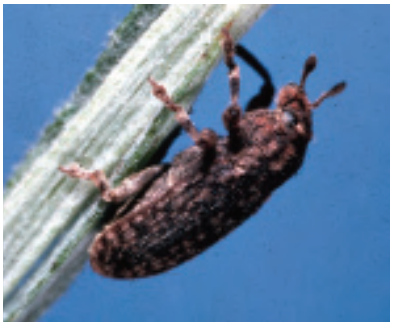
Yellow Starthistle Management Guide



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CHAPTER 1: Introduction and Spread

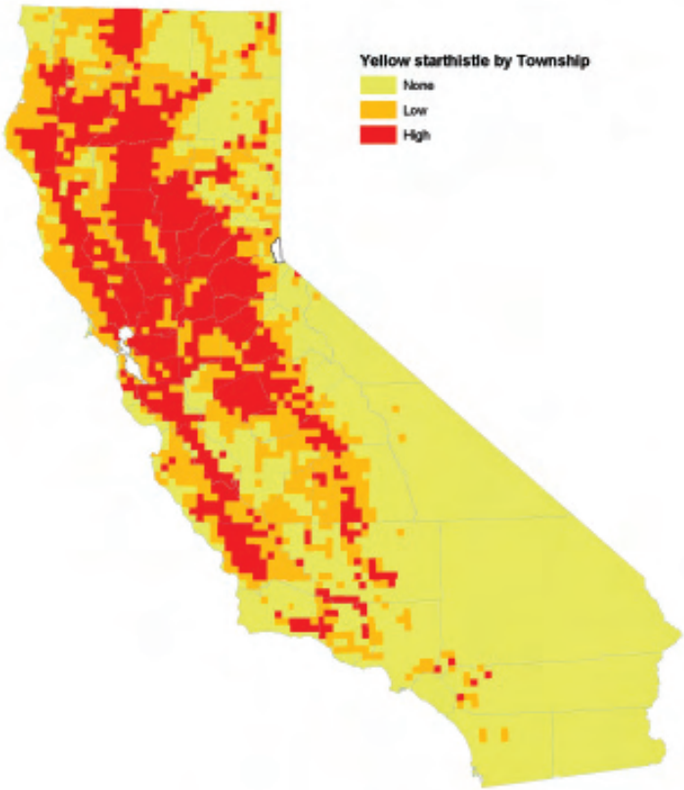
Introduction to North America

The center of origin of yellow starthistle (*Centaurea solstitialis* L.) is believed to be Eurasia, where it is native to Balkan-Asia Minor, the Middle East, and south-central Europe (Maddox 1981). Its introduction into North America probably occurred in California after 1849 as a seed contaminant in Chilean-grown alfalfa seed, known then as Chilean clover (Gerlach *et al*. 1998). Historical records indicate that alfalfa was first introduced to Chile from Spain in the 1600s and from Chile to California at the time of the gold rush. Despite its Spanish origins, alfalfa came to California only from Chile before 1903. After 1903, it is likely that alfalfa was also introduced from Spain, France, Italy, and perhaps Turkestan.

Worldwide distribution of yellow starthistle. *Maddox* et al. *1985.*

Spread and Distribution in California

It has been speculated that the introduction of yellow starthistle into California occurred in multiple steps (Gerlach 1997a, b). The first report of alfalfa cultivation was near Marysville, California, in 1851. Before the 1870s alfalfa was grown primarily along river levees near Sacramento, Marysville and San Francisco. These areas were characterized by deep, well-drained soils and easy access to drinking and irrigation water. Both animal and alfalfa forage were distributed only short distances. As a result, yellow starthistle infestations that accompanied alfalfa stands were fairly localized. From 1870 to about 1905 much of the surrounding areas previously consisting of dry-farmed wheat and barley fields were converted to both dryland and irrigated alfalfa fields. During this period, yellow starthistle established as dense local populations in these areas and along adjacent roadsides. The use of tractors and other equipment spread starthistle seed to other locations, including grain fields. Gerlach (1997a) indicates that yellow starthistle in California probably decreased between 1920 and 1940, most likely due to changes in crop production techniques and the widespread use of inorganic herbicides, such as



Distribution of yellow starthistle in California. *This 2002 map, based on survey data by township, illustrates how widespread the plant is in the state. At 14 million acres, it is California's most widespread weed. Data collected by the California Department of Food and Agriculture. (Pitcairn, Schoenig, Yacoub and Gendron 2006)*

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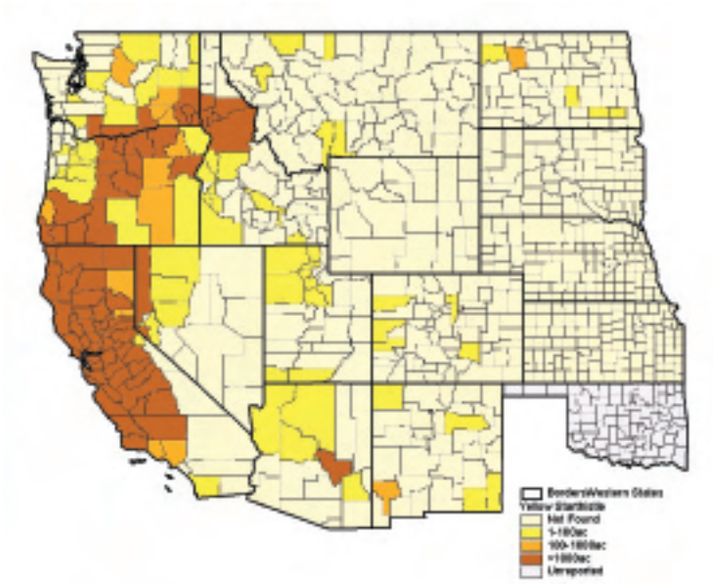

Distribution of yellow starthistle in western states. *While plains states have many grassland weeds that threaten California, yellow starthistle is one grassland weed spreading from California. Data provided in 2001 by state weed coordinators and compiled by Eric Lane, Colorado Weed Coordinator.*

sodium arsenite and sodium chlorate, along roadsides. However, around the 1930s or 1940s yellow starthistle began to invade foothill grasslands on both sides of the Central Valley. In this way, yellow starthistle became an integral part of the grazing/weed dynamic of the rangeland system, in which wildlife and livestock participated in the spread of the plant. By 1958, the weed was estimated to have invaded over one million acres in California (Maddox and Mayfield 1985).

Since the 1960s, three factors have contributed greatly to the further spread of yellow starthistle: an extensive road building program, increased suburban development, and expansion in the ranching industry. These factors all contributed to the rapid and long-range dispersal of seed and the establishment of new satellite populations (Gerlach *et al*. 1998). Over the past 40 years, yellow starthistle has spread into rangeland, native grasslands, orchards, vineyards, pastures, roadsides, and wasteland areas. The infestation area reached nearly eight million acres in California by 1985 (Maddox and Mayfield 1985). Today, it is thought to have spread to over 15 million acres, and can be found in 56 of the 58 counties in California (Pitcairn *et al*. 1998b).

Spread to Other States

Introduction of yellow starthistle from California to other western states occurred in the 1870s and 1880s (Gerlach 1997a, Roché 1965). The first report outside of California was in Bingen, Washington (Sheley *et al*. 1999b). These first introductions were also likely through contamination

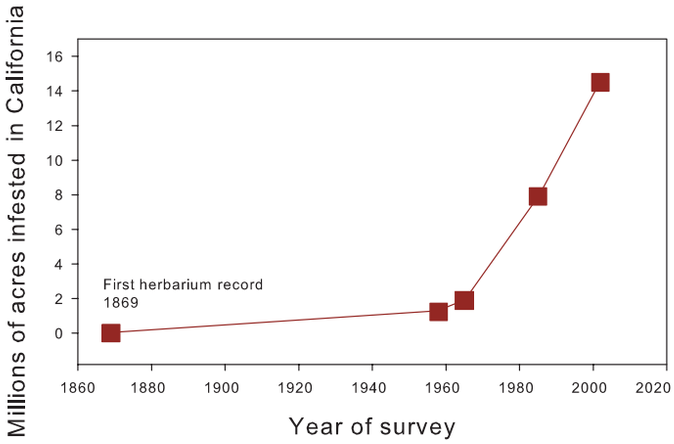

Fig. 1. Expansion in California. *A comparison of estimated infestation area in California shows a rapid expansion over the last 50 years (Pitcairn* et al. *2006).*

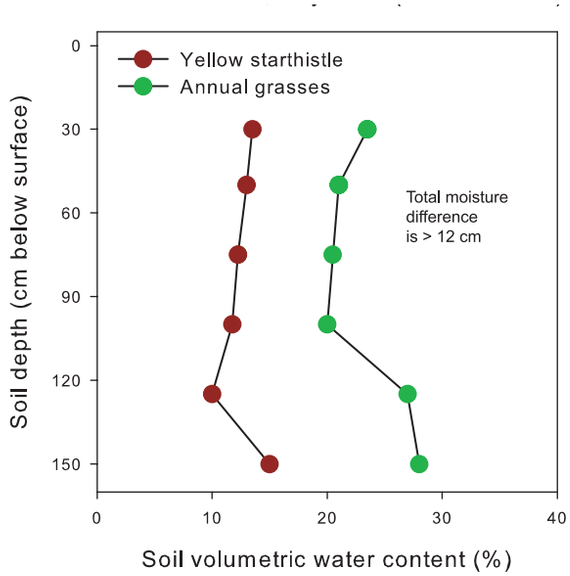

Fig. 2. Soil moisture under yellow starthistle compared to annual grasses. *The volumetric water content of soil under yellow starthistle is reduced compared to soil under annual grasses near UC Davis, July 1996 (Gerlach 2003).*

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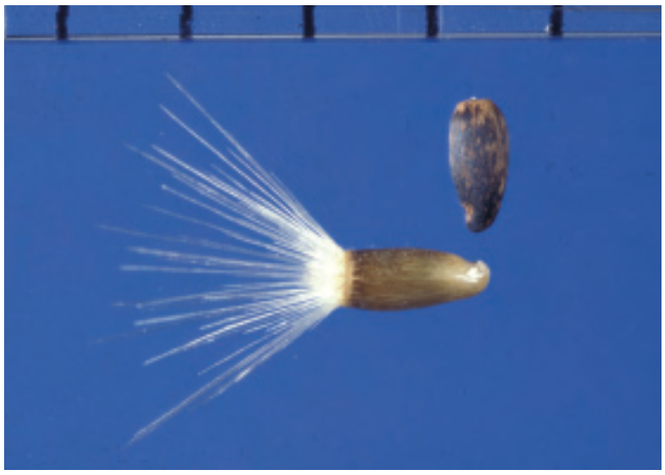

Seed dispersal. *Yellow starthistle seeds have stiff bristles that attach to fur or clothing, facilitating dispersal. (Photo: J. Clark)*

Contaminated hay. *If hay contaminated with yellow starthistle is moved offsite, it can become a source of new infestations. (Photo: J. McHenry)*

of alfalfa seed (Gerlach 1997a). During the 1920s, yellow starthistle expanded rapidly in grasslands in the Pacific Northwest states. By the mid-1980s it was estimated to occupy 280,000 acres in Idaho, 135,000 acres in Oregon, and 148,000 in Washington (Sheley *et al*. 1999b). In 1989, the rate of spread of yellow starthistle was determined to be 7,000 to 20,000 acres of rangeland per year in the west (Callihan *et al*. 1989) and by 1994 it was estimated to be spreading at twice that rate (15,000 to 50,000 acres per year) (Sheley and Larson 1994).

Today, yellow starthistle can be found in 23 of the 48 contiguous states, extending as far east as New York (Maddox *et al*. 1985). It has also extended into Canada from British Columbia to Ontario. Beyond this continent, yellow starthistle is now found in nearly all Mediterranean climates and most temperate areas of the world (Maddox *et al*. 1985).

Mechanisms of Spread

Human activities are the primary mechanisms for the long distance movement of *C. solstitialis* seed. Seed is transported in large amounts by road maintenance equipment and on the undercarriage of vehicles. The movement of contaminated hay and uncertified seed are also important long distance transportation mechanisms. Locally, seed is transported in lesser amounts and over short to medium distances by animals and humans. The short, stiff, pappus bristles are covered with microscopic, stiff, appressed, hair-like barbs that readily adhere to clothing and to hair and fur. The pappus is not an effective long distance wind dispersal mechanism as wind dispersal moves seeds only a few feet (Roché 1992).

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CHAPTER 2: Impact

Economics

Yellow starthistle is considered one of the most serious rangeland, grassland, and wildland weeds in the northwestern United States. It can also infest grain fields and other agricultural areas where seeds can contaminate grain harvest and lower crop quality and value.

Taxpayers incur significant direct costs for both regional and statewide control of yellow starthistle by public agencies on public lands, including costs of materials and labor for treatments such as prescribed burning, herbicide application and mowing. In California, about 0.5 million acres of yellow starthistle are managed at about $25 per acre for a cost of about $12.5 million annually in management. Taxpayers also fund the California Department of Food and Agriculture's biological control program for statewide management of this noxious weed (Jetter *et al*. 2003).

Yellow starthistle is a major consumer of groundwater, costing the state millions of dollars in lost water for wildlife, agriculture and municipal uses (Gerlach 2004). It can also reduce land value and reduce access to recreational areas (DiTomaso *et al*. 1998b, Roché and Roché 1988).

On military bases such as Fort Hunter Liggett, yellow starthistle can severely impact training exercises and can impair the use of equipment (e.g., snagged parachutes, torn clothing) or clog air filters on vehicles. In addition, yellow starthistle can cause mechanical injury to humans (particularly to the face) when the spines are encountered (Miller 2003).

Failure to control yellow starthistle may impose substantial costs on neighboring properties (Jetter *et al*. 2003). If a rancher, public land manager, or homeowner does not control yellow starthistle, it may spread onto surrounding land, whether rangeland, farmland, roadside, or wilderness area.

These impacts are explored in more detail in the following sections.

Horse with chewing disease. *Horses poisoned by yellow starthistle develop a neurological condition and mouth ulcers. (Photo: J. McHenry)*

Rangelands

Although no comprehensive economic assessments have been conducted for yellow starthistle, millions of dollars in losses occur annually from interference with livestock grazing and forage harvesting procedures, and reduced yield and forage quality of rangelands (Callihan *et al*. 1982, Roché and Roché 1988). In a study conducted at the Sierra Foothill Research and Extension Center, it was estimated that a 20-31% infestation of yellow starthistle reduced livestock carrying capacity by about 10-15% (Connor 2003). It was also speculated that heavier infestations could reduce the carrying capacity of rangeland by over 50%. Over the entire state of California, it is estimated that yellow starthistle control expenditures and loss in forage value result in combined losses of 6% to 7% of the value of pasture (S. Schoenig, California Department of Food and Agriculture, pers. comm.).

Cattle, sheep (*Ovis*), and goats (*Capra*) will graze on yellow starthistle in early spring and up to the bolting stage. Because of the spiny flower heads, livestock will not graze yellow starthistle once it begins to mature (Maddox *et al*. 1985, Sheley *et al*. 1999a, Thomsen *et al*. 1993, 1996a). Thus, yellow

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starthistle can greatly increase the cost of managing livestock. Although the nutritional component of yellow starthistle leaves is highly digestible by ruminants during the growing season (Callihan *et al*. 1995), its nutrient value declines as the plants mature. Measures of protein and acid detergent fiber (ADF) content indicate that yellow starthistle has acceptable nutritional value as a component of a ruminant's diet (Thomsen *et al*. 1989). In the bolting to early bud stage, protein content was 11 to 13% and ADF was 28 to 32%. However, an analysis of the nutritional status of cattle manure in the fall indicated that yellow starthistle-infested pastures contain considerably less crude protein and total digestible nutrients compared to uninfested pastures (Barry 1995) and do not provide the required quality of forage in summer and fall (Connor 2003).

Toxicity to Horses

Numerous reports have characterized the toxic effect of yellow starthistle on horses (Cheeke and Shull 1985, Cordy 1978, 1954a, b, Kingsbury 1964, Larson and Young 1970, Martin *et al*. 1971, McHenry *et al*. 1990, Mettler and Stern 1963, Panter 1990, 1991, Young *et al*. 1970). When ingested by horses, yellow starthistle causes a neurological disorder of the brain called nigropallidal encephalomalacia or "chewing disease." Continued feeding results in brain lesions and mycosal ulcers in the mouth (Kingsbury 1964). There is no known treatment for horses that have been poisoned by yellow starthistle. In most cases the animals die from starvation or dehydration (Panter 1991).

The poisoning is a chronic condition affecting the horse primarily after the animal has ingested fresh or dried plant material over an extended period, typically a 30 to 60 day period, at cumulative fresh weight of 60 to 200% their body weight (Panter 1990, 1991). Cheeke and Shull (1985) reported the lethal dose to be 2.3 to 2.6 kg yellow starthistle per 100 kg of body weight per day. The clinical signs of poisoning include drowsiness, difficulty in eating and drinking, twitching of the lips, tongue flicking, and involuntary chewing movements. The peak months of poisoning are midsummer (June-July) and more importantly mid-fall (October-November) (Cordy 1954a, b, 1978). The summer peak is associated with the rapid growth phase following spring and the second peak is likely due to autumn rainfalls that stimulate growth of plants surviving through the summer.

It is suspected that repin, a sesquiterpene lactone isolated from yellow starthistle, may be responsible for symptoms in horses (Akbar *et al*. 1995; Merrill and Stevens 1985). In another study, researchers provided evidence suggesting that amino acids aspartate and glutamate may also be involved (Roy *et al*. 1995).

Yellow starthistle poisoning is generally most dangerous when it is the only feed available or when it is a significant contaminant of dried hay. In some cases, however, horses acquire a taste for yellow starthistle and seek it out even when other forage is available (Panter 1991). In northern California in 1954, it was estimated that at least 100 cases of horse poisoning by yellow starthistle occurred annually (Cordy 1954b). Because starthistle toxicity is generally recognized today, veterinarians and researchers note that cases of yellow starthistle poisoning in horses are now relatively uncommon (Segall, UC Davis School of Veterinary Medicine, pers. comm.).

Interestingly, it appears that only horses are affected by ingestion of yellow starthistle. Mules and burros seem unaffected. However, all grazing animals can sustain damage to their eyes from the plant's long, sharp spines (Carlson *et al*. 1990).

Roadsides and Recreational Areas

In addition to rangeland, pastures and grasslands, yellow starthistle is the most important roadside weed problem in much of central and northern California (Anonymous 1999, Maddox *et al*. 1985).

Yellow starthistle along roadside. *Infestations spread through equipment and vehicles. Roadside infestations often represent the leading edge of spread.*

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Its spread along roadsides probably occurs with the movement of contaminated soil, vehicles and equipment, particularly mowers. These roadside infestations tend to represent the leading edge of movement into new areas, where they then spread into grassland and rangeland habitats (Schoenig 1999).

Many recreational areas, including trails and campgrounds, streamsides, hunting areas, and recreational vehicle parks are contaminated with yellow starthistle. Such infestations reduce or eliminate access, resulting in an economic impact on both private and public areas.

Wildlands

Yellow starthistle infestations may reduce wildlife habitat and forage, displace native plants, and decrease native plant and animal diversity (Sheley and Larson 1994). Dense infestations also threaten natural ecosystems and nature reserves by fragmenting sensitive plant and animal habitat (Scott and Pratini 1995).

Severe infestations of yellow starthistle can form near-monotypic stands, dramatically impacting plant diversity in these areas. In a study at Sugarloaf Ridge study in Sonoma County, California, total plant diversity increased significantly when yellow starthistle was controlled using multiple years of prescribed burning compared to unburned plots (DiTomaso *et al*. 1999a). This increase in diversity remained higher than untreated plots for two years following the final treatment (Kyser and DiTomaso 2002).

Hastings and DiTomaso (1996) suggest that invasion of California grasslands by yellow starthistle may be caused, in part, by fire suppression and reductions in fire frequency in these ecosystems. At Sugarloaf Ridge, for example, yellow starthistle invaded grasslands in the 1980s following 60 years of fire suppression. Once present, heavy infestations of yellow starthistle may change the fire regime by changing fuel characteristics at a given site. This may keep the community perpetually off-balance and not allow the re-establishment of native species. Once established as a dense stand on a site, yellow starthistle does not provide sufficient fine fuel to carry fire when still green (Hastings and DiTomaso 1996). Later in the season, dried skeletons of yellow starthistle can provide fuel for late-summer wildfires.

Yellow starthistle in wildlands. *Many natural areas in California are heavily infested with yellow starthistle. At Sugarloaf Ridge State Park, grasslands are dominated by starthistle. This photo shows the potential of prescribed fire in controlling starthistle (background left, compared to unburned foreground).*

Water Consumption

Recent studies indicate that yellow starthistle significantly alters water cycles and depletes soil moisture reserves in annual grasslands and foothill woodland ecosystems in California (Benefield *et al*. 1998, DiTomaso *et al*. 2000b, 2003b, Dudley 2000, Enloe 2002, Enloe and DiTomaso 2004, Gerlach *et al*. 1998) and in perennial grasslands in Oregon (Borman *et al*. 1992). Because of its high water usage, yellow starthistle increases water conservation costs and threatens both human economic interests and native plant ecosystems (Dudley 2000). The California Water Resources Control Board has acknowledged that control of weeds could significantly conserve water. Based on a conservative estimate of starthistle coverage in the Sacramento River watershed, Gerlach (2004) estimated that yellow starthistle may cause an annual economic loss of $16 to $75 million in water conservation costs alone. This amounts to approximately 46,000 acre-feet (15 billion gallons) of water loss from the Sacramento River watershed each year through transpiration by yellow starthistle (Gerlach 2004). An estimate for Siskiyou County suggested that the potential water loss to yellow starthistle would be more than 26,400,000 gallons of water per year (Enloe 2002).

Depletion of soil moisture by yellow starthistle can result in a loss of 15 to 25% of mean annual

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precipitation (Gerlach 2004). Because these infestations use deep soil moisture reserves earlier than associated natives such as blue oak (*Quercus douglasii*) or purple needlegrass (*Nassella pulchra*), native species can experience drought conditions even in years with normal rainfall (Benefield *et al*. 1998; Gerlach *et al*. 1998).

Excessive water use by yellow starthistle could decrease water levels in streams and lakes, reducing water availability for recreational activities. Decreased stream flows may also reduce or delay spawning of anadromous fish and degrade fisheries water quality through effects of reduced flow on water temperature (Jetter *et al*. 2003).

Bee Industry

Not every aspect of yellow starthistle is detrimental. The weed is regarded as an important honey plant and late-season food source for bees in California (Edwards 1989, Goltz 1999). In 1959, about 150,000 bee colonies utilized yellow starthistle as a source of pollen and nectar. At that time honey from yellow starthistle was valued at $150,000 to $200,000 annually (Maddox *et al*. 1985). No recent economic estimates have been made for the value of yellow starthistle in honey production.

Bees extract yellow starthistle nectar. *A range of bees use the nectar, including bumble bees (pictured here) and commercial honey bees. (Photo: B. Villegas)*

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CHAPTER 3. Biology and Ecology

Yellow starthistle is a winter annual widely distributed in the Central Valley and adjacent foothills of California. It is currently spreading in mountainous regions of the state below 7,000 feet elevation and in the Coast Ranges, but is less commonly encountered in the desert, high mountains and moist coastal sites. It is typically found in full sunlight and deep, well-drained soils where annual rainfall is between 10-60 inches.

Yellow starthistle competes well in both stressed conditions and more favorable environments created by disturbance (Gerlach and Rice 2003). In more favorable sites, yellow starthistle can grow larger and produce more seeds than many competing species. Its extended growing and flowering season allows it to persist within relatively closed grassland vegetation and take advantage of residual soil moisture resources not used by annual grass species (Gerlach 2000). A detailed examination of yellow starthistle biology and ecology is undertaken below.

Taxonomy and Identification

All 12 species of *Centaurea* in California are non-native and nine have purple to white flowers (Hickman 1993). The three yellow-flowered species include *Centaurea solstitialis* (yellow starthistle), *Centaurea melitensis* (tocalote, Napa or Malta starthistle), and *Centaurea sulphurea* (Sicilian or sulfur starthistle). In addition to yellow flowers, these three species also have long sharp spines associated with their flowerheads. In other western states, *Centaurea macrocephala* (bighead knapweed) also has yellow flowers but does not have long sharp spines on the flowerheads (Roché 1991c). In California, *Centaurea melitensis* is also considered invasive (Cal-IPC 2006), particularly in the southern part of the state (DiTomaso and Gerlach 2000b). However, it flowers earlier in the year, does not form such dense populations, is less vigorous, and is far less invasive than yellow starthistle.

Three yellow-flowered Centaureas. *From left to right: tocalote, Sicilian starthistle, and yellow starthistle.*

Reproduction

FLOWERING AND POLLINATION

Yellow starthistle typically begins flowering in late May and continues through September. Unlike other yellow-flowered *Centaurea* species, yellow starthistle has a very low level of self-fertilization (Barthell *et al*. 2001, Gerlach and Rice 2003, Harrod and Taylor 1995, Maddox *et al*. 1996, Sun and Ritland 1998). Thus, a significant amount of cross-fertilization insures a high degree of genetic variability within populations.

Honeybees play an important role in the pollination of yellow starthistle, and have been reported to account for 50% of seed set (Maddox *et al*. 1996). Bumblebees are the second most important floral visitor to starthistle flowers, but several other insects also contribute to fertilization of the ovules (Harrod and Taylor 1995).

In a study conducted by Barthell *et al*. (2001) on Santa Cruz Island in California, investigators found that honeybees visited yellow starthistle 33 times more than native bees. By comparison, native bees visited a native gumplant species (*Grindelia camporum*) 46 times more than honeybees. In addition, they found that when honeybees were excluded from visiting starthistle but native bees were not, the average seed head weight of yellow starthistle significantly declined. The authors concluded that honeybees and yellow starthistle may act as invasive mutualists, increasing the survivorship of each other.

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TIMING OF FLOWER AND SEED DEVELOPMENT

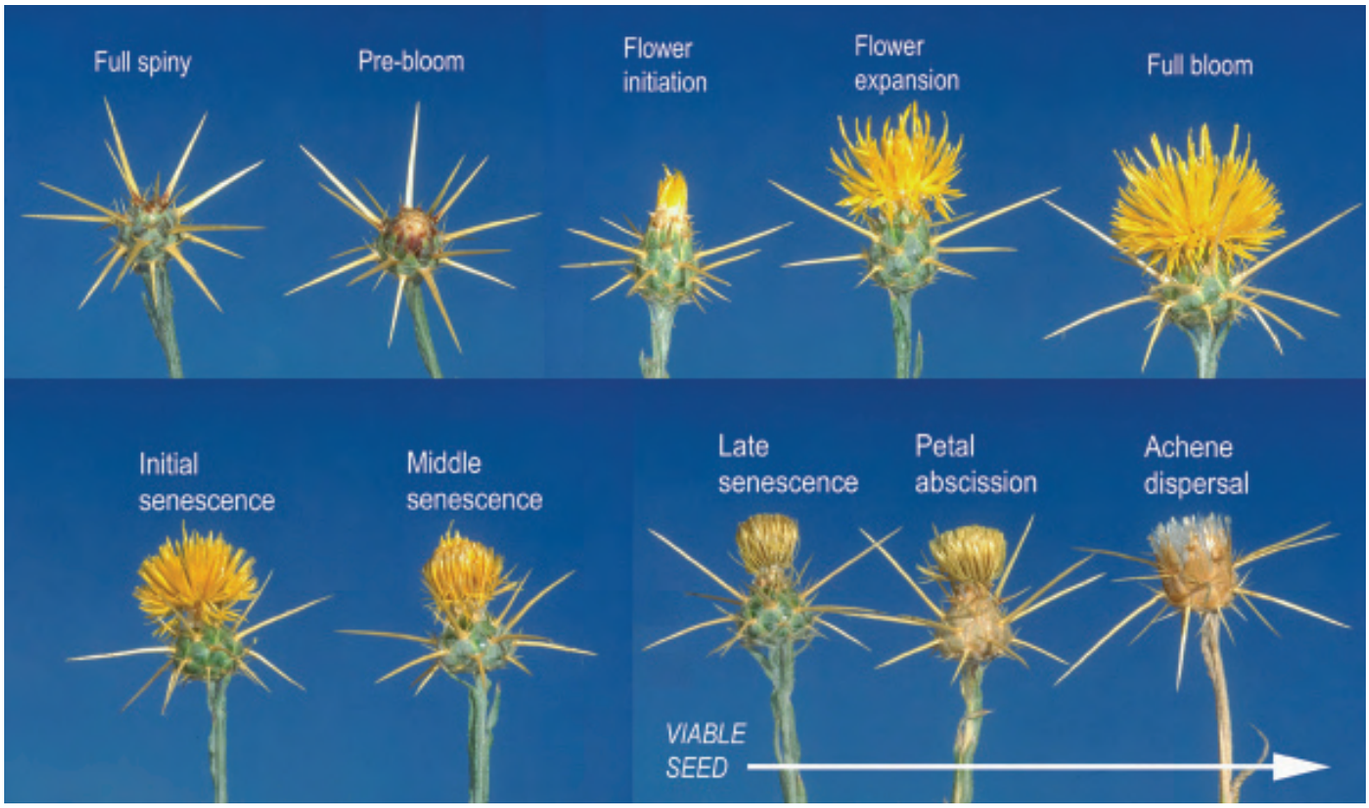
On average, seed heads require approximately 21 days to progress from pre-bloom to petal abscission (Benefield *et al*. 2001). Flowers remain in full bloom for just over two days before they began to senesce. Senescence requires an additional 14 days.

The time period from flower initiation to the development of mature viable seed is only eight days. In one study, no germinable seeds were produced until 2% of the spiny heads in a population had initiated flowering (Benefield *et al*. 2001). By the time 10% of the heads were in flower, numerous viable seeds had already been produced. Thus, to prevent seed production, it is most practical to gauge timing of late season control practices around flower initiation, as this stage is easily recognized. Effective long-term control may be compromised if control practices are delayed too long after flower initiation, allowing production of viable seed. Therefore, to prevent new achene recruitment, late-season control options such as tillage, mowing, prescribed burning, and herbicides should be conducted before approximately 2% of the total spiny heads have initiated flowering.

SEED DISPERSAL

Unlike most other species in the genus *Centaurea*, yellow starthistle produces two morphologically distinct achenes, one type with a distinct pappus, and the other with a pappus either poorly developed or absent (Callihan *et al*. 1993). The pappus-bearing achenes are light to dark brown with tan striations throughout. By comparison, the non-pappus-bearing achenes are dark brown to black without striations. Non-pappus-bearing achenes occur in a single ring around the periphery of the head, whereas pappus-bearing achenes occur in many rings in the center of the seed head. Development of achenes occurs centripetally, from the outer non-pappus-bearing achenes to the inner pappus-bearing achenes (Maddox *et al*. 1996). Of the total achenes produced, between 75% and 90% are pappus-bearing and 10% to 25% are non-pappus-bearing (Benefield *et al*. 2001, Maddox 1981, Roché 1965).

The pappus-bearing seed are usually dispersed soon after the flowers senesce and drop their petals. However, non-pappus-bearing seeds can be retained in the seed head for a considerable period



Life stages. *A yellow starthistle flowerhead goes through predicable stages from bud through senescence. Viable seed set is the critical point for those seeking to control the plant. (Photo: J. Clark)*

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Winged stems. *Before bolting, yellow starthistle develops winged stems with increased surface area that help the plant dissipate summer heat.*

Bolting. *Bolting is a stage of vigorous shoot growth during the time of greatest light availability.*

Early flowering stage—time to mow. *To prevent seed production, late-season control techniques should be used when plants are in the early flowering stage, as shown here.*

Yellow starthistle "Q-tips." *Following flowerhead senescence and seed dispersal, yellow starthistle stems retain white cottony tips into the winter.*

of time, extending into the winter (Callihan *et al*. 1993). These seeds have no wind dispersal mechanism and most simply fall to the soil just below the parent plant. With pappus-bearing seed, the pappus is not an effective long distance wind dispersal mechanism. Roché (1991a, 1992) reported that 92% of yellow starthistle seed fall within two feet of the parent plant, with a maximum dispersal distance of 16 ft over bare ground with wind gusts of 25 miles/hr. By comparison, birds such as pheasants, quail, house finches, and goldfinches feed heavily on yellow starthistle seeds and are capable of long distance dispersal (Roché 1992). Human influences, including vehicles, contaminated crop seed, hay or soil, road maintenance, and moving livestock, can also contribute to rapid and long distance spread of the seed.

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Germination and Dormancy

SEED PRODUCTION AND TYPES

Average seed production per seed head ranges from about 35 to over 80 achenes (Benefield *et al*. 2001, Maddox 1981, Pitcairn *et al*. 1998c), depending upon the site. Large plants can produce over 100,000 seeds. The number of seed heads and achenes per seed head can vary dramatically and are often determined by soil moisture and other soil properties (Maddox 1981; Pitcairn *et al*. 1997; Roché 1991b).

Yellow starthistle infestations have been reported to produce 57-114 million achenes per acre (DiTomaso *et al*. 1999a, Maddox 1981, Callihan *et al*. 1993).

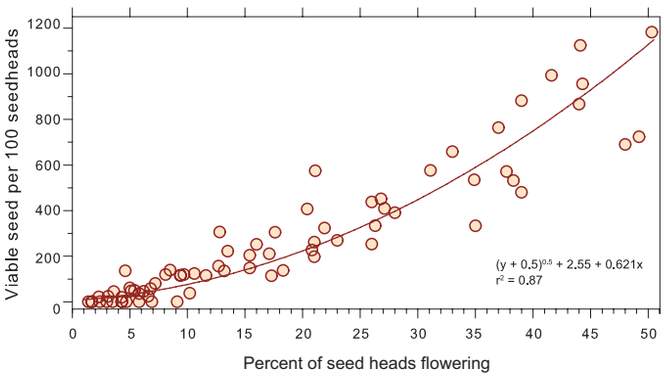

Fig. 3. Viable seed production in relation to flowering stage. *Percentage of yellow starthistle heads that are flowering can be used by managers as an indicator of seed maturation in order to time late-season treatments (Benefield* et al. *2001).*

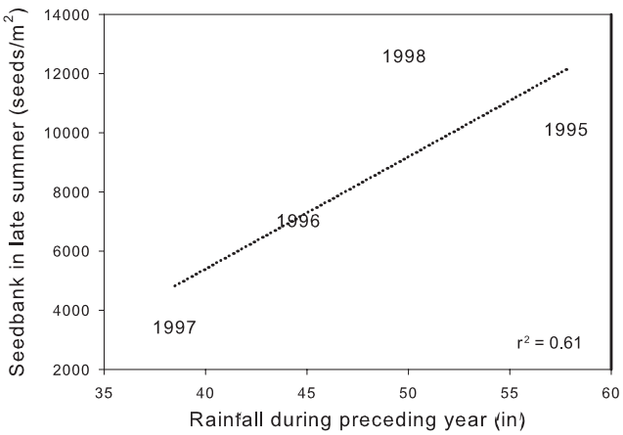

Fig. 4. Seedbank in relation to yearly rainfall. *The number of yellow starthistle seeds in the soil is positively correlated with the preceding year's rainfall, in this study at Sugarloaf Ridge State Park 1995-98 (G.B. Kyser, unpubl. data).*

GERMINATION

Over 90% of yellow starthistle achenes are germinable one week after seed dispersal (Benefield *et al*. 2001, Joley *et al*. 1997, 2003, Roché *et al*. 1997, Roché and Thill 2001, Sheley *et al*. 1983, 1993). Maximum germination of yellow starthistle achenes (nearly 100%) occurs when seeds are exposed to moisture, light and constant temperatures of 10, 15, or 20 °C, or alternating temperatures of 15:5 or 20:10 °C (Joley *et al*. 1997, Roché *et al*. 1997). At temperatures above 30 °C

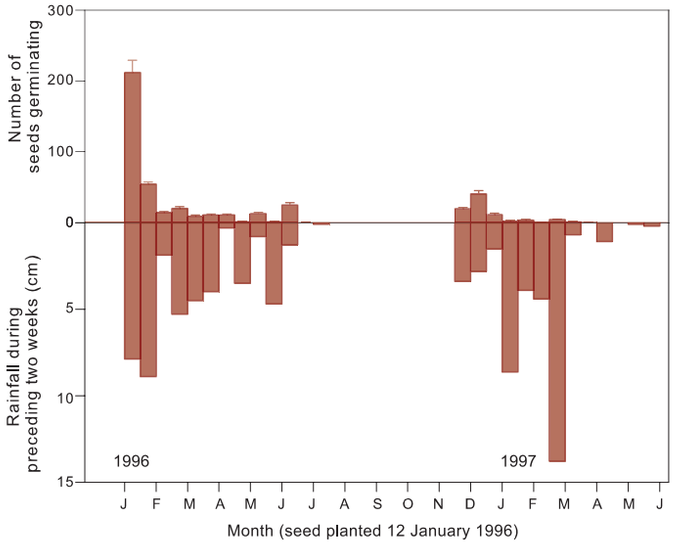

Fig. 5. Germination in relation to recent rainfall. *Germination of yellow starthistle seed shows a correlation with rainfall during the preceding two weeks (Benefield* et al. *2001).*

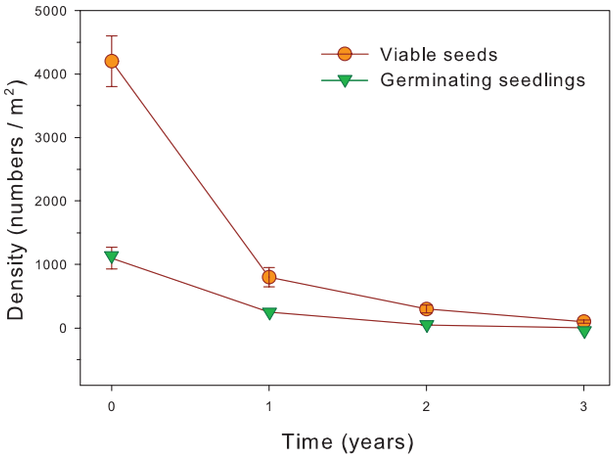

Fig. 6. Decline in seedbank. *When the introduction of new seeds is prevented, the yellow starthistle seedbank declines almost completely over three years (Joley* et al. *1992).*

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germination is dramatically reduced (Joley *et al*. 1997, Roché *et al*. 1997). Yellow starthistle appears to have a light requirement for germination (Joley, unpublished data).

Because nearly all viable seeds are able to germinate at the dispersal stage, yellow starthistle may not have an innate or induced dormancy mechanism. Interestingly, achenes will germinate only within a narrow, relatively cool temperature range shortly after dispersal. This ensures that seeds do not germinate, and then dry up, following an occasional late summer thunderstorm. However, with ongoing exposure to higher temperatures and low moisture, as would occur in later summer, achenes experience an after-ripening that allows germination over a wider range of temperatures (Enloe, unpublished data).

SEASONAL GERMINATION PATTERN

Maddox (1981) and Benefield *et al*. (2001) reported that yellow starthistle seed germination was closely correlated with winter and spring rainfall events. Although emergence was highest after early season rainfall events, germination occurred throughout the rainy season. The extended germination period increases the difficulty of controlling yellow starthistle populations during the late winter and early spring, as subsequent germination often results in significant infestations. Consequently, effective late-season control strategies such as mowing, tillage, prescribed burning, or postemergence herbicides should be conducted after seasonal rainfall events are completed, but before viable seeds are produced. In addition, the use of preemergence herbicides applied from late fall to early spring should provide residual control extending beyond the rainy season.

SEED LONGEVITY AND SEEDBANK DEPLETION

From a land manager's perspective, it is important to know the longevity of yellow starthistle achenes in the soil seedbank.

Although some studies have suggested that seeds can survive as long as ten years in the soil (Callihan *et al*. 1989, 1993), most studies in California show a more rapid rate of depletion. In one study, yellow starthistle achenes on the soil surface were depleted by 80% after one year with no additional recruitment, and by three years only 3.9% of the original seeds had not germinated and were still viable (Joley *et al*. 1992). In another experiment, one year of prescribed summer burning in Sonoma County, California, reduced the seedbank of yellow starthistle by 74%; three consecutive years of burning, with no further seed recruitment, depleted the seedbank by 99.6% (DiTomaso *et al*. 1999a). This suggests that the longevity of viable seeds under normal field conditions in California may be shorter than previously believed. Joley *et al*. (2003) reported that nearly all achenes from the soil seedbank were depleted after four years. Microbial degradation and invertebrate predation of yellow starthistle achenes probably contribute significantly to the rapid depletion of the soil seedbank.

These recent findings indicate that yellow starthistle management programs may require only two to four years of control to dramatically reduce the soil seedbank and thus the infestation. For long-term sustainable management to be achieved, land managers must prevent achene recruitment from the remaining seedbank germinants or from new introduction of achenes from off-site sources.

Growth and Establishment

SEEDLING ESTABLISHMENT

High germination rates can result in extremely dense seedling populations. In many areas, a significant amount of self-thinning occurs and only a small fraction of seedlings reach reproductive maturity (Larson and Sheley 1994). Thus, in heavily infested areas, starthistle populations produce far more seed than are necessary to reinfest the area year after year. Seedlings are most likely to establish in soils with deep silt loam and loam with few coarse fragments (Larson and Sheley 1994).

ROOTS

Following germination, yellow starthistle allocates resources initially to root growth, secondarily to leaf expansion, and finally to stem development and flower production (Sheley *et al*. 1983, 1993, Roché *et al*. 1994). Root growth during the winter and early spring is rapid and can extend well beyond three feet in depth (DiTomaso *et al*. 2003b). Starthistle roots elongate at a faster rate and to greater depths than potentially competitive species, including weedy annual grasses and clovers (Sheley *et al*. 1993). During this same time period, rosettes expand slowly. In a study conducted in Washington by Roché *et al*. (1994), roots grew at a mean rate of 0.5 cm per day

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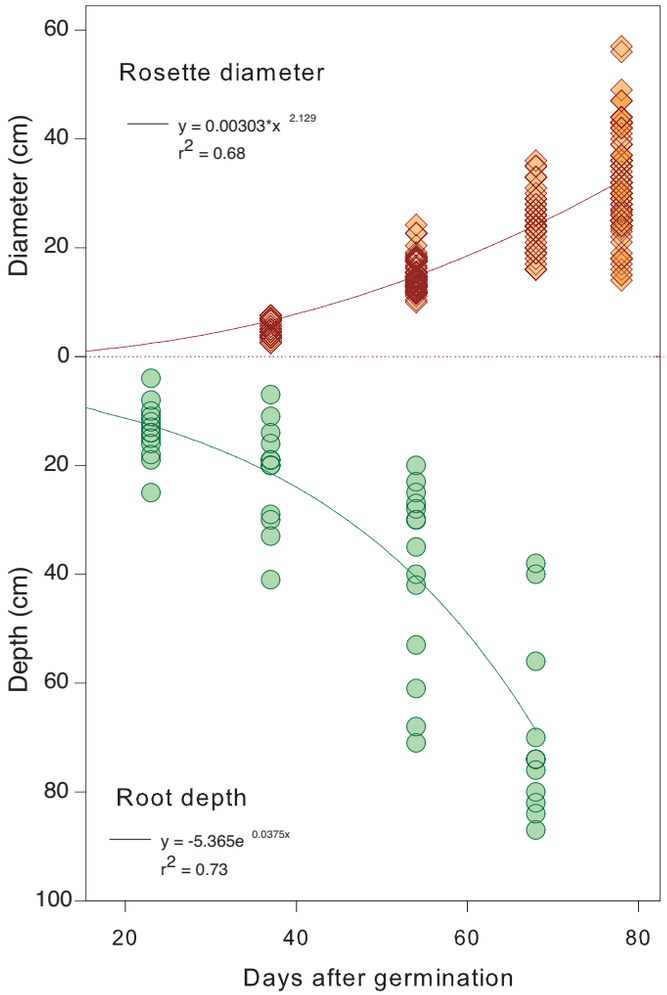
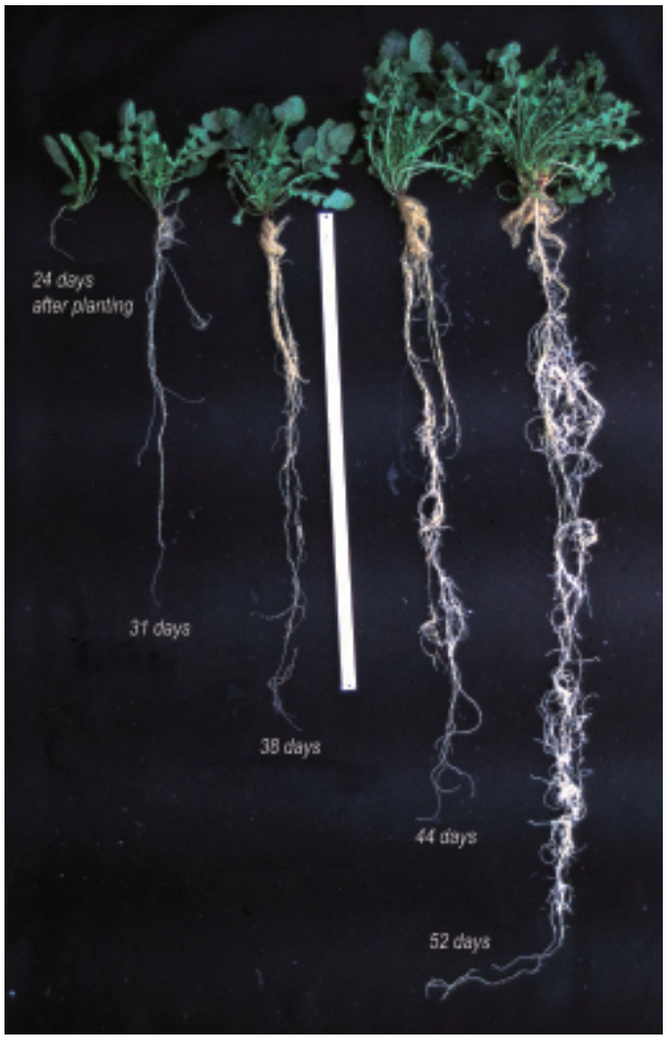


Fig. 7. Growth of roots and rosettes. *While yellow starthistle rosettes grow slowly during the winter, roots are elongating rapidly (DiTomaso* et al. *2003b).*



Root growth. *Roots of yellow starthistle plants grow deep rapidly, even in the rosette stage.*

and as fast as 2.1 cm per day; 140 days after planting, roots grew out the bottom of 123 cm long (4 ft) tubes. While root growth was rapid during the winter months, there was little above-ground rosette expansion. In another study using minirhizotron tubes in the field, DiTomaso *et al*. (2003b) showed that root depth increased exponentially with time. By 64 days after planting, roots reached depths of 0.6 m (2 ft); within 80 days (end of March), roots in most plots extended beyond 1 m. Plants grown in tubes grew roots beyond 2 m (6 ft) after two months.

Rapid germination and deep root growth in yellow starthistle extends the period of resource availability into late summer, long after seasonal rainfall has ended and shallow-rooted annual grasses have senesced. By extending the period of resource availability, competition is reduced at the reproductive stage. This can greatly benefit starthistle by ensuring ample seed production into the dry summer months (Sheley *et al*. 1993).

The potential density of yellow starthistle in a particular site can be closely associated with soil depth and thus late season water storage capacity. Roché *et al*. (1994) demonstrated a direct relationship between the number of starthistle plants per unit area and the soil moisture depth.

Shading of young rosettes can reduce root growth dramatically (Roché *et al*. 1994). In one study, roots of unshaded yellow starthistle reached a depth of 60 cm (2 ft) in 94 days; plants grown under 80% or 92% light reduction took 138 and 163 days, respectively (DiTomaso *et al*. 2003b).

Since yellow starthistle plants germinate over an extended time period beginning with the first

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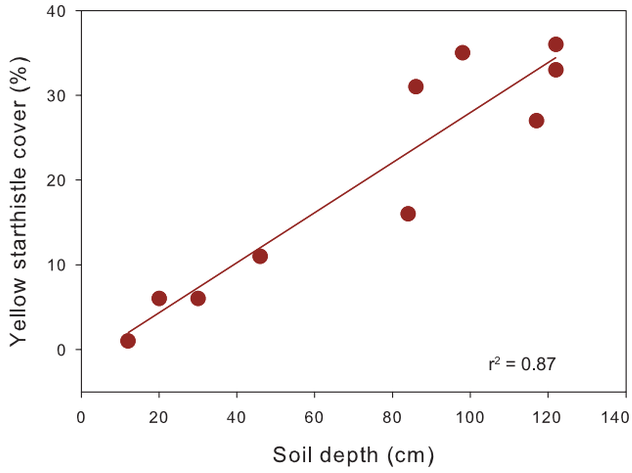

Fig. 8. Effect of soil depth. *Roché* et al. *(1994) found a positive correlation between soil depth and yellow starthistle cover.*

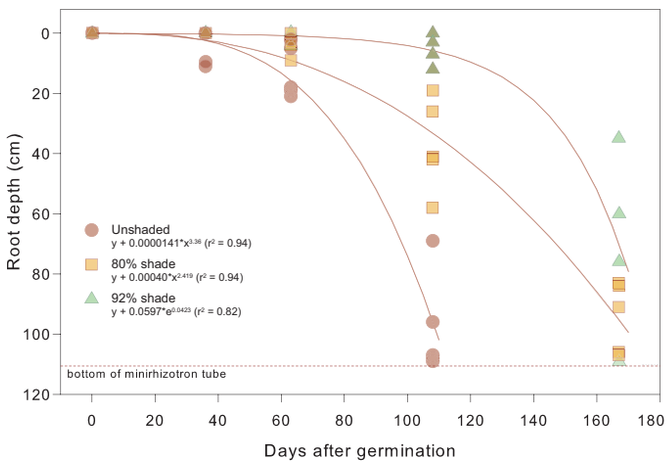

Fig. 9. Effect of shading on root growth. *Yellow starthistle seedlings show dramatically slower root growth under shaded conditions (DiTomaso* et al. *2003b).*

fall rains and ending with the last spring rain event, a typical stand of starthistle includes plants in several stages of development. Dense stands have both large canopied plants receiving full sunlight and an understory of smaller shaded plants. For these smaller plants, light suppression is a significant factor regulating root growth. The roots of larger plants exposed to full sunlight quickly grow to great depths, while roots of shaded plants in the understory occupy shallower depths for longer periods of time (DiTomaso *et al*. 2003b). Under these conditions, soil moisture is depleted from all depths in the soil profile.

SHOOTS

Seedlings that germinate in late fall or early winter pass the winter as basal rosettes. Rosettes develop slowly throughout the early spring. In the Central Valley and foothills of California, bolting typically occurs in late spring; by early to mid-summer, spines appear on developing seed heads. Around the time of bolting, yellow starthistle foliage develops pubescence and a waxy grayish coating that reflects a considerable amount of light. This reduces the heat load and the transpiration demand during hot dry summer months. Winged stems add surface area and also dissipate heat like a radiator (Prather 1994). These characteristics, as well as a deep root system, allow yellow starthistle to thrive under full sunlight in hot and dry conditions. Vigorous shoot growth coincides with increased light availability as neighboring annual species senesce and dry up. Moreover, the presence of spines on the bracts surrounding the seed head provides protection against herbivory. This is particularly important during the vulnerable flowering and seed development stages.

Senescence typically occurs in fall when moisture becomes limiting and plants are exposed to frost. Flowers can abort development before completion. Senesced stems can contain the non-pappus-bearing seeds for about a month until the spiny bracts and phyllaries fall off. Flowerhead receptacles contain fine chaff that gives the seed heads a cotton-tip appearance. In contrast, Malta starthistle (tocalote) and Sicilian (sulfur) starthistle do not have cotton-tip seed heads after senescence. Stems of yellow starthistle degrade slowly and may remain erect for a year or more.

Light, Temperature and Water Use Patterns

LIGHT

When yellow starthistle rosettes grow in full sunlight, they grow compact and flattened to the soil surface. However, in grasslands where they receive less light, rosettes grow larger leaves and develop a more erect growth form that may reach 25 cm (10 in) in height. This upright form allows them to capture more light until the reproductive shoots bolt through the senescing grass canopy in late spring (Roché *et al*. 1994).

Dense yellow starthistle seedling cover can significantly suppress the establishment of annual grasses

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and forbs. However, yellow starthistle rosettes are also very susceptible to light suppression; if shaded, they will produce short roots, larger leaves, more erect rosettes, and fewer flowers than plants in full sunlight (Roché and Roché 1991, Roché *et al*. 1994). Consequently, yellow starthistle does not survive well in shaded areas, and is less competitive in areas dominated by shrubs, trees, taller perennial forbs and grasses, or late season annuals. For this reason, infestations are nearly always restricted to disturbed sites or to open grasslands dominated by annuals.

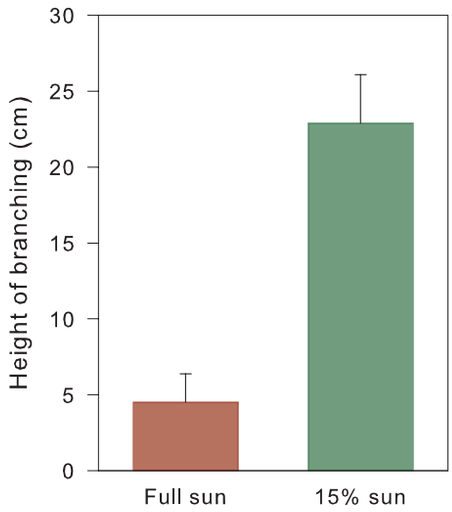

Fig. 10. Effect of shading on rosette growth. *One hundred days after germination, yellow starthistle rosettes grown in shade are elongated compared to plants grown in full sun (C.B. Benefield, unpubl. data).*

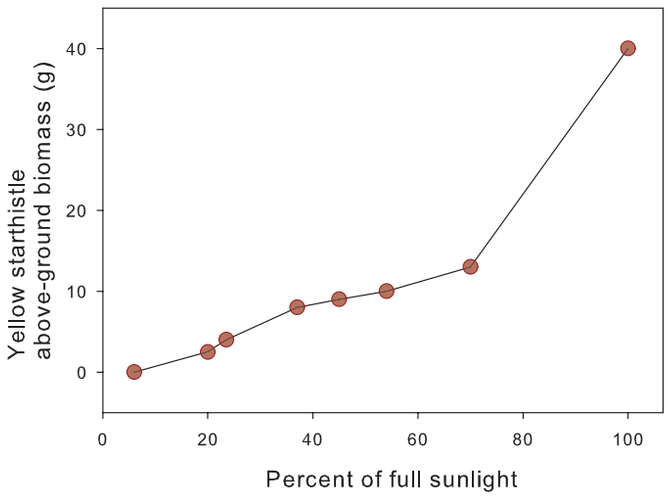

Fig. 11. Effect of sunlight on biomass production. *Yellow starthistle biomass production is strongly correlated with availability of sunlight (Roche* et al. *1994).*

TEMPERATURE

Yellow starthistle plants are insensitive to photoperiod and lack a vernalization requirement (Roché *et al*. 1997, Roché and Thill 2001). This allows late germinating plants to continue flowering as long as moisture is adequate, or until newly developing buds are killed by frost. In areas with mild winters, plants can act as biennials. However, in cold-winter areas such as eastern California or other western states, mature plants rarely survive the winter. Whereas seedlings can survive extended frost periods, mature plants are not considered to be frost tolerant. Cold hardiness appears to be lost during the transition from vegetative to reproductive phases.

WATER USE

Heavy infestations of yellow starthistle in grasslands with loamy soils can use as much as 50% of annual stored soil moisture (Gerlach, unpublished data). In deep soils on the floor of California's Central Valley, starthistle can significantly reduce soil moisture reserves to depths greater than 6.5 feet, and in foothill soils three feet deep it can extract soil moisture from fissures in the bedrock (Gerlach *et al*. 1998).

COMPETITION WITH INTRODUCED ANNUAL GRASSES

Shallow versus deep root partitioning between yellow starthistle and competing vegetation can greatly influence the susceptibility of grasslands to starthistle invasion (Brown *et al*. 1998). Since the root systems of most annual species are comparatively shallow, there is little competition for moisture between yellow starthistle and annual grasses during late spring and early summer. In addition to utilizing deep soil moisture, yellow starthistle can also survive at extremely low soil water potential as compared to annual grasses (Gerlach 2004).

Seasonal moisture can also influence the competitive advantage between yellow starthistle and annual grasses. Under dry spring conditions, early maturing annual grasses have an advantage over late season annuals, as they utilize the available moisture and complete their life cycle before the later maturing species, such as starthistle (Larson and Sheley 1994). In contrast, under moderate or wet conditions, starthistle has an advantage by continuing its growth later into the summer and fall and producing more seed.

Thus, in grassland systems, yellow starthistle would be at a competitive advantage 1) in com-

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munities dominated by annual grasses, 2) in areas with deep soil, and 3) in years with moderate to high spring rainfall (Sheley and Larson 1992). Under these conditions, yellow starthistle would mature later, have increased seed production, and have little competition for deep soil moisture. In annual grasslands, yellow starthistle would be disadvantaged by shallow soils and low spring rainfall.

COMPETITION WITH NATIVE SPECIES

The use of soil moisture by yellow starthistle is similar to that of perennial grasses (Borman *et al*. 1992). Like yellow starthistle, perennial grasses also have an extended growing season. These factors account for increased competition between yellow starthistle and perennial species, compared to annual species.

The characteristics that enable yellow starthistle to invade grasslands can threaten native species and ecosystems processes. Native species such as blue oak (*Quercus douglasii*) and purple needlegrass (*Nassella pulchra*) depend on summer soil moisture reserves for growth and survival (Gerlach *et al*. 1998). Yellow starthistle, however, uses deep soil moisture reserves earlier than blue oak or purple needlegrass. Thus, from the perspective of native species, infested sites can experience drought conditions even in years with normal rainfall (Gerlach *et al*. 1998).

Heavy yellow starthistle infestations can remove large amounts of stored soil moisture through plant transpiration (Gerlach *et al*. 1998). Most soils in California grasslands store about 12 inches of rainfall for each 3.25 ft of soil depth. In most years annual grasses reduce soil moisture reserves by about 4 inches of stored rainfall in the top 3.25 ft of soil. By comparison, yellow starthistle can reduce soil moisture levels by 8 inches of stored rainfall for each 3.25 ft of soil depth – about the same as a mature oak tree. As a result, large yellow starthistle populations transpire at least an additional 4 inches of rainfall for each 3.25 ft of soil depth during average rainfall years and about 8 inches during wet years (Gerlach *et al*. 1998).

Species shown to be the most competitive with yellow starthistle are those that occupy a similar root zone (Brown *et al*. 1998), including many native perennial grasses. Increased species diversity, particularly with overlapping community resource use patterns, can also reduce invader success (Brown *et al*. 1998, DiTomaso, unpublished data).

Management

The goal of any management plan should be not only controlling the noxious weed, but also improving the degraded community, enhancing the utility of that ecosystem, and preventing reinvasion or invasion by other noxious weed species. To accomplish this usually requires a long-term integrated management plan. Development of a management program and selection of the proper tool(s) also may depend on other factors such as weed species and associated vegetation, initial density of yellow starthistle infestation, effectiveness of the control techniques, years necessary to achieve control, environmental considerations, chemical use restrictions, topography, climatic conditions, and relative cost of the control techniques. A number of considerations can influence the choice of options, most important being the primary land-use objective. These objectives may include forage production, preservation of native or endangered plant species, wildlife habitat development, and recreational land maintenance.

There are a number of control options available for the management of yellow starthistle, including grazing, mowing, manual removal, perennial grass or broadleaf reseeding, burning, application of herbicides, and release of biological control agents. Recent emphasis has been on the development of integrated systems for the long-term sustainable management of yellow starthistle. Such systems include various combinations of control techniques. In many cases, three or more years of intensive management may be necessary to significantly reduce a yellow starthistle population. Although uncommon, it is possible to substantially reduce the infestation with one year of control. However, a more established starthistle population with a large residual seed bank usually requires a longer-term management program (DiTomaso 2000).

When developing a yellow starthistle management program, it is important to consider the advantages (benefits) and disadvantages (risks) of each approach and to judge how it may best fit into a long-term program. It is possible that several different strategies can prove successful in a given location. Successful programs incorporate persistence, flexibility, and, most importantly, prevention of new seed recruitment (DiTomaso *et al*. 2000b). Advantages, disadvantages, risks, timing, and strategic role for each control option are discussed below.

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CHAPTER 4: Mechanical Control

Mechanical control of weeds usually means cutting or uprooting them. Mechanical control options for yellow starthistle include hand pulling, hoeing, tillage, and mowing.

Hand Pulling or Hoeing

Hand pulling and hoeing are the oldest methods of weed control. Although they are labor intensive and often relatively ineffective for the control of perennial weeds, they typically cause minimal environmental impact.

ECONOMICS

Depending on the size of the infestation, manual control of yellow starthistle can be relatively cheap or very expensive. If only a few plants require removal, the cost can be minimal. However, hand-weeding a large area may require several people and can cost dramatically more than other control options.

METHODS AND TIMING

Manual removal of yellow starthistle is most effective for controlling small patches or in maintenance programs where plants are sparsely located in the grassland system. This usually occurs with a new infestation or in the third year or later in a long-term management program. It can also be an important tool in steep or uneven terrain where other mechanical tools (e.g., mowing and tillage) are impossible to use (Woo *et al*. 1999). To ensure that plants do not recover it is important to detach all above ground stem material. Leaving even two inches of rooted stem can result in recovery if leaves and buds are still attached to the base of the plant (Benefield *et al*. 1999). The best timing for manual removal is after plants have bolted but before they produce viable seed (early flowering). At this time, plants are easy to recognize and some or most of the lower leaves have senesced. Hand removal is particularly easy in areas with competing vegetation. Under this condition, starthistle will develop a more erect, slender stem with few basal leaves. These plants are relatively brittle and easy to remove. In addition, they rarely have leaves attached at the base and, consequently, rarely recover, even when a portion of the stem is left intact.

Hand tools. *Shovels, lopper, and hoes are effective for small, sparsely-spaced populations. (Photo: G. Kyser)*

A larger starthistle population can be controlled through physical removal by starting at the outward edge of the population and moving in (Fuller and Barbe 1995). This technique requires repeated visits, but it ensures that no new seeds are produced and minimizes unnecessary soil disturbance. Using this method, it is possible to control relatively large starthistle-infested areas (up to 40 acres) with low impact. Cost of control will depend on the extent and density of the infestation.

RISKS

When using manual removal techniques, it is important to minimize soil disturbance around the removed plants. Soil disturbance can create sites for re-establishment of new seedlings or rapid invasion by another undesirable species (DiTomaso 1997).

In addition, trampling of habitat by large numbers of people in these sites can damage sensitive native species and further disturb the soil. The potential also exists for physical injury when removing plants once the spines have developed. This risk is minimized with appropriate protective clothing and gloves.

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Tillage. *Harrowing, a kind of tillage, damages the roots and separates shoots from roots in young plants.*

Tillage

Tillage is more common in agricultural areas than in non-crop areas. On occasion, tillage can be used in rangelands, along roadsides, and in utility rights-of-way. Tillage using plows or discs can control annual weeds by burying plant parts. This is more effective on annuals than perennials. In contrast, tillage using harrows, knives, and sweeps can be used to damage root systems or to separate shoots from roots in younger plants, and can also be used to damage roots in larger plants (Thomsen *et al*. 1996b).

ECONOMICS

If equipment is already available the cost of tillage may be reasonable, but is generally still higher than the use of chemical control. In this case, the costs incurred are generally associated with labor, fuel and equipment maintenance. Costs increase when repeated tillage is necessary.

METHODS AND TIMING

Early summer tillage will control yellow starthistle provided the roots are detached from the shoots. Repeated cultivation can be used in the same season if rainfall stimulates additional germination between tillage practices (Thomsen *et al*. 1996b). This will rapidly deplete the starthistle seedbank, but may also deplete seedbanks of desirable species. To be effective, this method must be conducted before yellow starthistle produces viable seeds. Tillage is often used on cropland and probably accounts for the rarity of starthistle as an agricultural weed. It is occasionally used on roadsides. In wildlands and rangelands, tillage usually is not an appropriate option for control of yellow starthistle.

RISKS

Tillage must be applied when the surface soil is dry, or fragmented plant segments can re-grow and possibly magnify the problem. Despite its effectiveness in controlling annual weeds, it can damage important desirable species, expose the soil for rapid reinfestation if subsequent rainfall occurs (DiTomaso and Gerlach 2000a), and prolong the longevity of yellow starthistle propagules by burying seeds deep in the soil profile. It addition, it can alter soil structure (e.g., by compaction), increase erosion, and cause the loss of soil moisture by exposing subsoil. Heavy equipment also produces fuel exhausts and raises dust, including fine particles $\leq$10 microns in diameter (PM10) (DiTomaso 1997).

Deck mower. *(Photo: G. Kyser)*

Flail mower. *(Photo: G. Kyser)*

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Pincushions. *If mowed too early, yellow starthistle may recover and form a "pincushion" of low-growing flowerheads.*

Mowing

Mowing is a popular control technique along highways and in recreational areas and has less impact on the environment than tillage. Various power mowers can be used depending on topography and the need to avoid rocks and non-target plants. A handheld string trimmer (weed whip) may be used for mowing in small areas.

ECONOMICS

Although mowing can be a cost-effective method for control of starthistle, it is not feasible in many locations due to rocks and steep terrain. Costs are generally associated with labor, fuel, and equipment maintenance, as well as owning or leasing the appropriate equipment.

METHODS AND TIMING

Success with mowing depends on proper timing and the growth form of the plant. Mowing is most successful at the spiny to early flower stage. Mowing too early, before yellow starthistle seed heads reach the spiny stage, may allow starthistle to recover and also can suppress competing vegetation, thus enhancing light penetration and increasing the starthistle problem. Even repeated mowing, if conducted too early, will not control starthistle and may even extend its life cycle. On the other hand, mowing after plants have produced viable seed will not substantially reduce the seedbank and the following year's infestation. Regardless of timing, in non-crop areas mowers often must be set high (four inches or above) to avoid striking rocks and other obstacles, but higher mowing can be less effective in controlling starthistle.

Despite the limitations of mowing, Thomsen *et al*. (1994a, 1997) and Benefield *et al*. (1999) demonstrated the successful use of mowing for yellow starthistle control. Thomsen *et al*. (1994a, 1997) consistently demonstrated over 90% control of yellow starthistle using two timely mowings per year over a three-year period. Benefield *et al*. (1999) showed that mowing at the early flowering stage, before viable seed production, was most effective in controlling yellow starthistle.

These researchers also demonstrated that the success of mowing as a control strategy depends partly on the plant's growth form and branching pattern. Yellow starthistle plants growing among other plants in grassland tend to have an erect, high-branching growth form and are effectively controlled by a single mowing at the early flowering stage. Plants grown in the open tend to have a sprawling, low-branching form and are not controlled well even with repeated mowing at the proper timing.

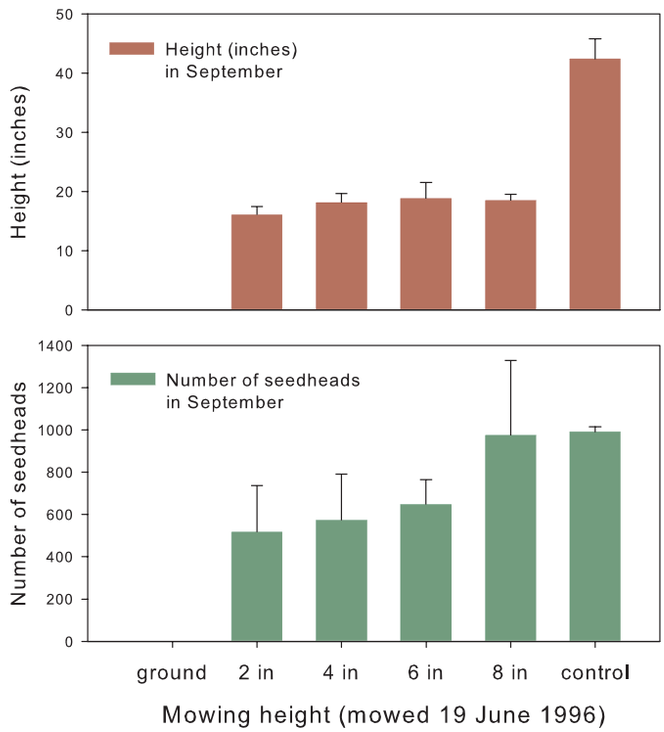

Fig. 12. Effect of mowing height on seed heads. *Mowing yellow starthistle above the basal branches does not prevent development of seed heads (Benefield* et al. *1999).*

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Mowing may be a useful strategy for small landowners who do not wish to use herbicides. A few land managers have successfully controlled yellow starthistle using continuous mowing over multiple years. However, since mowing is a late season management tool, in most cases it is best employed in the latter years of a long-term management program or in a lightly infested area.

RISKS

Mowing is a popular control technique along highways and in recreational areas. It has less impact on the environment than tillage. Like tillage, however, it can produce fuel exhaust and PM10. In this case, the particles are very small plant fragments, often detached hairs. When mowing is conducted in rocky areas, there is a risk of sparks (from metal blades striking rocks) igniting the dried vegetation. This occurred during a yellow starthistle control mow at Fort Hunter Liggett (A. Hazebrook, Fort Hunter Liggett, pers. comm.).

Perhaps the greatest risk with mowing is the impact on the plant community. Mowing can injure late growing native forb species (Rusmore 1995) and reduce fall and winter forage for wildlife and livestock (DiTomaso 1997, DiTomaso *et al*. 2000b). Proper timing can minimize these risks, whereas mowing at the wrong time can increase noxious weed populations (DiTomaso 1997).

Mowing may also decrease the reproductive efforts of insect biocontrol agents. For example, mowing yellow starthistle during the early flowering stage—which is most effective—may cause significant damage to seed-feeding biocontrol agents.

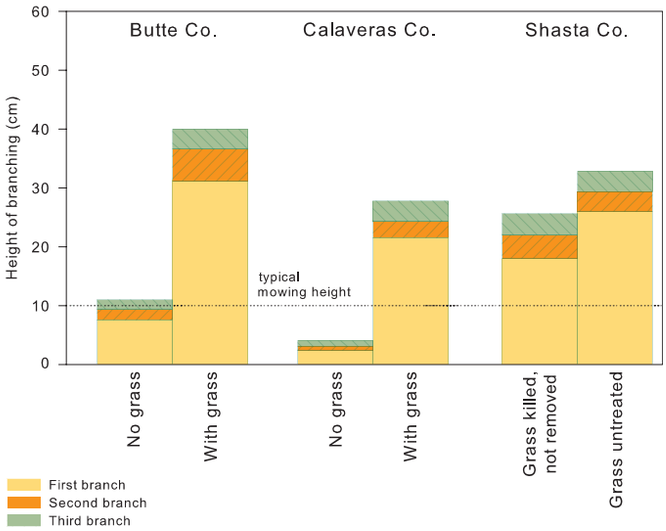

Fig. 13. Effect of cover on branching habit. *Yellow starthistle develops different branching patterns depending on whether it is grown in open sun or among grasses in a grassland. A typical mowing height of 10 cm (4 inches) is shown for comparison (Benefield* et al. *1999).*

Two branching patterns. *Yellow starthistle rosettes in full sunlight grow compact and flattened (top). In grasslands where they receive less light, rosettes develop a more erect growth form (bottom). The erect form is more susceptible to mowing.*

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CHAPTER 5: Cultural Control

Cultural control techniques involve manipulation of the environment by non-mechanical means such as controlled burning, grazing management, or revegetation programs.

Grazing

A successful grazing program significantly reduces the population of yellow starthistle, limits damage to desirable vegetation, achieves goals for livestock production, and supports an integrated weed management strategy (Frost and Launchbaugh 2003). Used properly, grazing management can also minimize the spread of noxious weeds in rangeland systems.

The specific goal of livestock (cattle, goats or sheep) grazing for weed control is to manipulate the pattern of defoliation so that the target weed is at a competitive disadvantage relative to other more desirable plants in the community (Frost and Launchbaugh 2003). This can be achieved either by (1) timing the grazing so as to damage the target species when it is most vulnerable, or (2) controlling the behavior of the grazing animals so they concentrate their efforts primarily on the target weed.

Although grazing can help to manage yellow starthistle populations, it is important to note that grazing alone will not provide long-term management or eradication of yellow starthistle. It can, however, be a valuable tool in an integrated management program.

Cattle grazing. *When used as part of an integrated management program, grazing can reduce the growth and spread of yellow starthistle and other noxious weeds. (Photo: C. Thomsen)*

ECONOMICS

One advantage over other methods for the control of yellow starthistle is that grazing animals can convert the weed into a saleable product (Frost and Launchbaugh 2003). However, some significant costs can be associated with grazing, including the purchase or lease of the animals, maintaining them in proper health, and monitoring their grazing activity to minimize harm to desirable forage. This may require the use of a herder or penning animals at night. Other expenses can include stock dogs, fencing, and sometimes supplemental feeding, especially late in the season when the nutritive value of yellow starthistle is low (Frost and Launchbaugh 2003). Without this supplemental feed, production losses can occur.

METHODS AND TIMING

Different grazing strategies have different advantages. For example, grazing at moderate levels can minimize impact on native plants and reduce soil disturbance, while intensive grazing will counteract inherent dietary preferences of livestock, resulting in equal impacts on all forage species including weeds, and multispecies grazing will distribute the impact of livestock grazing more uniformly among desirable and undesirable species (Olson 1999).

Short periods of intensive grazing have been widely adopted in other countries (DiTomaso 2000). In this system pastures are intensively grazed from 3 to 5 days, often with the use of electric fencing. The pasture is subsequently allowed to recover for at least a month before grazing is repeated. Forage is not completely grazed and recovery occurs rapidly. This can increase total season forage production and the stocking capacity of the area.

As an added benefit of short duration intensive

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grazing, the remaining forage reduces light penetration to the soil surface and can suppress weed establishment and growth. In contrast, conventional grazing practices allow animals to forage grasses and other plants nearly to the soil surface. Yellow starthistle has been shown to be very susceptible to light suppression (Roché *et al*. 1994). Shading reduces seedling survival rates. Weber (1985) noted that Roché delayed spring grazing of wheatgrass and was able to control starthistle because ungrazed, taller wheatgrass plants blocked sunlight from the starthistle rosettes.

Intensive time-controlled grazing can also minimize the grazers' ability to avoid less palatable noxious weed species. High stocking rates may force cattle to graze typically less preferable species, including yellow starthistle. This should result in a more uniform composition of range plant species and more balanced competitive relationships among native and non-indigenous species (Olson 1999).

Because so many animals are required to be successful, practice of high intensity grazing on a large scale is limited. It has been estimated that 1900 head of cattle would be needed to properly treat 1000 acres (Connor 2003). Furthermore, for effective control, grazing would have to continue beyond the time when yellow starthistle is most palatable, thus compromising livestock production.

Timing also can be critical to the success of grazing for yellow starthistle control. The ideal time to graze is when plants are most susceptible to defoliation or when the impact on desirable vegetation is minimal. Thomsen *et al*. (1989, 1990, 1993) showed that properly timed (May and June) intensive grazing by cattle or goats resulted in reduced

Spiny stage. *At the spiny stage, cattle and sheep will not graze yellow starthistle, but goats will continue to browse it.*

Table 1. Comparison of grazing characteristics of cattle, sheep and goats (Frost and Launchbaugh 2003)

Animal	Digestive systems	Feeding behavior	Classification
Cattle	Large rumens adapted to ferment fibrous material	Best for managing fibrous herbaceous vegetation, prefer grasses but will also graze yellow starthistle at the bolting stage	Grass and roughage eaters
Sheep	Large rumen adapted to ferment fibrous material	Can selectively graze and tolerate high fiber content, diet dominated by forbs, will control yellow starthistle when grazed at bolting stage, but not in rosette stage	Forb and roughage eaters, more easily managed by human herders, used for strategic grazing
Goats	Large liver mass that allows processing of secondary compounds less digestible or more toxic to other grazers	Mouths designed to strip leaves from woody plants and chew branches, will also feed on yellow starthistle in the spiny stage	Browsers used often to control woody species

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growth, canopy cover, survivability, and reproductive capacity of yellow starthistle. Repeated high-intensity cattle grazing reduced flowering heads of yellow starthistle by 78-91% (Thomsen *et al*. 1993). These plants were grazed after the stems had bolted but before the development of spiny seed heads. Cattle and sheep tend to avoid starthistle once the buds produce spines, whereas goats continue to browse plants even in the flowering stage (Thomsen *et al*. 1993). For this reason, goats have become a more popular method for controlling yellow starthistle in relatively small infestations. Thomsen *et al*. (1990, 1993) also reported that grazing the weed during the bolting stage could provide palatable high protein forage (8 to 14%). This can be particularly useful in late spring and early summer when other annual species have senesced.

Selecting the proper grazing species is important to successful management. In the case of yellow starthistle, cattle, sheep and goats have all been shown to be effective tools, but each has a slightly different feeding behavior that may affect the level of yellow starthistle control under a particular set of conditions (see Table 1).

Although grazing alone may not provide adequate long-term control of yellow starthistle, it is most valuable for its potential to increase the effectiveness of other control methods. For example, goat grazing has been shown to increase the subsequent efficacy of herbicides on leafy spurge (*Euphorbia esula*) (Lym *et al*. 1997). It is possible that grazing may also increase the effectiveness of postemergence herbicides on yellow starthistle, although this has not been studied.

RISKS

Conventional grazing or intensive overgrazing can lead to the invasion of yellow starthistle and many other rangeland weeds (Billings 1994). Improperly timed grazing can lead to rapid selection for yellow starthistle. For example, in late winter or early spring livestock primarily feed on young grasses with an erect growth form, causing little damage to seedling yellow starthistle rosettes. This practice increases light penetration through the canopy and stimulates yellow starthistle growth during the late spring and early summer. Thomsen *et al*. (1993) showed that the density of yellow starthistle increased if sheep grazed while plants were in the rosette stage. On the other hand, livestock grazing in the mid- to late summer months will avoid spiny yellow starthistle plants, thus allowing heavy seed production and the next year's survival of the weed.

Excessive trampling by livestock can increase the density of yellow starthistle (Miller *et al*. 1998). Grazing also can spread noxious weeds over a wide range when seeds become attached to hair or when they remain intact after passing through the digestive system (DiTomaso 1997). In some cases, grazing can select for a particular weed or group of weeds. Animals forage around these plants, eliminating their competition. This selective pressure can lead to more rapid infestation.

Grazing can also be very non-selective and may endanger sensitive non-target species. Goats, for instance, are typically browsers and can effectively control certain noxious species. However, they can forage both desirable and undesirable species when confined and may even strip the bark off trees. Livestock can also trample desirable sensitive species.

Prescribed fire. *California Department of Forestry & Fire Protection conducts a prescribed burn at Sugarloaf Ridge State Park in California.*

Prescribed Burning

Fire has been an important factor in the development and continuance of most grassland systems. As a result, many native grassland plants appear adapted to periodic disturbance by fire. The hard seeds of some broadleaf plants such as legumes may require scarification by fire. Other species mature before the fire season begins and drop their seed to the ground, where grassland fire temperatures are

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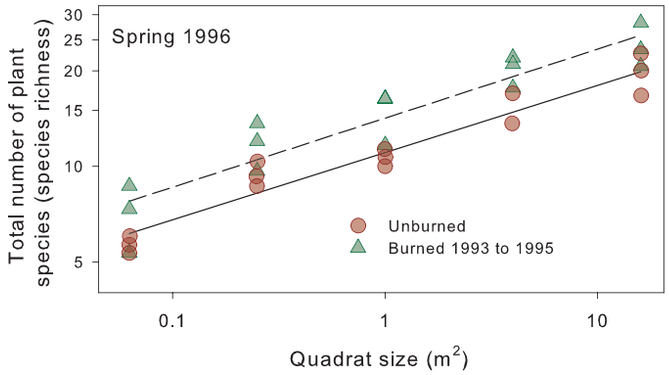

Fig. 14. Effect of burning on yellow starthistle cover. *An increase in plant species richness was found following three years of burning to control yellow starthistle, Sugarloaf Ridge State Park (DiTomaso* et al. *1999a).*

not hot enough to kill seeds. Because native plants have fire adaptations such as hard seeds and early maturation, prescribed burning has been shown to favor germination and establishment of many species, particularly legumes (Kyser and DiTomaso 2002). In contrast, late-season noxious weeds, including yellow starthistle and annual grasses such as barbed goatgrass (*Aegilops triuncialis*), medusahead (*Taeniatherum caput-medusae*) and ripgut brome (*Bromus diandrus*), have all shown potential for control by prescribed burning (DiTomaso *et al*. 1999a).

By shifting the competitive advantage to fire-adapted species, prescribed burning in California grasslands can increase plant diversity as well as control noxious weeds. In the first growing season after the burn, plant diversity and species richness often increase (Hastings and DiTomaso 1996, DiTomaso *et al*. 1999a). Two or more years of burning have resulted in both a reduction in yellow starthistle and a dramatic increase in perennial grasses such as purple needlegrass (*Nassella pulchra*) and California barley (*Hordeum brachyantherum*), legumes, and filaree (*Erodium* spp.).

Prescribed burns also recycle nutrients trapped in the dried vegetation and remove the thatch layer, thus increasing light exposure at the soil surface and allowing the upper layer of soil to warm quickly in spring. This can enhance germination of seeds of desirable plants, but also has been shown to cause an increase in subsequent fall and winter germination of yellow starthistle seed still in the seedbank. In many cases, this enhanced germination will actually increase the starthistle infestation in the year following a burn (DiTomaso *et al*. 2003a). This helps to deplete the yellow starthistle soil seedbank, but it means that controlling starthistle in the year after a burn is critical.

Native forbs return. *Native forbs especially benefited from reintroduction of a burn regime at Sugarloaf Ridge.*

Native grass resprouting. *In the winter following burns at Sugarloaf Ridge, the native bunchgrass* Nassella pulchra *resprouts from old clumps.*

Results after three annual burns. *Three years of burning at Sugarloaf Ridge shifted the competitive advantage from yellow starthistle to fire-adapted native plants.*

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In deciding whether to use prescribed burning in management, it may be helpful to refer to the historic burn regime, e.g., every 2 to 10 yr at Sugarloaf Ridge (Finney and Martin 1992). The goal of the management program may be to return an area to its historic burning regime. Several years of consecutive burns may constitute excessive disturbance and may not achieve the intended result.

The goal of a successful burn program for yellow starthistle is to reduce or, in time, eliminate the soil seedbank. At the end of a consecutive three-year burn regime in Sugarloaf Ridge State Park in Sonoma County, the yellow starthistle seedbank and seedling populations in the burned sites dropped to less than 0.5% that of adjacent unburned sites (DiTomaso *et al*. 1999a). This corresponded to a 91% reduction in yellow starthistle vegetative cover during the summer following the third year of burning.

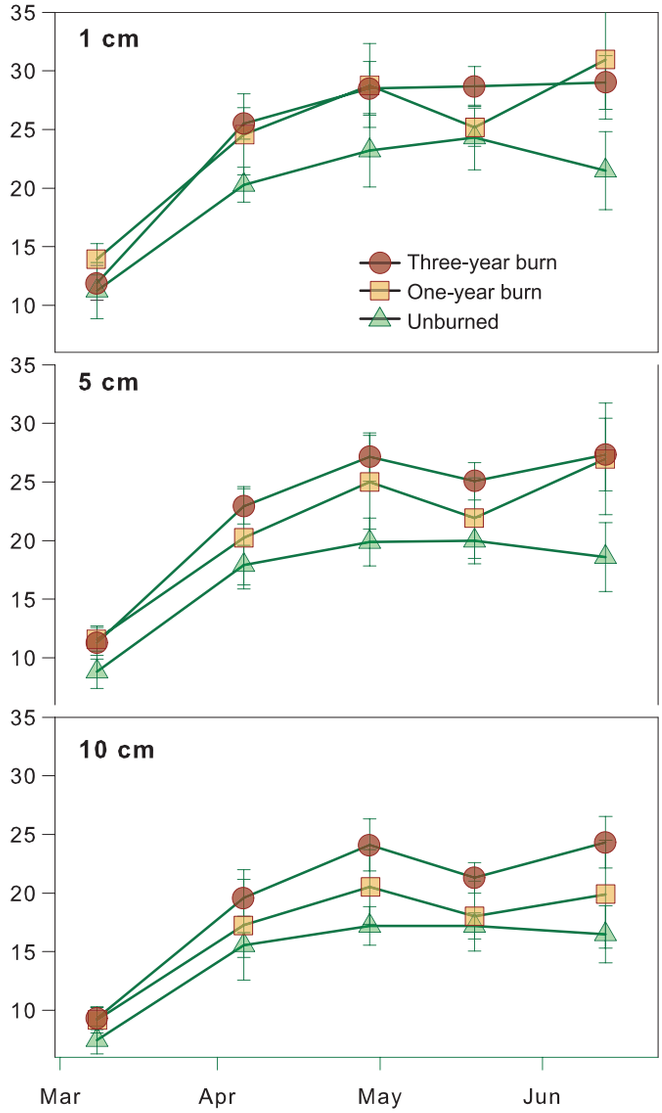

Fig. 15. Effect of burning on soil temperature. *In the spring after burning at Sugarloaf Ridge State Park to control yellow starthistle, higher soil temperatures were measured compared to unburned sites (DiTomaso* et al. *1999a).*

ECONOMICS

The economics of conducting a prescribed burn can vary depending upon the area and cooperation with federal, state or local agencies. At the Sierra Foothill Research and Extension Center in Yuba County, the cost of burning for yellow starthistle control was not substantially less than that for applying herbicide. Out-of-pocket expenses for labor, fuel, minor equipment repairs, permits, and seed and fertilizer for firebreaks totaled $23 per burned acre (Connor 2003). In this study, California Department of Forestry and Fire Protection (CDF) crews provided no-cost assistance with fire ignition and control. CDF assistance is available to private landowners, but there are many more requests annually than can be filled. At Fort Hunter Liggett, with the help of local fire groups, the cost for prescribed burning was only $0.60 to $1.00 per acre (A. Hazebrook, Fort Hunter Liggett, pers. comm.). It is important to remember that in most cases financial liability for escapes is the responsibility of the land owner unless he or she can get into one of the limited number of CDF programs available (Connor 2003).

METHODS AND TIMING

As with mowing, the success of burning depends on proper timing. The best time for burning is in early to mid-summer (late June to early July in most areas of California), which may not be feasible in some areas. At this time starthistle is in the very early flowering stage (similar to ideal mowing timing) and will not have produced viable seeds, whereas seeds of most desirable species will already have dispersed and grasses will have dried to provide adequate fuel.

In some cases, yellow starthistle seedlings have been controlled using winter or early spring "flaming" techniques, in which heat is applied to wet plants with a propane torch (Rusmore 1995). This reduces the risk of escaped fires and avoids major air quality issues. However, this technique is

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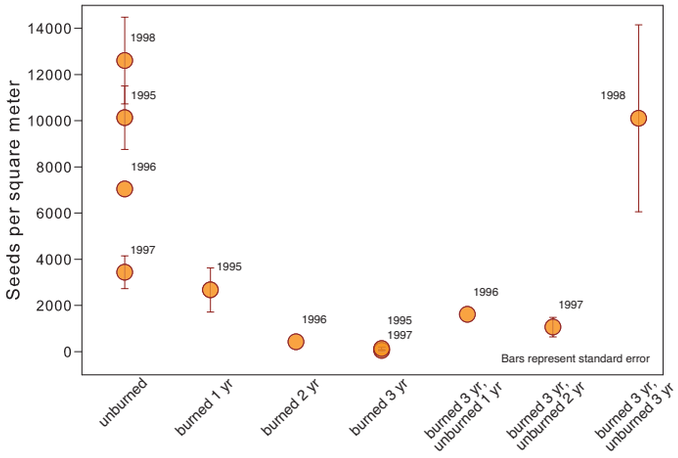

Fig. 16. Effect of burning on seedbank. *At Sugarloaf Ridge State Park, yellow starthistle soil seed density was monitored during a three-year burn project and for three years after burning ceased. The seedbank was greatly reduced but recovered quickly in the absence of followup management (Kyser and DiTomaso 2002).*

Timing for burns. *Burning for control of yellow starthistle is most successful at the beginning of flowering, when other plant species are dry but yellow starthistle seed is not yet viable.*

somewhat non-selective and the control of yellow starthistle has proven inconsistent. When spring drought follows a flaming treatment, control of starthistle can be excellent (Rusmore 1995). In contrast, a wet spring can lead to complete failure and increased starthistle infestation, particularly since competing species may be dramatically suppressed. Fall or winter burns may not control yellow starthistle, but will likely stimulate germination of the seedbank. If a successful management method is employed in the following spring or summer, it is possible to more rapidly deplete the seedbank, thus reducing the long-term cost of management.

In a study by Kyser and DiTomaso (2002) at Sugarloaf Ridge State Park, a site burned three consecutive years (1993-1995) was monitored for an additional four years (1996-1999). Following the cessation of the burn program, the grassland degraded rapidly as the competitive advantage shifted away from fire-adapted forbs. These species, particularly native legumes, gradually declined, as did total species richness. Within three years the burned grassland was not significantly different from the unburned area, with the exception that yellow starthistle population levels remained significantly lower. These results indicate that reduction in yellow starthistle by means of burning at Sugarloaf Ridge did not result in a stable community but rather a community in transition back to yellow starthistle-dominated grassland. (It should be noted that adjacent areas remained infested, providing a ready source of yellow starthistle seed.) It was concluded that without periodic fire and/or intensive management (e.g., herbicides or controlled grazing), and in the absence of many of the original dominant grassland species (Heady 1973), the community is at constant risk of invasion (Kyser and DiTomaso 2002). A follow-up management program is essential to the long-term control of yellow starthistle. This can include spot herbicide treatments or a mechanical control method.

The ability to use repeated burning depends on climatic and environmental conditions, as well as

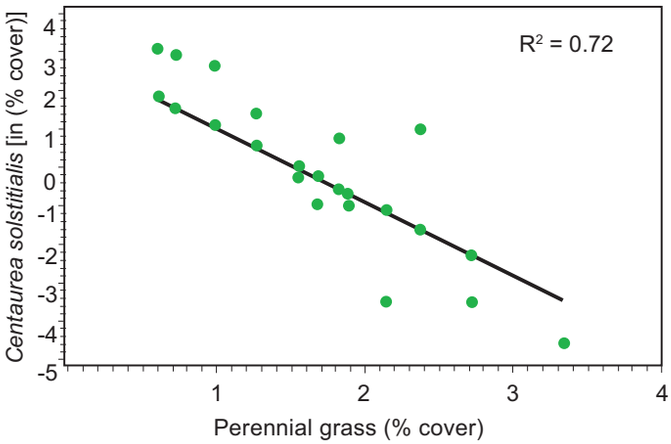

Fig. 17. Competition with perennial grasses. *A negative correlation between yellow starthistle cover and cover of perennial grass indicates that the two plant types compete directly (Enloe 2002).*

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political and sociological concerns. Even when these obstacles are overcome, fuel loads may not be sufficient to allow multiple-year burns. Consequently, prescribed burning may be most appropriate as part of an integrated approach. A combination of burning and other control techniques, such as herbicide treatments or intensive grazing, may be more practical and still prove to be very effective.

RISKS

There are a number of risks associated with prescribed burning as a method of controlling yellow starthistle and other invasive plants. For one, air quality issues and requirements, including PM10 emissions, can be a significant problem when burns are conducted adjacent to urban areas (Campbell and Cahill 1996). This potential problem can be avoided by conducting burns only in more isolated regions. Public relations problems can be minimized by educating residents of the intended goals of the project prior to the burn.

Another major risk of prescribed burning is the potential of fire escapes. This is particularly true when burns are conducted during the summer months. This can be minimized by proper preparation and through involvement of local and state fire departments.

Because of these air quality and fire escape concerns, public agencies have restricted prescribed burns to periods of proper wind, humidity, and temperature parameters (Connor 2003). Given these restrictions, plus the ever-present possibility of variable weather during desired burn periods, it can be problematic to achieve a burn within the time period required for weed control.

Another potential risk is that continuous burning may increase soil erosion and impact the plant composition within a site. Species that complete their life cycle before the burn will be selected for, while those with later flowering times will be selected against. In some areas, burning can lead to rapid invasion by other undesirable species with wind-dispersed seeds, particularly members of the sunflower family. Although this is a potential concern, and a few plants are negatively impacted by continuous burning for yellow starthistle control, the survival of most native species is enhanced by burns (Hastings and DiTomaso 1996).

Perhaps the most overlooked risk of burning is the impact fire may have on small animals and insects unable to escape the burn. For example, burning for control of yellow starthistle during the summer undoubtedly damages seed head feeding biocontrol insects and their larvae.

Reseeding. *This site in Siskiyou County, California, was reseeded with wheatgrass as part of a yellow starthistle control program.*

Revegetation

Before the introduction of annual grasses, perennial bunchgrasses were the primary native species in rangelands west of the Rocky Mountains. Bunchgrass species included *Festuca idahoensis, Poa secunda, Festuca kingii, Pseudoroegneria spicata, Leymus cinereus, Elymus elymoides*, *Achnatherum hymenoides, Hesperostipa comata,* and *Achnatherum occidentalis* (Billings 1994). These perennial grass species do not have high seedling vigor nor do they readily recover from grazing (Callihan and Evans 1991). With the introduction of exotic annual grasses and livestock,

Seed drill. *A seed drill attachment used for reseeding.*

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Competitive planting. *Wheatgrass, here shown establishing along seed drilling rows, can be used to out-compete yellow starthistle after other management methods have removed it.*

Two years after reseeding. *Wheatgrass was planted two years ago on this site in Siskiyou County*

native perennial grass plants were overgrazed and quickly replaced by introduced winter annual grasses (Young and Longland 1996).

During the past half-century, many noxious broadleaf species have expanded their range in the western United States. Although this can be associated with soil disturbance by human activities, it is also due to selection by livestock overgrazing the annual grasses. Spiny broadleaf species such as yellow starthistle tend to be avoided by livestock. This can favor a rapid shift in the dominant species within these communities (Callihan and Evans 1991). Many of these broadleaf species produce extensive taproot systems that extract more deep soil moisture than do annual grasses, thus they remain green longer into the dry season. In addition, these invasive broadleaf species typically produce a large number of seeds (Roché *et al.* 1994).

Revegetation seeks to replant an area with competitive species that have wildland or forage value. These can be native perennial bunchgrasses or other species. In a revegetation program designed to suppress noxious weeds, one major challenge is choosing a species or combination of species that is more vigorous than the invasive weed. Only a limited number of species have proven to be aggressive enough to displace invasive species, and the proper species choice varies depending on the location and objective. Perennial bunchgrasses are among the most common species used for revegetating western grasslands, but broadleaf species such as legumes can also be used in revegetation programs to suppress rangeland weeds. In addition to using a competitive species, seeded species also need to be adapted to the soil conditions, elevation, climate, and precipitation level of the site (Jacobs *et al.* 1999).

Reseeding rangeland. *A land manager using a seed drill on rangeland.*

Because of its extended dry season, revegetation in California is more difficult than in other western states. Summer rainfall can be critical to the establishment and survival of native perennial grasses. In Siskiyou County, where the summer weather pattern is more similar to the Great Basin states, average rainfall between May and September is around 4 inches. In contrast, the Sacramento and San Joaquin valleys average 0.75 inches or less of precipitation during that same time period.

ECONOMICS

The primary limitation to the use of native species in revegetation programs is their high cost. Few producers are available and the demand for seed

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is low. This increases the cost of seed and reduces availability of genetically endemic biotypes of native species. In many cases, the cost of using native seed can be in the hundreds to even thousands of dollars per hectare. Access to seeding equipment can also be a major limitation. Drill seeders are not often available and cannot be used in steep terrain or rocky sites. Broadcast seeding reduces the chances of successful establishment.

In a native legume and perennial grass restoration effort at Fort Hunter Liggett, reseeding cost between $500 and $2000 per acre) (A. Hazebrook, Fort Hunter Liggett, pers. comm.). In this trial, the native species represented 5 to 30% of the total vegetative cover two years after seeding.

METHODS AND TIMING

In the absence of adequate surface soil moisture during the critical spring growing season, revegetation programs are likely to fail (Roché *et al*. 1997). In California, it is not uncommon to experience a month of more without precipitation during the rainy season. Under these conditions, germinated seedlings cannot survive and a fall reseeding timing program may fail. In contrast, a spring reseeding may not survive under conditions of low spring rainfall. Although there has been little work in this area, winter may prove to be the best time for reseeding; however, it is generally the most difficult time to transport equipment into the site.

The method of revegetation can also determine the level of success. Revegetation can be accomplished by broadcast seeding or interseeding forage grasses and/or legumes into existing communities, or by drill seeding into plowed, disked, herbicide-treated, or no-till rangeland (Jacobs *et al*. 1999). Drill seeding programs are considerably more successful than those utilizing broadcast seeding techniques. Broadcast seeding disperses seeds on the top of the soil, so the seeds are more susceptible to predation or decay. In addition, if the seeds germinate on the soil surface they have a higher probability of desiccating under subsequent dry conditions.

The choice of species that best fit the intended use of the site is also important. For example, if livestock grazing is the primary objective of a revegetation program, a perennial grass with high forage production may be the appropriate choice (Jacobs *et al*. 1999).

Clover cover crop. *When used as a cover crop, crimson clover (*Trifolium incarnatum*) reduced yellow starthistle cover by up to 90%.*

Perennial grasses are the most successful in competing with rangeland weeds. For the long term, however, it is best to use a combination of species with various growth forms when designing seed mixes. In other regions of the country, seed mixtures of grasses with legumes improved the rate of microbial and soil structure recovery compared to grasses alone (Jacobs *et al*. 1999). Seed mixtures are expensive, however, and their use may limit the options for noxious weed control (e.g., using selective herbicides). Thus, a revegetation program may require initial seeding with perennial grasses during the weed management phase followed by subsequent reseeding with broadleaf species. Under this condition, revegetation programs may take several years to succeed.

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Revegetation programs for yellow starthistle control generally rely on reseeding with native species or perennial grasses (Callihan *et al*. 1986, Johnson 1988, Jones and DiTomaso 2003, Larson and McInnis 1989a, Lass and Callihan 1995a, Northam and Callihan 1988a, b, c, 1990a, b, Prather *et al*. 1988, Prather and Callihan 1989a, b, 1990, 1991). These programs try to eliminate not only starthistle, but also the invasive annual grasses that create an ecosystem susceptible to starthistle invasion. Revegetation with desirable and competitive plant species can be the best long-term sustainable method of suppressing weeds, while providing high forage production. In western states other than California, competitive grasses used in revegetation programs for yellow starthistle management include crested wheatgrass (*Agropyron desertorum*), intermediate wheatgrass (*Elytrigia intermedia* [=*Agropyron intermedium, Thinopyrum intermedium*]), thickspike wheatgrass (*Agropyron dasystachyum*), big bluegrass (*Poa ampla*), Bozoisky Russian wildrye (*Psathyrostachys juncea*), sheep fescue (*Festuca ovina*), tall oatgrass (*Arrhenatherum elatius*), or orchardgrass (*Dactylis glomerata*) (Borman *et al*. 1991, Ferrell *et al*. 1993, Prather and Callihan 1991, Sheley *et al*. 1999b). These species provide good livestock forage and a sustainable option for rangeland maintenance.

Ideally, competitive, endemic, native species should be re-established. The native perennial grass species most commonly studied include purple needlegrass (*Nassella pulchra*), blue wildrye (*Elymus glaucus*), and creeping wildrye (*Leymus triticoides*) (Jones and DiTomaso 2003). Some native perennial broadleaf species, such as common gumplant (*Grindelia camporum*), are also used. In preliminary studies in the Sacramento Valley (Jones and DiTomaso 2003), blue wildrye or combinations of blue wildrye and common gumplant were very effective in preventing the encroachment and establishment of yellow starthistle. In many other cases non-native perennial grasses or legumes with high forage quality and quantity are used in revegetation programs, as it is not always practical or economical to use native species.

In Oregon, subterranean clover (*Trifolium subterraneum*) has been used for reseeding programs in foothill ranges (Sheley *et al*. 1993). This species is effective in annual grass dominated rangelands because of its rapid germination and establishment. However, it establishes inconsistently in yellow starthistle-dominated grasslands because starthistle has similar patterns of initial growth.

In California, Thomsen *et al*. (1996a, 1997) and Thomas (1996, 1997) tested several legume species for their competitive effect on yellow starthistle. Thomsen *et al*. (1996a, 1997) found that subterranean clover varieties were somewhat competitive against yellow starthistle when combined with grazing and mowing. Subterranean clover was also palatable and self-seeding, and produced flowers and seeds below the bite of grazing animals. Used as a sole control option, however, the clover did not provide adequate seasonal control of starthistle. Thomas (1996, 1997) used a combination of subterranean clover and/or crimson clover (*Trifolium incarnatum*) as a cover crop in starthistle-infested pasture. In a completely infested field, Thomas (1997) reported an 80 to 90% reduction in yellow starthistle one year after planting with crimson clover. Unlike subterranean clover, crimson clover does not appear to be self-sustaining over a long time period.

RISKS

Introducing competitive species into infested non-crop areas as part of a control program is essential to sustainable management of noxious weeds. Preferably, competitive, endemic, native species should be re-established. For example, native willows (*Salix* spp.) and cottonwoods (*Populus* spp.) have been used to replace saltcedar in riparian areas. However, in most cases, particularly rangeland environments, endemic native species do not appear capable of outcompeting noxious weeds.

In yellow starthistle-infested areas, many studies have used more competitive non-native species. Although non-native, these species provide good livestock forage and a sustainable option for rangeland maintenance. A potential concern is that, once established, many of these species, especially the perennial grasses, can develop into near monocultures. This can have a dramatic impact on total plant and animal diversity within these sites. In addition, it is important to ensure that an introduced species will not itself become invasive and spread from the planted area into wildlands. For example, Harding grass (*Phalaris aquatica*) is a perennial

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bunchgrass native to the Mediterranean region that was planted commonly as high-value pasture forage, but has escaped to colonize wildland areas and displace native species (Harrington and Lanini 2000).

Even the use of native species in revegetation efforts presents potential problems. Native seed collected in one area of the state but used in a revegetation program in a different region may be genetically different, due to ecotypic variability. It has been argued that over time, as a result of genetic contamination, the native population may lose its adaptive advantage in its evolved ecosystem (Knapp and Rice 1997).

Because of the ecological diversity within California, no single species or combination of species will be effective under all circumstances. Although pubescent wheatgrass has proved successful in Siskiyou County, it may not be appropriate in most other areas of the state that lack summer rainfall. Unfortunately, few studies have been conducted on the restoration of yellow starthistle-infested grasslands, particularly with native species. Major questions yet to be addressed include what combinations of species to use in various environments, which species or combination of species will aggressively compete with yellow starthistle, and how to economically establish these species.

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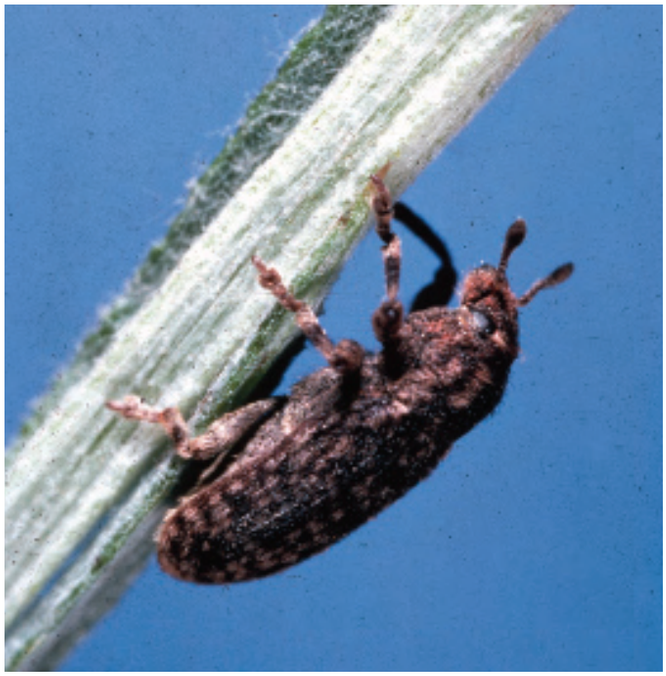
CHAPTER 6: Biological Control

Biological control is the use of natural enemies (biological control agents) to control a target weed. The objective is to establish self-sustaining populations of the biological control agents that will proliferate and attack the target weed throughout its range. Most noxious weeds in North America are exotic and without specialized natural enemies that occur in their area of origin. As a result, these plants have a competitive advantage over our native species, which have their own specialized herbivores and diseases.

Use of biological control to manage a noxious weed differs from other methods in that management measures are not directed at particular patches or infestations. Biological control agents are living organisms and land managers cannot accurately direct their activity. Instead, the goal of these programs is to release control agents at strategic locations throughout the infested area with the intention that the control agent will establish, build up high populations, and spread throughout the infestation. Eventually, all areas infested by the target weed will be colonized. The establishment, build-up, and spread of a control agent usually requires years, so this method is directed at long-term control of the weed. Biological control methods do not eradicate; rather they provide sustained suppression of the target weed populations. Insect agents can achieve this by defoliation, seed predation, boring into roots, shoots and stems, or extracting plant fluids. All these effects can reduce the competitive ability of the plant relative to the surrounding vegetation (Wilson and MacCaffery 1999).

Many years are necessary to research, test, and release biological controls for use on a target weed. As a result, biocontrol is usually developed for the most damaging and widespread weeds. In the development of weed biological control, scientists examine the target weed in its area of origin and identify the most promising natural enemies for use as potential agents. These natural enemies are subjected to a series of host-specificity tests to examine their safety for introduction into the United States. A high degree of host-specificity is critical for successful biological control of a weed, and natural enemies that attack agricultural crops or related native species are rejected. For yellow starthistle, research on biological control began in the mid 1960s and continues today.



Bud weevil. Bangasternus orientalis *is one of many biocontrol agents released in California to control yellow starthistle. (Photo: B. Villegas)*

Natural Enemies Associated with Yellow Starthistle Control

INSECTS

The United States Department of Agriculture (USDA), Agricultural Research Service Exotic and Invasive Weed Research Unit in Albany and the California Department of Food and Agriculture (CDFA) Biological Control Program are actively pursuing several biological control agents for use against yellow starthistle in California and the

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Table 2. Distribution, impact and publications on yellow starthistle seed head insects

Species	Common Name	Distribution	Impact	References
Bangasternus orientalis	bud weevil	Wide	Low	Campobasso *et al*. 1998 Maddox *et al*. 1986, 1991 Maddox and Sobhian 1987 Pitcairn *et al*. 2004 Sobhian 1993a Sobhian *et al*. 1992
Chaetorellia australis	peacock fly	Limited	Low	Balciunas and Villegas 1999 Maddox *et al*. 1990 Turner *et al*. 1996 Pitcairn *et al*. 2004 Villegas *et al*. 1997, 2000b White *et al*. 1990
Chaetorellia succinea (accidental introduction)	false peacock fly	Wide	Moderate	Balciunas and Villegas 1999 Pitcairn *et al*. 1998a, 2003, 2004 Pitcairn 2002 Villegas 1998 Villegas *et al*. 1997, 1999, 2000b
Eustenopus villosus (=E. hirtus)	hairy weevil	Wide	Moderate	Clement *et al*. 1988 Connett and McCaffrey 1995 Fornasari *et al*. 1991 Fornasari and Sobhian 1993 Pitcairn *et al*. 2004 Villegas *et al*. 2000a
Larinus curtus	flower weevil	Limited	Low	Fornasari and Turner 1992 Pitcairn *et al*. 2004 Sobhian and Fornasari 1994 Villegas *et al*. 1999, 2000c
Urophora sirunaseva	gall fly	Wide	Low	Maddox *et al*. 1986 Pitcairn *et al*. 2004 Sobhian 1993b Turner 1994 Turner *et al*. 1994 White and Clement 1987 White *et al*. 1990

General articles on insect biological control of yellow starthistle

Topic	References
Discovery	Clement 1990, 1994 Clement and Sobhian 1991
Effects of natural insect populations on starthistle	Johnson *et al*. 1992 Pitcairn *et al*. 1999b
Reviews	Jette *et al*. 1999 McCaffrey and Wilson 1994 Pitcairn *et al*. 2000c, 2004 Rosenthal *et al*. 1991 Turner 1992 Turner and Fornasari 1992 Wood 1993

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Peacock fly. *Although* Chaetorellia australis *has established populations on yellow starthistle, it has not established in densities sufficient to produce a significant reduction in starthistle. (Photo: B. Villegas)*

Release in the field. *Biocontrol agents are released only after years of host-specificity testing. (Photo: M. Pitcairn)*

Hairy weevil. Eustenopus villosus *is the most damaging biological control insect established against yellow starthistle. It feeds by chewing a small hole in young flower buds and feeding on the soft internal tissues. This feeding damage kills young buds and stops their development. (Photo: B. Villegas)*

western United States. Six insect species and a rust disease have been introduced against yellow starthistle in the United States. Of the six insects, five have established (see Table 2). Three of these are widespread: the bud weevil (*Bangasternus orientalis*), hairy weevil (*Eustenopus villosus*), and gall fly (*Urophora sirunaseva*). Two of the other insects, the peacock fly (*Chaetorellia australis*) and the flower weevil (*Larinus curtus*), occur only in a few isolated locations and have failed to build up numbers high enough to substantially reduce seed production. The sixth insect, *Urophora jaculata*, failed to establish and does not occur here. In addition to the five insects established as control agents, another insect, the false peacock fly (*Chaetorellia succinea*) was accidentally released in southern Oregon in 1991 and is now widespread throughout California (Balciunas and Villegas 1999). The false peacock fly is not an approved biological control agent and did not undergo host specificity testing prior to

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its accidental introduction. Fortunately, follow-up surveys of commercial safflower crops and native *Cirsium* thistles showed the fly to be fairly host specific to yellow starthistle (Villegas *et al*. 1999, 2000b; Balciunas and Villegas 1999).

All of the insects released for control of yellow starthistle attack the flower heads. All deposit their eggs either inside or on the immature flower buds and their larvae feed directly on the developing seeds or destroy the disk area on which the seeds develop. A statewide survey of the seed head insects found the false peacock fly to be the most common insect—it was recovered at 99% of the sample locations. The second most common insect was the hairy weevil, which was found at 80% of the sample locations (Pitcairn *et al*. 2003).

Several plant pathogens are known to attack yellow starthistle seedlings and rosettes in California: *Sclerotinia minor*, *Colletotrichum gloeosporioides* and a new species of *Ascophyta* (Woods 1996, Woods and Fogle 1998, Pitcairn *et al*. 2000b). All three species are naturally present in California. Seedlings of yellow starthistle were observed to be infested with *Ascophyta* n. sp. during two winters at one location in central California (Woods 1996). Unfortunately, infestations by *Ascophyta* n. sp. have not been observed since then. More commonly, *S. minor* and *C. gloeosporioides* have been observed to cause high mortality rates in starthistle seedlings at several locations, particularly in areas where skeletons of previous years starthistle plants provide shading. Both of these pathogens are not host specific and are able to infect important crops

False peacock fly. *Accidentally introduced, the false peacock fly is one of the most common seed head insects found on yellow starthistle. (Photo: B. Villegas)*

Biological control damage. *Buds attacked by the hairy weevil* (E. villosus) *early in development fail to flower (upper center). (Photo: B. Villegas)*

including lettuce (Pitcairn *et al*. 2000b). In contrast to *Ascophyta* n. sp., these pathogens are more aggressive at warmer temperatures, causing symptoms characterized by wilting and yellowing (Woods and Fogle 1998). It is important to note that none of these pathogens has been approved for use as a biological control agent and land managers need to rely on naturally occurring infection if their benefits are to be realized. It may be possible to isolate a host-specific form of *S. minor* or *C. gloeosporioides* that could be used as a mycoherbicide for use in infested grasslands, but this is many years away from development.

Under laboratory conditions, Klisiewicz (1986) looked at the effect of several pathogenic fungi on yellow starthistle rosettes. The species evaluated included *Fusarium oxysporum* f. sp. *carthami*, *Verticillium dahliae*, *Phytophthora* spp., *Botrytis cinerea*, and *S. sclerotiorum*. Starthistle plants developed symptoms following innoculation and,

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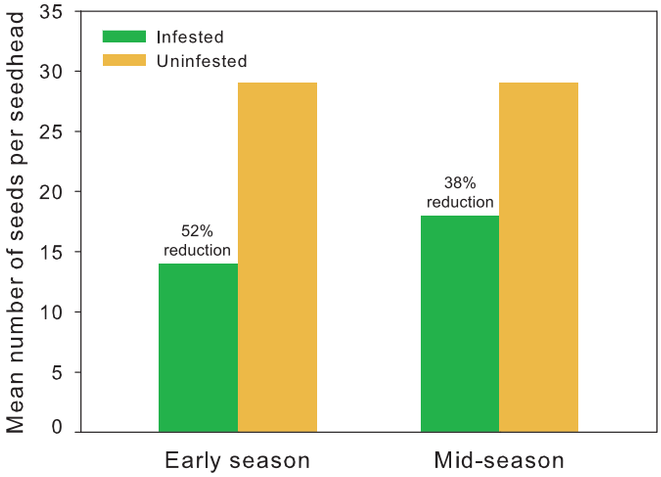

Fig. 18. Effect of insect control agent on seed production. *In a 1999 study near Folsom, CA, insect control agents reduced yellow starthistle seed production (mean number of seeds per head) by 45% on average (M.J. Pitcairn and J.M. DiTomaso, unpubl. data).*

with the exception of *B. cinerea*, the diseases were frequently lethal. However, with the exception of *S. sclerotiorum*, none of these pathogens has been observed to attack starthistle under field conditions. As with the endemic seedling pathogens, none of these diseases is host specific and, thus, all have the potential to attack other economically or ecologically important plant species.

Recently, the Mediterranean rust fungus (*Puccinia jaceae* var. *solstitialis*) has been approved for release in the western United States. Research on this pathogen was initiated in 1978 from isolates collected in Turkey. Since then, the pathogen has undergone a long series of host specificity tests in the USDA-ARS quarantine lab in Fort Detrick, Maryland. The test results showed that this pathogen is highly host-specific, it can infect only a couple of exotic *Centaurea* species, and that its preferred host is yellow starthistle (Shishkoff and Bruckart 1993). The first release of this rust occurred on a private land trust in Napa County in 2003 (Woods *et al*. 2004). In 2004, releases occurred at 25 locations in 22 counties, and, in 2005, releases occured at 99 locations in 38 counties. The rust attacks the leaves and stem of the rosettes and early bolts of starthistle, causing enough stress to reduce the number of flower heads and seed production. Thus, it complements the damage caused by the seed head insects. Preliminary laboratory data suggest that it is well suited to the environmental conditions found in California (Bennett *et al*. 1991), but it is too early to know for sure. It may be limited to areas with sufficient dew period to allow sustained infection during spring; however, this is yet to be determined.

Current Status of Yellow Starthistle Biological Control

The combined impact of five of the insects (except the peacock fly) has been evaluated at three long-term study sites in central California (Pitcairn *et al*. 2002). The hairy weevil and the false peacock fly are the most abundant insects and appear to cause the largest amount of seed destruction. The other three insects failed to build up high numbers and have had little impact on seed production. Since 1995, seed production at the three study sites has steadily declined due to the steady increase in attack by the hairy weevil and the false peacock fly. Recently, the density of mature plants has declined at two sites (Pitcairn *et al*. 2002). Although it is too early to know the stable level of control provided by the seed head insects, as of 2004 mature plant density had declined over 50% at both sites. It is important to note that these sites experienced no

Seed head damage. *This seed head has been damaged by the false peacock fly (*Chaetorellia succinea*). (Photo: B. Villegas)*

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disturbance from grazing, mowing, or other control methods and it is likely that the endemic plant community also contributed to the suppression of yellow starthistle through interspecific competition. By comparison, control of yellow starthistle at disturbed sites, such as along roadsides, may not occur due to the lower level of plant competition.

Two additional biological control agents are now under preparation for use in California. The first is the Mediterranean rust disease, discussed above. It is expected that infection of the rosette and stem leaves by this disease will stress the plant causing reduced growth, fewer number of seed heads, or possibly early death. The second biological control agent (not yet released) is the rosette weevil (*Ceratapion bassicorne*). This weevil deposits its eggs on young rosettes and its larvae burrow into the root and up into the bolting stem. Field observations in Turkey show that attack by the weevil results in shorter plants with fewer seed heads compared to unattacked plants (Uygur *et al.* 2005). Infection by the rust and attack by the rosette weevil occur in late winter through spring. This will be followed by the attack of the seed head insects in summer. It is hoped that these two new biological control agents will complete a guild of herbivores and pathogens sufficient to control yellow starthistle in the western United States.

Mediterranean rust fungus. Puccinia jaceae *var.* solstitialis *on yellow starthistle. (Photo: D. Woods)*

Choice of Biological Control Agents

Of all the seed head insects, only two, the hairy weevil and the false peacock fly, have proven to consistently build up high numbers and cause a substantial amount of seed destruction (Pitcairn and DiTomaso 2000, Woods *et al*. 2002, Pitcairn *et al*. 2003). The combination of these two insects has been reported to reduce seed production by 43 to 76% (Pitcairn and DiTomaso 2000). Balciunas and Villegas (1999) reported a 78% reduction in seed production when seed heads contained false peacock fly larvae alone. The hairy weevil is an approved agent and is available for use to landowners. The false peacock fly is not a permitted biological control agent and therefore is unavailable. Despite this, the false peacock fly is a very common insect and is found almost everywhere that yellow starthistle is known to occur (Pitcairn *et al*. 2003). It is likely that the false peacock fly is already present at locations identified for yellow starthistle control (to check this, see monitoring methods, below). In developing a biological control program, it is recommended that efforts be directed at establishing the hairy weevil throughout the infested area; it is expected that the false peacock fly will build up on its own.

While the rust has been released in California, its continued release and establishment is regulated

Damage by hairy weevils. *Yellow starthistle plants may respond to damage caused by adult hairy weevils by emitting sap around the damaged area. (Photo: B. Villegas)*

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by the California Environmental Protection Agency (CalEPA) and will likely not be available for general use. Current releases by CDFA are permitted under an experimental use permit and are limited to 10 acres per year. The goal of the CDFA distribution effort is to establish the rust in all regions where yellow starthistle is known to occur. Rusts produce millions of spores that are easily transported by wind. It is expected that, once established, the rust will spread on its own throughout the nearby yellow starthistle populations. In contrast, CDFA and other state agricultural departments will distribute the rosette weevil at no cost to the user. It is unknown when the rosette weevil will be ready for distribution.

Methods and Timing

SELECTION OF RELEASE SITES

The objective of a biological control program is to establish self-sustaining populations of the biological control agents at locations throughout the infested area. First, release sites must be identified for the biological control agents. The release site should contain at least one acre of yellow starthistle that is undisturbed by farm equipment, vehicular traffic, livestock (no grazing), mowing, and pesticide use. These sites are small refugia that allow the control agent to reproduce and build up high numbers that eventually spread outward into adjacent yellow starthistle populations. To build up their population, the control agents require yellow starthistle to reproduce and develop. Insects are killed if the plant is destroyed before flower maturation. The release site should have a moderately dense infestation of yellow starthistle; however, the plant population should not be so dense that plants are stressed and stunted. Ideal release sites are areas where application of herbicides is not permitted, such as near stream corridors, or areas that are inaccessible by equipment such as hillsides or ravines. It is not necessary to release insects everywhere on a landscape. Rather, a few locations strategically spread throughout the property are sufficient. Distance between release locations can be as much as a five miles and still result in effective spread and coverage by the biological control agents.

Post-release monitoring. *After release, biocontrol insects are carefully monitored for effectiveness and spread. (Photo: M. Pitcairn)*

RELEASE OF THE HAIRY WEEVIL

The hairy weevil has one generation per year. It overwinters under plant litter near the base of yellow starthistle plants, along fence rows, or at the base of trees (Pitcairn *et al.* 2004). It terminates its diapause in late spring when adults can be seen feeding on young buds on the newly bolted yellow starthistle plants. Collection of the hairy weevil for distribution to new areas is best during late June and early July when females are beginning to deposit eggs into the seed heads. In California, the hairy weevil are available at no cost to the user from each County Agricultural Commissioner's Office. For each release, only 100 weevil adults are necessary to establish a viable population. If more weevils are available, it is best to distribute them to as many different locations as possible, rather than concentrating them at one or two release sites.

Monitoring Seed Head Insects

HAIRY WEEVIL

The presence of the seed head insects is best determined by looking for adult insects sitting on the flower buds or by observing damage caused by each of the insects "(Pitcairn *et al.* 2004). The hairy weevil is very destructive to the seed head and its damage is distinctive. Both males and females feed on the young undeveloped flower buds by chewing a small hole in the base of the bud and eating away the developing tissue (Connett and McCaffrey 2004). This feeding damage causes the whole young bud (buds with diameters less than 1/8 inch) to die and turn brown. At locations with high populations of hairy weevils, most of the young flower buds may be killed by their feeding damage. Following destruction of its early

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flower buds, the plant responds by developing flowers along the stems. This substantially changes the architecture of the plant. Undamaged plants have the flowers located at the top of the plant on long stems, while plants damaged by *E. villosus* are less bushy with flowers located close to the branches on short stems. Later, the female weevil oviposits by chewing a hole in the side of the flower head and depositing an egg inside the head. The hole is then filled with a black plug by the female to protect the egg. The plant responds to the chewing damage by emitting a dark sap that fills in around the damaged area of the flower head. This type of damage can be seen in July and August. The black plug is easily seen on the outside of the flower head. Sometimes the area around the plug is distorted and the dark sap oozes out of the head. Adult hairy weevils are active during the day and can be observed sitting on the seed heads and stems of yellow starthistle plants. Adults can be captured with a sweep net passed through the plants.

FALSE PEACOCK FLY

False peacock flies can be detected by looking for ovipositing adults or by tearing apart seed heads and observing the larvae and pupae. The adult flies are slightly smaller than a housefly, and have blond bodies with brown stripes on clear wings. They are easily seen sitting on the seed heads during the day. The female oviposits by inserting her ovipositor between the bracts of the unopened flower bud and depositing several eggs. After hatching, the larvae burrow throughout the seed head and feed on the developing seeds. When ready to pupate, the larva becomes a swollen pupal capsule that is blond in color and approximately 1/10 inch long. The pupae are usually located near the base of the bracts. They can be seen by breaking open the seed head. Adults can be captured with a sweep net passed through the plants.

OTHER SEED HEAD INSECTS

The larvae of the gall fly, *U. sirunaseva*, produce hard, woody galls inside the seed head (Pitcairn *et al.* 2004). They occur like small hard nuts inside the head, approximately 1/10 inch in diameter. The adult flies frequently forage among the seed heads. The adult gall fly is approximately half the size of the false peacock fly and their bodies are black with yellow legs while their wings are clear-colored with black marks across the surface.

Presence of the bud weevil, *B. orientalis,* at a site is best indicated by the presence of eggs on or directly below the flower buds. The eggs are round, black ball-like structures glued to the stem. Within the black structure is a single yellow egg. The female secretes the black material covering the egg to adhere the egg to the plant and to protect it from desiccation.

Economics

The major advantage of weed biological control is that it is considered to be environmentally safe, cost-effective, and self-sustaining. The high cost of developing biological control is borne upfront in the foreign exploration, host testing, and permitting of candidate biological control agents. However, the significant long-term benefits of a successful biocontrol program make it very cost-effective. Once approved and released, distribution of the agents is generally conducted by federal and state agencies. In California, the California Department of Food and Agriculture and the Offices of the County Agricultural Commissioners distribute biological control agents at no cost to the land manager. Ideally, if biological controls are successful, weed populations will slowly decline and become much easier to manage using conventional control methods. In very successful programs, biological controls may eliminate the need for additional control efforts altogether. Some costs may result from the delay between release of the agents and the time when their populations have increased sufficiently to cause a reduction in the plant populations. This delay may be substantial. For yellow starthistle, 4-6 years elapsed before reduction in starthistle populations was observed at the two long-term monitoring sites.

Risks

Despite the overwhelmingly positive aspects of biological control, some risks do exist. These risks are associated with the introduction of an exotic organism and can result in direct or indirect impacts to non-target species. Direct impacts occur with feeding on non-target plant species. Indirect non-target impacts consist of changes in abundance of endemic predators (such as field mice) that may alter foraging behavior and exploit a new resource. This can lead to changes in the community food web.

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Host-specificity testing of candidate biological control agents has been shown to be a good indicator of host use in the exotic habitat. A review of insects introduced into North America for use as biological control agents showed that all have performed as expected, and that no plants identified as unsuitable during host testing became targets after release of the agents in the field (Pemberton 2000). Approximately 10% of the control agents examined do attack some native plant species, but these were predicted by the host specificity testing. All of these agents were released prior to 1970 when attack on weedy native plants was considered beneficial. Today, attack on native plants is undesirable and the required level of host-specificity of biological control agents has increased.

For yellow starthistle, none of the seed head insects has been observed to attack any native non-target plant species. Based on genetic similarity, yellow starthistle is most closely related to other species in the tribe Cardueae. Within this tribe are safflower (*Carthamus tinctorius*), artichoke (*Cynara scolymus*), sunflower (*Helianthus annuus*) and *Cirsium*, a genus of native thistles (Stevens *et al*. 1990, Keil 2004). Many surveys of these potential non-target species have been performed (Villegas *et al*. 1999, 2000b; Balciunas and Villegas 1999), and no evidence of non-target use of agricultural and native plants has yet been observed. Some use of other exotic plants by yellow starthistle bioagents has been observed. For example, the hairy weevil will attack several exotic *Centaurea* species, including Sicilian starthistle (*C. surphurea*), Malta starthistle or tocalote (*C. melitensis*), and spotted knapweed (*C. maculosa [=C. biebersteinii]*). All are exotic noxious weeds. Thus, the risk of direct non-target attack by the yellow starthistle insects is extremely low.

The risk of indirect impacts also appears to be very low for the biological control agents of yellow starthistle. Pearson *et al*. (2000) found that gall flies used as biocontrol agents on spotted knapweed (*Centaurea maculosa*), caused indirect increases in populations of deer mice by providing a food source over the Montana winter. However, a similar scenario is unlikely with yellow starthistle, because yellow starthistle favors mild-winter areas and is an annual plant which dies by winter.

Hairy weevil damage. *This yellow starthistle bud will never open due to damage from the hairy weevil. (Photo: B. Villegas)*

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CHAPTER 7: Chemical Control

Herbicides are a widely used method for controlling weeds, both in agricultural and non-crop environments. They can be applied to rangeland and grasslands by a number of methods, including fixed-wing aircraft, helicopter, ground applicators, backpack sprayers, and rope wick applicators.

Economics

Herbicides are generally considered the most economical and effective method of controlling yellow starthistle. At the Sierra Foothill Research and Extension Center, 300 acres were treated for yellow starthistle control at a cost of $12/acre for chemical (4 oz Transline®/acre) plus $14.50/acre for application by helicopter (Connor 2003). (In a similar large-scale control project at Fort Hunter Liggett in 2000, the cost of a helicopter application of Transline® at 8 oz product/acre was $40 (A. Hazebrook, Fort Hunter Liggett, pers. comm.)). The field was broadcast treated for 2 to 3 consecutive years. Follow-up maintenance (spot spraying) cost an average of $2.50/acre per year. The 5-year total for two broadcast applications of Transline® and 3 years of follow-up treatment was $60.50 per acre.

For comparison, foothill rangelands generate typical annual rents of $10-12 per acre (Connor 2003). In this example, revenues of $12/acre per year would just cover the total cost of controlling yellow starthistle over a 5-year period. Thus it can be financially difficult to implement a long-term management plan, despite the relative low cost of control and the long-term benefits.

Methods and Timing

For yellow starthistle control, herbicides are an appropriate tool on large infestations, in highly productive soils, around the perimeter of infestations to contain their spread (Sheley *et al*. 1999b), and for spot treatments of escaped patches or satellite populations. Most available compounds used for starthistle control in grasslands provide postemergence (foliar) activity; very few give preemergence (soil active) control. A few herbicides provide both excellent postemergence activity and a significant period of preemergence control, e.g., aminopyralid and clopyralid (the most widely used chemicals for yellow starthistle control), picloram, and imazapyr (see Table 3).

Treatment from an ATV. *Application of herbicide for yellow starthistle control in rangeland can be made using a boom mounted on an ATV.*

PREEMERGENCE HERBICIDES

Preemergence herbicides must be applied before seeds germinate to be effective. The long germination period of yellow starthistle requires that a preemergent material have a lengthy residual activity, extending close to the end of the rainy season. Applications should be made before a rainfall, which will move the material into the soil. Because these materials adhere to soil particles, offsite movement and possible injury of susceptible plants could occur if the soil is dry and wind occurs before rain. When yellow starthistle plants have already emerged, it can be effective to combine a postemergence herbicide (to control emerged plants) with a preemergence herbicide (to provide residual control of any subsequent germination) (Callihan and Lass 1996, DiTomaso *et al*. 1999c).

A number of non-selective preemergence herbicides will control yellow starthistle to some level, including simazine, diuron, atrazine, imazapyr, imazapic, metsulfuron, sulfometuron, chlorsulfuron,

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Table 3. Commonly used herbicides for yellow starthistle control

Common name	Trade name	Registered in California	Mode of action	Weed Spectrum	Soil residual	Effective timing
2,4-D	Weedar®, Weedone® and many others	Yes	Growth regulator	Broadleaf species	Less than 2 weeks	Postemergence only, from seedling to bolting
Aminopyralid	Milestone™	Yes, in 2006	Growth regulator	Certain broadleaf families (between clopyralid and picloram)	Full season	Effective both pre- and postemergence; applied fall, winter or spring
Chlorsulfuron	Telar®	Yes	Amino acid synthesis inhibitor	Mainly broadleaf species	At least 2 months	Preemergence only
Clopyralid	Transline®	Yes	Growth regulator	Certain broadleaf families (e.g., Apiaceae, Asteraceae, Fabaceae, Polygonaceae, Solanaceae)	Most of the season	Effective both pre- and postemergence; applied fall, winter or spring
Dicamba	Banvel®, Vanquish®	Yes	Growth regulator	Broadleaf species	Less than 1 month	Postemergence only, from seedling to bolting
Glyphosate	Roundup®, and others	Yes	Amino acid synthesis inhibitor	Non-selective	None	Postemergence only, from seedling to early flowering
Imazapyr	Stalker®, Chopper®, Arsenal®, Habitat® (for aquatic use only)	Yes; not in rangelands	Amino acid synthesis inhibitor	Non-selective	Full season	Mainly as a preemergence treatment, postemergence control with seedlings or rosettes
Metsulfuron	Escort®	No	Amino acid synthesis inhibitor	Broadleaf species	At least 2 months	Fairly effective; preemergence only
Picloram	Tordon™	No	Growth regulator	Broadleaf species, weak on mustards	Up to 3 years	Effective both pre- and postemergence; applied fall, winter or spring
Triclopyr	Garlon®, Remedy®	Yes	Growth regulator	Broadleaf species	Less than 1 month	Postemergence only, good on seedlings, fair on mature plants

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bromacil, tebuthiuron, oxyfluorfen and prometon. All these compounds are registered for use on right-of-ways or industrial sites (although not all in California), but few can be used in rangeland, pastures, or wildlands. In rangeland, only metsulfuron (not registered in California) and to some degree chlorsulfuron (recently registered for pastures or rangeland in California) provides selective control of yellow starthistle without injuring desirable grasses.

- **Atrazine** (Aatrex®) is a photosynthetic inhibitor that can control yellow starthistle at rates of 1 to 1.5 lb a.i. (active ingredient)/acre (Lass and Callihan 1994a, b, Lass *et al*. 1993). Since atrazine is primarily a root-absorbed chemical, applications should be made before seedlings emerge. Because of ground and surface water concerns, this product is a restricted-use herbicide and requires a permit from the County Agricultural Commissioner (in California) for its purchase or use. It is not typically used for control of yellow starthistle, except along roadsides or on industrial sites.

- **Tebuthiuron** (Spike®) is also a photosynthetic inhibitor that is used for total vegetation control. It will control yellow starthistle preemergence, but will also injure other herbaceous and woody vegetation (Callihan *et al*. 1991). It is generally used in utility sites and almost never used in grasslands or wildlands.

- **Chlorsulfuron** (Telar®) and **sulfometuron** (Oust®) are registered for roadside and other non-crop uses and are effective at controlling yellow starthistle when applied at 1 to 2 oz a.i./acre. **Metsulfuron** (Escort®) is registered in other western states, but not California, for use in rangelands. These compounds provide excellent pre- to postemergence control of many weed species, particularly broadleaf species. Metsulfuron is safest on grasses, chlorsulfuron is safe on most grasses but will injure some, and sulfometuron is the most non-selective and will injure most grasses. Little postemergence activity occurs on yellow starthistle with these three compounds. The best control is achieved when applications are made before weeds emerge (Callihan *et al*. 1991, DiTomaso *et al*. 1999b, Lass and Callihan 1995b, Whitson and Costa 1986). Metsulfuron appears to be more inconsistent than chlorsulfuron, sometimes providing good control and other times giving poor control. Chlorsulfuron and metsulfuron do not have postemergence activity on yellow starthistle; if plants have emerged, these chemicals must be used in combination with 2,4-D, dicamba, or triclopyr. In one study, when chlorsulfuron (1 or 2 oz a.i./acre) was combined with 2,4-D or triclopyr, yellow starthistle control improved to near 90% (DiTomaso *et al*. 1999b).

POSTEMERGENCE HERBICIDES

A limited number of postemergence herbicides are registered for use in California rangelands, pastures, and wildlands. They include 2,4-D, dicamba, triclopyr and glyphosate. These postemergence herbicide treatments generally work best on seedlings. However, they are not effective for the long-term management of starthistle when used in spring, as they have little or no soil residual activity and will not control yellow starthistle plants germinating after application. Since yellow starthistle can germinate throughout winter and spring when-

Herbicide effectiveness based on rosette size. *Postemergence herbicides such as 2,4-D, dicamba, and triclopyr are most effective when rosettes are small (bottom). On larger rosettes (top), glyphosate is a better choice.*

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Backpack spray rig. *A hand-pumped sprayer can be an economical way to treat small patches, such as spot treatments in a follow-up program. (Photo: G. Kyser)*

ever moisture is available, achieving control with a single application is generally not possible. A treatment following the first flush of seedlings opens the site up for later flushes. Waiting until later in the rainy season to apply a postemergence herbicide allows a greater number of seedlings to be treated, but larger plants will require higher herbicide rates and may not be controlled (DiTomaso *et al*. 1999c). As a result, repeated applications of broadleaf selective postemergence herbicides are often necessary (DiTomaso *et al*. 1999b). This is expensive and increases the risk of drift to non-target species.

The most effective way to use postemergence compounds for starthistle control is to incorporate them into latter stages of a long-term management program. In particular, they are effective when used to spot-treat escaped plants or to eradicate small populations in late season when starthistle is easily visible but has yet to produce viable seeds. By using spot applications in late season, total herbicide use and expenses can be reduced because only small sections or individual plants are treated. It is important to note that plants should not be treated when under severe stress. Drought stress especially can reduce the efficacy of most herbicides.

Glyphosate will kill other plants as well as starthistle, so it should be applied carefully in areas where starthistle is growing among desirable plants. Similarly, 2,4-D will cause damage to late season broadleaf species, including desirable natives.

- **2,4-D** (many trade names) can provide acceptable control of yellow starthistle if it is applied at the proper rate and time. Treating in the rosette growth stage provides better control than later applications. Amine and ester forms are both effective at the small rosette growth stage, but amine forms reduce the chance of off-target vapor or drift movement.

  Application rates of 0.5 to 0.75 lb a.e. (acid equivalent)/acre will control small rosettes. Applications made later in the season, when rosettes are larger or after bolting has been initiated, require a higher application rate (1 to 2 lb a.e./acre) to achieve equivalent control (DiTomaso *et al*. 1999b, Northam and Callihan 1991, Whitson and Costa 1986). 2,4-D is a growth regulator selective herbicide and will control other broadleaf plants, but generally will not harm grasses. It has little, if any, soil activity. Drift from 2,4-D applications is common, particularly from the ester formulations. 2,4-D is a restricted use pesticide, requiring a permit for use.

- **Dicamba** (Banvel™ or Vanquish™) is very effective at controlling yellow starthistle at rates as low as 0.25 lb a.e./acre (Callihan and Schirman 1991b). When yellow starthistle rosettes are small, about 1 to 1.5 inches across, the 0.25 lb a.e./acre rate works well, but higher rates (0.5 to 1.0 lb a.e./acre) are needed if plants are larger (Northam and Callihan 1991). Applications made in late rosette to early bolting stages have provided excellent control, although earlier treatments are better.

  Dicamba is also a growth regulator selective herbicide that controls many broadleaf plants, but generally will not harm grasses. Its soil activity is very short. Like 2,4-D, it also is available as both an amine and ester formulation. Drift from dicamba applications is common, especially from the ester formulation. Dicamba is a restricted use pesticide, requiring a permit to use.

- **Triclopyr** (Garlon™ 3A or 4), at 0.5 lb a.e./acre provides complete control of yellow starthistle seedlings. Larger plants require higher rates, up to 0.75 or 1.5 lb a.e./acre (DiTomaso *et al*. 1999b, Northam and Callihan 1991). Higher rates can give almost complete control (Callihan *et al*. 1991), but are too expensive and may be above labeled rates. Like 2,4-D and dicamba, triclopyr is a growth regulator herbicide with little or no soil residual activity. It

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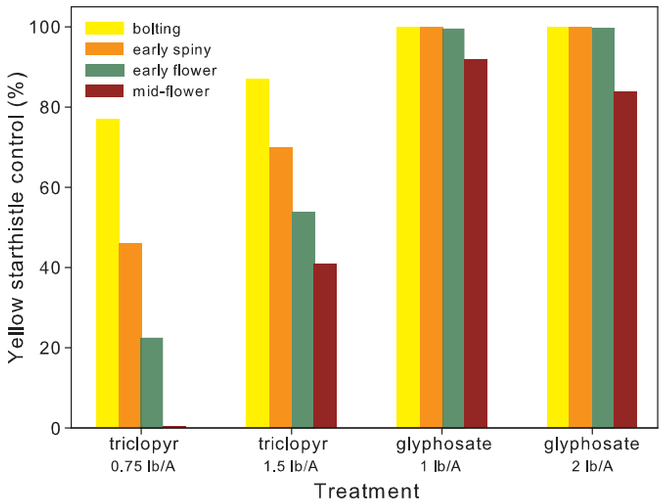

Fig. 19. Late-season control with glyphosate and triclopyr. *Trials at UC Davis showed that glyphosate provided more effective late-season yellow starthistle control than triclopyr (DiTomaso* et al. *1999b).*

is foliar-absorbed and active on broadleaf species, and typically will not harm grasses. Triclopyr is formulated as both an amine (Garlon™ 3A) and ester (Garlon™ 4). The ester formulation is more likely to drift than the amine form. Triclopyr does not seem to be as effective as either dicamba or 2,4-D for older starthistle plants.

- **Glyphosate** (Roundup® and many others) controls yellow starthistle at 1 lb a.e./acre (DiTomaso *et al*. 1999b). Good coverage, clean water, and actively growing yellow starthistle plants are all essential for adequate control. Unlike the growth regulator herbicides, glyphosate is non-selective and kills most plants, including grasses. It has no soil activity. A 1% solution of glyphosate also provides effective control of yellow starthistle and is used at this concentration for spot treatment of small patches. Glyphosate is a very effect method of controlling starthistle plants in the bolting, spiny, and early flowering stages at 1 to 2 lb a.e./acre. However, it is important to use caution when desirable late season grasses or forbs are present. If perennial plants have senesced and dried up for the season, they will not be damaged by glyphosate.

- **Natural-based products** include acetic acid, acetic/citric acid combinations, plant essential oils, pine oil, and pelargonic acid. These compounds have also been tested for the control of yellow starthistle. Acetic acid and acetic/citric acid provided no long-term control when applied to plants in the rosette, bolting and spiny stage. An acetic/citric acid combination (15% each) applied at 200 gallons/acre did give control of yellow starthistle when complete coverage was achieved in the early flowering stage. However, in order to achieve complete coverage, the herbicide had to be applied horizontal to the soil surface (DiTomaso and Kyser, unpublished data), increasing drift and applicator exposure. Single treatments with essential oils, pine oil, or pelargonic acid all gave poor control. Multiple treatments were required to achieve effective control (Young 2003).

LATE-SEASON STARTHISTLE CONTROL

Glyphosate, dicamba, and high rates of clopyralid and triclopyr are effective on yellow starthistle in the bolting stage (DiTomaso *et al*. 1999b). Triclopyr is probably the weakest of these four compounds. Surfactants should be used in all late season treatments except those with glyphosate (DiTomaso *et al*. 1999b). Late-season applications are typically made during the spring or early summer, when warm weather may cause ester formulations to volatilize and drift. Therefore, amine formulations of 2,4-D, dicamba, and triclopyr are more appropriate than ester forms.

Glyphosate is the most effective chemical for yellow starthistle control after bolting. The best time to treat with glyphosate is after annual grasses or broadleaf species have completed their life cycle, but prior to yellow starthistle seed production (<5%

Vinegar trials. *Acetic acid + citric acid used as a contact herbicide was found to be ineffective on large yellow starthistle plants.*

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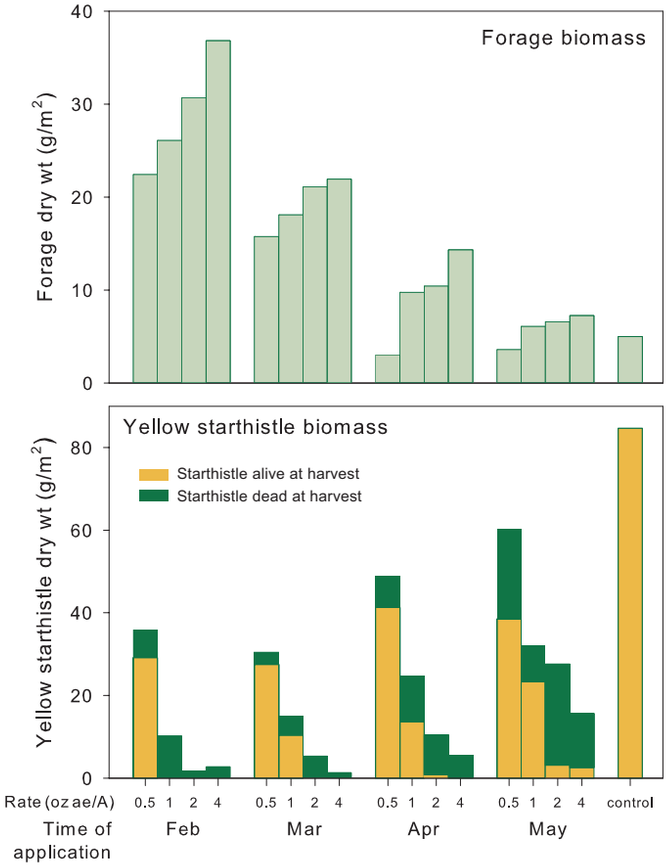

Fig. 20. Effect of clopyralid rate and timing on forage and yellow starthistle. *In a number of studies – like this trial in Siskiyou County – early control of yellow starthistle with clopyralid resulted in early release of desirable species and enhanced forage production (DiTomaso* et al. *1999b).*

of the spiny heads in or past flowering). Control is less effective when mature plants show physical signs of drought stress. If clopyralid was previously applied in late winter or early spring, glyphosate can be used in a broadcast or spot treatment follow-up program to kill uncontrolled plants before they produce seed. It can also be used to prevent the proliferation of potential clopyralid-resistant plants. Broadcast treatment with glyphosate is not recommended when desirable perennial grasses or broadleaf species are present.

PRE- AND POSTEMERGENCE HERBICIDES

The most effective herbicides for season-long control of yellow starthistle are those that provide postemergence control of seedlings and rosettes, as well as soil residual activity for at least a couple of months until spring rainfall is completed. Of the compounds that have these characteristics, clopyralid, aminopyralid, and picloram are the most effective and are the least injurious to grasses. Picloram is not registered in California.

- **Imazapyr** (Stalker®, Arsenal®, Chopper®, Habitat®) is a branched-chain amino acid inhibitors with the same mode of action as chlorsulfuron, metsulfuron, and sulfometuron.

  Imazapyr is also a broad spectrum herbicide with both pre- and postemergence activity on yellow starthistle (Northam and Callihan 1991). It is not very effective on yellow starthistle and will damage most broadleaf species, including shrubs and trees. Unlike the growth regulator compounds, imazapyr will also cause significant injury to grasses.

- **Clopyralid** (Transline®, Stinger®). Prior to the mid-1990s, few herbicides were available in California for season-long control of yellow starthistle in pasture, rangeland or wildland areas. With the registration of clopyralid in California in 1998, ranchers and land managers gained a highly selective herbicide available for starthistle management. It is a growth regulator with similar activity to 2,4-D, dicamba, triclopyr, aminopyralid, and picloram. Unlike 2,4-D, dicamba, and triclopyr, clopyralid has excellent soil (preemergence) as well as foliar (postemergence) activity. However, it is a much slower acting compound than the other postemergence growth regulators and often requires two months to control starthistle, particularly when applied during the winter months. Injury symptoms are typical of other growth regulators and include epinastic bending and twisting of

Treatment with clopyralid. *Contrast between untreated (left) and treated area shows the effect of aerial application of clopyralid in an infested field in Yolo County, CA.*

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the stems and petioles, stem swelling and elongation, and leaf cupping and curling. These symptoms are followed by chlorosis (yellowing), growth inhibition, wilting and eventual mortality. At low concentrations, the young leaf tips may develop narrow feather-like extensions of the midrib.

Clopyralid is very effective for the control of yellow starthistle at low rates (1.5 to 4 oz a.e./acre; 4 to 10 oz product/acre) and in a broad timing window from January through March. In addition, it does not appear to negatively impact insect biological control agent populations (Pitcairn and DiTomaso 2000) or toads (DiTomaso *et al*. 2004) and has a very low toxicology profile (signal word: Caution) with no grazing restrictions.

Soil properties

Clopyralid is weakly adsorbed to soil, does not volatilize, and is not photodecomposed to any degree. It is degraded by microbial activity and has an average half-life in soil of between 12 and 70 days, depending on the soil type and climate. The major metabolite is CO_2. The mobility of clopyralid in soil is considered moderate (average K_{OC}= 6 mL/g), so some leaching potential does exist (Vencill 2002). A validated computer-modeling program (EPA's PRZM) predicted that clopyralid residue would reach a maximum depth of 18 inches, 73 days after application in a highly permeable fine sand; no residue was predicted for all soils by 6 months after application (Dow AgroSciences 1998). Field dissipation and lysimeter studies, along with modeling, have indicated that under normal use patterns, the potential for downward soil movement of clopyralid is not as great as physical and chemical properties would predict.

Selectivity

Clopyralid is a very selective herbicide and does not injure grasses or most broadleaf species. However, depending on the timing of application, it does damage or kill most species in the legume family (Fabaceae) as well as the sunflower family (Asteraceae), and this may not be a desired outcome in a control program with the goal of increasing native plant diversity or enhancing a threatened native plant population susceptible to the herbicide. It can also cause some injury in members of the nightshade (Solanaceae), knotweed (Polygonaceae), carrot (Apiaceae), and violet (Violaceae) families (Reever Morghan *et al*. 2003). In contrast, many other broadleaf species, including species in the mustard family (Brassicaceae) and filarees (*Erodium* spp.), are very tolerant to the herbicide.

Treatment timing and forage. *The test plot at left was treated in early spring, removing yellow starthistle and allowing growth of desirable forage. The plot at right was treated in late spring. Although this treatment also controlled yellow starthistle, it was too late for forage to fill in.*

Rate and timing

Clopyralid provides excellent control of yellow starthistle seedlings and rosettes at its registered use rates from 1.5 to 4 oz a.e./acre (Carrithers *et al*. 1997, DiTomaso *et al*. 1999b, Gaiser *et al*. 1997, Johnson 2000, Lass and Callihan 1995b, Northam and Callihan 1991, Wrysinski *et al*. 1999). Season-long control can be obtained with one application anytime from December through April, but maximum grass forage is obtained with earlier treatments (DiTomaso *et al*. 1999b). The most effective time for application is from January to March, when yellow starthistle is in the early rosette stage. Applications earlier than December may not provide full season control and treatments after May usually require higher rates.

Clopyralid is also effective on plants in the bolting and bud stage, but higher rates (4 oz a.e./acre) are required. Applications made after the bud stage will not prevent the development of viable seed (Carrithers *et al*. 1997, Gaiser *et al*. 1997).

Combinations and adjuvants

When clopyralid is used to control seedlings, a surfactant is not necessary (DiTomaso *et al*. 1999b). However, when treating older plants or plants exposed to moderate levels of drought stress, surfactants can enhance the activity of the herbicide.

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Herbicides and litter. *Although some soil herbicides can get tied up in litter, this has not been a problem with clopyralid. This penetration is important, since many seedlings, like those above, are surrounded by a thick layer of litter.*

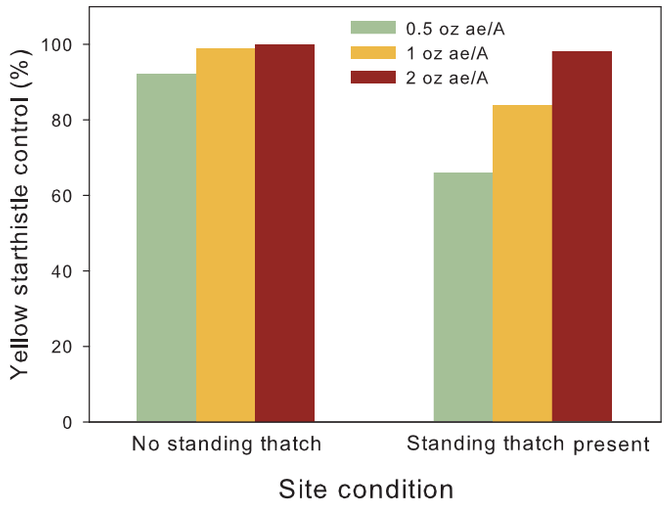

Fig. 21. Effect of standing litter on control with clopyralid. *Presence of standing litter (yellow starthistle skeletons) resulted in reduced control with clopyralid at very low rates but had little effect at realistic application rates (DiTomaso 1999).*

A combination of clopyralid and 2,4-D amine is sold as Curtail® in western states other than California. It can be used at 0.25 to 1 pint/acre after the majority of starthistle rosettes have emerged but before bud formation. A combination of triclopyr and clopyralid (Redeem™) can also be effective (DiTomaso, pers. obs.).

Interestingly, a study using a combination of clopyralid (for control of yellow starthistle) and glyphosate (for control of annual grasses) in a perennial grass restoration trial found that the two used in combination gave much worse control of yellow starthistle than clopyralid used alone and the same rate (Enloe, pers. obs.).

Clopyralid can also be applied using liquid fertilizer as a carrier (Evans 1998). This can provide effective control of starthistle and enhance the growth of desirable grasses and broadleaf species in a single pass.

Effects on forage

The time of clopyralid treatment can dramatically affect forage yield. In one study in Siskiyou County, forage biomass was maximized with an early season clopyralid treatment (December to March), while late season treatments (April to June) resulted in reduced forage (DiTomaso *et al.* 1999b). Reduced forage following later treatments was likely due to competition between yellow starthistle and young forage grasses during the early spring months. Early season treatments not only increased forage production but also gave better control, because yellow starthistle was in the early rosette stage at the time of application. In Yolo County, early season treatments resulted in increased filaree (*Erodium* spp.) production in the year of treatment, but lower grass forage the following spring. In contrast, clopyralid or aminopyralid treatment later in the season, when yellow starthistle was in the bolting stage, nearly doubled the grass forage yield the following spring compared to untreated plots and winter treatments. This was presumably due to the suppressive effect of yellow starthistle on filaree in the treatment year, which allowed the release of annual grasses in the following spring.

Effect of standing or soil litter

Some herbicides 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 clopyralid. In one study it was found that control of yellow starthistle was better in the presence of the previous year's starthistle skeletons than in areas where skeletons were removed (DiTomaso *et al.* 1999b). This difference was attributed to the reduced number of seedlings present in the area shaded by skeletons. Consequently, fewer seedlings were available to escape injury in the shaded plots.

- **Picloram** (Tordon™) is the herbicide most widely used to control yellow starthistle in western states other than California, where it is not registered. It

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acts much like clopyralid, but gives a broader spectrum of control and has much longer soil residual activity. Picloram is applied (usually with a surfactant) at a rate between 0.25 lb and 0.375 lb a.e./acre in spring when plants are still in the rosette through bud formation stages (Callihan *et al*. 1989, Callihan and Lass 1996, Callihan and Schirman 1991a, b, Carrithers *et al*. 1997, Gaiser *et al*. 1997, Larson and McInnis 1989b, Lass and Callihan 1995b, Northam and Callihan 1991, Whitson and Costa 1986). This is typically from late winter to early spring. This treatment can provide effective control for two to three years (Callihan *et al*. 1989). Although well developed grasses are not usually injured by labeled use rates, young grass seedlings with less than four leaves may be killed (Sheley *et al*. 1999b).

- **Aminopyralid** (Milestone™) is closely related chemically to clopyralid and picloram. In preliminary studies, the compound is extremely effective on yellow starthistle at rates about half that of clopyralid. It is considered to have slightly longer soil residual activity than clopyralid but considerably less soil activity than picloram. The best timing for application of aminopyralid seems to be between December and the end of March in the foothills and Central Valley of California, but in higher elevations and more northern regions this would extend to April or May. Its selectivity also falls between the two other related compounds. In addition to yellow starthistle, it has also been shown to be very effective on knapweeds, many other thistles, and fiddlenecks (*Amsinckia* spp.). Like clopyralid, it is also active on members of the sunflower family (Asteraceae), legume family (Fabaceae), carrot family (Apiaceae), nightshade family (Solanaceae), and a few other families. Many other characteristics of the herbicide are similar to clopyralid, including the soil mobility and toxicological properties. Aminopyralid was designated a reduced risk pesticide by EPA, because of its excellent toxicological and environmental profile.

"Hockey stick" wick applicator. *A rope wick is an alternative to spot spraying and reduces the likelihood of herbicide drift. (Photo: G. Kyser)*

CO_2 sprayer. *A backpack sprayer using compressed CO_2 can be used with a spray boom for broadcast treatments, or for spot treating at a distance of 20 feet with a focused nozzle spray. (Photo: G. Kyser)*

Herbicide Application Techniques

Two major application techniques are used when applying herbicides for controlling yellow starthistle: broadcast application and directed application. The choice between the two techniques depends mostly on the size and density of the infestation.

In a broadcast application, the spray solution is applied uniformly over the entire treated area. This is typically done on large, dense infestations, for example in the early years of a control program. The kind of herbicide used is usually selective and/or soil-active, e.g., clopyralid or aminopyralid, and is usually applied early in the season when plants are small.

Broadcast applications are commonly made using boom sprayers. A boom sprayer consists of several spray nozzles mounted in a row (the spray boom) and connected to a pump and spray tank. Boom sprayers can be carried by tractors, ATVs, trucks, airplanes, or helicopters. Hand-held spray booms, powered by hand-pumped or CO2 backpack units, are also available but usually are not used for broadcast treatments over large areas.

In a directed application (also called spot treatment), herbicide solution is applied to individual plants or small patches. This is a common technique

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Helicopter spraying. *Helicopter application can be used for large infestations but care must be taken to reduce drift. (Photo: J. Clark)*

during the follow-up and monitoring phase of a control program after the yellow starthistle population has been significantly reduced. Directed application can be done late in the season when yellow starthistle plants are large and visible, other plants have senesced, and nonselective herbicides such as glyphosate may be used.

Small hand-held booms (one to six nozzles), attached to backpack units, may be used to treat individual plants or small patches. Gun sprayers, which resemble a garden-hose trigger nozzle, may be operated from trucks, ATVs, or backpack units. These sprayers are commonly used to treat along roadsides, ditchbanks, and fencerows.

It is possible to achieve selective control of yellow starthistle with otherwise non-selective or relatively non-selective postemergence herbicides by employing a ropewick or wick applicator. The most common applicators are the hockey stick types, but a variety of vehicle-mounted boom wipers are also common. This technique can be used as an alternative to spot spraying for the control of weeds with stems above the desirable pasture species. The ropewick method for treating with glyphosate applies more concentrated material (16%-50% solution, v/v), but generally uses less chemical. However, it requires greater application time and may be more labor intensive. As a benefit, this application method reduces the potential for herbicide drift and injury to adjacent sensitive areas. For example, yellow starthistle can be treated by this method around vernal pools, streams and other bodies of water, or in areas with rare and endangered species or other desirable plants. It is most effective on yellow starthistle when plants have reached the spiny stage.

The Brown Brush Monitor is a tractor-pulled 8-foot rotary mower with a set of spray nozzles under the mower deck, aft of the mower blade. It is designed to apply herbicide immediately after cutting weeds, and thus actually represents an integrated management approach. This equipment is still in the testing phase, but may have great utility, particularly in roadside management programs. For roadside yellow starthistle control it offers a number of advantages compared to treating alone. For example, application after mowing allows the spray solution to reach the basal leaves and lower stems, which should increase the effectiveness of the herbicide. In addition, removal of a tall overstory means a greater percentage of the remaining canopy comes into contact with spray solution. With the nozzles under the mower deck the application can still be made under windy conditions, with minimal risk of drift. And finally, both a mowing and chemical application can be accomplished in a single pass.

Risks

The potential risks associated with herbicide use have been widely publicized both in the scientific literature and the popular press. Although these risks are often greatly exaggerated, improper use of herbicides can cause problems such as spray or vapor drift, water contamination, animal or human toxicity, selection for herbicide resistance in weeds, and reduction in plant diversity.

SPRAY AND VAPOR DRIFT

Herbicide drift may injure susceptible crops, ornamentals, or non-target native species. Drift can also cause non-uniform application and/or reduce efficacy of the herbicide in controlling weeds (DiTomaso 1997). Several factors influence drift, including spray droplet size, wind and air stability, humidity and temperature, physical properties of herbicides and their formulations, and method of application. For example, the amount of herbicide lost from the target area and the distance it moves both increase as wind velocity increases. Under inversion conditions, when cool air is near the surface under a layer of warm air, little vertical mixing of air occurs. Spray drift is most severe under these conditions, since small spray droplets fall

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slowly and can move to adjoining areas even with very little wind. Low relative humidity and high temperature cause more rapid evaporation of spray droplets between sprayer and target. This reduces droplet size, resulting in increased potential for spray drift.

Vapor drift can occur when an herbicide volatilizes. The formulation and volatility of the compound determine its vapor drift potential. Potential of vapor drift is greatest under high temperatures and with ester formulations. Ester formulations of 2,4-D and triclopyr are very susceptible to vapor drift and should not be applied at temperatures above 80ºF.

Nozzle height depends on the type of application (e.g., airplane, helicopter, ground sprayer) and determines the distance a droplet falls before reaching the weeds or soil. Greater application heights, such as aerial applications, result in more potential for drift. For one thing, the droplets are in the air for a longer time. In addition, wind velocity often increases with height above the ground. Finally, aerial applications are more likely to be above any inversion layer, which inhibits downward movement of herbicide droplets and increases the potential for long distance drift.

A number of measures can be taken to minimize the potential for herbicide drift. Chemical treatments should be made under calm conditions, preferably when humidity is high and temperatures are relatively low. Ground equipment (versus aerial equipment) reduces the risk of drift, and rope wick or carpet applicators nearly eliminate it. Use of the correct formulation under a particular set of conditions is important. For example, applying ester formulations of postemergence herbicides during the hotter periods of the summer is not recommended.

In a study conducted at Fort Hunter Liggett (DiTomaso *et al.* 2004), a helicopter application of Transline® (clopyralid) at 6 oz product/acre was made to a large yellow starthistle-infested grassland. Clopyralid drift from the site was monitored within a 30 m buffer zone between the edge of the treatment area and a stream adjacent to the infestation. The stream water was also monitored immediately after herbicide treatment. Several vernal pools within the treatment zone (also with 30 m buffers) were also monitored for herbicide drift. Even with a slight 5 mph wind moving toward the water source, there was no herbicide detected in the stream. The 30 m buffers around vernal pools also provided adequate protection. Thus, applied properly, the drift potential for clopyralid is minimal even with an aerial application and a slight breeze toward a sensitive aquatic site.

GROUNDWATER AND SURFACE WATER CONTAMINATION

Most herbicide groundwater contamination results from "point sources." Point source contaminations include spills or leaks at storage and handling facilities, improperly discarded containers, and rinsing equipment in loading and handling areas, e.g., into adjacent drainage ditches. Point sources are characterized by discrete locations discharging relatively high local concentrations. These contaminations can be avoided through proper calibration, mixing, and cleaning of equipment.

Non-point source groundwater contaminations of herbicides are relatively uncommon. They can occur, however, when a soil-mobile herbicide is applied in an area with a shallow water table. In this situation, the choice of an appropriate herbicide or alternative control strategy can prevent contamination of the water source.

Surface water contamination can occur when herbicides are applied intentionally or accidentally into ditches, irrigation channels or other bodies of water, or when soil-applied herbicides are carried away in runoff to surface waters. Herbicide may be applied directly into surface water for control of aquatic species. In this case, there is a restriction period prior to the use of this water for human activities. In many situations, alternative methods of herbicide treatment, including rope wick application, will greatly reduce the risk of surface water contamination when working near open water.

Loss of a preemergence herbicide through erosion may occur when a heavy rain follows a chemical treatment. Herbicide runoff to surface waters can be minimized by monitoring weather forecasts before applying herbicides. Application of preemergence herbicides should be avoided when forecasts call for heavy rainfall. Precipitation between 0.5 and 1 inch should help a preemergence herbicide to percolate into the soil profile, thus minimizing the subsequent risk of surface runoff.

TOXICOLOGY

When used improperly, some herbicides can pose a health risk. This can be minimized with proper safety techniques. Applicators should follow label

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directions and wear appropriate safety apparel. This is particularly important during mixing, when the applicator is exposed to the highest concentration of the herbicide. Although animals can also be at some risk from herbicide exposure, most herbicides registered for use in non-crop areas, particularly natural ecosystems, are relatively non-toxic to wildlife. To prevent injury to wildlife, care should be taken to apply these compounds at labeled rates.

The trend in herbicide toxicity of the past 25 years has been toward registration of less toxic compounds. From 1970 to 1994, the percentage of herbicides with an LD_{50} value (lethal dose in mg herbicide/kg fresh animal weight which kills 50% of male rats) of between 1 and 500 mg/kg decreased from 15 to 7%, while herbicides in the least toxic category (>5000 mg/kg) increased from 18 to 42%. In addition, the average LD_{50} of herbicides registered in the United States increased from 3031 to 3806 mg/kg (DiTomaso 1997, Herbicide Handbook 1970, 1983, 1994).

HERBICIDE RESISTANCE

Selection for herbicide-resistant weed biotypes is greatly accelerated by continuous use of herbicides, particularly those with a single mode of action. The first case of herbicide resistance in yellow starthistle was detected in 1989 in Dayton, Washington (Gibbs *et al*. 1995, Sterling *et al*. 1991, 2001). Callihan and Schirman (1991a, b) concluded that continuous use of picloram had selected for picloram-resistant starthistle. Resistant plants were 3 to 35 times more tolerant than a susceptible population, depending on the site of application and growth conditions (Fuerst *et al*. 1994, 1996). This population was also cross-resistant to clopyralid, dicamba and fluroxypyr, which have a similar mode of action as picloram (Valenzuela-Valenzuela *et al*. 1997), but not to triclopyr or 2,4-D, which also have the same mode of action (Fuerst *et al*. 1994). Although this resistant biotype has been studied (Fuerst *et al*. 1996, Prather *et al*. 1991, Sabba *et al*. 1998), the specific mechanism has yet to be elucidated. However, it has been determined that the gene conferring resistance is recessive and resistant plants are much less fit than susceptible plants (Sterling *et al*. 2001). This may explain why this population has not spread since its discovery.

Although cases of herbicide resistance in wildland and rangeland weeds are very rare (DiTomaso 2004), the development of picloram-resistant starthistle indicates the potential for development of resistance to clopyralid if the herbicide is used year after year. Integrated approaches for the control of invasive weeds can greatly reduce the incidence of herbicide resistant biotypes.

EFFECTS OF HERBICIDES ON PLANT DIVERSITY

Continuous broadcast use of a single type of herbicide will often select for the most tolerant plant species. 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. With yellow starthistle, for example, treatment with Transline® (clopyralid) can lead to a dramatic increase in the population of fiddlenecks (Amsinckia spp.) or tarweeds (Hemizonia spp.), or more likely, an increase in undesirable annual grasses such as medusahead (Taeniatherum caput-medusae), ripgut brome (Bromus diandrus), downy brome (Bromus tectorum), or barbed goatgrass (Aegilops triuncialis).

Population shifts through repeated use of a single herbicide may also reduce plant diversity and cause nutrient changes that decrease the total vigor of the range (DiTomaso 1997). For example, legume species are important components of rangelands, pastures, and wildlands and are nearly as sensitive to clopyralid as yellow starthistle. Repeated clopyralid use over multiple years may have a long-term detrimental effect on legume populations. Thus, herbicide use in rangelands is generally better when incorporated as part of an integrated weed management system.

Interestingly, Northam and Callihan (1989) found that the number of plant species per 10 square feet in a yellow starthistle-infested area increased from 11 to 12 following clopyralid treatment. In contrast, more non-selective postemergence herbicides, including 2,4-D and dicamba, decreased the number of species per 10 square feet to less than 9. This experiment, however, measured species changes after only a single year of treatment. Multiple years of herbicide application may have a more negative impact on plant diversity.

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CHAPTER 8: Developing a Strategic Management Plan

Prevention

Yellow starthistle infests 10 to 15 million acres in California but has the potential to infest nearly 40 million acres (Pitcairn *et al*. 1998b). Preventing its introduction into new areas is the most cost-effective method for starthistle management and is an essential component of a noxious weed management strategy. The major elements of a management program are preventing introduction or reinvasion of yellow starthistle seed, reducing the susceptibility of the ecosystem to yellow starthistle establishment, developing effective education materials and activities, and establishing a program for early detection and monitoring (DiTomaso 2000).

AVENUES OF INTRODUCTION

Yellow starthistle can encroach by establishing small infestations in relatively close proximity to a larger infestation (Sheley *et al*. 1999a). This can be through natural means including wind, water, and animal dispersal mechanisms. To prevent this type of encroachment, neighboring weed infestations on adjacent lands should be contained. The most effective method of containment is to spray the borders of infested areas with herbicide (Sheley *et al*. 1999c).

In many cases, however, yellow starthistle and other noxious weeds are introduced onto grasslands through human-related activities. Seeds or plant parts can be introduced as contaminants of hay or animal feed. This type of spread can be prevented by using certified weed-free feed (Sheley *et al*. 1999c). Transporting soil contaminated with starthistle seed can start new infestations and is a common means of introducing yellow starthistle along roadsides or in construction sites.

Livestock can move starthistle seeds from one area to another in their feces or by transporting seed attached to hair or mud. Seed dispersal by animals can be minimized by avoiding livestock grazing in weed-infested areas during flowering and seeding stages or by holding animals for seven days before moving them to uninfested areas (Sheley *et al*. 1998).

Equipment and vehicles driven through infested landscapes can transport yellow starthistle seed to uninfested areas. Even human clothing can transport seed, particularly in soil stuck to shoes and boots. Equipment and clothing should be cleaned immediately after leaving an infested site.

It is especially important to control or prevent weed invasions along transportation corridors, including roadsides, waterways, and railways. These areas are typically disturbed sites and, consequently, are susceptible to noxious weed establishment (DiTomaso 2000).

SUSCEPTIBLE LANDSCAPES

Yellow starthistle often establishes following disturbances, either natural or through human activity. Although starthistle can invade some undisturbed areas, disturbance usually allows for more rapid establishment and spread. Following soil disturbance, sites should be monitored to prevent establishment and subsequent seed production in these susceptible areas. In many cases, disturbed sites should be revegetated with desirable species to slow the invasion of yellow starthistle.

Proper grazing can maintain desired plants and provide a more competitive environment. Overgrazing should be avoided and grazed plants should be allowed to recover before re-grazing. This ensures that grasses remain healthy and vigorous, maximizing their competitiveness and reducing the potential for starthistle encroachment (Sheley *et al*. 1999c). Revegetation with aggressive perennial grasses can prevent establishment of starthistle (Enloe *et al*. 1999a, 1999b, 2000, Jones and DiTomaso 2003). However, communities most resistant to weed infestations are usually composed of a diversity of plant species. This diversity allows for maximum niche occupation and resource capture (Sheley *et al*. 1999a).

EDUCATIONAL PROGRAMS

Employees and the public can be made aware of noxious weed issues by a number of methods. Information

can be made available through brochures, posters, internet websites, calendars, scientific papers, and other written media. Educational programs can be conducted for landowners, land managers, or the general public. These can include public seminars, professional symposia, school programs, and volunteer field workshops conducted by University Extension, 4-H clubs, church groups, environmental organizations, scouts, and other such groups. The media also play an important role in educating the public through radio or television news stories, public service announcements, newspaper articles, public displays, or even roadside bulletin boards. All these educational activities facilitate greater cooperation among private, federal, state, and county agencies, industries, landowners, and the general public. In addition, they increase the potential for early detection and rapid response to new starthistle infestations.

EARLY DETECTION AND MONITORING

The most effective means of controlling noxious weeds is to recognize potential weed problems early, control them before they reproduce and spread, and monitor the site regularly to maintain adequate follow-up control (Rejmanek and Pitcairn 2002). Understanding the potential threats that may exist on surrounding property can provide an early warning system for weed invasion. One successful method for preventing yellow starthistle invasion is to regularly inventory the area by field surveys or aerial photography and remove individual weed plants before they become well established (Sheley *et al*. 1999c).

Eradication

Eradication is not often practical for yellow starthistle, but in previously uninfested areas it may be possible to eradicate new small invasions. An effective eradication program is closely tied to prevention. The keys to successful eradication are early recognition of yellow starthistle populations and rapid response to prevent reproduction and the development of a seedbank. Control options in an eradication program are typically limited to mechanical removal, including hand pulling, and herbicide treatment. The objective is to completely eliminate the species from that site, not to manage the population. Eradication is not complete until all viable starthistle seeds are depleted from the soil.

Eradication efforts are usually confined to smaller infestations of a few acres. These can be satellite populations adjacent to large infestations or isolated invasions far from other infestations. In some cases, eradication efforts can focus on the borders of large infestations (Zamora and Thill 1999). Different plans may be developed for small (<10 acres) or large (>100 acres) starthistle infestations. Financial resources, available technology, potential benefits, and social and geographical constraints will limit the size of the area that can be targeted for starthistle eradication (Zamora and Thill 1999). Large eradication programs may require revegetation to completely eliminate yellow starthistle. However, it is unlikely that infestations larger than 2500 acres can be eradicated (Rejmanek and Pitcairn 2002).

Developing a Management Strategy

An effective yellow starthistle 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, or recreational land maintenance; and 3) preventing reinvasion of starthistle or invasion of other noxious species. All these goals are tied together with improving the degraded rangeland community and reestablishing a functioning ecosystem. To accomplish these goals, land managers need to understand the land use objectives, management limitations, and ecology of the system.

Understanding the land use objectives of a weed management strategy is critical to determining the proper management approach. Management strategies will differ whether the primary goal is to enhance forage, restore native vegetation or endangered species, or increase recreational value. In addition, selection of the proper management techniques depends on a number of factors including weed species, effectiveness of the control techniques, availability of control agents or grazing animals, length of time required for control, environmental considerations, chemical use restrictions, topography, climatic conditions, and relative cost of the control techniques (Sheley *et al*. 1999a).

One of the most important steps in developing a noxious weed management strategy is to locate and map lands infested with the weed(s) (Sheley *et al*. 1998). Knowing where infestations occur can help decide land use objectives, determine the control methods to be used, and identify areas where

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eradication, containment, or management can be achieved. In addition, this information can prevent unnecessary herbicide treatments.

Weed infestations should be identified on a map. Records should indicate weed species present, areas infested, weed density, rangeland under threat of invasion, soil and range types, and other site factors pertinent to weed management (Sheley *et al.*1998). Continual monitoring will be necessary to prevent new or reinvading populations from becoming established. A number of monitoring techniques can be used, including hand drawing infested sites on a map, using GPS (global positioning system) units and plotting the data using GIS (geographical information system) programs (Cooksey and Sheley 1998), or employing more complex techniques such as aerial remote sensing (Lass *et al.* 1995, 1996, 2000, Shafii *et al.* 2004).

An understanding of the biology and ecology of

Table 4. Summary of control options

Mechanical

Hand pulling, hoeing, weed whipping	
Advantages	Excellent when only a few plants persist or when new small infestations occur. Good method for organizing volunteer programs; requires little training.
Disadvantages	Difficult to use with large or dense infestations.
Risks	Can be labor intensive and cause physical injury. Care should be taken to minimize soil disturbance.
Timing	After bolting to very early flowering.
Best fit in strategic management plan	Excellent in final years of a long-term management plan. Late season strategy allows for flexibility. Can save cost compared to other treatments when starthistle population is low.

Tillage	
Advantages	Can provide excellent control in agricultural areas, orchards, vineyards, roadsides, urban areas and other sites where tillage is possible.
Disadvantages	Not usually practical in wildlands or rangeland systems.
Risks	Increased erosion, non-selective control, soil disturbance can lead to invasion of other undesirable weeds.
Timing	At end of rainy season but before viable seeds are produced.
Best fit in strategic management plan	In non-agricultural areas where it is practical, tillage is a good first or second year option where yellow starthistle density is high. Not as practical when starthistle populations are low. In agricultural areas, tillage can be used every year.

Mowing	
Advantages	Relatively inexpensive. Removes skeletons.
Disadvantages	Generally will not provide complete control. Can damage late season natives. Only practical in relatively flat, accessible areas.
Risks	Improper timing or growth form of starthistle can lead to increased infestation. In rocky areas, sparks from rocks contacting blades can start fires. Flying debris can also be dangerous to humans.
Timing	Very early flowering stage ($\leq$2% of spiny heads in flower).
Best fit in strategic management plan	Useful in later years of a long-term control program. Late season method that gives more flexibility to choose most appropriate control option depending on the level of infestation and growth form of plant. With moderate infestation and erect growth form, mowing can be a very effective method.

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Table 4. Summary of control options *(continued)*

Cultural

Grazing	
Advantages	Good forage when grazed at proper time. Can release small forbs from shade suppression if area is not too overgrazed.
Disadvantages	Generally will not provide complete control.
Risks	Poisonous to horses through ingestion, mechanical injury to eyes of other livestock if grazed in spiny stages. May have negative impact on ecosystem when vegetation is overgrazed. High grazing pressure can disturb soil and create sites for invasion of other weeds.
Timing	From time yellow starthistle begins to bolt to development of spiny seed heads. Goats can be used longer into season.
Best fit in strategic management plan	Good in early or later years of a long-term control program. In first year of a control program, grazing should be combined with other control options. In later years, it can be used to maintain low levels of starthistle. Proper grazing can be a good method of preventing reinfestation.

Prescribed burning	
Advantages	Very effective control when complete burn can be achieved. Can stimulate native plants, particularly legumes and perennial grasses. Releases the yellow starthistle seedbank for control the following year.
Disadvantages	Harmful to biological control agents. May injure some late season natives.
Risks	Escaped fires and air quality issues. Can cause animal mortality.
Timing	Very early flowering stage ($\leq$2% of spiny heads in flower).
Best fit in strategic management plan	Can be used in the first, second or third year of a long-term management strategy. If burning can be used only once, it is probably best in the first year when an herbicide can be applied in the second year. Because fire will stimulate yellow starthistle germination it should not be used in the last year of a long-term program.

Revegetation	
Advantages	Can give long-term sustainable control and good forage or diversity. If grazed properly may provide sustainable control of yellow starthistle.
Disadvantages	Expensive and requires a good understanding of the system. Success may be dependent on weather patterns, particularly when plants are becoming established.
Risks	When a non-native species is used, it may spread to become invasive in areas it is not desired. Can reduce diversity if a reseeded species becomes a monoculture.
Timing	Late fall to early spring, depending on the area and whether an integrated approach is used.
Best fit in strategic management plan	First year strategy nearly always integrated with chemical control to assist in establishment of desired species. Can also be used in second year after weed populations have been reduced after first year control program.

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Table 4. Summary of control options *(continued)*

Biological control

Advantages	Can reduce yellow starthistle seed production by 50-75%. With potential new introductions of insects or pathogen, there is the possibility of long-term and sustainable management.
Disadvantages	Not successful when used as the sole control option.
Risks	Small risk that organisms might shift host to native or economically important species.
Timing	All effective organisms well distributed, no timing issues to be concerned with.
Best fit in strategic management plan	Should be part of any integrated management strategy, even those that are harmful to the insect, e.g. prescribed burning. Organisms quickly recover and will provide some inhibition in seed production.

Chemical control

2,4-D (many names), dicamba (Banvel®, Vanquish®), triclopyr (Garlon®, Remedy®)	
Advantages	Good postemergence control of broadleaf weeds.
Disadvantages	Can injure desirable broadleaf species. Does not provide residual control of seeds germinating after treatment. Grazing restrictions.
Risks	Herbicide drift. Applicator safety.
Timing	Most effective when applied to seedlings, but can control mature plants to nearly the flowering stage. Triclopyr not as effective as 2,4-D or dicamba on larger plants.
Best fit in strategic management plan	Can be used as a late season spot treatment in a follow-up program. Best used when treating starthistle plants growing in close proximity to desirable perennial grasses. Not effective as broadcast applications in early years of a long-term management strategy.

Glyphosate (Roundup®)	
Advantages	Very effective for starthistle control, including late season when plants are in bolting, spiny or early flowering stage.
Disadvantages	Non-selective control. Will injure desirable broadleaf or grass species. Does not provide residual control of seeds germinating after treatment. Grazing restrictions.
Risks	Herbicide drift. Applicator safety.
Timing	Although it controls seedlings, it is best used to manage mature plants from bolting to early flowering stage. Should not be applied to drought stressed plants.
Best fit in strategic management plan	Can be used as a late season spot treatment in a follow-up program or to small patches in a prevention program. Not effective as broadcast applications in early years of a long-term management strategy.

Chlorsulfuron (Telar®), Metsulfuron (Escort®)	
Advantages	Good preemergence control of starthistle and excellent control of other invasive weeds, particularly mustards such as perennial pepperweed. Will not injure most grasses.
Disadvantages	Metsulfuron is not registered in California. No postemergence control.
Risks	Herbicide drift. Applicator safety. Can leach with excess water.
Timing	Fall when used alone, but best to treat in late winter or early spring if in combination with 2,4-D, dicamba, or triclopyr.

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Table 4. Summary of control options *(continued)*

Chemical control *(continued)*

Chlorsulfuron (Telar®), Metsulfuron (Escort®) (continued)	
Best fit in strategic management plan	Not often used for control of yellow starthistle. Can be used when other invasive weeds are present, particularly those in the mustard family. Metsulfuron provides less control than chlorsulfuron. (Imazapyr (Stalker®, Chopper®, Arsenal®) has same mode of action and similar effect on yellow starthistle, but is not registered for use in rangeland.)

Clopyralid (Transline®) and Aminopyralid (Milestone™)	
Advantages	Provide excellent control at low rates. Give both pre- and postemergence activity for full season control. Low toxicity. No grazing restrictions. Very selective, no injury to grasses and many broadleaf species.
Disadvantages	Can injure legumes (Fabaceae) and other desirable members of the sunflower family (Asteraceae). May lead to selection for other invasive annual grasses. Resistant biotypes have been reported for other herbicides with this mode of action, but only in Washington.
Risks	Herbicide drift. Applicator safety.
Timing	From late fall to early spring is best, when plants are in rosette stage. Can still get good control in mid-spring, but may have to use higher rates. In states other than California, a combination of 2,4-D and clopyralid (Curtail®) can be used in spring.
Best fit in strategic management plan	Very effective in the first year of a long-term management strategy. Can also be used in the second year.

Picloram (Tordon™)	
Advantages	Provides excellent control. Has both pre- and postemergence activity. Active in soil for at least two seasons. No injury to grasses.
Disadvantages	Not registered for use in California.
Risks	Reported to be in groundwater in other states where it is used heavily. Herbicide drift. Applicator safety.
Timing	Best when applied in spring.
Best fit in strategic management plan	May be used in combination with biological control and perennial grass revegetation. Because of its long residual activity, it is not typically used in other integrated strategies.

yellow starthistle is necessary for long-term management. It is also important to be familiar with characteristics of the ecosystem. This can include an awareness of other species present (both weeds and desirable plants), the potential for invasion into uninfested sites in the area, impact of the management strategy on sensitive species and habitats, and ecosystem parameters such as soil conditions and rangeland types.

A coordinated effort among interested parties, including landowners, agencies, the public, and environmental organizations, can lead to a more effective management plan. A cooperative program can eliminate duplication of effort, reduce avenues for reintroduction, consolidate equipment and labor costs, and decrease the risk of repeating previous failures. In addition, coordinated management teams can obtain cost-sharing grants to manage large infestations more effectively. This coordination is typically achieved through development of a Weed Management Area.

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Implementing a Strategic Plan

Implementing a strategic plan is the most critical stage in yellow starthistle management. This step typically requires input from weed management experts. Before any option can be employed, financial considerations must be addressed and a budget must be prepared to keep project costs within reasonable limits. Funding limitations may require prioritizing areas of greatest concern. For example, the decision to revegetate must consider direct costs (seedbed preparation, seeds and seeding, follow-up management), indirect costs (risk of failure, non-use during establishment period), and benefits (increased forage, improved ecosystem function, soil conservation) (Jacobs *et al*. 1999, Smathers *et al*. 1985).

Control options should include a site-appropriate integration of mechanical, cultural, biological, and chemical techniques. Regardless of the approach employed, annual monitoring and evaluations should be conducted to determine the adequacy of the management plan (Sheley *et al*. 1999c). Changes in the management approaches may be necessary to adjust to any unforeseen problems and improve the strategy.

A long-term commitment of three or more years usually will be necessary to deplete the weed seedbank. It is not unusual for a yellow starthistle infestation to appear more vigorous after a single year of control (Callihan and Lass 1996). It will require a significant reduction in the starthistle seedbank and an increase in seedbanks of competing species before dramatic results can be observed.

Once the desired objectives have been attained, a yearly follow-up program will be necessary to prevent starthistle reinfestation. This may involve annual hand pulling, spot herbicide treatments, or even periodic mowing or burning (DiTomaso 2000). In addition, changes in grazing practices may be required to ensure that rangeland conditions do not become susceptible to rapid reinfestation. If follow-up is not made for two to three years following a control program, the grassland will usually become reinfested in a short time.

CLOPYRALID IN A STRATEGIC MANAGEMENT PLAN

In most circumstances, clopyralid can be an important component in a yellow starthistle management program. For example, clopyralid is often an effective first year option in a multi-year program. This is particularly true in heavily infested areas. The herbicide can substantially reduce the starthistle population, thus depleting much of the seedbank. Because clopyralid is typically used in late winter to very early spring before starthistle seedlings and young grasses begin to compete for soil moisture, the control of yellow starthistle will result in high grass forage production during that growing season (DiTomaso *et al*. 1999b). If yellow starthistle seedling numbers in the second winter are also very high, a second year of treatment may be needed. However, in subsequent years it may be advantageous to delay the use of clopyralid or other preemergence herbicides until the extent of the problem can be evaluated. Possibly a prescribed burn, mowing or physical removal can be used instead. In some instances one or two years of control can reduce the starthistle infestation to low or even insignificant levels. When this occurs, an additional broadcast application of clopyralid or another herbicide would be unnecessary.

Examples of Integrated Management Strategies

Each control methods has its own strengths and limitations (see Table 4). However, most often a single method does not give sustainable control of a range 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, but these choices must be tailored to the site, economics, and management goals. Typically, control techniques must be used in a particular sequence to be successful.

CASE STUDY 1. COMBINATION OF HERBICIDES AND REVEGETATION WITH A PERENNIAL BUNCHGRASS

In order to develop an integrated approach for starthistle control in rangeland, an experimental project was established on a site near Yreka, California (Siskiyou County) heavily infested with yellow starthistle (Enloe *et al*. 1999a, b, 2000, 2005). The goal of this revegetation project was to develop sustainable high quality range conditions, improved wildlife habitat, and long-term starthistle control without the need for continued herbicide treatments.

In this severely degraded rangeland site, a March treatment with glyphosate and clopyralid (1, 2 or 3 years) was used to provide a window of reduced competition for the subsequent establish-

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ment (March planting) of drill seeded pubescent wheatgrass ('Luna' pubescent; *Thinopyrum intermedium*) (Enloe 2002, Enloe *et al*. 2005). Roché *et al*. (1997) reported that pubescent wheatgrass was highly effective in suppressing yellow starthistle in Washington. Although not a native species, wheatgrass seed was considerably less expensive than native perennial grass seed. In addition, it provides good forage and is not considered invasive (Enloe 2002).

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 to establish with a single year of treatment. Once pubescent wheatgrass seedlings survived the first year, additional applications of clopyralid did not improve their establishment. In the absence of any treatment with clopyralid and glyphosate, pubescent wheatgrass establishment was very limited. Untreated plots developed very poor stands over the six-year period, with slightly less than 10% cover (Enloe *et al*. 2005).

Once the wheatgrass was established, it provided near complete suppression of yellow starthistle (as well as other exotic annual grasses and forbs) without the need for additional control methods. Treatments with clopyralid alone (without reseeding wheatgrass) gave good control of yellow starthistle, but the plant community was susceptible to invasion by noxious annual grasses. In particular, downy brome (*Bromus tectorum*) was released from competition with starthistle and increased dramatically. Within a couple of years after the final herbicide treatment, the site reverted to yellow starthistle (Enloe *et al*. 2005).

In this same project, Enloe (2002) also considered the reintroduction of grazing. He found that the best timing for grazing was early in the season prior to flower development, when the perennial grass was least susceptible to damage. Unfortunately, this was also the time that yellow starthistle was least susceptible to damage. Grazing the perennial grass when it was most susceptible (also the susceptible timing for yellow starthistle) reduced the competitiveness of the perennial grass and increased the starthistle population.

The results of this study illustrate the use of an integrated approach for the long-term management of yellow starthistle. This approach is compatible with the survival of yellow starthistle biocontrol agents, which are already widespread in the state.

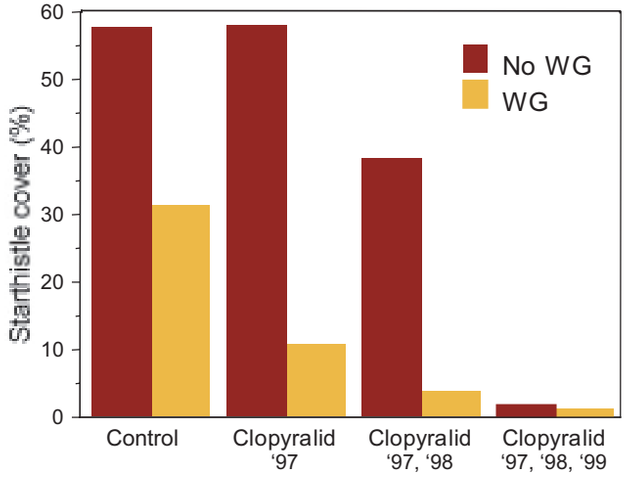

Fig. 22. Effectiveness of clopyralid with revegetation. *In this study, clopyralid in combination with revegetation with wheatgrass (WG) produced the greatest reduction in late season yellow starthistle cover (Enloe* et al. *2005).*

CASE STUDY 2. LONG-TERM MANAGEMENT USING PRESCRIBED BURNING, CLOPYRALID AND BIOCONTROL

Fire has been an important factor in the development and continuance of most grassland systems. In addition, it can be an effective tool for managing yellow starthistle infestations, as well as enhancing native plant diversity and increasing the survival of competitive native perennial grasses. However, repeated use of burning can negatively impact air

GPS-guided helicopter application. *A helicopter with on-board GPS was used to accurately apply clopyralid in a long-term management study at Fort Hunter Liggett. (Photo: A. Hazebrook)*

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quality and compromise establishment of biocontrol agents. Prescribed burns take a great deal of coordination and can lead to catastrophic wildfires should they escape containment. Consequently, it is unlikely that ranchers or land managers would be able to obtain permits and utilize local fire departments to conduct repeated burnings over multiple years.

The continuous use of clopyralid also can have undesired outcomes. For example, legume species are important components of rangelands, pastures, and wildlands; repeated clopyralid use over multiple years may have a long-term detrimental effect on their populations. Another possible drawback to the continuous use of clopyralid is the potential to select for other undesirable species, particularly annual grasses such as medusahead (*Taeniatherum caput-medusae*) or barb goatgrass (*Aegilops triuncialis*). Furthermore, the potential exists for the development of resistance to clopyralid if the herbicide is used year after year.

As a result, studies were designed to evaluate an integrated strategy combining clopyralid and prescribed burning for management of yellow starthistle and improvement of rangeland function (DiTomaso *et al*. 2003a). Surprisingly, the order in which the two techniques were used gave very different responses. When clopyralid was used in the first year and a prescribed burn was used in the second year, the population of yellow starthistle in the year after the two treatments was higher than in the untreated areas. This was presumably due to stimulation of yellow starthistle germination in fall and winter after the burn. In contrast, 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. Thus, the stimulation in starthistle seed germination after the burn probably depleted the seedbank more rapidly, and those seedlings were controlled by the subsequent clopyralid 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 program sooner.

An additional benefit of incorporating a prescribed burn into the yellow starthistle management program is the control of noxious annual grasses. In this study (DiTomaso *et al*. 2003a), both ripgut brome and medusahead were dramatically reduced when a burn was included in the management strategy.

This integrated approach was also tested in a large-scale management project at Fort Hunter Liggett (FHL), a 165,000-acre military installation in Monterey County, California. At least 12% of FHL is covered by grassland vegetation (Jones and Stokes 1992) and is dominated by annual nonnative grasses and forbs (Osborne 1998). Yellow starthistle has increased dramatically over the past two decades, expanding its range along riparian corridors and in grasslands and woodlands. It interferes with military training, recreational activities, and livestock and wildlife grazing at the installation.

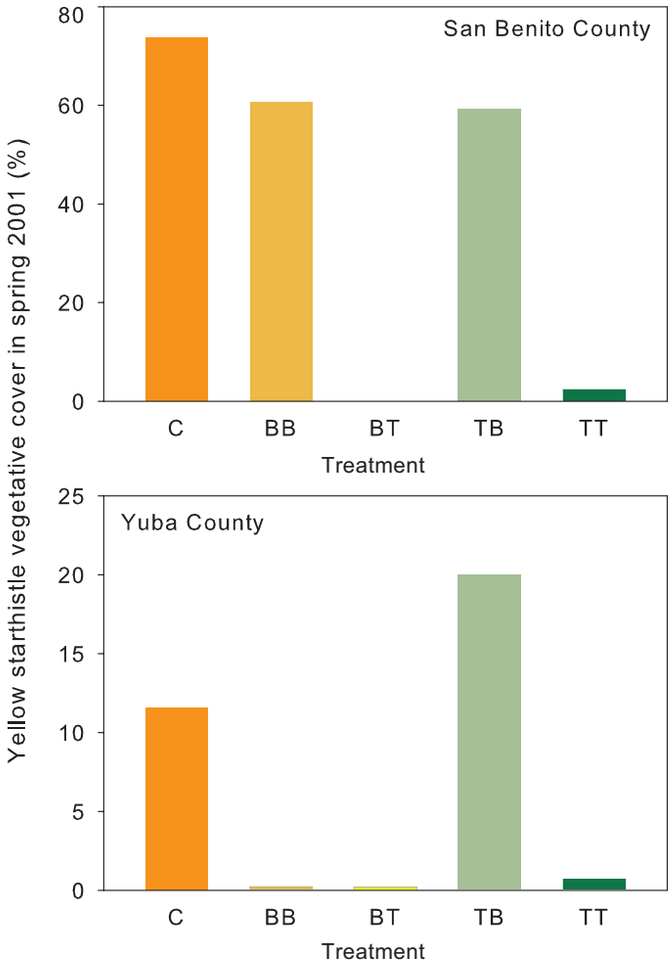

Fig. 23. Effectiveness of burning integrated with clopyralid. *Yellow starthistle cover was greatly reduced by a first year burn followed by a second year clopyralid treatment, but reversing the treatments produced poor results (DiTomaso* et al. *2006). C = untreated control, BB = burned for two years, BT = burned first year & clopyralid second year, TB = clopyralid first year & burned second year, and TT = treated with clopyralid for two years.*

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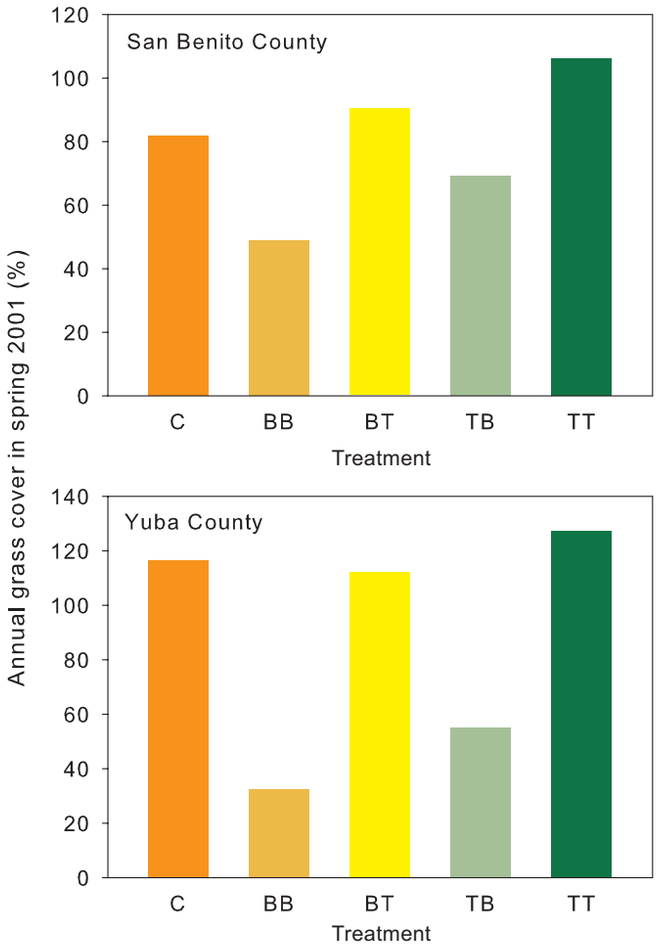

Fig. 24. Effect of burning + clopyralid on annual grasses. *In integrated burn/clopyralid trials at two sites, annual grass cover was reduced in the year following a burn (DiTomaso* et al. *2006). See Fig. 23 for abbreviations.*

In addition, the weed has displaced native plants and decreased animal habitat. In 1999, it was estimated that approximately 20,000 acres (or 12%) of FHL land was infested with yellow starthistle.

The integrated control methods used in the small plot studies (e.g., herbicide application and prescribed burning) were applied to several infested areas of FHL ranging in size between 30 and 300 acres over a period of two to three years (1999-2002) (Torrence *et al*. 2003a, b, Miller 2003). Following the burning or herbicide treatments, follow-up maintenance was used in those areas that had received at least two consecutive years of treatment. In addition, hairy weevils were introduced in several areas of the base to assist in the long-term maintenance program, and populations were monitored throughout the study (Joley *et al*. 2002).

In one yellow starthistle-infested site at FHL, a first year prescribed burn (1999) was followed by a fixed-wing aerial application (2000) of 6 oz product/acre clopyralid. In the following year (2001) a helicopter was used to aerially broadcast clopyralid at the same rate. These treatments gave over 99% control of yellow starthistle in 2002. The second herbicide treatment was probably unnecessary in this situation, as 98-99% control of yellow starthistle was achieved even after the first application (2000).

After three years of treatment, a follow-up maintenance plan was implemented to prevent any potential reinfestation. A 5-acre subplot was designated for hand pulling. Yellow starthistle plants were present but relatively sparse (approximately 88 plants/acre). Maintenance in the 5-acre subplot required 35 minutes. A total of 408 plants were hand-pulled. A first year maintenance cost estimate was estimated at $5.25/acre, based on three technicians each paid $15/hour (Miller 2003).

It is useful to note failures in management techniques. For example, in another yellow starthistle-infested site on FHL, a first year burn (1999) was followed by a second year (2000) aerial application of clopyralid (8 oz product/acre). The summer evaluation in the following year (2001) indicated that yellow starthistle control was approximately 98% in

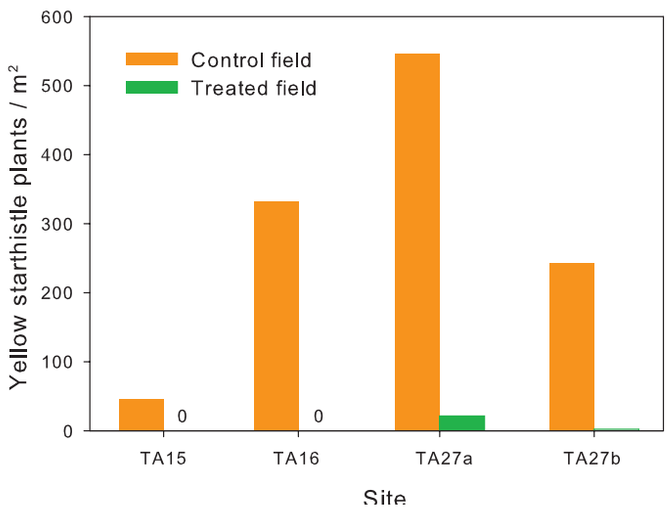

Fig. 25. Effectiveness of burning followed by clopyralid treatment. *Results from integrated burn/clopyralid trials were confirmed in large-scale applications at Fort Hunter Liggett (Miller 2003.). Treated fields showed few if any yellow starthistle plants.*

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this site. However, in the third year (summer 2001) the site was burned again. In the year following the burn, starthistle control decreased to 95%. When a follow-up maintenance program using handpulling was employed in 2002, the estimated population of yellow starthistle was 25.8 plants/m^2. In contrast to the $5.25 cost per acre previous described in the successful management area, this site required an estimated 395 hours an acre to handpull the remaining yellow starthistle plants, with estimated costs at $4819/acre (Miller 2003). The second burn was counterproductive.

This project demonstrated that yellow starthistle populations could be controlled with two years of properly timed, intensive management. This integrated management program is now used on more than 4,500 acres of FHL (Anonymous 2003). 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. Following this successful intensive management regime, yellow starthistle seeds in the seedbank should decline as seed production is prevented each year.

CASE STUDY 3. USING CLOPYRALID IN COMBINATION WITH BIOCONTROL AGENTS

Using another integrated approach, Pitcairn *et al*. (1999a, 2000a) hypothesized that combining clopyralid applications with insect biocontrol agents might provide for more effective long-term control of yellow starthistle. An initial clopyralid application would reduce plant density and the seed bank. In subsequent years, biocontrol insect attacks on escaped plants should slow the rate of reinfestation by impacting the few seed heads available. A field test of this hypothesis found that following a clopyralid treatment in early 1997, biocontrol agents suppressed seed production by 76% in 1997 and 43% in both 1998 and 1999 (Pitcairn and DiTomaso 2000). In addition, the reduction in starthistle resulting from the herbicide treatment did not affect the ability of the insects to attack the seed heads of escaped plants. It is hoped that seed destruction by established biological control agents can delay reinfestation by 4-6 years and thereby reduce the need for continuous herbicide treatments. This would lower the economic cost of long-term management of yellow starthistle.

CASE STUDY 4. MOWING OR GRAZING WITH REVEGETATION

Thomsen *et al*. (1996a, 1997) developed a long-term integrated approach for yellow starthistle control using combinations of grazing, mowing, and clover plantings. For example, seeding with subterranean clover (*Trifolium subterraneum*), grazing three times, and mowing once at the early flowering stage resulted in 93% reduction in yellow starthistle seed production and a dramatic increase in standing dry matter (Thomsen *et al*. 1996a). In another experiment, two timely repeated mowings combined with a subterranean clover planting gave nearly complete control of yellow starthistle (Thomsen *et al*. 1997).

OTHER EXAMPLES

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*. 1994b). 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.

In Australia, the technique of applying sub-lethal applications of 2,4-D amine in combination with heavy stocking rates of grazing sheep is a long-accepted integrated approach for control of thistles (Dellow 1996).

Conclusion

Research by many scientists and land managers during the past 20 years has demonstrated that a variety of weed control techniques can be effective on yellow starthistle management. These include the mechanical, cultural, chemical and biological tools described in this report. However, it is clear that integrated approaches using combinations of these methods can be more effective for long-term suppression of yellow starthistle and for recovery of more functional and productive ecosystems. As in any weed management program that seeks to deplete a plant's seedbank and to prevent new seed recruitment from off-site sources, managers must recognize that any control tool or combination of techniques may still require subsequent follow-up to prevent re-invasion of yellow starthistle or another invasive plant. This report aims to give land managers the benefit of currently accumulated knowledge when they work to design effective programs to control one of our most serious invasive plants.

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Appendix

Metric unit conversions

1 acre	=	0.405 hectares		
1 lb/acre	=	1.121 kg/hectare	=	1121 grams/hectare
1 oz/acre	=	0.070 kg/hectare	=	70.1 grams/hectare
1 gallon/acre	=	9.354 liters/hectare		
1 pt/acre	=	0.585 liters/hectare		
1 acre-foot	=	325,851 gallons	=	9227 cubic meters
1 inch	=	2.54 cm	=	25.4 mm
10 square feet	=	0.929 square meters		

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