COMMON SENSE
PEST CONTROL QUARTERLY

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Alternatives to Glyphosate

Drawing courtesy Diane Kuhn

An Invitation to Join

B · I · R · C

The Bio-Integral Resource Center

BIRC, A NON-PROFIT CORPORATION, WAS FORMED IN 1979 to provide practical information on the least-toxic methods for managing pests. The interdisciplinary BIRC staff and an international network of advisors and research associates have designed highly effective alternative solutions to a wide variety of pest problems throughout the world. This work has been based on the principles of 'Integrated Pest Management' or 'IPM'.

IPM IS A DECISION-MAKING PROCESS that considers the whole ecosystem in determining the best methods for managing pests. The objective of an IPM Program is to suppress the pest population below the level that causes economic, aesthetic, or medical injury. IPM strategies are designed to be the least disruptive of natural pest controls, human health, and the general environment. Horticultural, physical, mechanical, biological, least-toxic chemical, and educational tactics are integrated to solve pest problems with a minimal reliance on pesticides.

THE IPM APPROACH HAS GAINED FAVOR with government and business because it is cost-effective. Community groups and pest management professionals are enthusiastic about IPM programs because the use of toxic materials is reduced while better pest control is achieved.

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BIRC MEMBERS RECEIVE ONE OR BOTH OF OUR JOURNALS, the *Common Sense Pest Control Quarterly* and *The IPM Practitioner.* Members are entitled to consultations by phone or correspondence on an individual pest problem each membership year. Just write a description of the problem and send it to BIRC. Our technical staff will research the problem and provide you, if possible, with least-toxic solutions. BIRC memberships are tax-deductible to the extent allowed by law.

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If you have a specific pest management question, first check our website, www.birc.org. Often you will find a publication that covers your problem. If you do not find the solution on our website, you can write us with a description of the pest and the problem. Include scientific names of the pest. You can also email this information to birc@igc.org. We will respond as quickly as possible.

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Least-Toxic Herbicides

By William Quarles

About 280 million pounds of glyphosate are applied each year, nearly a pound for each person in the U.S. Much of it is applied to genetically modified crops, but it is also used for weed control in urban and suburban landscapes, home lawns, golf courses, and schools (USGS 2015; Duke and Powles 2009).

Amounts applied have increased five-fold since 1998, causing the EPA to increase residues allowed on food items such as soybeans. Systemic glyphosate cannot be washed off, and residues cannot be destroyed by cooking (Kruger et al. 2014; EFSA 2009). There is widespread contamination of breakfast cereal, wine, and other commodities. Glyphosate has been found in the bodies of 93% of people tested in the U.S. (Detox 2016). A study of senior citizens showed urinary concentrations of glyphosate increased about 6-fold between 1999 and 2016 (Mills et al. 2017).

According to the International Agency for Research on Cancer (IARC), glyphosate is a probable human carcinogen, and thousands of lawsuits have been filed against Bayer and Monsanto (Guyton et al. 2015; NYT 2018). The EPA safety threshold of 1750 parts-per-billion (ppb) for human exposures in the U.S. may not protect the population. European standards are 500 ppb for the general population and 100 ppb for pest control operators (Quarles 2017a). Glyphosate formulations such as Roundup® are considerably more toxic than glyphosate (Defarge et al. 2018). Applicators are most at risk, and a jury trial in California resulted in a $289 million dollar award to a landscape professional dying of non-Hodgkins lymphoma (NYT 2018).

IPM Methods

Glyphosate alternatives in GMO crops are needed because of weed resistance (Culpepper 2006). But stacked trait alternatives using herbicides such as dicamba have developed their own problems, such as crop damage from herbicide drift (Quarles 2017b). Alternatives are also needed for roadside weed control, for municipal landscapes, for golf courses, playing fields, and weed control in home lawns and gardens. Cities are especially concerned about potential liability and are actively seeking alternatives (NYT 2018).

IPM methods can provide a comprehensive solution to weed management. These include weed mapping, cultural controls, mulching, microbials, mechanical controls, steaming, flaming, solarization, allelopathy, and application of least-toxic herbicides (Quarles 2001; Quarles 2003). The IPM approach is reviewed in the second article in this issue. This article will emphasize least-toxic herbicides.

Photo courtesy Pharm Solutions

Concentrated vinegar is corrosive, and personal protection must be used. Residuals degrade quickly to carbon dioxide and water.

Least-Toxic Herbicides

Herbicides are either pre-emergent or post-emergent. Corn gluten meal is the only pre-emergent least-toxic herbicide (Quarles 1999; Quarles 2001). Post-emergent products currently available are broad-spectrum contact herbicides that kill weeds by desiccation or oxidation. The products are mostly soaps, fatty acids, essential oils, or mixtures of these. Results are immediate and dramatic. They will kill foliage, but not root systems. Initial effectiveness can approach 100%, but foliage grows back. These herbicides should be evaluated after four weeks to see if reapplication is needed. They are best for broadleaf annuals, and are more effective with repeated application, and good plant coverage (Smith-Fiola and Gill 2017; Wilen and Neal 2016).

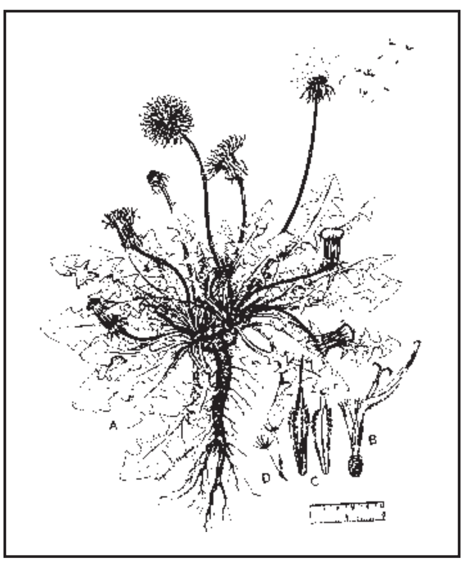
Important variables are concentration and coverage volume. Effectiveness increases with concentration and the number of gallons per acre of solution applied. For instance, 15% vinegar applied at 68 gal/acre gives about the same results as 30% vinegar applied at 34 gal/acre (Evans et al. 2009). Since these herbicides work by desiccation, sunny days, higher humidity, and warmer temperatures can be helpful (Brainard et al. 2013). Least-toxic herbicides have low residual toxicity to mammals and the environment. But substances such as concentrated vinegar (acetic acid) are corrosive and must be handled with care. If consumers have sensitivity to odors of clove, oranges, or vinegar, fatty acid or soap herbicides might be the best choice (Quarles 2010).

Upfront costs of least-toxic herbicides are greater than those of glyphosate. But glyphosate costs are underestimated. Upfront costs do not include environmental damage such as destruction of monarch butterfly habitat, disruption of soil ecology requiring more fertilizer applications, or the payment of expensive lawsuits (NYT 2018; Hartzler 2010; Pleasants and Oberhauser 2012; Quarles 2017b).

Corn Gluten Meal

Good results with corn gluten meal require skill and patience. You cannot apply it too early, you cannot apply it too late. Best results follow applications 3-5 weeks before weed germination. Application rates are about 40 lbs/1000ft^2 (Quarles 1999; Christians 1995). Some of the weed suppression may be due to the fertilizer effect on turfgrass, so there is an interaction between weed cover and the kind of turfgrass. In stands of Kentucky bluegrass, *Poa pratensis*, weeds such as crabgrass, dandelion, and clover see 90% reduction. Better results have been seen in lawns rather than in weed suppression along roadsides. Corn gluten meal is pre-emergent and has no post emergent effects (Barker and Prostak 2014).

Abouziena et al. (2009) found that corn gluten meal suppressed a number of persistent weeds in greenhouse tests. At four weeks after treatment, stranglervine was 55% controlled, wild mustard 99%, black nightshade 92%, sicklepod 97%, velvetleaf 87%, and redroot pigweed 72%. Efficacy in potting soil was greater than in sandy soil for wild mustard, annual ryegrass and goosegrass.



Corn gluten meal can suppress dandelions in turfgrass.

Vinegar

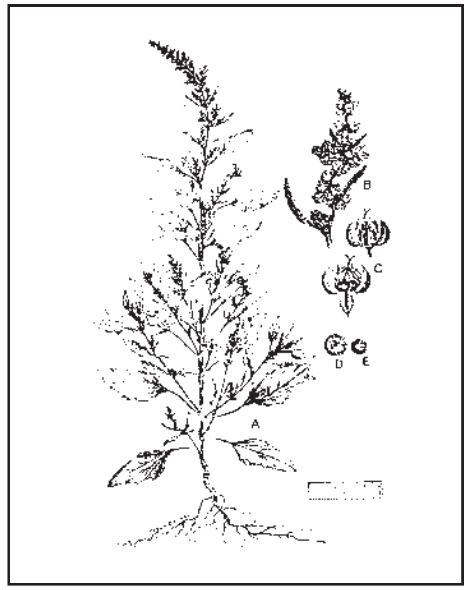
Vinegar (acetic acid) is an herbicide with low environmental impacts. It is registered for spot treatment on organic farms and on lawns (Lewis 2011; OMRI 2018). Acetic acid shows little potential for bioaccumulation and easily biodegrades to carbon dioxide and water. It could be used to control unwanted vegetation along roadsides and range lands; for control of weeds by homeowners around yards, brick walls and patios; for weed control in cracks in pavements (USDA 2002).

The acetic acid in vinegar can kill several important weed species. Vinegar from the grocery store contains 5% acetic acid. More concentrated solutions are more effective weed killers. USDA researchers have shown that water containing 10, 15 or 20% acetic acid killed 80-100% of annual weeds tested, including giant foxtail, *Setaria faberi*; up to three inches in height, common lambsquarters, *Chenopodium album*; up to five inches, smooth pigweed, *Amaranthus hybridus*; up to six inches, and velvetleaf, *Abutilon theophrasti*; up to nine inches (USDA 2002).

For its tests, the USDA used a commercially supplied white vinegar distilled from grain, with acetic acid concentrations ranging from 5-30%. They also made use of an apple vinegar at concentrations up to 14% acetic acid. Acetic acid should be handled carefully, as concentrated solutions could burn the skin or eyes. It has very strong "vinegary" smell, but when used outside the smell dissipates quickly (USDA 2002; Quarles 2002).

Ordinary 5% household vinegar is effective only for very small weeds, 3-5 inches or so in height. But products containing 20% acetic acid can be effective for larger weeds. A field test in Oklahoma showed that acetic acid was more effective for broadleaf weeds than grasses. Broadleaf control was about 84%. Overall weed control including crabgrass ranged from 44 to 63%. Control increased with concentration and spray volume, and 100 gal/acre was optimal. Adjuvants such as canola oil had little added effect (Webber et al. 2005).

Chinery and Weston (2001) tested acetic acid at several concentrations on small turf plots in New York. Weeds were quackgrass, crabgrass, ground ivy, dandelion, and plantain.



Least-toxic herbicides are effective for broadleaf weeds such as lambsquarters, *C. album*.

By 72 hrs weed control was 95-100%. Good weed control (>80%) was seen for 5 weeks with one application of the concentrated (20% acetic acid) products. Control with vinegar (5%) only lasted two weeks. Effects of concentrated acetic acid were more persistent than with Scythe™ (see below), which showed about 60% control after five weeks. The products were very effective for crabgrass, broadleaf plantain, and ground ivy.

When 30% acetic acid was applied to a number of early stage broadleaf and narrowleaf weeds in greenhouse tests, control was excellent (95-100%) at four weeks after treatment except

Vinegar or fatty acids can control crabgrass, *Digitaria* spp.

for sicklepod (62%), crowfootgrass (25%), and yellow nutsedge (58%) (Abouziena et al. 2009).

Fatty Acids

Fatty acids can kill weeds by desiccation. When fatty acids ranging from two carbons to ten were tested, the best for desiccation of beans before harvest were C8 (caprylic acid), and C9 (pelargonic acid or nonanoic acid). Capric acid (C10) also had high effectiveness. Emulsifiers and adjuvants increased effectiveness of the acids (Coleman and Penner 2006).

A fatty acid product called Scythe™ (see Resources) is commercially available. The major fatty acid in Scythe is pelargonic acid. Pelargonic acid occurs naturally in foods, and in seeds, where it may act as a germination inhibitor. The material has low toxicity to mammals, and like other fatty acids is metabolized for energy, releasing carbon dioxide and water. It is a moderate skin irritant, and a severe eye irritant. It has low toxicity to birds, bees and fish and does not persist in the environment (Mycogen 1999; Savage and Zorner 1996).

Pelargonic acid is a fast-acting broadspectrum herbicide that has no soil activity. It can be used in seedbeds, next to shrubs and other ornamentals. It is non-volatile, and will not harm plants unless it is sprayed on them. Best results are seen when applied on a hot day, and results are seen in minutes. Spray foliage to wet, but not to the point of runoff. It should not be applied just before rain, as it will just wash away. Recommended spraying rates are 5-10% in water.

Scythe can be hazardous to aquatic invertebrates, and should not be applied directly to water. Protective gloves, clothing and goggles should be used when applying it. Scythe is not labeled for weed control in food crops, and is not an organic formulation (Mycogen 1999; Savage and Zorner 1996).

A mixture of caprylic and capric fatty acids (Suppress®) is also effective for weed control. For instance, woolly distaff thistle, *Carthamus lanatus*, is considered one of the worst pasture weeds in North America. Application of 100 gal/acre of 9% Suppress applied at the bud stage (0.3-0.9 m) reduced weed cover by 88%. Mowing plus Suppress reduced weed cover by 95%(DiTomaso et al. 2017).

Soap

Various soaps have been used as least-toxic postemergent herbicides. These materials are relatively benign, and in fact, soaps are salts of fatty acids. Herbicidal soaps work best on annual weeds, since they only destroy exposed foliage. They do not translocate to kill perennial roots, but will kill perennial foliage. Repeated applications stop photosynthesis, and the plant dies from lack of food. BioSafe, Certis and other companies sell herbicidal soap (see Resources).

Essential Oils

In high enough concentration, essential oils such as orange oil (limonene) and oil of cloves (eugenol) are phytotoxic. These ingredients are active components of least-toxic herbicides (see Resources). Essential oils are volatile, and leave very few residuals. However, they should not be used if you have any sensitivity to orange oil, oil of cloves, thyme or other active ingredients (Quarles 2010).

Redroot pigweed, *Amaranthus* spp., can be controlled by least-toxic herbicides.

Least-toxic herbicides are not very effective for sedges, *Cyperus* spp.

Essential oils give better control when they are applied to small weeds. For instance, a limonene formulation, GreenMatch®, gave 96% control of 19-day old pigweed, *Amaranthus* spp. But only 17% control of 26-day old plants (Lanini 2010).

Commercial formulations often combine essential oils with vinegar (see Resources). Some of the formulations are so concentrated, they can burn or irritate the skin and eyes, so care in handling should be used (Smith-Fiola and Gill 2017).

Combination Products

Phydura® contains 20% citric acid, 15% clove oil, 10% malic acid, 55% lactose, potassium oleate and water. Label directions are applications in borders, driveways, sidewalks, around mature tree bases, around buildings, fence rows, greenhouses, school grounds, and around flower beds. (Phydura 2010).

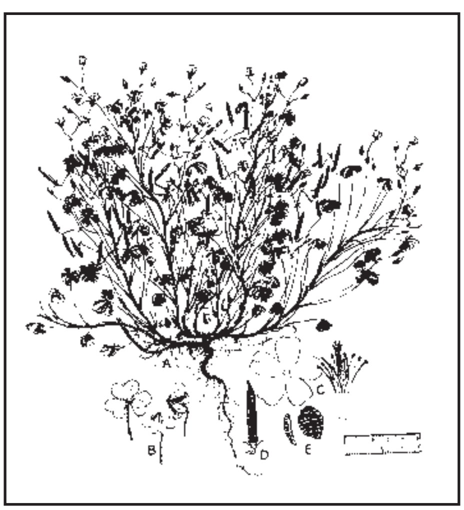
Addition of organic acids such as malic and citric acid to pelargonic acid or caprylic acid lowers the pH of solution. The fatty acids are less ionized and penetrate weeds more effectively. Effectiveness of pelargonic acid on velvetleaf, *Abutilon threophrasti*, and lambsquarters, *Chenopodium album*, at four days after treatment increased from 34 to 58% with addition of citric acid (Coleman and Penner 2008). Effectiveness of caprylic acid increased with surfactants and citric acid (Penner et al. 2011).

Iron herbicides can control plantain, *Plantago* spp.

Iron HEDTA

Iron chelated with hydroxy EDTA (Fe(III) HEDTA) can control broadleaf weeds in turf. Weeds controlled include oxalis, dandelion, white clover, Canada thistle, plantain, ground ivy, chickweed and others. The weeds absorb more of the iron than turfgrass, leading to oxidative damage of weeds, while turfgrass is left unharmed. Cool season grasses such as tall fescue are resistant, but iron herbicides should not be used on bentgrass because of possible damage (Smith-Fiola and Gill 2014).

Landscape maintenance companies typically apply the herbicide once every three weeks with a limit of four applications a season. Three applications can reduce broadleaf weeds by 95%. Applications should not be done at temperatures greater than 80°F (30°C) because of possible turfgrass discoloration. Iron should not be applied to drought stressed turf or within three hours of expected rainfall. Staining of hard surfaces such as white concrete may occur (Smith-Fiola and Gill 2014).



Iron herbicides can control oxalis, *Oxalis* spp.

Iron HEDTA can cause eye and skin irritation. According to the EPA, iron HEDTA has low toxicity to mammals, birds, fish, and no toxicity to honeybees. However, caution should be used on applications near shallow ponds, as amphibians might be affected (EPA 2009).

Products such as EcoSense®, Fiesta®, and Iron X® are labeled for lawns, turf, golf courses, parks, athletic fields, patios, driveways, and sidewalks (see Resources).

OMRI Certified Organic Products

Avenger® (limonene), AXXE® (soap), Final San® (soap), Green Gobbler® (30% acetic acid), Herbor® G (essential oil and soap), Summerset All Down® (acetic acid, citric acid), Suppress® (caprylic and capric acid), Phydura® (citric acid, clove oil), and Weed Zap® (clove oil, cinnamon oil) are all OMRI certified for use in organic agriculture (OMRI 2018). Weed Pharm® (20% acetic acid) is certified for use in organic agriculture by the Washington State Dept. of Agriculture (PharmSolutions 2018).

Comparison Tests

A number of alternative herbicides were tested in small turf plots by the University of California Statewide IPM. For suppression of white clover or hairy fleabane, the best herbicides were Suppress (fatty acids), Final San (soap), Weed Pharm (20% vinegar) and Fiesta (Fe(III) HEDTA). Costs per 1000ft^2 were similar: Suppress ($7.49), Weed Pharm ($7.80), Final San ($12.94) and Fiesta ($8.15) (Wilen and Neal 2016).

In 20 field trials across the U.S. clove oil and vinegar were tested for control of brown mustard, *Brassica juncea*. Concentrations of 7.5% clove oil (5.8 gal/acre) or 15% vinegar (11.4 gal/acre) were needed for effectiveness. Products worked better at higher relative humidity. Cloud cover was not a factor, and higher temperatures improved control with vinegar, but not clove oil. Control of grassy weeds was poor (Brainard et al. 2013).

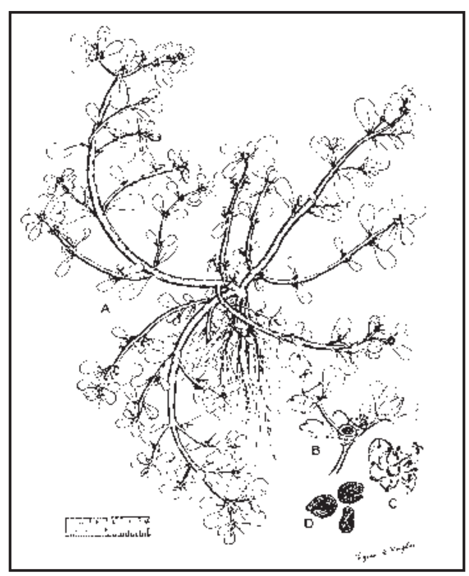
Home and Garden

Weed management in the lawn and garden depends on location. In lawns, corn gluten meal, iron HEDTA, spot treatment with least-toxic herbicides, weed pulling by hand or with tools can do the job. In planting beds, mulching or solarization may be appropriate. Sidewalk weeds can be controlled by flaming (see second article) or least-toxic herbicides (Quarles 1999; Quarles 2003).

Agriculture

Spot treatments of certified least-toxic herbicides can be used in organic fields. Seedbeds can be treated with burndown cover sprays to destroy germinating weeds before crop plants are seeded or transplanted. Sprays of 10-40% clove oil controlled nettle, *Urtica urens*, and purslane, *Portulaca oleracea* but not rye, *Secale cereale.* Clove oil is generally best for small broadleaf annual weeds (Boyd and Brennan 2006).

Flaming, steam and limonene were tested in a non-bearing almond orchard. Better than 95% control was seen initially, but effects lasted only 3-4 weeks. About 53% control with limonene was seen after five weeks. Limonene was the most expensive option (Shrestha et al. 2012). Mulched cover crops are effective options for weed control in orchards and vineyards. Cultivation is more economical and effective than applications of limonene in vineyards (Shrestha et al. 2013).



Clove oil sprays have controlled purslane, *Portulaca oleracea.*

Application of 68 gal/acre of 15% acetic acid reduced weeds in organic onions. Early treatment led to a 60% reduction in the amount of handweeding necessary to produce high yields. Early treatment of sweet corn with 34 gal/acre of 20% acetic acid led to similar yields as hand weeding (Evans and Bellinder 2009). Results with herbicidal soap in organic onions have been inconsistent (Webber et al. 2011; Johnson et al. 2018).

Municipal Landscapes

In Canada, treatment of Canada thistle, *Cirsium arvense*, with 5-8% vinegar every 2-3 weeks weakened it enough that it did not overwinter into the second year. Vinegar cost less than traditional herbicide treatments because municipal employees did the applications. Goats were also cost effective once fencing had been established (Booth and Skelton 2009).

Roadside Weed Control

Mulching, least-toxic herbicides, and flaming were tested as alternatives for weed control along roadsides in Massachusetts. Mulching was the most effective and most expensive option. Weed control with flaming and least-toxic herbicides such as clove oil, limonene or pelargonic acid only lasted five weeks. For weed control throughout a season, repeated applications were needed. Pelargonic acid was the most economical alternate herbicide tested (Barker and Prostak 2014).

In California, five monthly applications of 5-7% acetic acid provided 83%-85% control of hare barley, slender oat, broadleaf filaree, medusahead, yellow starthistle, and buckhorn plantain. Five applications of 15-30% essential oils led to 86% control of slender oat at 109 days, 80% control of soft chess at 66 days, and 83% control of hare barley at 66 days. But only 20% control of foxtail fescue was seen at 109 days (Young 2004).

Vinegar has controlled Canada thistle, *Cirsium arvense.*

Conclusion

Least-toxic herbicides can be an important alternative to glyphosate. Benefits are less environmental destruction, less weed resistance, and less potential liability. Drawbacks are sometimes corrosive formulations that must be handled with care. Broadleaf weeds are controlled better than grassy weeds. To maintain control, repeated applications may be needed. Upfront costs are more than glyphosate and efficacy may be somewhat less, depending on the weed species. Least-toxic herbicides are most effective when they are part of an integrated vegetation management program.

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Resources

All Down® (23% acetic acid, 14% citric acid)—Summerset Products, 130 Columbia Court, Chaska, MN 55318; www.sumersetproducts.com.

Avenger® (limonene)—Avenger Organics, 3057 Summer Oak Place, Buford, GA 30518; www.avengerorganics.org.

AXXE® (ammonium nonanoate soap)—BioSafe, 22 Meadow St., East Hartford, CT 06108; www.biosafesystems.com.

Corn Gluten Meal—Harmony Farm Supply, Sebastopol, CA; www.harmonyfarmcom. Gardens Alive, Lawrenceburg, IN; www.gardensalive.com. Peaceful Valley Farm Supply, Grass Valley, CA; www.groworganic.com.

Distributors of Least-Toxic Herbicides—Harmony Farm Supply, Sebastopol, CA; www.harmonyfarm.com. Arbico Organics, Tucson, AZ; www.arbico.com. Nature's Control, Medford, OR; www.naturescontrol.com.

Fiesta® (iron HEDTA)—Scotts, Marysville, OH. www.scotts.com.

Final San® (22% soap)—Certis, 9145 Guilford Rd., Ste 175, Columbia, MD 21046; www.certisusa.com.

Green Gobbler® (30% acetic acid)—Eco-Clean, 570 Oak St., Copaigue, NY 11726; www.greengobbler.com.

Iron X® (iron HEDTA)—Gardens Alive, 5100 Schenley Place, Lawrensburg, IN 47025; www.gardensalive.com.

Phydura® (15% clove oil, 20% citric acid)—Soil Technologies, 2103 185th Street, Fairfield, IA 52556; www.soiltechcorp.com.

Scythe® (57% pelargonic acid)—Gowan, 370 South Main Street, Yuma, AZ 85364, www.gowanco.com.

Suppress® (47% caprylic and 32% capric acids)—Westbridge, 1260 Avenida Chelsea, Vista, CA 92081; www.westbridge.com.

Weed Pharm® (20% acetic acid)—Pharm Solutions, 2023 East Sim's Way Pt. Townsend, WA 98368; www.pharmsolutionsinc.com.

Weed Zap® (45% clove oil, 45% cinnamon oil)—JH Biotech, 4951 Olivas Drive, Ventura, CA 93003; www.jhbiotech.com.

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IPM for Weeds

By William Quarles

The best way to manage weeds is with an IPM program. Prevention can be combined with monitoring, proper landscape design, mulching, mechanical and physical methods, flaming, and least-toxic herbicides in an overall approach to control weeds. Though biological control of weeds with insects and pathogens can be useful, this approach is probably beyond the resources of the average homeowner. Also microbial control of weeds so far is a niche market with limited commercial success (Quarles 2010).

Prevention of weeds is important. Make sure that your garden seeds are not contaminated with weed seeds. If you apply manure, make sure it has been disinfested by hot composting. Avoid using soil contaminated with weed seeds. Inspect nursery stock to make sure it is free of weed seeds or the vegetative parts of perennial weeds. If weeds have sprouted in your garden, make sure you remove them before they go to seed (Miller 1975; Elmore 1993b).

For lawns, use grass seed of known composition. Topsoil added to lawns should come from reliable sources, and should be inspected for weed seeds before use. Topsoil is a major source of nimblewill, *Mulenbergia* sp.; bermudagrass, *Cynodon dactylon*; and quackgrass.

Good cultural practices such as proper watering and fertilization can help prevent lawn weeds. Bermudagrass weeds in bluegrass lawns are encouraged by summer fertilization. Bluegrass should be fertilized in the fall or early spring (Deal 1966; Daar 1992a). Weeds such as dandelion are encouraged by potassium and lime. Cutting the grass at the proper height and periodic aeration of the soil will discourage weeds (Quarles 2003a). Allelopathic turfgrass is commercially available that suppresses common lawn weeds (Quarles 2009).

Thresholds and Monitoring

The IPM approach involves monitoring and setting thresholds. The idea of monitoring is to reproducibly scout a defined area for weeds, and record the results. If your lawn or garden is large, you might decide to divide it into transects, which are lines of division which can be imagined or defined by string. With monitoring and a weed map you are able to quantify what otherwise will be a more subjective weed threshold. Monitoring also allows treatments to be more quantitatively evaluated.

To monitor weeds in your lawn or garden, make a map of the unwanted vegetation. Note which weed species are present and decide upon a level of tolerance. Some weeds are actually beneficial for your garden. Sunflower (Asteraceae), parsley (Apiaceae) and mustard (Cruciferae) weed families provide nectar for beneficial insects. Weeds such as English daisy, *Bellis perennis*; cornflower, *Centaurea cyanus*; and yarrow, *Achillea millefolium* have attractive flowers (Bugg 1992).

Photo courtesy of Jennifer Bates

Shredded yardwaste makes an effective and inexpensive mulch.

Weed Signatures

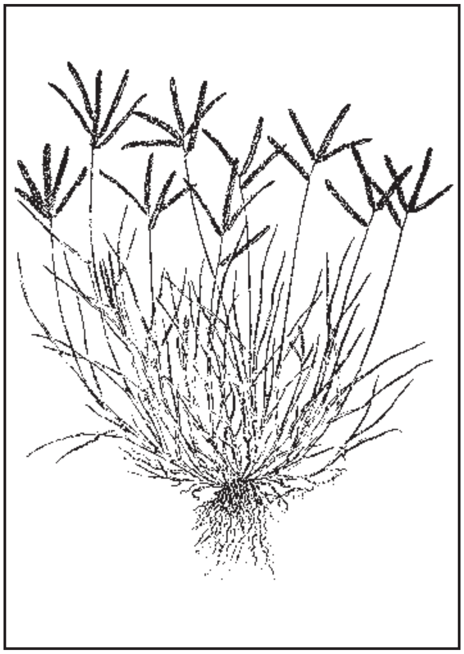
A weed map can also be a map of nutrients and conditions. Weed appearance can define conditions just as though a sign were posted. For instance, spurge, *Euphorbia* spp.; black medic, *Medicago lupulina*; goosegrass, *Eleusine indica* and knotweed, *Polygonum* spp. are indications of sites that are too dry. Moneywort, *Lysimachia* sp; annual bluegrass, *Poa annua*; liverwort, *Hepatica* sp. and alligatorweed, *Alternanthera* sp. are indications of chronically wet conditions. Broadleaf plantain, *Plantago* sp.; annual bluegrass, corn speedwell, *Veronica arvensis*; and goosegrass show up when soil is too compacted. Red sorrel, *Rumex acetosella*, often shows up in soils that are too acidic. Sites low in nitrogen support clovers, birdsfoot trefoil, *Lotus corniculatus*; and black medic. If you know weed signatures, you can change the conditions that led to their establishment (Neal 1993; see Quarles 2001).

Landscape Design

Weeds can be designed out of ornamental beds by proper choice of plants. Groundcovers, trees, and shrubs can be used to shade the ground so weeds will not grow. Newly planted shrub beds can be seeded with fast-growing annuals such as sweet alyssum, *Lobularia maritima*; farewell-to-spring, *Clarkia amoena*; and scarlet flax, *Linum grandiflorum* var. *rubrum* to smother and crowd out weeds. Fast-growing groundcovers can be used along pathways and in areas hard to access and cultivate (Daar 1995).

In landscapes, intelligent use of irrigation water can minimize weeds. Drip irrigation allows water to be delivered only to ornamentals, not to weeds. Pruning and shaping plants to increase their vigor will help reduce weed germination and growth (Elmore 1993b).

Flowers can be chosen that suppress weeds. For instance, sunflowers are allelopathic (see below), and root exudates tend to suppress competing weeds (Rice 1987; Saggese et al. 1985). Shrubs such as manzanita, *Arctostaphylos glauca*; *Salvia leucophylla*; *S. apiana*; *S. millifera*, and *Artemisia californica* will suppress annual weeds (Friedman 1987; Muller 1971; Hanawalt 1971). Weeds can also be suppressed in new plantings by landscape fabrics or other mulches (see Mulches below).



Goosegrass, *Eleusine indica*, is a sign of dry, compacted soil.

Low growing groundcovers can crowd out weeds in planting beds.

Raised beds can make weeding easier.

Native Plants

A good weed control strategy is to remove weeds by cultivation and replant with hardy native species adapted to the site. California alone has 5,000 species of native plants belonging to more than 1100 genera, and other states also have a rich botanical bounty. Native plants are generally very hardy, and hardy plants compete well against aggressive exotic weeds. Native plants can be used to crowd out problematic weeds along roadsides. In California, some lawns have been entirely replaced by plantings of California poppy, *Eschscholzia californica*, and other native plants (Quarles 2003b; Quarles 2009).

For groundcovers and borders to crowd out invasive weeds, California has 31 native *Clarkia* spp. These free-flowering annuals bloom from late spring and into summer. They can be grown from seed and will thrive in sunny areas. Especially striking is red ribbons Clarkia, *C. concinna*. Other good native annual ground covers are blue lips, *Collinsia grandiflora*; California gilia, *G. achilleaefolia*; tidy tips, *Layia* spp.; and baby blue eyes, *Nemophila menziesii* (Schmidt 1980). Some of these plants also encourage beneficial insects (Quarles and Grossman 2002).

Drought-resistant plants such as native fremontia, *Fremontia californicum*; California lilacs, *Ceanothus* spp.; sages, *Salvia* spp., buckwheats, *Eriogonum* spp.; and manzanitas, *Arctostaphylos* spp. can be planted to crowd out invasive weeds. Difficult areas such as slopes can be covered with coyote bush, *Baccharis pilularis*, a plant that grows quickly with or without water and is considered to be indestructible. This genus secretes substances that suppresses weeds growing around it (Schmidt 1980; Jarvis et al. 1985). Native grasses and forbs have been established on many California roadways, reducing herbicide applications (Brown et al. 1994; Daar 1994).

California perennials that can be used to combat weeds include one of the earliest spring flowers, grand hound's tongue, *Cynoglossum grande*. One of the 76 species of wild California buckwheat, *Eriogonum* spp. can be combined with other hardy perennials such as yellow yarrow, *Eriophyllum confertiflorum*; coyote mint, *Monardella villosa*; and fragrant sage, *Salvia clevelandii* (Schmidt 1980).

Photo courtesy of Br. Alfred Brousseau

Native plants such as California poppy can crowd out weeds.

Organic Mulches

Mulches are a good way to control weeds in ornamentals, lawn borders, around trees and in a vegetable garden. A mulch can be any protective substance that covers the soil. Organic mulches include straw, sawdust, rice hulls, and shredded bark. Mulches should be applied deep enough to prevent weeds, but not so deep as to prevent moisture from reaching the soil. A mulch four inches thick is usually sufficient. Organic mulches are best for prevention of annual or biennial weeds. Perennial weeds such as quackgrass, thistles, or milkweed push up through organic mulches. At the end of the season, mulches can be worked into the soil to provide valuable organic material. Good areas to mulch are in-between rows of row crops, borders, and around trees to give a buffer zone for mowing (Synder 1975).

Prunings from trees, lawn clippings, leaves and other greenwaste materials from your yard can be effective mulches (Elmore 1996). Relatively inexpensive electric shredders are available from garden supply stores to make a good mulch from yard prunings. Old newspapers can be used for mulch. Several layers must be used, and an organic mulch and stones can be added to the top to prevent papers from blowing in the wind (Quarles 2008).

Sheet Mulches

Sheet mulches are often used to convert lawns or other areas to planting beds. Sheet mulches are built in layers like lasagna. Layers of paper or cardboard rich in carbon are alternated with layers of material high in nitrogen such as grass clippings or manure. Existing vegetation is knocked flat or mowed, then compost is added at about 50 lbs/100 ft^2 (2.5 kg/m^2). The site is soaked with water, and large plants are added. Then a layer of cardboard or newspapers is added to suppress weeds. Two layers of cardboard are enough for weed control. The cardboard is kept wet, and two inches of compost is added. On top of that, a 2-5 inch surface mulch of shredded yard waste, leaves, straw, wood chips or other organic material should be used (Quarles 2008).

Synthetic Mulches

Plastic mulches consist of polyethylene sheets, or polypropylene and polyester fabrics. Fabrics may be spunbound, woven, or non-woven materials. For weed control, black polyethylene or other opaque material is used. Clear polyethylene is used for solarization (see below), but cannot be used as a mulch for weed control, as weeds will germinate and grow underneath this material. Black plastic also helps warm the soil, speeding germination and early root development. Black polyethylene mulch works best on row crops or in new ornamental plantings, as it is difficult to cut and fit around existing shrubbery or plants in a flower border, unless it is used in new planting beds (Synder 1975; Elmore 1993b).

Photo courtesy of Jennifer Bates

Landscape fabric or cardboard can be used to mulch medians.

Comparative studies have found that black polyethylene suppresses weeds better than polypropylene in some cases (Elmore and Tafoya 1993). But the various plastic landscape fabrics are better than black polyethylene in areas where irrigation is practiced, as they allow the water to drain through. Landscape fabrics often have longer lifetimes than polyethylene and are also sold in sheets of convenient sizes that may be easier to use in ornamental plantings (Hembree 1995). Spunbound nonwoven landscape fabrics suppress perennials such as johnsongrass, *Sorghum halepense*, better than meshed, non-woven fabrics. In some California tests, woven polypropylene fabric suppressed purple nutsedge, *Cyperus* sp. better than 10 cm (4 in) of organic mulch (Elmore and Tafoya 1993).

Usually, an organic mulch of some type is used on top of the landscape fabric to prevent sun damage to the material and to help with weed control. Annual weeds are controlled well by synthetic mulches, but perennials may not be completely suppressed (Elmore 1991).

Woven polypropylene lasted longer than Typar® landscape fabric in California's hot San Joaquin Valley (Hembree 1995). Both these mulches effectively suppressed broadleaf weeds, grasses, and nutsedge (Walker and Prather 1996). In general, black polyethylene and any of the landscape fabrics will suppress weeds. Choice should be guided by expense and effective lifetime of the material.

Photo courtesy of Jennifer Bates

This mulched median shows no sign of weeds.

Which Mulch?

Drawbacks to synthetic mulches are that they become ineffective as they degrade. Then they are hard to remove without destroying a planting bed. Natural gardeners may also find addition of plastic to landscapes unappealing. Organic mulches are always welcomed, and the best mulch is waste material that would otherwise be discarded (Quarles 2008). Although any organic mulch will suppress weeds, there is some evidence that bark may be more effective than straw, because the bark contains alleopathic substances (see Allelopathy below). Many gardeners also prefer bark or pine needles because they feel it is more aesthetically pleasing than straw or other mulches. Most mulches make the soil alkaline, but pine needles make it acidic, which is perfect for acid-loving plants (Quarles 2008).

Deeper mulches are more suppressive than shallow ones. A 2-inch (5.1 cm) mulch is usually ineffective, 4 or 6 inch (10.1- 15.2 cm) mulches are needed. Both synthetic or organic mulches will help control water loss and reduce irrigation needs. Synthetic combined with organic conserves moisture better than either alone. Straw stops evaporation better than grass clippings or wood shavings. Finely pulverized mulches exclude light better than coarse ones, but weed seeds tend to germinate in these mulches (Elmore and Tafoya 1993).

Allelopathic Mulches

Allelopathic mulches can also be used for weed suppression in the vegetable garden. As plants grow, they release biochemicals that either suppress or encourage the plants growing around them (Muller 1971; Rice 1987; Putnam and Weston 1986; Einhellig 1995). This phenomenon has been observed and written about since Theophrastus in 300 BC, but it was given the name "allelopathy" by Molisch in 1937 (Rizvi et al. 1992). For the purpose of this article, only weed suppressive allelopathic effects are considered. Weed allelopathy is one reason that crop rotation is such a successful pest control strategy. Weeds adapted to one crop may not thrive with another crop. In gardens, the same crop should not be grown in the same area each year, as weeds adapted to the crop will proliferate (Dunham 1973; Kempen 1992).

Allelopathy can be manipulated to reduce weeds in crops in several ways. One way is to plant allelopathic cover crops that suppress weeds. The cover crop is then either used as a living mulch, or the cover crop is killed and left as a weed suppressive residue while an economic crop such as corn, soybeans, fruit crops and vegetables are planted (Weston 1996).

Good allelopathic crops are rye, *Secale cereale*; wheat, *Triticum aestivum*; buckwheat, *Fagopyrum esculentum*; black mustard, *Brassica nigra*; and sorghum-sudangrass hybrids. For instance, yields of broccoli in California were increased up to 50% just by intercropping allelopathic wild mustard, *Brassica campestris* (Weston 1996; Jiménez-Osornio and Gliessman 1987).

Tomatoes transplanted into a rye mulch, then hand weeded gave yields greater than with herbicide production. Corn has been raised in rye mulch with good yields. Less success has been seen with squash (Weston 1996; Shilling et al. 1985; Dilday et al. 1997). In cold climates, sorghum-sudangrass can be planted in late summer. Crops can then be planted in the freeze-killed allelopathic mulch (Weston 1996).

Weed Suppressive Crops

Another way to exploit allelopathy is to chose weed-suppressive crop varieties. Reports of allelopathic cucumbers, rice, oats, soybeans, Jerusalem artichokes, and sunflowers have been published (Weston 1996; Aldrich 1987; Saggese et al. 1985; Dilday et al. 1997; Walker and Buchanan 1982; Putnam and Tang 1986a). Celery and celery residues will suppress weeds and other crops, such as radishes and lettuce, but not celery or carrots (Bewick et al. 1994). In warm climates, squash interplanted with corn helps suppress weeds (Anaya et al. 1992).

The best way to get rid of a persistent perennial weed such as yellow nutsedge, *Cyperus esculentus*, in a garden is to grow sweet potatoes. Sweet potatoes are allelopathic to this weed and plantings can reduce nutsedge by 90% (Harrison and Peterson 1991). Pigeon pea, *Cajun cajunus*, also suppresses nutsedge (Hepperly et al. 1992).

Soil Incorporation

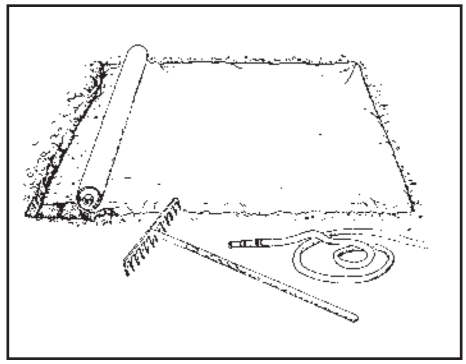
Another way allelopathy can be used is deliberate incorporation of allelopathic weed residues into the soil. About 90 weed species show some degree of allelopathy (Putnam and Weston 1986). Shoots of fresh marigolds, *Tagetes patula*, when worked into the soil, cause preemergent suppression of a number of broadleafed weeds, but do not inhibit growth of corn and beans (Altieri and Doll 1978). Cutleaf evening primrose, *Oenothera laciniata*; and bulbous buttercup, *Ranunculus bulbosus*; are selectively allelopathic. Incorporation of residues reduce sicklepod and cocklebur growth, but increase soybean yields (Dilday et al. 1997). Citral, citronellol and geraniol, which are components of lemongrass, *Cymbopogon citratus*, inhibit germination of spiny pigweed, *Amaranthus spinosus*; but do not interfere with the growth of tomato (Rizvi and Rizvi 1992b).

Shaded Tillage

One reason that mulches suppress weeds is that many weed seeds need light in order to germinate. Tillage at night can reduce weed germination by 80% (Hartmann and Nezadal 1990; Melander 1998). Shaded tillage can also help prevent the germination of weeds. Just shading the rototiller or plow with a tarp or cloth can reduce the number of broadleaf weeds by 40% (Ezzell 1992). Shaded tillage is more effective at suppressing small-seeded weeds such as lambsquarters and annual bluegrass than weeds with larger seeds (Ascard 1994).

Solarization

At least 30 common broadleaved weeds and grasses can be controlled by solarization (Bell 1991). Some of these are perennial weeds that are very difficult to manage. The best time to get rid of them is before a desirable crop is planted. Plots can be rototilled to 4 inches (10.2 cm), leveled, then irrigated. After irrigation and before plots dry out cover with clear plastic, at least 1.5 mil (0.0015 in) thick. Edges of the plastic sheets are buried in soil trenches to keep them in place. In California experiments, plots were solarized in June, July or August. Six weeks of solarization was just as good as 9, 12 or 14 weeks. Success was seen with bermudagrass and johnsongrass (Elmore 1993a).



Solarization requires sheets of clear plastic.

Solarization for weed control is best where there is abundant sunshine. Difficult weeds such as purple nutsedge, *Cyperus rotundus*, and yellow nutsedge, *C. esculentus* have been controlled in Florida with solarization (see Quarles 1997). The disadvantage of solarization is the land must remain without a crop for at least 4-6 weeks during the summer.

Physical and Mechanical Methods

Pulling weeds by hand is the oldest method of weed control. Hand pulling is very effective for annual weeds before they have set seed. On some young perennials, hand pulling can also be effective. Plants are best removed when the ground is moist, and with perennials, vegetative parts must be removed from the garden to prevent resprouting.

Simple hand tools also have a long history. Hand tools and farm machinery are used to uproot plants, bury them, or destroy topgrowth. In agriculture, tillage implements such as the spike-toothed harrow, the disk harrow, the rod-weeder, the rotary hoe and

Photo courtesy of Steve Ash

Weeding tools can help manage weeds.

shovel cultivators are commonly used. Flame cultivators cultivate between rows and kill weeds in crop rows by heat (Dunham 1973; Balsari et al. 1994; Parish 1990).

For backyard gardening, a standard hoe, a hula hoe, a trowel, a dandelion knife, and an electric flail mower can handle many weed problems. For deep-rooted weeds or brush removal, an axe-like pulaski might be useful. In a larger vegetable garden, a powered rototiller might be necessary to provide cultivation.

A hoe can be used to scrape broadleaf annual weeds off at the soil surface. The weeds are destroyed as they dry in the sun. Annual weedy grasses should be chopped out just below the soil surface. For larger areas, a rototiller can be used. Cultivating when moist, then allowing to the soil to dry will increase the control. Larger weeds may be mowed or flailed with a weed-whip such as the Weedeater (Elmore 1993b).

For weeds such as Canada thistle in a garden, repeated hoeing may be enough for control. It may be necessary to put in erect growing plants such as okra, eggplant, corn, zinnias, and cosmos that will tolerate regular cultivations (Sylwester 1966).

Drawing by Diane Kuhn

A hoe is an essential gardening tool.

In ornamental gardens and lawns, one troublesome weed early in the year is bermuda buttercup, *Oxalis pes-caprae*. These plants can be controlled by either pulling them up or cutting them down. They can be best pulled up when the parent bulb on this perennial is exhausted, usually in December. Oxalis is best cut down when the plant has 15-30 leaves. Use a Weed Whacker™ or other brand of flail mower. To avoid spreading the weed, do not move soil infested soil from one part of the garden to another (Drlik 1996).

For removing brushy weeds around the home, there is no need to use herbicides. With tools like the Weed Wrench™ (see Resources), tough weeds such as Scotch broom, *Cytisus scoparius*, can be removed within three minutes without greatly disturbing the soil and encouraging other weeds to germinate (Daar 1992b). For removing dandelions, the Weed Hound™ is very convenient (see Resources).

Flame Weeding

For weeds in sidewalks, gardens or lawns, flaming is inexpensive and is not labor intensive. Flame weeders can now be purchased at hardware stores or ordered from national suppliers (see Resources). The object of flaming is to burst plant cells, causing loss of fluids and thermal denaturation of proteins and DNA. Disrupting the photosynthetic apparatus in this way causes the weed to wilt and die. Overheating and charring the plant may cause a stimulation of growth from the remaining roots, requiring another flaming of the sprout. For optimum heating, hold the wand about an inch or more above the plants and move it slowly back and forth. To treat large areas, waving the wand back and forth over an area in a scythe-like motion may be the most effective way. After flaming, the weed may not wilt and die for several hours. Dead weeds can either be removed and composted, or incinerated to ashes on the spot, leaving a mineral source for further plantings (Daar 1992; Swiadon 1998).

Best on Broadleaf Weeds

Flaming works best on broadleaf annual weeds, but can also kill grasses and perennial weeds in some circumstances. One experiment showed that two flamings, about 7 days apart, reduced biomass of perennial ryegrass, *Lolium perenne*, or annual bluegrass, *Poa annua* by about 80%. Plants were not killed, but flowering was interrupted (Rask et al. 2012). Weeds are most susceptible when they are at an early growth stage. This means that most weeds should be flamed when they are 1-2 inches (2.5-5.0 cm) high. Some weeds, such as lambsquarters, *Chenopodium album*, or common groundsel, *Senecio vulgaris*, are especially susceptible and can be killed at later stages. Mature grasses are especially resistant, as they form a protective sheath that shields the growing tip from the flame. Resistance of grasses means that flamers can be used to remove broadleaf weeds without damaging a lawn.

Resistant weeds and grasses can still be killed by flaming, but several treatments may be necessary. The first flaming causes the weed to dieback, but the root is not killed, and resprouting occurs. The weed should then be flamed again before photosynthesis resupplies the plant with nutrients. Even resistant mature

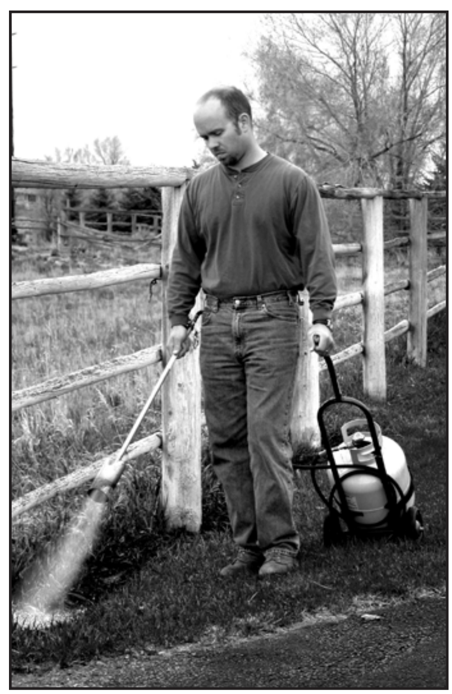


Photo courtesy of Flame Engineering

A handheld flamer is a useful weeding tool.

Resources

Flamers—Arbico, Tucson, AZ; www.arbico.com. Harmony Farm Supply, Sebastopol, CA; www.harmonyfarm-supply.com. Peaceful Valley Farm Supply, Grass Valley, CA; www.groworganic.com.
Hand Tools—A.M. Leonard, Piqua, OH; www.amleo.com. Local Hardware Store
Organic Mulches (Planter's Paper, Ewe Mulch, Rice Hulls)—Harmony, Peaceful Valley, Arbico see above
Weed Hound® (dandelions)—Hound Dog Products (Ames True Temper)—Camp Hill, PA; www.hound-dog.com.
Weed Wrench™, Uprooter™, Pullerbear™—www.weed-wrench.com; www.uprooter.com; www.pullerbear.com.
Synthetic Mulches (Weed Block®, Typar®, Tree Circles®)—Arbico, Harmony, Peaceful Valley see above

annuals such as johnsongrass and Canada thistle, *Cirsium arvense* can be killed with repeated flaming (Daar 1992; Swiadon 1998).

Conclusions

Prevention can be combined with monitoring, proper landscape design, mulching, mechanical and physical methods, flaming, and least-toxic herbicides in an overall approach to control weeds. Control choices are dictated by the soil conditions and ecological interactions at each particular site. Choices are often a tradeoff between cost and effectiveness. Toleration of some weeds will help maintain the critical balance between aesthetics and labor intensive management methods.

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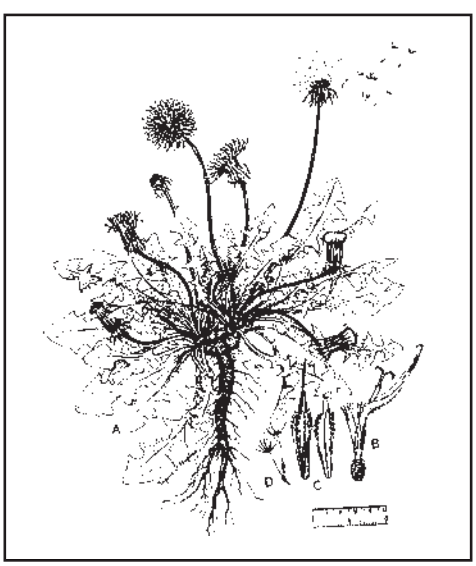

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