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,

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

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.*

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

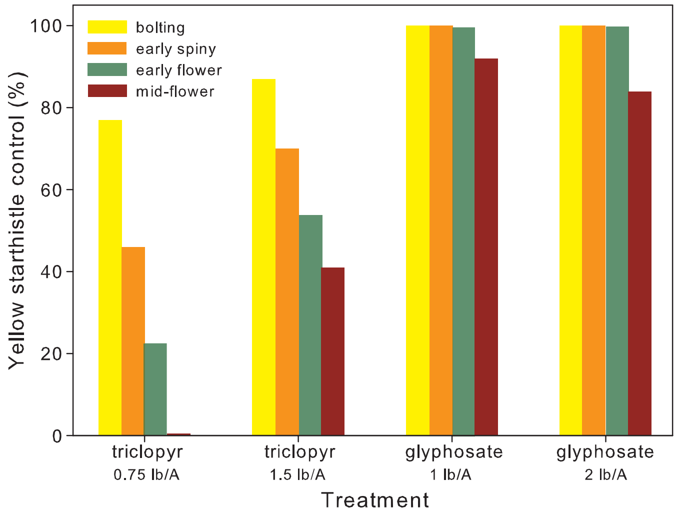

Fig. 19. Late-season control with glyphosate and triclopyr. *Trials at UC Davis showed that glyphosate provided more effective late-season yellow starthistle control than triclopyr (DiTomaso* et al. *1999b).*

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.*

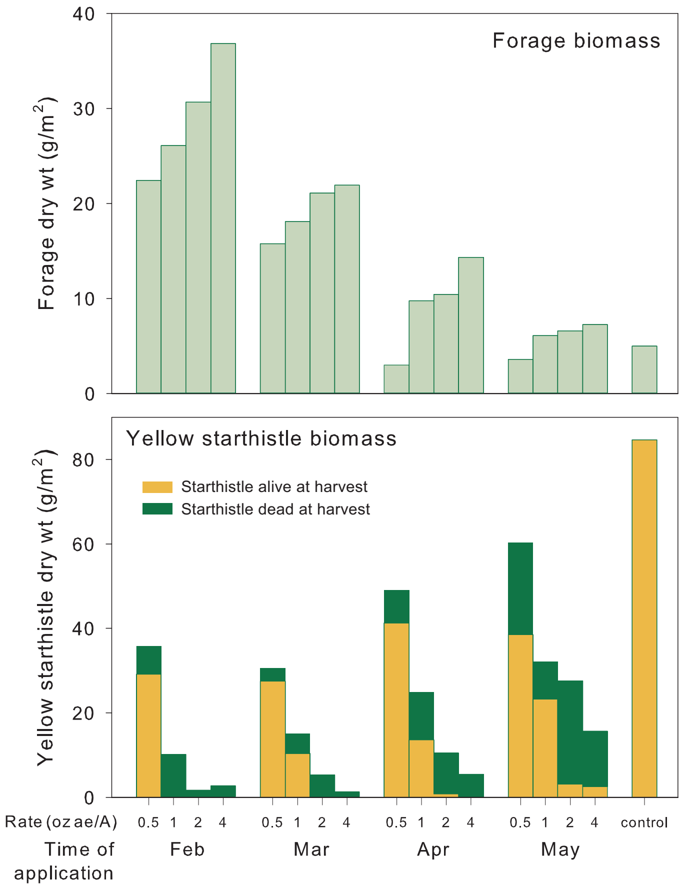

Fig. 20. Effect of clopyralid rate and timing on forage and yellow starthistle. *In a number of studies – like this trial in Siskiyou County – early control of yellow starthistle with clopyralid resulted in early release of desirable species and enhanced forage production (DiTomaso* et al. *1999b).*

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.*

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.

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.*

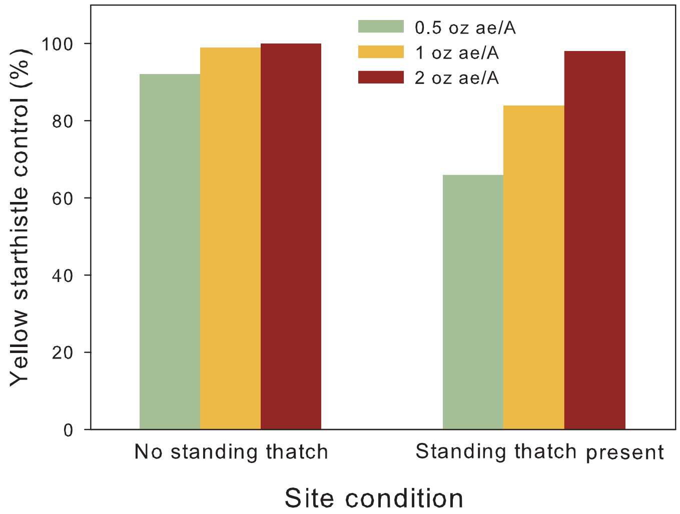

Fig. 21. Effect of standing litter on control with clopyralid. *Presence of standing litter (yellow starthistle skeletons) resulted in reduced control with clopyralid at very low rates but had little effect at realistic application rates (DiTomaso 1999).*

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 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.

***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)*

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

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 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 80°F.

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 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.