning for management of yellow starthistle (DiTomaso et al. 2003). Results of small-scale plot studies indicate that prescribed burning stimulated the germination of yellow starthistle seed in the subsequent rainy season. This helped to deplete the seed bank more rapidly. Thus, a first-year prescribed burn followed by a second-year clopyralid treatment gave nearly complete control of yellow starthistle in the year after the last treatment. This strategy may reduce the number of years necessary to intensively manage yellow starthistle and allow land managers to transition into a follow-up management and reseeding program sooner. The reverse order gave very poor control, suggesting that an integrated approach should not end with a prescribed burn.

An additional benefit of integrating prescribed burning into a yellow starthistle management program is the control of noxious annual grasses. When ripgut brome and medusahead coexisted with yellow starthistle, burning contributed to the reduction of all three invasive species (DiTomaso et al. 2003).

With the results of these small-scale studies, a large-scale integrated approach was used at Fort Hunter Liggett in Monterey County, California (Miller 2003; Torrence et al. 2003a, b). After two or three years of treatment, which included a first-year burn followed by one or two years of clopyralid, yellow starthistle control was excellent. At that time, a follow-up maintenance plan was implemented to prevent any potential reinfestation.

This project demonstrated that yellow starthistle populations could be controlled with two years of properly-timed, intensive management. The most successful long-term, large-scale yellow starthistle control treatment was to follow a first-year prescription burn with a broadcast clopyralid application treatment the next year. However, a follow-up program should be instituted immediately in order to prevent invasive plant resurgence to previous levels.

Because of the ecological diversity within California, no single species or combination of species will be effective in providing ecological resistance against invasive weeds under all circumstances. While pubescent wheatgrass *(Thinopyrum intermedium)* has proven successful for yellow starthistle suppression in Siskiyou County (DiTomaso et al. 2000; Enloe et al. 2005), it may not be appropriate in many other areas of the state that lack summer rainfall or where native grasses are the landscape objective (see Stromberg et al., Chapter 21)

Though perennial grasses have been shown to be most successful in competing with grassland weeds, a combination of species with various growth forms can also be effective. This diversity allows for maximum niche occupation and more sustained resource capture over the growing season (Sheley et al. 1999; Dukes 2001a, b). For example, seed mixtures of grasses with legumes improved the rate of microbial and soil structure recovery compared to grasses alone (Jacobs et al. 1999). Seeding with a variety of species, however, makes it difficult to choose control techniques (such as herbicides) that will not harm one of the seeded species. This is particularly true if grasses are seeded with broadleaf species and the weeds that are being controlled are broadleaf species. A revegetation program may require initial seeding with perennial grasses during the weed management phase, followed by subsequent seeding with desirable broadleaf species. Revegetation is generally a slow process and may take several years to be successful. It is most successful when combined with other management techniques.

Developing a Management Strategy

The major elements of a grassland weed management program are preventing introduction or reinvasion of invasive weed seed, reducing the susceptibility of the ecosystem to invasive plant establishment, developing effective educational materials and activities, and establishing a program for early detection and monitoring (DiTomaso 2000).

An effective invasive weed management strategy should include three major goals: (1) controlling the weed; (2) achieving land use objectives such as forage production, wildlife habitat and ecosystem preservation, protecting diversity or endangered species, or recreational land maintenance; and (3) preventing reinvasion or invasion of other noxious species. All these goals are tied together with improving the degraded grassland community and reestablish a functioning ecosystem.

Integrated Approaches to Weed Management

As previously discussed, a single method does not generally give sustainable control of a grassland weed. A successful long-term management program should be designed to include combinations of mechanical, cultural, biological, and chemical control techniques. There are many possible combinations that can achieve the desired objectives, and these choices must be tailored to the site, economics, and management goals. See "Case studies of integrated management strategies" for more elaboration (Sidebar 22.1).

Even when a single control method does provide effective control over a number of years, it may not be practical. For example, repeated burning can be effective for the control of some annual grasses and yellow starthistle, but this approach is often prohibited. Thus, it may be necessary to incorporate other control methods, along with burning, into a long-term management strategy (DiTomaso et al. 2006; Kyser and DiTomaso 2002).

When an integrated strategy is employed, it may be important to employ a particular sequence of approaches. For example, in a revegetation effort along a yellow starthistle–infested canal and roadside, the first step was to intensively manage starthistle (Brown et al. 1993; Thomsen et al. 1994). The second step was to reseed with competitive, deep-rooted native perennial grasses. In the final stage, native broadleaf forbs such as California poppy and lupines were seeded into the system.

Biological control can also play a key part in the success of an integrated control program. For example, Huffaker and Kennett (1959) reported on the success of the biological control program for the management of common St. Johnswort. They noted that maximal improvement of the rangeland was achieved when the biocontrol agent was used in combination with moderate timely grazing. This combination prevented the expansion of ripgut brome in the grassland sites previously occupied by common St. John's wort.

In a review, Lym (2005) described the numerous situations in which the successful use of biological control insects (*Aphthona* spp.) for leafy spurge *(Euphorbia esula)* depend on the use of other conventional weed control methods. Integration of *Aphthona* spp. with herbicides, grazing, or burning gave more rapid and better leafy spurge control that any method used alone.

Finally, it is important to emphasize that the ultimate objective of any control strategy is to develop a "healthy" functional ecosystem. Competitive background vegetation in grasslands will not only reduce the potential establishment of invasive plants, but can also enhance the effectiveness of other control strategies, including biological control (McEvoy and Coombs 1999). As an example, the seed feeding insects for yellow starthistle can have attack rates of greater than 90% (DiTomaso et al. 2006), yet reduce seedset by only about 50–60% (Woods et al. 2004). In a system with competitive vegetation, a reduction of this level may suppress starthistle to an acceptable and sustainable level.