ELEMENT STEWARDSHIP ABSTRACT

for

Centaurea solstitialis L.

Yellow starthistle, golden starthistle, yellow cockspur, St. Barnaby's thistle

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THE NATURE CONSERVANCY

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SCIENTIFIC NAME

Centaurea solstitialis L.

SYNONYMS

None

COMMON NAME

yellow starthistle

Centaurea comes from the Greek word *Centaur* that means spearman or piercer. The Latin term *solstitium* refers to the summer solstice or the longest day of the year, and –*alis* means "pertaining to." Thus, the specific epithet *solstitialis* means pertaining to the longest day of the year. This is in reference to the ability of *C. solstitialis* to flower very late into the summer.

OTHER COMMON NAMES

golden starthistle, yellow cockspur, St. Barnaby's thistle

DESCRIPTION AND DIAGNOSTIC CHARACTERISTICS

Invasive erect winter annuals (sometimes biennials) mostly to 1 m tall (occasionally to 2 m tall) with spiny yellow-flowered heads,.

Cotyledons oblong to spatulate, base wedge-shaped, tip +/- squared, glabrous, 6-9 mm long, 3-5 mm wide. First few leaves typically oblanceolate. Subsequent rosette leaves oblanceolate, entire to pinnate-lobed. Later rosette leaves 15 cm long, typically deeply lobed +/- to midrib. Lobes mostly acute, with toothed to wavy margins. Terminal lobes largest, triangular to lanceolate. Leaves of rosettes under reduced light levels are larger and more erect. Surfaces +/- densely covered with fine cottony hairs that +/- hide stiff thick hairs and leaf surfaces.

Stems stiff, openly branched from near or above the base or sometimes not branched in very small plants. Stem leaves alternate, mostly linear or +/- narrowly oblong to oblanceolate. Lower stem leaves sometimes +/- deeply pinnate-lobed. Margins smooth, toothed, or wavy. Leaf bases extend down the stems (decurrent) and give stems a winged appearance. Largest stem wings typically to ~ 3 mm wide. Foliage grayish- to bluish-green, densely covered with fine white cottony hairs that +/- hide thick stiff hairs and glands. Rosette leaves typically withered by flowering time.

Taproots grow vigorously early in the season to soil depths of 1 m or more, giving plants access to deep soil moisture during the dry summer and early fall months.

Plants flower from May to December in California, but have a narrower flowering period in more northern states with shorter seasons. Flowerheads are ovoid, spiny, solitary on stem tips, and consist of numerous yellow disk flowers. Vigorous individuals of yellow starthistle may develop flower heads in branch axils. Involucre (phyllaries as a unit) is approximately 12-18 mm long. Phyllaries are palmately spined, with one long central spine and 2 or more pairs of short lateral spines. Phyllaries are more or less densely to sparsely covered with cottony hairs or with patches at the spine bases. The central spine of the main phyllaries are 10-25 mm long, stout, yellowish to straw-colored throughout. Lateral spines occur typically in 2-3 pairs at the base of the central spine. The corollas are yellow, and mostly 13-20 mm long. The number of flowers per head varies and depends upon growing conditions, but generally ranges between 30 and 100. The flowers are insect-pollinated, and are mostly self-incompatible.

Flowerheads produce two types of achenes (seeds), both glabrous, approximately 2-3 mm long, with broad bases. Achenes are +/- barrel-shaped, +/- compressed, and laterally notched at the base. Flowers at the periphery of the flowerheads produce dull dark brown, often speckled with tan, achenes that are darker and have no pappus. This seed type represents between 10 and 25% of the total seed and often remain in the seedheads until late fall or winter. The central flowers produce glossy, gray or tan to mottled cream-colored and tan seeds with a short stiff, unequal, white pappus (2-5 mm long). This represents the majority of seed produced (75-90%), and dispersal occurs soon after dried flower remnants are detached from heads.

Plants usually senesce in late summer or fall. Heads shed the central spines, but tightly retain a ball of dense fuzzy gray hairs (chaff) on the receptacle. Often a dense layer of thatch develops on heavily infested sites.

STEWARDSHIP SUMMARY

C. solstitialis is a winter annual that can form dense impenetrable stands that displace desirable vegetation in natural areas, rangelands, and other places. It is best adapted to open grasslands with deep well-drained soils and average annual precipitation between 10 and 60 inches (25 and 150 cm) per year. *C. solstitialis* originated from southern Europe but was introduced from Chile to California during the gold rush. It has spread rapidly since the mid-1900s and is now estimated to infest 15-20 million acres (6-8 million ha) in California and a couple of additional million acres in other western states.

Control of *C. solstitialis* cannot be accomplished with a single treatment or in a single year. Effective control requires suppression of seed production. An integrated approach using several methods is the most ecologically sound strategy for long-term management of *C. solstitialis*.

Mechanical, cultural, biological and chemical control options are available for management of *C. solstitialis*. Mowing can be used as a mechanical option for *C. solstitialis* control provided it is well timed and used on plants with a high branching pattern. Cultural control options include grazing, prescribed burning, and re-vegetation with competitive species.

Sheep, goats or cattle are effective in reducing *C. solstitialis* seed production when grazed after plants have bolted but before spines form on the plant. Goats will eat starthistle even in the spiny stage.

In California, burning is best performed at the end of the rainy season when flowers first appear. *C. solstitialis* should be green at this time and will require desiccated vegetation to burn. Most annual vegetation other than *C. solstitialis*, particularly grasses, should have dried and shed their seeds by this time. Burning can also increase the recovery and density of perennial grasses.

Re-vegetation programs using perennial grasses or legumes can be effective for management of *C. solstitialis* but establishment may be difficult in areas without summer rainfall.

Six biological control agents of *C. solstitialis* have been imported from Europe and are well established in the western United States. Of these the most effective are the hairy weevil (*Eustenopus villosus*) and the false peacock fly (*Chaetorellia succinea*). These insects attack the flower/seed head, and directly or indirectly reduce seed production by 43 to 76%. They do not, by themselves, provide sustainable management of *C. solstitialis*, but can be an important component of an integrated approach.

Clopyralid and picloram (not registered in California) are the most effective herbicides for full season control of *C. solstitialis*. Unlike most postemergence herbicides, they provide both foliar and soil activity. The best timing for application is when *C. solstitialis* is in the early rosette stage. Clopyralid gives one season of control and is generally used at 1.5 oz a.e./acre, 4 oz product/acre (110 gm a.e./ha; 290 gm product/ha). Picloram has longer soil residual activity than clopyralid (two to three years) and is applied at 0.25 lb and 0.375 lb a.e./acre (0.28 kg and 0.42 kg a.e./ha). Glyphosate is a non-selective herbicide that is also effective on *C. solstitialis*. It will control bolted plants at 1 lb a.e./acre, 0.33 gal product/acre (1.1 kg a.e./ha; 9.4 liters product/ha) or 1% solution and can be used as a late season spot treatment to small infestations or escaped plants.

INTRODUCTION, SPREAD, AND DISTRIBUTION

The center of origin of *C. solstitialis* is believed to be Eurasia, where it is native to Balkan-Asia Minor, the Middle East and southcentral Europe (Maddox 1981). Its introduction in North America probably occurred sometime after 1849 as a seed contaminant in Chilean-grown alfalfa seed, also known 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 origin from Spain, the source of alfalfa in California before 1903 was only from Chile. After 1903, it was likely that alfalfa was also introduced from Spain, France, Italy, and perhaps Turkestan.

The spread of *C. solstitialis* into California occurred through a multiple step process (Gerlach 1997a, b). Before the 1870s alfalfa was grown primarily along river levees near Sacramento, Marysville and San Francisco. At this time, *C. solstitialis* infestations that accompanied alfalfa stands were fairly localized and found only in California. 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, *C. solstitialis* established as dense local populations in these areas and along adjacent roadsides. Introduction of *C. solstitialis* 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. 1999). These first introductions were likely through contamination of alfalfa seed (Gerlach 1997a).

The use of tractors and other equipment spread seed to other locations, including grain fields. During the 1920s, *C. solstitialis* expanded rapidly in grasslands within the Pacific Northwest states. At the same time, *C. solstitialis* infestations 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 sodium arsenite and sodium chlorate, along roadsides (Gerlach 1997a). However, around the 1930s or 1940s *C. solstitialis* began to invade the foothill grasslands in California. Thus, *C. solstitialis* now became a part of the grazed rangeland system. By 1958, it was estimated to have invaded over 1 million acres (400,000 ha) of California (Maddox and Mayfield 1985).

Since the 1960s three factors greatly contributed to its further spread, including extensive road building programs, increased suburban development, and an expansion in the ranching industry (Gerlach et al. 1998). Over the past 40 years, *C. solstitialis* has spread exponentially to infest rangeland, native grasslands, orchards, vineyards, pastures, roadsides, and wasteland areas. Infestations reached nearly 8 million acres (3 million ha) in California by 1985 (Maddox and Mayfield, 1985). In the mid-1980s *C. solstitialis* was estimated to occupy 280,000 acres (113,000 ha) in Idaho, 135,000 acres (55,000 ha) in Oregon, and 148,000 acres (60,000 ha) in Washington (Sheley et al. 1999). In 1989, Callihan et al. estimated that *C. solstitialis* was expanding in rangelands by 7,000-20,000 acres/year (2800-8000 ha/yr) in the west. By 1994, the rate of spread was estimated to be twice as rapid (Sheley and Larson 1994).

RANGE

Today, *C. solstitialis* has been estimated to infest over 15 million acres (6 million ha) in California, and can be found in 56 of the 58 counties in the state (Pitcairn et al. 1998). Nationally, the weed is 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. Globally, *C. solstitialis* is found in most of the temperate areas around 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. Once at a new location, 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 moves seeds less than a few feet (less than a meter) (Roché 1992).

IMPACTS

Rangelands

Although no economic assessments have been conducted for *C. solstitialis*, millions of dollars in losses probably occur from interference with livestock grazing and forage harvesting procedures, and lower yield and forage quality of rangelands (Callihan et al. 1982, Roché and Roché 1988). Because of the spiny nature of *C. solstitialis*, livestock and wildlife avoid grazing in heavily infested areas. Thus, infestations can greatly increase the cost of managing livestock. Although the nutritional component of *C. solstitialis* leaves is highly digestible by ruminants during the growing season (Callihan et al. 1995), its nutrient value declines as the plants mature. *C. solstitialis* in the pre-spiny stage contains between 8 to 14% protein (Thomsen et al. 1990). However, an analysis of the nutritional status of cattle manure in the fall indicated that *C. solstitialis*-infested pastures contain considerably less crude protein and total digestible nutrients compared to uninfested pastures (Barry 1995).

Other non-crop areas

In addition to rangeland, pastures and grasslands, *C. solstitialis* is also an important weed problem along roadsides, and an occasional problem in dryland cereals, orchards, vineyards, cultivated crops, and wastelands (Maddox et al. 1985). It can also reduce land value and reduce access to recreational areas (DiTomaso et al. 1998, Roché and Roché 1988). In addition, *C. solstitialis* infestations can reduce wildlife habitat and forage, displace native plants, and decrease native plant and animal diversity (Sheley and Larson 1994). Dense infestations not only displace native plants and animals, but also threaten natural ecosystems and nature reserves by fragmenting sensitive plant and animal habitat (Scott and Pratini 1995). *C. solstitialis* invasions on the Agate Desert Preserve in southwest Oregon threatens *Lomatium cookei*, a globally rare plant species (Randall 1994).

Water consumption

C. solstitialis significantly depletes soil moisture reserves in annual grasslands in California (Benefield et al. 2001, Dudley 2000) and in perennial grasslands in Oregon (Borman et al 1992). Because of its high water usage, *C. solstitialis* threatens both human economic interests as well as native plant ecosystems (Dudley 2000). Gerlach estimated (Dudley 2000) that *C. solstitialis* might cause an annual economic loss of $16 to $56 million in water conservation costs in the Sacramento River watershed alone.

Toxicity to horses

When ingested by horses, *C. solstitialis* causes a neurological disorder of the brain called nigropallidal encephalomalacia or "chewing disease." Continued feeding results in brain lesions and ulcers in the mouth (Kingsbury 1964). There is no known treatment for horses that have been poisoned by *C. solstitialis*. In most cases poisoning destroys the animal's ability to chew and swallow and death occurs through 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 30 to 60 days, 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 *C. solstitialis* 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.

C. solstitialis 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 *C. solstitialis* 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 *C. solstitialis* occurred annually (Cordy 1954). Because the toxicity and identification of *C. solstitialis* is better understood today, cases of poisoning in horses are now relatively uncommon. It appears that only horses are affected by ingesting *C. solstitialis*. Other animals, including mules and burros are not susceptible to the toxic effect of the weed. However, all grazing animals can sustain damage to their eyes from the plant's long, sharp spines (Carlson et al. 1990).

HABITAT

C. solstitialis is best adapted to open grasslands with average annual precipitation between 10 and 60 inches (25 to 150 cm) per year. It is generally associated with deep well-drained soils. Although populations can occur at elevations at high as 8,000 ft (2,400 m), most large infestations are found below 5,000 ft (1,500 m).

BIOLOGY AND ECOLOGY

Reproduction

C. solstitialis typically begins flowering in late May and continues through September, sometimes into December or later. There are very low levels of self-fertilization in *C. solstitialis* (Harrod and Taylor 1995, Maddox et al. 1996, Sun and Ritland 1998).

Honeybees play an important role in the pollination of *C. solstitialis*, and can account for 50% of seed set (Barthell et al. 2001, Maddox et al. 1996). Bumblebees are the second most important floral visitor to flowers, but several other insects also contribute to fertilization of the ovules (Barthell et al. 2001, Harrod and Taylor 1995).

On average, seedheads require 21 days to progress from pre-bloom to petal abscission (Benefield et al. 2001). The time period from flower initiation to the development of mature viable seed is only 8 days. To prevent seed production, it is most practical to gauge timing of late season control practices around flower initiation, as this stage is easily recognizable. To prevent new seed 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.

Average seed production per seedhead ranges from about 35 to over 80 seeds (Benefield et al. 2001, Maddox 1981), depending upon the site. Large plants can produce over 100,000 seeds. *C. solstitialis* infestations can produce 50-100 million seeds per acre (20-40 million seeds/ha) (DiTomaso et al. 1999a, Maddox 1981). Of the total seeds produced, between 75% and 90% are pappus-bearing and 10% to 25% are non-pappus-bearing (Benefield et al. 2001, Maddox 1981, Roché 1965).

Seed dispersal

The pappus-bearing seeds are usually dispersed soon after flowers senesce and drop their petals. However, non-pappus-bearing seeds can be retained in the seed head for a considerable period of time, extending into the winter (Callihan et al. 1993). These seeds have no wind dispersal mechanism and most fall to the soil just below the parent plant. With pappus-bearing seed, the pappus is not an effective long distance wind dispersal mechanism. About 92% of *C. solstitialis* seed fall within 2 feet (60 cm) of the parent plant, with a maximum dispersal distance of 16 ft (4.9 m) over bare ground even at wind gusts of 25 miles/hr (40 km/hr) (Roché 1991, 1992). By comparison, birds such as pheasants, quail, house finches, and goldfinches feed heavily on *C. solstitialis* seeds and are capable of transporting seed greater distance (Roché 1992). Human influences including vehicles, contaminated crop seed or hay, road maintenance, and moving livestock can also contribute to rapid and long distance spread of the seed.

Germination and dormancy

Over 90% of *C. solstitialis* seeds are germinable one week after seed dispersal (Benefield et al. 2001, Joley et al. 1997, Roché et al. 1997, Sheley et al. 1983, 1993). Maximum germination of *C. solstitialis* seeds (nearly 100%) occurs when seeds are exposed to moisture, light and temperatures of 10, 15, or 20^{o}C (Joley et al. 1997, Roché et al. 1997). At temperatures above 30^{o}C germination is dramatically reduced (Joley et al. 1997, Roché et al. 1997). When exposed to light and moisture germination occurs rapidly (typically by 24 h) with nearly all seed germinating within 96 hours (Sheley et al. 1983, 1993). However, with increasing exposure to higher temperatures and low moisture (within 1 month of dispersal), as would occur in later summer, many seeds undergo secondary dormancy and do not germinate under adequate light and moisture conditions. This ensures that all seed do not germinate following an occasional late summer thunderstorm, where subsequent seedling mortality would occur when no additional moisture is received over an extended time period.

Although germination occurs throughout the rainy season (October to June), emergence is highest after early fall rainfall events. The extended timing of germination increases the difficulty of controlling *C. solstitialis* populations during the late winter and early spring, as subsequent germination often results in significant infestations.

In a study conducted in Idaho, the average longevity of non-pappus-bearing and pappus-bearing seeds was six and ten years, respectively (Callihan et al. 1989, 1993). Even after six years of burial, 9% of the pappus-bearing seed germinated. However, in other studies conducted in California, over 95% of the seed either emerged or were damaged two or three years after natural dispersal to the soil surface (DiTomaso et al. 1999a, Joley et al. 1992). This suggests that *C. solstitialis* seeds may be relatively short-lived under normal field conditions where seeds are predominantly dispersed on the soil surface. Furthermore, microbial degradation and invertebrate predation of *C. solstitialis* seeds contribute significantly to the rapid depletion of the soil seedbank (Benefield et al. 2001).

Growth and establishment

Seedling establishment, root and shoot growth
In exposed areas, high germination can result in extremely dense seedling populations. Seedlings are more likely to establish in soils with deep silt loam and loam with few coarse fragments (Larson and Sheley 1994). In many areas, a significant amount of self-thinning occurs and only a small fraction of seedlings reach reproductive maturity (Larson and Sheley 1994, Sheley and Larson 1994a). Thus, in heavily infested areas, *C. solstitialis* populations produce far more seeds than are necessary to re-infest the area year after year.

Following germination, *C. solstitialis* 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 3 feet (1 m) in depth. *C. solstitialis* roots elongate at a faster rate and to greater depths than potentially competitive species, including weedy annual grasses and clovers (Sheley et al. 1993). Rapid germination and deep root growth in *C. solstitialis* 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.

Shading of young rosettes can have a dramatic affect on root growth (Roché et al. 1994). Reduced root growth is correlated with increased shading (DiTomaso, unpublished data). Since *C. solstitialis* plants germinate over an extended time period beginning with the first fall rains and ending with the last spring rain event, the resulting canopy is often composed of plants in several stages of development. In dense stands of *C. solstitialis,* the population consists of both large canopied plants receiving full sunlight and an understory of smaller shaded plants. Thus, light suppression is likely 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 underneath the *C. solstitialis* canopy occupy shallower depths for longer periods of time. Under these conditions, soil moisture is rapidly depleted from all depths in the soil profile and *C. solstitialis* strongly competes with other shallow-rooted desirable species, as well as many deep-rooted perennials.

Seedlings that germinate following autumn rains overwinter as basal rosettes. Rosettes develop slowly in the early spring. Bolting typically occurs in late spring or early summer and by mid-summer spines appear on developing seedheads. At the more mature stages of development, the hairs and waxy grayish coating on the foliage of *C. solstitialis* reflect a considerable amount of light. This reduces the heat load and transpiration demand during the hot and dry summer months. The winged stems add surface area and also act to dissipate heat like a radiator (Prather 1994). These characteristics, as well as a deep root system, allow *C. solstitialis* to thrive under full sunlight in hot and dry conditions. Vigorous shoot growth coincides with increased light availability as neighboring annual species senescence and desiccate. Moreover, the presence of spines on the bracts surrounding the seedhead provides protection against herbivory. This is particularly important during the vulnerable flowering and seed development stages.

C. solstitialis plants are insensitive to photoperiod and lack a vernalization requirement (Roché et al. 1997). This allows late germinating plants to flower and set seed within one year provided adequate moisture is available. Flowering continues until newly developing buds are killed by frost. In climates with milder winters, plants can act as biennials. However, in colder climates, mature plants rarely survive the winter. In contrast, seedlings can survive extended frost periods. Cold tolerance (hardiness) appears to be lost during the transition from vegetative to reproductive phases.

Senesced stems can contain the non-pappus-bearing seeds for about a month until the spiny bracts fall off. The receptacles of the flowerheads contain abundant amounts of fine chaff giving the old seedheads a cotton-tip appearance. Stems of *C. solstitialis* degrade slowly and may remain erect for at least one year.

Water, light and temperature

Heavy infestations of *C. solstitialis* in grasslands with loamy soils can use as much as 50% of annual stored soil moisture (Gerlach, unpublished data). In deep soils, *C. solstitialis* can significantly reduce soil moisture reserves to depths greater than six feet (1.8 m) (Gerlach et al. 1998).

Seasonal moisture can influence competition between *C. solstitialis* and annual grasses. Under dry spring conditions, early maturing annual grasses have an advantage over late season annuals, like *C. solstitialis,* as they utilize the available moisture and complete their life cycle earlier (Larson and Sheley 1994). In contrast, under moderate or wet conditions, *C. solstitialis* has an advantage by continuing its growth later into the summer and fall and producing more seed. Thus, in grassland systems, the greatest advantage for *C. solstitialis* occurs in areas 1) dominated by annual grasses, 2) with deep soil, and 3) in years with moderate to heavy spring rainfall (Sheley and Larson 1992). Under these conditions, *C. solstitialis* matures later, has increased seed production, and has little competition for deep soil moisture.

C. solstitialis rosettes are very susceptible to light suppression, and 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, *C. solstitialis* 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 open grasslands dominated by annuals or disturbed sites. Even in areas dominated by *C. solstitialis*, the level of competition for light can be so intense that seedlings will vigorously compete with each other, accounting for the low rate of seedling survival through self-thinning.

ECONOMIC USES

Bee industry

Not every aspect of *C. solstitialis* is detrimental. It is regarded as an important honey source plant in California and other western states.

MANAGEMENT

The goal of any management plan should be not only controlling the invasive weed, but also improving the degraded community, enhancing the utility of that ecosystem, and preventing reinvasion or invasion by other weed species. This usually requires a long-term integrated management plan.

It is important to consider the advantages and disadvantages of each approach and to judge how each option may best fit into a long-term program. It is possible that several different strategies can prove successful in a given location. The consistent components of a successful program should include persistence, flexibility, and, most importantly, preventing new seed recruitment (DiTomaso et al. 2000). A list of management options for the control of *C. solstitialis* can be seen at http://wric.ucdavis.edu/yst/.

Mechanical control

Mechanical control options for *C. solstitialis* typically include hand pulling, hoeing, weed whipping, tillage or mowing.

Hand pulling, hoeing or weed whipping

Manual removal of *C. solstitialis* is most effective with small patches or in maintenance programs where plants are sporadically 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. These methods can also be an important in steep or uneven terrain where other mechanical tools (e.g., mowing) are impossible to use (Woo et al. 1999). To ensure that plants to not recover it is important to detach all above ground stem material. Leaving even a 2 inch (5 cm) piece of the 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 (i.e. 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, *C. solstitialis* will develop a more erect slender stem with few basal leaves. These plants are relatively brittle and easy to remove. In addition, they usually lack leaves at the base and, consequently, rarely recover even when a portion of the stem is left intact.

Tillage

Tillage is effective, and is occasionally used on roadsides. It is also often used in agricultural lands which probably accounts for the uncommon occurrence of *C. solstitialis* as a cropland weed. In wildlands and rangelands, tillage is usually not appropriate because it can damage important desirable species, increase erosion, alter soil structure, and expose the soil for rapid re-infestation if subsequent rainfall occurs (DiTomaso and Gerlach 2000).

Mowing

Mowing may be an alternative strategy for small landowners that do not wish to use herbicides. It is a popular control technique in recreational areas and has less impact on the environment than tillage. A few land managers have successfully controlled *C. solstitialis* using continuous mowing over multiple years. However, since mowing is a late season management tool it is best employed in the later years of a long-term management program or in a lightly infested area. This gives the land manager the ability to assess the level of infestation and the flexibility of choosing the most appropriate and cost effective option, which can include mowing. If only a few plants are present, hand pulling may be a better choice than mowing.

Although mowing can be a cost-effective control method, it is not feasible in many locations due to rocks and steep terrain. Even when mowing is employed, it is not always successful and can decrease the reproductive efforts of insect biocontrol agents, injure late growing native forb species (Rusmore 1995), and reduce fall and winter forage for wildlife and livestock (DiTomaso 1997, DiTomaso et al. 2000). In addition, its success depends on proper timing and the growth form of the plant. Mowing too early or late will usually increase the *C. solstitialis* problem. Plants with an erect, high-branching growth form are effectively controlled by a single mowing at the early flowering stage, while sprawling low-branching plants cannot be controlled even with repeated mowings at the proper timing. Despite its limitations, mowing conducted at the early flowering stage, before viable seed production, can be very effective for *C. solstitialis* control.

Grazing
Properly timed (May and June) intensive grazing by cattle, sheep or goats can reduce growth, canopy cover, survivability, and reproductive capacity of *C. solstitialis* (Thomsen et al. 1989, 1990, 1993). Grazing should be conducted after the stems bolt but before spiny seedheads develop. Cattle and sheep avoid *C. solstitialis* 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 *C. solstitialis* in relatively small infestations.

Grazing the weed during the bolting stage could provide palatable high protein forage (8 to 14%) (Thomsen et al. 1989). This can be particularly useful in late spring and early summer when other annual species have senesced. Grazing alone will not provide long-term management or eradication of *C. solstitialis*, but can be a valuable tool in an integrated management program.

Prescribed burning
Properly timed prescribed burning will control some important noxious annual grasses, such as barbed goatgrass (*Aegilops triuncialis*), medusahead (*Taeniatherum caput-medusae*) and ripgut brome (*Bromus diandrus*), as well as late flowering broadleaf species such as *C. solstitialis* (DiTomaso et al. 1999a).

Burning should be timed to coincide with the very early *C. solstitialis* flowering stage. At this time *C. solstitialis* has yet to produce viable seed, whereas seeds of most desirable species have dispersed and grasses have dried to provide adequate fuel. Fire has little if any impact on seeds in the soil.

In addition to controlling *C. solstitialis*, burning will reduce the thatch layer, expose the soil, and recycle nutrients held in the dried vegetation. In the first growing season after the burn, plant diversity will often increase, particularly native perennial grasses and forbs.

Despite its effectiveness, air quality issues can be a significant problem when burns are conducted adjacent to urban areas. A major risk of prescribed burning is the potential of fire escapes. This risk is greatest when burns are conducted during the summer months. In some areas, burning can lead to rapid invasion by other undesirable species with wind-dispersed seeds, particularly members of the sunflower family.

The ability to use repeated burning depends on climatic and environmental conditions. In areas where resources are ample and total plant biomass is abundant, two or three consecutive years of burning may be practical. However, in other environments or years, fuel loads may not be sufficient to allow multiple year burns. Consequently, prescribed burning may be a more appropriate option as part of an integrated approach.

In addition to summer burning, *C. solstitialis* seedlings have been controlled using winter or early spring flaming techniques (Rusmore 1995). This technique is somewhat non-selective and the control of *C. solstitialis* is inconsistent. When spring drought follows a flaming treatment, control of *C. solstitialis* can be excellent (Rusmore 1995). In contrast, a wet spring can lead to complete failure and increased *C. solstitialis* infestation, particularly since competing species may be dramatically suppressed.

Re-vegetation

Re-vegetation programs for *C. solstitialis* control generally rely on re-seeding with native or high forage non-native perennial grasses (Callihan et al. 1986, DiTomaso et al. 2000, Enloe et al. 2000, Johnson 1988, Larson and McInnis 1989, Lass and Callihan 1995, Northam and Callihan 1988a, 1988b, 1988c, 1990a, 1990b, Prather et al. 1988, Prather and Callihan 1989a, 1989b, 1990, 1991). Re-vegetation with desirable and competitive plant species can be the best long-term sustainable method of suppressing weed invasions, establishment, or dominance, while providing high forage production.

Because of the ecological diversity within most grassland ecosystems, no single species or combination of species will be effective under all circumstances. Unfortunately, few studies have been conducted on the restoration of *C. solstitialis* infested grasslands using a wide diversity of species, particularly natives.

In western states, competitive grasses used in re-vegetation programs for *C. solstitialis* management include non-native perennial grasses such as crested wheatgrass (*Agropyron desertorum*), intermediate wheatgrass (*Elytrigia intermedia [=Agropyron intermedium]*), pubescent wheatgrass (*Thinopyrum intermedium*), Bozoisky Russian wildrye (*Psathyrostachys juncea*), sheep fescue (*Festuca ovina*), tall oatgrass (*Arrhenatherum elatius*), or orchardgrass (*Dactylis glomerata*), as well as the native perennial grasses including big bluegrass (*Poa ampla*) and thickspike wheatgrass (*Elymus lanceolatus* subsp. *lanceolatus* [=*Agropyron dasystachyum*]) (Borman et al. 1991, Enloe et al. 2000, Ferrell et al. 1993, Prather and Callihan 1991, Sheley et al. 1999). These species provide good livestock forage and a sustainable option for rangeland maintenance.

In those parts of California with a Mediterranean climate, re-vegetation programs for control of *C. solstitialis* are more difficult that those in other western states where summer rainfall is critical to the establishment and survival of native perennial grasses.

In addition to perennial grasses, non-native crimson clover (*Trifolium incarnatum*) and subterranean clover (*Trifolium subterraneum*) were used for re-seeding programs in foothill ranges of Oregon and California (Sheley et al. 1993, Thomas 1997). Used as a sole control option, however, *T. subterraneum* did not provide adequate seasonal control of *C. solstitialis*.

Re-vegetation projects for *C. solstitialis* control nearly always rely on integrated strategies. In most cases, it is difficult to establish desired plants without the management of competing vegetation, including *C. solstitialis* and annual grasses. The goal of these re-vegetation projects is to develop sustainable high quality range conditions and improved wildlife habitat capable of providing long-term *C. solstitialis* control without the need for continued herbicide treatments.

Biological control

Insects

Six insects have become established for the control of *C. solstitialis* in the western United States. These include three species of weevils (seed-head weevil [*Bangasternus orientalis*], flower weevil [*Larinus curtus*], and the hairy weevil [*Eustenopus villosus*]), and three species of flies (seed-head fly [*Urophora sirunaseva*], peacock fly [*Chaetorellia australis*], and the false peacock fly [*Chaetorellia succinea*]). All six insects attack the flower heads of *C. solstitialis* and produce larvae that develop and feed within the seedhead (Balciunas and Villegas 1999).

Of the four insects that are well established in California (Villegas et al. 2000) only two, *Eustenopus villosus* and *Chaetorellia succinea*, have any significant impact on reproduction (Pitcairn and DiTomaso 2000, Pitcairn et al. 1999, 2000). The combination of these two insects reduces seed production by 43 to 76% (Pitcairn and DiTomaso 2000). Although this level of suppression is not sufficient to provide long-term *C. solstitialis* management, the use of biological control agents can be an important component of an integrated management approach. A more successful biological control program will likely require the introduction of plant pathogens or other insects capable of severely damaging or feeding on roots, stems, or foliage. Biocontrol researchers continue to search for such insects or pathogens in *C. solstitialis*' native range.

Plant pathogens

The most widely studied pathogen for *C. solstitialis* control is the Mediterranean rust fungus *Puccinia jaceae*. It can attack the leaves and stem of *C. solstitialis*, causing enough stress to reduce flowerhead and seed production. It is well suited to environmental conditions found in California and other areas of infestation in North America (Bennett et al. 1991). The organism is currently under investigation and has not been released for use.

Herbicides

Clopyralid (Transline®, Stinger®) and picloram (Tordon®) provide postemergence control of *C. solstitialis* seedlings and rosettes, as well as soil residual activity for at least one season. These compounds give the best control of *C. solstitialis* and are the least injurious to grasses. Picloram is not registered in California.

Clopyralid gives excellent control of *C. solstitialis* at very low rates (1.5 to 4 oz a.e./acre; 100-280 g a.e./ha). The timing for application is broad, usually ranging between January and May. 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 many species in the legume family (Fabaceae), as well as the sunflower family (Asteraceae). It can also cause some injury is members of the nightshade (Solanaceae), knotweed (Polygonaceae), carrot (Apiaceae), and violet (Violaceae) families. Clopyralid is also effective on plants in the bolting and bud stage, but higher rates (4 oz a.e./acre; 280 g a.e./ha) are required. Applications made after the bud stage will not prevent the development of viable seed (Carrithers et al. 1997, Gaiser et al. 1997). 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. A combination of clopyralid and 2,4-D amine (Curtail®) has also been used for *C. solstitialis* control in western states other than California. It can be used at 0.25 to 1 pint/acre (0.3-1.2 liter/ha) after the majority of *C. solstitialis* rosettes have emerged but before bud formation.

Picloram is the most widely used herbicide to control *C. solstitialis* in western states other than California. It 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 (0.28-0.42 kg a.e./ha) in late winter to spring when plants are still in the rosette through bud formation stages (Callihan et al. 1989). This treatment can provide effective control for about two to three years. 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. 1999).

A limited number of postemergence herbicides are registered for use in rangelands, pastures, and wildlands. They include 2,4-D (many trade names), dicamba (Banvel®, Vanquish®), triclopyr (Garlon 3A®, Garlon 4®, Remedy®), and glyphosate (Roundup®). These postemergent herbicide treatments generally work best on seedlings. They are not effective for the long-term management of *C. solstitialis* when used in spring, as they have no soil residual activity and will not control plants germinating after application.

The most effective way to use postemergence compounds for *C. solstitialis* control is to incorporate them into later stages of a long-term management program. In particular, they are effectively used to spot-treat escaped plants or to eradicate small populations in late season when *C. solstitialis* is easily visible but has yet to produce viable seed.

2,4-D (0.5 to 0.75 lb a.e./acre; 0.56-0.84 kg a.e./ha), dicamba (0.25 to 1.0 lb a.e./acre; 0.28-1.1 kg a.e./ha) and triclopyr (0.5 or 1.5 lb a.e./acre; 0.56-1.7 kg a.e./ha) are growth regulator herbicides that can provide acceptable control of *C. solstitialis* when applied at the rosette growth stage. Amine forms are as effective as ester forms at the small rosette growth stage, but amine forms reduce the chance of off-target movement. Glyphosate controls *C. solstitialis* at 1 lb a.e./acre (1.1 kg a.e./ha) (DiTomaso et al. 1999b). Good coverage, clean water, and actively growing *C. solstitialis* plants are all essential for adequate control. Unlike the growth regulator herbicides, glyphosate is non-selective and controls most plants, including grasses. A 1% solution of glyphosate also provides effective control and is used at this concentration for spot treatment of small patches. Glyphosate is a very effect method of controlling *C. solstitialis* plants in the bolting, spiny, and early flowering stages at 1 to 2 lb a.e./acre (1.1-2.2 kg a.e./ha). However, it is important to use caution when desirable perennial grasses are present. In late season treatments, except with glyphosate and ester formulations, a surfactant should be added to the herbicide formulation.

A number of non-selective preemergence herbicides will control *C. solstitialis* to some level, including simazine, diuron, atrazine, imazapyr, imazapic, metsulfuron, sulfometuron, chlorsulfuron, bromacil, tebuthiuron, oxyfluorfen and prometone. 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 (Escort®) (not registered in California) and to some degree chlorsulfuron (Telar®) (not registered for pastures or rangeland in any state) provides selective control of *C. solstitialis* without injuring desirable grasses. Both these compounds are used at 1 to 2 oz a.i./acre (70-140 g a.i./ha). Chlorsulfuron and metsulfuron do not have postemergence activity on *C. solstitialis* and therefore, must be used in combination with 2,4-D, dicamba, or triclopyr to provide effective control of *C. solstitialis* in grasslands.

Integrated approaches

Most often a single method is not effective in the sustainable control of *C. solstitialis* and other range weeds. A successful long-term management program should be designed to include combinations of mechanical, cultural, biological, and chemical control techniques. There are many possible combinations that can achieve the desired objectives, and choices will have to be tailored to the site, economics, and management goals. Sometimes the control techniques must be in a particular sequence to be successful. The most effective sequence includes early season control strategies in the first year or two of a management program, followed by late season options in the later years.

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